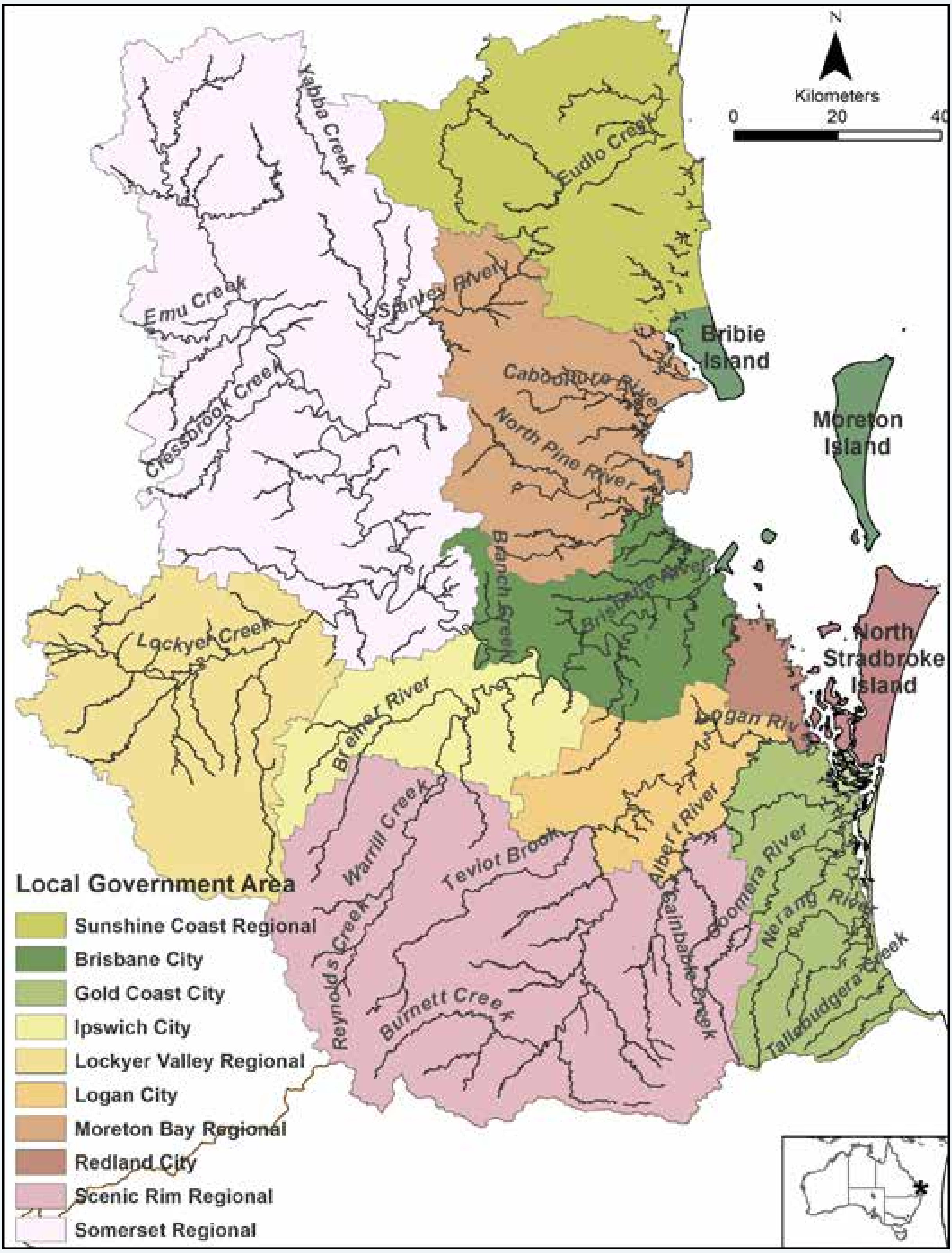
Moreton Bay *Quandamooka* & Catchment

Past, present, and future

IR Tibbetts, PC Rothlisberg, DT Neil, TA Homburg,

DT Brewer & AH Arthington (Eds)

2019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Local Government Area
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Gold Coast City
Ipswich City
Lockyer Valley Regional
Logan City
Moreton Bay Regional
Redland City
Scenic Rim Regional
Somerset Regional

Moreton Bay *Quandamooka* and Catchment

Editors

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This book is dedicated to the future stewards of Moreton Bay *Quandamooka* and the lands and waterways of its catchment

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Preface

Moreton Bay *Quandamooka* and its catchment cover a large area of approximately 23,000 km^2 and nurture the lives and livelihoods of millions of people. Burgeoning populations, urbanisation and industrialisation have put various components of this system under substantial pressure. There is some urgency to take a closer look at its current health so, from the 1st to 3rd November 2016 we did just that in the form of the Moreton Bay *Quandamooka* and Catchment Forum.

The Forum revisited many of the issues addressed at the Moreton Bay & Catchment Conference of 1996 (see the proceedings volume Moreton-Bay-and-Catchment 1998 at https://ian.umces.edu/blog/2014/01/30/moreton-bay-and-catchment/) and brought together people with expertise and a passion for the Bay and the health of the lands and waters in its catchment. From the outset, our position was that this meeting should be a partnership among institutions, entities and individuals. Ideally, it should not only deliver an update of research, but also find a new way forward so that we would not have to wait another 20 years for a broad collaborative opportunity to engage in research, governance and citizen science to foster positive outcomes for the Bay and catchment.

We succeeded with the Forum, in part, due to the kind offers from particularly dedicated individuals to act as leaders of the discipline areas (called Clusters by the organisers) which, with some modifications, later became the basis of the chapters of this volume. They recruited experts and managed the process of putting together a series of presentations designed to cover the latest information available on their topic.

Some 170 attendees from a wide diversity of backgrounds and disciplines signed on, and most got to hear all of the presentations. Chaired by the Cluster Leaders, the first two full days were assigned to a rapid-fire series of ten-minute talks that summarised the current state of knowledge on a wide range of topics, and identified key research, management and legislative priorities. The third day was reserved for a series of synthesis meetings led by Cluster Leaders that drew on the evidence heard during the first two days. Significant moments included an impassioned talk on Respect and Recognition (Mind the Gap) by Darren Burns of the Quandamooka Yoolooburrabee Aboriginal Corporation (QYAC); Andrew Davidson's very amusing and insightful talk on catchment planning, with his Duggie (dugong) awards, represented as star ratings in his formal paper with Darryl Low Choy in this volume; and Justine Kemp's sobering analysis of regional pre- vs post-"European" sediment erosion histories. We also learned about a planned development at Toondah Harbour that would violate Moreton Bay's Ramsar status as a Wetland of International Significance – a designation that is meant to protect habitat for migratory waders (shorebirds) and other wetland values. No doubt others will have their own significant moments, but perhaps *the* most significant few minutes of the entire forum occurred when John Goodman of the Goodman Foundation pledged $500,000 to establish The Moreton Bay Foundation. A remarkable family who are now likely to have made a singularly important contribution to the well-being of the Bay and its catchment.

The Forum was followed by two years of work led by Ian Tibbetts, Tamara Homburg and the Cluster Leaders, seeking papers from contributors, organising independent peer reviewers, all guided by a dedicated group of volunteer editors. We met in coffee shops, restaurants and offices to thrash out the structure and means of publishing this volume. It has been a process filled with interesting challenges, including how to fund the book's publication. That issue was resolved with the realisation of The Moreton Bay Foundation (TMBF) and the decision to publish electronically. We expect this first TMBF publication will be quickly followed by others, adding to a compendium of knowledge about the Bay and its attendant systems.

The Moreton Bay *Quandamooka* and Catchment Forum of 2016 was an important event; both for what it achieved at the time, and what it has sparked since; particularly the establishment of the multi-institutional and independent Moreton Bay Foundation Limited. We are convinced, as are the founding members of TMBF (The Goodman Family Foundation, QYAC, The University of Queensland, Griffith University, and Queensland University of Technology), that we now have a mechanism that will ensure: future partnerships in research and restoration; independent advice to government - a voice for the Bay; and a focus around which to regularly meet to review where we are and what we must do to secure a brighter future for Moreton Bay and its catchment. We have found our new way forward.

The editors,

Ian R Tibbetts[1-3], Peter C Rothlisberg[4], David T Neil[2], Tamara A Homburg[2], David T Brewer[4], Angela H Arthington[5]

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The Editors wish to warmly thank the following Cluster Leaders for their excellent and sustained commitment to the project: Ms Diane Aylward (Education), Dr Sam Capon (History and Change in Moreton Bay), Prof. Rod Connolly (Industry), Dr Justine Kemp (History and Change in Moreton Bay), Ms Jennifer Loder (Citizen Science), Prof. Catherine Lovelock (Habitats, Biodiversity and Ecosystem Function), Prof. Darryl Low Choy (Indigenous Knowledge & Culture), Prof. Stuart Phinn (Water Quality, Land-Use and Land-Cover), Dr David Rissik (Moreton Bay Marine Park), Dr Chris Roelfsema (Citizen Science), and Prof. Helen Ross (Communities and Values).

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List of hitherto anonymous manuscript reviewers for whose efforts the editors are most grateful.

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Abbreviations: ARI, Australian Rivers Institute, Griffith University; CSIRO, Commonwealth Science and Industrial Research Organisation; HLW, Healthy Land and Water; JCU, James Cook University; NSW, New South Wales; NOAA, National Oceanic and Atmospheric Administration; QUT, Queensland University of Technology; UQ, University of Queensland; UNSW, University of New South Wales; USC, University of the Sunshine Coast; USQ, University of Southern Queensland; UTas, University of Tasmania.

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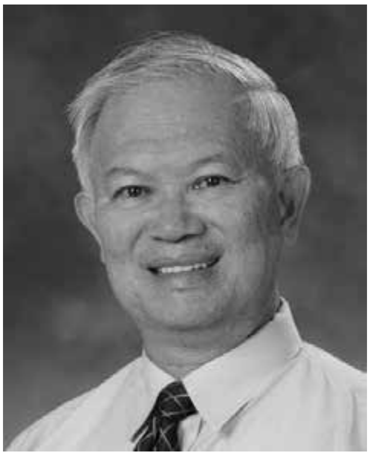
Appendices

Maps of Moreton Bay and catchment

Chapter 1 - Indigenous Knowledge and Culture

Cluster Leader: Emeritus Professor Darryl Low Choy, AM, MBE, RFD, Griffith University, Nathan Qld 4111.



Dr Darryl Low Choy is Professor (Emeritus) of Environmental and Landscape Planning at Griffith University. He leads research into climate change adaptation for human settlements, community-led planning, resilient communities' response and recovery from natural hazards, and indigenous landscape values in regional planning. He investigates catchment-scale landscape planning for water sensitive cities in an age of climate change including South East Queensland centred on Moreton Bay and its associated catchments. He undertakes research in partnership with peri-urban Indigenous communities in Queensland, Victoria and South Australia focussed on understanding contemporary Australian Aboriginal connections to 'Country' with implications for planning and landscape management. It includes understanding Indigenous landscape values, Indigenous communities' adaptation to climate change, and proposals to imbed Indigenous protocols and knowledge into tertiary built environment programs (architecture, landscape architecture and planning). He is a Fellow of the Environmental Institute of Australia and New Zealand, a Registered Planner and Fellow of the Planning Institute of Australia. He has completed a number of major secondments to State Government planning initiatives, including the 2005 and the 2009 SEQ Regional Plans. He serves on a number of government boards and committees that deal with environmental planning and NRM matters. He is the Chair of the Quandamooka Yoolooburrabee Aboriginal Corporation's (QYAC) Land & Sea Management Committee.

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Quandamooka Country: The role of science and knowledge in Traditional Owner-led land and sea management

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Acknowledgements

We pay our respect to these lands and seas that comprise Quandamooka Country that has provided for the Quandamooka Peoples for over 25,000 years.

We acknowledge and pay respect to the ancestors that walked and managed these lands for many generations.

We acknowledge the Quandamooka Elders who are the knowledge holders, teachers and pioneers.

We acknowledge the Quandamooka youth who are our hope for a brighter future and who will be our future leaders.

Abstract

The Quandamooka People, the Traditional Custodians of Moreton Bay, have nurtured this region and its land and sea resources for the past 25,000 plus years. Dispossessed of their Country through the colonial process, the Quandamooka People lost the ability to care for their Country. Fast forward to the Twenty-first Century, and we find the Quandamooka People, as an outcome of a Federal Court of Australia determination in 2011, are now recognised as the Traditional Owners of this land and sea country. Consequently, through their Prescribed Body Corporate (the Quandamooka Yoolooburrabee Aboriginal Corporation [QYAC]), they are not only back on their Country but are actively involved in caring for this land and sea country. This paper outlines QYAC's visionary and professional management approach to land and sea management. It discusses how QYAC is managing and safeguarding the *Quandamooka People's sanctuary* through a philosophy of shared use that safeguards Quandamooka's values, interests and vision. The paper introduces QYAC's Land and Sea management philosophy, which is based on contemporary modern day management practices involving an evidence-based approach. However, what is uniquely different in the QYAC case is its move towards fostering a resurgence of Quandamooka culture and environmental protection for their land and sea country. This has resulted in some ground-breaking initiatives that have seen the

blending of Traditional Knowledge and Traditional Science with Western Science to inform policy development and management decisions. Five selected case studies have been included to showcase a number of innovative management practices that demonstrate QYAC's leadership role in its many collaborative research and management activities. The paper also describes the important role of QYAC rangers in their caring-for-Country responsibilities. The paper demonstrates that QYAC has the experience and capacity to actively lead the management of this country in a Twenty-first century manner especially as this unique area moves towards World Heritage status.

Key words: QYAC, Indigenous values, Moreton Bay, Science, Aboriginal

Introduction

Moreton Bay lies at the heart of Quandamooka Country, the traditional lands of the Quandamooka Peoples, a First Nation of over 2000 traditional owners from South East Queensland, Australia. It encompasses Mulgumpin (Moreton Island), Minjerribah (Stradbroke Island), and the southern Bay islands (including St Helena, Peel, Cassim, Russell, Karragarra, Macleay and Coochiemudlo). Quandamooka Country extends into four local government areas (Brisbane City, Redland City, Logan City and Gold Coast City) and embraces the mainland from the mouth of the Brisbane River, south through the suburbs of Wynnum, Chandler, Lytton, Belmont, Tingalpa, then onto Cleveland taking in the Redland City coast, and further south to the Logan River (Fig. 1).

The Quandamooka Peoples, comprising the clan groups of the Nunukul and Goenpul from Minjerribah and Ngughi of Mulgumpin have inhabited this area now for over 25,000 years. The clan groups and their families have carried out their lifestyle and cultural practices in the Bay and on the islands for the full extent of their occupation. The Quandamooka have never ceded sovereignty of their Country and this issue remains live for the Quandamooka Peoples. The Quandamooka clans had their own laws, customs, beliefs and culture, which are still upheld and observed by the Quandamooka People who live, work and practice culture on their traditional lands and seas (1). More recently, the Bay islands were first settled by colonisers around 1825 (2).

Native Title Determination

Colonisation displaced many Traditional Owner groups from their Country and resulted in their inability to be on, and to care for, their Country in traditional ways. This has created a great sense of loss and despair for many Aboriginal people (2–5). However, the Quandamooka People have been able to maintain a continued practice of culture on their Country which was recognised on the 4th of July 2011 by Justice Dowsett, of the Federal Court of Australia, when he handed down a determination which recognised the Quandamooka People as being the Traditional Custodians and original inhabitants of Minjerribah and parts of Moreton Bay (1). This Federal Court of Australia determination recognized the Quandamooka People as having Native Title rights and interests over 54,408 ha of land and sea in the Moreton Bay area (Fig. 2) and included:

- exclusive native title rights (to possess, occupy, use and enjoy the area to the exclusion of all others) over about 2,264 ha of land;

- non-exclusive Native Title onshore rights over about 22,639 ha; and
- non-exclusive Native Title offshore rights over about 29,505 ha of offshore areas/

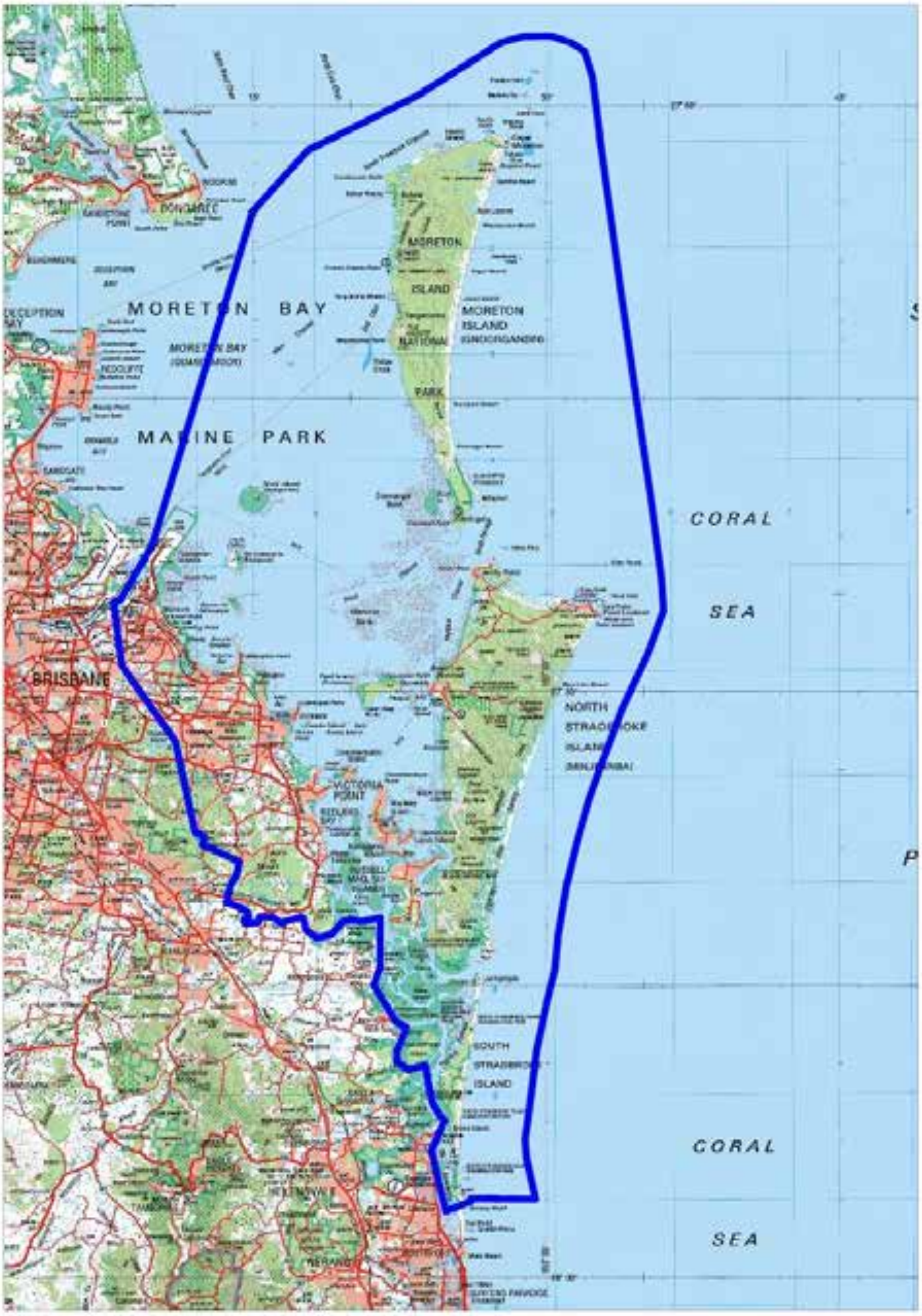

Figure 1. Quandamooka Country. (Source: Quandamooka Yoolooburrabee Aboriginal Corporation 2015 issues briefing for the Queensland Government and Parliament).

The Native Title rights with respect to Non-exclusive possession lands include:

- the right to live and be present on the area;
- the right to conduct ceremonies;

- the right to maintain places of importance and areas of significance to the native title holders;
- the right to teach on the area about the physical and spiritual attributes of the area;
- the right to light fires for the domestic purposes such as cooking; and,
- the right to take, use, share and exchange traditional natural resources and seawater for any non-commercial purpose.

On Non-exclusive waters, Quandamooka people have the right to be present on the area, including access and travelling across the area and they have the right to take Traditional Natural Resources for non-commercial, personal or communal purposes. These rights are recognised subject to State and Commonwealth laws and are subject to the law and customs of the Quandamooka People.

In addition to this formal recognition, the Quandamooka Peoples entered into Indigenous Land Use Agreements (ILUAs) with the Queensland Government and Redland City Council, which provided further rights and negotiated benefits. Currently there are two further claims in progress which seek to complete the acquisition of other areas of Quandamooka Country. They include: Quandamooka People #4 (Mulgumpin claim); and Quandamooka People #5 (Quandamooka Coast).

Quandamooka People have long standing spiritual and cultural obligations and tradition law and customs in respect to lands and waters that have become protected areas and marine parks under the Nature Conservation Act 1992, the Marine Park Act 2004, the Recreation Management Act 2006 and other lands and waters within Quandamooka Country.

Advent of the Quandamooka Yoolooburrabee Aboriginal Corporation

The Quandamooka Yoolooburrabee Aboriginal Corporation (QYAC) is a Prescribed Body Corporate (PBC) (more technically known as a Registered Native Title Body Corporate (RNTBC)) created in 2011 under the Native Title Act 1993 (NTA). The NTA requires Native Title groups to create a PBC to manage their recognised Native Title rights and interests. Specifically, QYAC manages the following on behalf of the Quandamooka People:

- Implementation of the Indigenous Management Agreement (IMA)
- Joint management of the Naree Budjong Djara (Our Mother Earth) National Park
- Operation and maintenance of the Quandamooka Peoples' Gift Fund
- Ownership and management of Minjerribah Camping
- Right to take and use traditional natural resources

QYAC is registered with the Office of the Registrar of Indigenous Corporations (ORIC). The Registrar is an independent statutory office holder who administers the Corporations (Aboriginal and Torres Strait Islander) Act 2006 (CATSI Act). QYAC is required to operate in compliance with the CATSI Act and is regulated by ORIC. QYAC is also the registered Cultural Heritage Body under the Aboriginal Cultural Heritage Act 2003 (Qld). It is responsible for cultural heritage management across the Quandamooka estate.

In addition, QYAC has a number of statutory obligations and key links with the following legislation:

- North Stradbroke Island Protection and Sustainability Act 2011 (Qld) (NSIPSA)

- Nature Conservation Act 1992 (Qld)
- Recreation Area Management Act 2006 (Qld)
- Planning Act 2016 (Qld)
- Native Title Act 1993 (NTA)

Figure 2. Quandamooka People Native Title Determination Areas (Source: http://www.qyac.net.au/NativeTitle.html)

QYAC also has a key role to play in the following local plans and strategies:

- North Stradbroke Island Economic Transition Strategy (NSI ETS)
- Quandamooka Action Plan
- North Stradbroke Island Indigenous Business Development Plan
- Quandamooka Aboriginal Community Plan

- Shaping SEQ: SEQ Regional Plan
- Redland City Council City Plan
- Gudjundabu Marumba Gubiyiyanya – Tourism for a Glad Tomorrow – A Five Year Strategy for Sustainable Tourism on Quandamooka Country
- Minjerribah Township Fire Management Strategies
- Dunwich (Goompi) Master Plan (in progress)

The NSIPSA, supported by the above-mentioned plans is the principal instrument to assist Minjerribah to move beyond a sand-mining economy to a more diversified and sustainable economy. Its resultant NSI ETS, complemented by these plans, is key to help focus the efforts of the Quandamooka People to make this transition in a culturally, environmentally and economically sustainable way (6).

QYAC's organisational structure is shown in Figure 3. The Quandamooka Aboriginal Land and Sea Management Agency (QALSMA) looks after all land and sea matters including joint management with the Queensland Parks and Wildlife Services (QPWS) of the Naree Budjong Djara (My Mother Earth) National Park. QALSMA also includes the Native Title and Cultural Heritage Unit and land and sea rangers (see more detailed outline of rangers below). A Land and Sea Management Advisory Committee overarches the operations of QALSMA, as well as providing strategic and policy advice to the QYAC Board through the CEO.

QYAC's overarching land and sea management vision

Land and sea management across Quandamooka Country is aligned to the QYAC Vision: *Quandamooka Peoples caring for Country in a viable economy using traditional and modern knowledge* (7). Of relevance to this vision is one of QYAC's eight Values, namely:

> *Walk in both worlds* – "sustainable ecosystems close to Brisbane"

This Vision is further expanded upon in the "*Quandamooka Action Plan 2013: Future Land Use Proposals for Minjerribah"*, which states:

> *We, the legal and traditional owners of Quandamooka country, reaffirm and take responsibility for the planning and future well-being of our ancestor's land, sea and sky and our people. In partnership with the mainstream community, we will create a future where our spirit, cultural values and the beauty of our lands and seas are conserved and restored.*
>
> *We will create a rich and harmonious community life, a vibrant and sustainable economy and a wide range of opportunities for local Quandamooka people. We will respect and strengthen our relationships to each other, to the wider community and to our country. We will teach our young people and the wider community about Quandamooka culture.*
>
> *We commit to strong community governance that enables our elders, families and young people to work together and manage our shared successes. We exercise self-determination and have meaningful input into decisions that affect our community and our country. Our sovereignty over our lands and waters is recognised and respected nationally and internationally.*
>
> *All community members will enjoy equal opportunities and work together in a unified way to shape a healthy and happy future for the generations that follow. We honour all those who have worked, and continue, to achieve the dreams and objectives of our people and satisfy the aspirations of our ancestors.*

A philosophy of shared use that safeguards Quandamooka's values, interests and vision

Developed by QYAC's Land and Sea Management Advisory Committee, this philosophy is encapsulated as an overarching Statement in a number of key Quandamooka and related initiatives. It states:

> *Quandamooka Country is the Quandamooka People's sanctuary that we have carefully managed for thousands of generations.*
>
> *We acknowledge that our physical, spiritual and emotional well-being and connection to country has been handed to us by our ancestors. Through our continued cultural practices we maintain, protect and nurture our cultural and natural values across all of Quandamooka Country for our children's children.*
>
> *Quandamooka People have always shared our sanctuary with others who respect our values. We must ensure that there is always sufficient space and time for Quandamooka People to access and enjoy country and resources, and to undertake cultural activities.*
>
> *While the Quandamooka People will continue to control how our sanctuary is shared, our sincerest wish is for visitors to feel welcome and be enriched through engagement with Quandamooka People, Country, and Culture.*

Consistent with this philosophy are a set of overriding principles that apply to all current and future activities on Quandamooka Country, namely:

1. Maximise ecological and cultural sustainability before economic benefit;
2. Maximise the material, cultural and environmental benefits for Quandamooka People;
3. Advance aspirations for the World Heritage listing of Quandamooka Country;
4. Ensure QYAC, the Quandamooka Peoples' Registered Native Title Body Corporate; plays the lead role in management and governance;
5. Provide sufficient space and time so that Quandamooka People always have access to enjoy country and cultural resources, and to undertake cultural activities;
6. Promote understanding, recognition and respect for Quandamooka culture and values;
7. Maximise employment, procurement, capacity building and participation for Quandamooka People;
8. Practice ethical behaviour and support reconciliation; and,
9. Eliminate waste and emissions on Quandamooka Country.

Hence the planning for all future activities on Quandamooka Country need to embrace these principles.

Research protocols and priorities

Consistent with the philosophy of shared use that safeguards Quandamooka's Values, Interests and Vision, QYAC has developed the following set of Research Engagement Protocols (8).

- Ethics: observe, understand and respect the ethical protocols of the local Aboriginal Traditional Owner groups;
- Mutual Understanding and Respect: engagement with Indigenous people requires both parties to work together and understand and respect the needs and values held by one another. Understand and operate within the local customs, protocols and law of Indigenous groups and be sensitive to local issues. Acknowledge the self-determination

of Indigenous people and treat them with equality and respect. Similarly, Indigenous people must understand the pressures and requirements of their engaged partner. Good engagement will be flexible to different cultural situations, time, content and custom. Good engagement will demonstrate this through positive cooperation and the creation of better outcomes for the engagement and community.

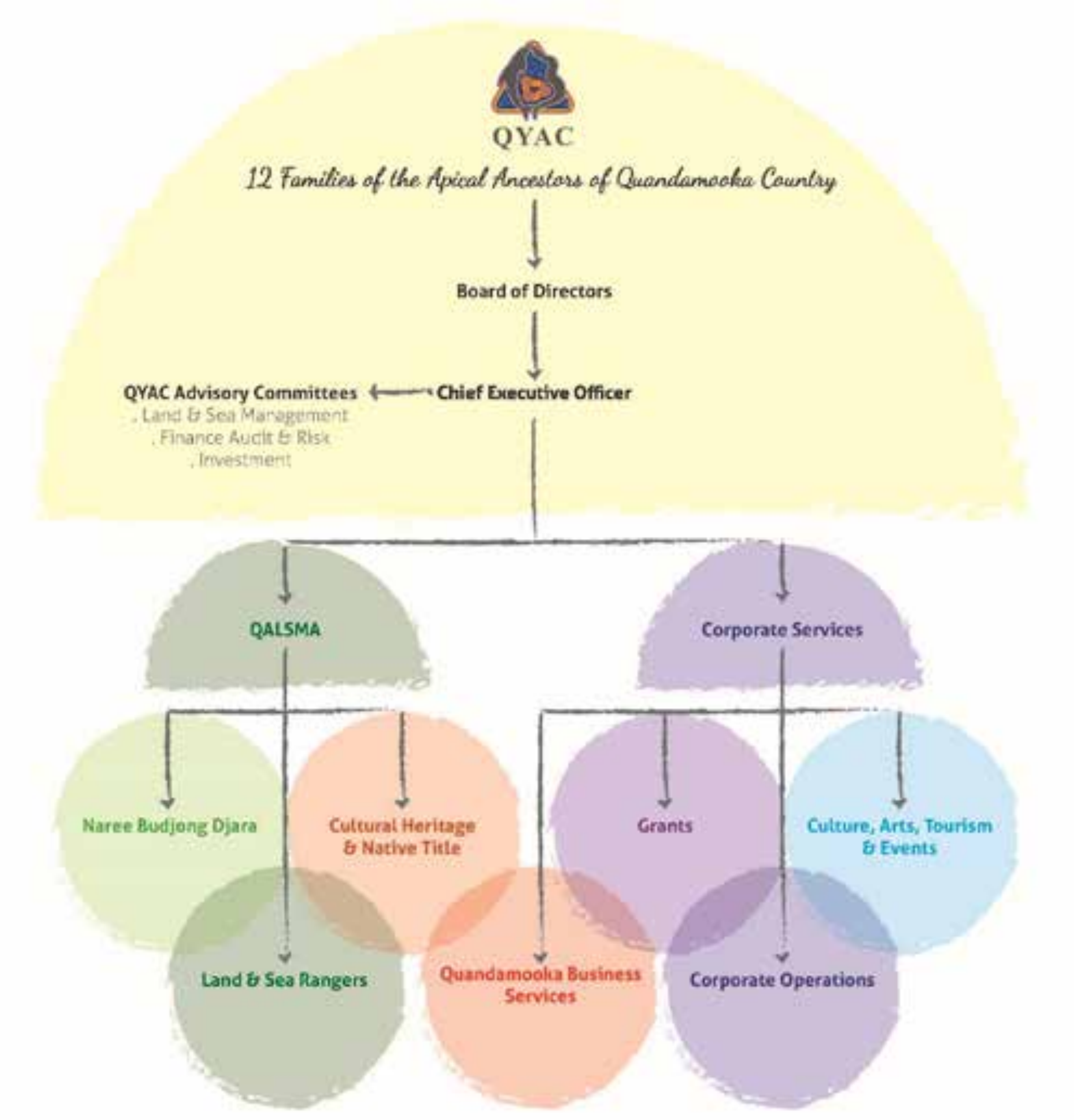

Figure 3: QYAC's outline organisational structure (Source: QYAC Annual Report 2017-18 (6)).

- Free Prior Informed Consent: Indigenous people want and are entitled to full information regarding all aspects of the engagement process and have the right to say 'yes' or 'no' through their traditional decision-making processes. Good engagement will provide this. (Nota Bene: *Free,* refers to consent obtained without coercion or manipulation; *Prior,* refers to meaningful, informed consent sought sufficiently in advance of the proposed activities; *Informed,* means that the process must involve consultation with and participation by people potentially affected with full disclosures of the proposed activity in an accessible and understandable form; and, *Consent,* must be indicated in writing and/or as an audio/visual recording).

- Equitable Benefit-Sharing: engagement must produce direct benefits to Traditional Owners and reinforce Traditional Owners' self-determination through their full and ongoing active participation and negotiation in the decision-making process for project planning and implementation according to local priorities.
- Participation, Collaboration and Partnership: Indigenous people have the right to full participation appropriate to their skills and experiences in relevant projects and processes.
- Reporting and Compliance: projects should include appropriate mechanisms and procedures for reporting on ethical aspects of the project and complying with engagement protocols and guidelines.
- Confidentiality: when requested by Traditional Owner knowledge holders and/or owners, confidentiality of this knowledge and/or of Traditional Owner intellectual property is to be strictly observed. This is an over-riding requirement to all other engagement principles.

QYAC encourages research that builds a more detailed picture of the species that occur in their land and sea country including their distribution and abundance, particularly for species of significance to Quandamooka as well as rare and threatened species. Better knowledge of the islands and surrounding waters will be very helpful for their ongoing management responsibilities.

QYAC is endeavouring to:

1. identify the significant gaps in knowledge about the island's and water's ecosystems and species and to encourage and facilitate research that aims to fill those gaps;
2. identify the threats that various species and habitats face and how they can be managed, including the priorities for that management;
3. better understand the geology and hydrology of the island, in particular, how water travels throughout the sand mass and its relationship with the terrestrial environment;
4. encourage research that better informs the management of fire on the islands, especially the importance of traditional techniques of the use of fire for landscape management; and,
5. establish long term management regimes that safeguard the biodiversity and ecosystems and cultural heritage of their *Country* that will play a crucial role in future cultural ecotourism activities. Research that aims to improve knowledge and inform management to ensure these systems remain healthy into the future is valuable.

QYAC's land and sea management philosophy

Evidence-based approach

QYAC has adopted a science (evidence) based approach to inform its planning and management initiatives in exercising its responsibilities as the agent for the Quandamooka Peoples. This management approach is evidence based and science informed, not science driven.

The goal is to fully utilise evidence based approaches to land and sea management (embracing land use planning and cultural resource management) that is supported by Citizen Science and Indigenous Knowledge and Science, consistent with QYAC's Strategic Vision: *Quandamooka Peoples caring for Country in a viable economy using traditional and modern knowledge*. In their use of conventional western science complimented by traditional knowledge and science, QYAC seeks opportunities to add a Citizen Science dimension to assist in this marriage of western science and traditional science.

Overarching principles of sustainability and resilience underpin all QYAC initiatives, includes monitoring and evaluation of ecological and cultural assets, and the use of an Adaptive Management Framework to manage ongoing activities.

Traditional Knowledge

QYAC's approach is fostering a resurgence of Quandamooka culture and environmental protection for their land and sea Country. This is enabling more Traditional Custodians of Quandamooka to care for Country.

The Traditional Custodians of Quandamooka have been gifted with Quandamooka Knowledge through observations and repeated practices for thousands of years. Quandamooka knowledge encompasses all things relating to the natural environment and often aligns with a western notion of scientific practice. It is derived from a dataset that is much longer than any scientific observation post-colonisation. The knowledge is also important as it tells a story and enables future custodians to use the same knowledge and expand on it. Quandamooka people have now enhanced the ways in which they use this knowledge to care for country by working with contemporary scientists and including their science into their practices where appropriate.

For many years Quandamooka Knowledge has been appropriated and ignored by non-community members. The Quandamooka Traditional and Cultural Knowledge expressed in this paper is Indigenous Knowledge and is being used in this paper with their consent. It cannot be used without the permission of the Quandamooka People (see Research Protocols).

This Chapter demonstrates the importance of Traditional Custodians to the lands and seas of Quandamooka Country, just as the lands and seas are important to the people. It explores the new westernised managerial role of the Quandamooka People and how that has enhanced the role for traditional practices of caring for country. It also looks at how traditional knowledge and aspects of contemporary caring for Quandamooka Country are playing a key role in contemporary traditional custodianship of the Bay, through fostering and managing scientific research and monitoring. It includes an assessment of current gaps identified, areas for increased improvement and influence of the Traditional Custodians and the benefits of this for the community.

Roles of rangers

QYAC rangers are an important source of scientific capability. Their location on Country and their knowledge of Country make them ideal collaborators for a range of science-based activities such as data collection and monitoring, but also for the provision of expert knowledge for management issues. Thus, the value of the ranger units has become increasingly important in the ongoing management of the Bay and islands.

As previously noted, QALSMA overseas more than 25 people within six Ranger Units working across the Quandamooka estate. They include four ranger groups directly employed through QYAC (DES Rangers, Indigenous Advancement Strategy Rangers (IAS), Naree Budjong Dara National Park (NBDNP) Joint Management Rangers (QYAC/QPWS), and Fee-for-Service rangers. In addition, there are the QPWS Rangers who are directly employed by QPWS and work under the joint, management framework of QYAC and QPWS, and the Minjerribah Camping Rangers who undertake work in the areas under the management of Minjerribah Camping (a company wholly owned by QYAC). Further explanation of each ranger unit's roles within QALSMA is outlined in Table 1.

These ranger units are the most involved Quandamooka People on Country and play a key role in managing their people's cultural heritage rights and interests. They are important representatives for the Quandamooka People, act as role models in the Quandamooka community and care takers of Country for those who are unable to due to work, family and modern life commitments (Fig. 4).

Given the current suite of management challenges and threats to Moreton Bay and its critical importance to the Quandamooka People, the broader community, and to various levels of government it is vital that the Quandamooka Ranger Program be strongly supported. This highly cost-effective program needs to be able to contribute and collaborate in future research initiatives, as well as continuing to complete the large workloads on which they currently are required to deliver.

Collaborative research

In exercising its leadership role in the management of Moreton Bay and its resources, QYAC engages and collaborates with a range of research organisations to provide important new knowledge to help manage their priority issues for the Bay. Collaborators include universities, agencies, consultants, expert volunteers and citizen scientists. For example, QYAC has been involved with a number of collaborative environmental monitoring programs that collect ongoing data about the status of key habitat types in the Bay, including coral reefs (Reef Check (Mulloy *et al.* (9), http://www.nrm.gov.au/indigenous-nrm/south-east-queensland/bays-reefs), seagrass communities (Seagrass-Watch) and mangroves (MangroveWatch). These programs aim to deliver a long-term view of the health of these critical ecological communities.

QYAC has also entered into a number of MoUs with universities, government agencies and Natural Resource Management organisations with the aims of facilitating ongoing collaborative research and gaining access to experts and appropriate world class knowledge and science. Examples include MoUs with the University of Queensland and Healthy Land and Water (HL&W), formerly South East Queensland Catchments. In the case of the latter, the partners worked collaboratively on a number of environmental projects that allowed QYAC to access HL&W's project delivery expertise and experience, which supported QYAC to further improve its capacity to conserve and protect the environment. In return, HL&W drew on the Quandamooka People's thousands of years of experience with managing its Country whilst building its capacity to become a culturally competent organisation.

Table 1. QALSMA ranger types and roles: DES, Department of Environment and Science; PM&C, Department of Premier and Cabinet; QPWS, Queensland Parks and Wildlife Service.

Ranger Type	Roles & Responsibilities	Activities	Funding Source
Indigenous Advancement Strategies Rangers	Estate management (mgt), visitor mgt, asset mgt, safety, marine mgt, pest mgt, fire mgt, cultural heritage within Quandamooka Country.	Marine compliance, Reef Check, MangroveWatch, Seagrass-Watch, freshwater surveys, weed eradication, feral animal control, control burning, fire trail maintenance, preserving cultural heritage with fire preparation, terrestrial compliance and education.	PM&C
Minjerribah Camping Rangers	Recreation area management – camping grounds, fire mgt.	Visitor management.	Minjerribah Camping
Fee For Service Rangers	Undertake works for Clients on a commercial basis where it aligns with the Quandamooka People's land and sea management principles.	Weed control, fire preparation, asbestos and contamination removal, land restoration, controlled burn activities, vegetation management.	Various clients who engage QYAC on a commercial basis.
DES Rangers – Indigenous Land & Sea Ranger Program	Visitor mgt, asset mgt, safety, marine mgt, pest mgt, fire mgt, estate mgt, cultural heritage mgt within Quandamooka Country.	Marine compliance, Reef Check, MangroveWatch, Seagrass-Watch, freshwater surveys, weed eradication, feral animal control, control burning, fire trail maintenance, preserving cultural heritage with fire preparation, terrestrial compliance and education.	DES
Naree Budjong Dara National Park (NBDNP) - Joint Management Rangers (QYAC/QPWS)	Estate mgt, visitor mgt, asset mgt, safety, pest mgt, fire mgt, cultural heritage mgt within NBDNP & Teerk Roo Ra National Park (TRRNP)	Marine compliance, Reef Check, MangroveWatch, Seagrass-Watch, freshwater surveys historical preservation at lazaret and peel island. Weed eradication, feral animal control, control burning, fire trail maintenance, preserving cultural heritage with fire preparation, terrestrial compliance and education.	DES – QPWS
QPWS Rangers – NBDNP	Estate mgt, visitor mgt, asset mgt, safety, pest mgt, fire mgt, cultural heritage mgt within NBDNP & TRRNP	Marine compliance, Reef Check, MangroveWatch, Seagrass-Watch, historical preservation at lazaret and Peel Island, weed eradication, feral animal control, control burning, fire trail maintenance, preserving cultural heritage with fire preparation, terrestrial compliance and education.	DES

Figure 4. Caring for Quandamooka Country – QYAC Rangers traverse many remote locations (e.g. 18 Mile Swamp). (Photo credit: QYAC)

Collaborative Management

The Bay is jointly managed through a range of Commonwealth and State legislation as well as through various instruments of the coastal Councils including Redland City, Logan City, Brisbane City and Moreton Bay Regional Councils and supported by the national NRM Regions Framework. The management of Quandamooka Country by its Traditional Custodians is part of this network and relies on strong partnerships and close collaborations with State government departments local authorities, and non-government organisations.

QYAC has recently entered into a range of partnerships with the State Government to help foster the collection of new knowledge and integrated management decisions. For example, in 2019 QYAC entered into an MoU with the Queensland State Government to help 'pave the way for education and training opportunities for Quandamooka people, UQ students and researchers through the development of joint ventures, including the integration of Quandamooka Ranger initiatives and UQ research' (Courier Mail 19/02/2019).

QYAC now has senior-level representation on a range of government-led fora set up to help manage the Bay. For example, QYAC sit on the Moreton Bay Fisheries Working Group which provides advice on fisheries management and resource sharing within the Bay. It is also a member of the State Government's Koala Advisory Council.

At the local government level, QYAC is partnering on a range of issues affecting management of the Bay. For example, Redland City Council are currently working with QYAC to develop a Coastal Hazard Adaptation Strategy to help manage current and future issues relating to coastal erosion, storm tide inundation and sea level rise.

A number of examples of the successful independent and collaborative research initiatives undertaken by QYAC in their management of Quandamooka Country, are set out below.

Case Study 1: ***Quandamooka World Heritage Tentative List nomination***

In November 2016, QYAC submitted to the Queensland State Government a Tentative List Nomination for World Heritages status over the Quandamooka Estate. QYAC has received expert advice that the nomination should be submitted as a mixed cultural-natural site. Therefore, QYAC presented a case which outlined the basis for a Tentative Listing based on Criterion (v) (cultural) and Criterion (x) (natural). Whilst it is recognised that the estate has many other values, it was felt appropriate to concentrate on the most prospective cultural and natural criteria. Only one criterion is required to be met for World Heritage listing.

The evidence presented for the cultural criterion is based on archaeological heritage of the Moreton Bay Islands which is an extensive, rich and diverse cultural record ranging over the last 20,000 years. It comprises over 1000 known sites, including shell middens, stone artefact scatters, stone artefact quarries, burials, scarred trees, earthen ceremonial rings, story places, pathways, and stone fish traps. Archaeological sites are found on all the Moreton Bay islands, although the type and character of the evidence varies according to a range of factors including the resource availability, accessibility, seasonal use and social factors.

The evidence presented for the natural criterion covers the unique marine, terrestrial and wetland habitats. The Quandamooka nomination is embedded in a comprehensive protected area legal framework (Marine Park, National park, Conservation Areas, Fish Habitat Areas, Ramsar wetlands, migratory bird agreements). A single zoning based management plan provides protection to the whole of the marine environment and similarly management plans are in place or under way for terrestrial components. The wetlands are protected, and of a size, diversity and condition to retain the critical habitats for migratory wader birds on the East Asia-Australasia Flyway. Australia is a signatory to international migratory bird agreements with Japan, China and Korea, of direct relevance to Moreton Bay wetlands.

QYAC is currently leading the progress on the nomination for World Heritage listing of Quandamooka Country. This process will involve the collation of a considerable range of significant scientific information to fully support the nomination and the access to world class researchers and scientists for advice and support.

Case Study 2: ***Guiding the planning and emergency response for fire events on Minjerribah***

Minjerribah contains numerous freshwater wetlands, cultural heritage sites and unique ecosystems. In January 2014, fires impacted 16,800 hectares of Minjerribah or roughly 80% of the terrestrial landscape. This area included as many as 150 recorded cultural heritage sites, many of which are among the oldest formerly documented archaeological sites on the East Coast of Australia.

The 2014 fires prompted QYAC to highlight with multiple levels of government the need to better manage fire on Minjerribah and reintroduce appropriate land management practices informed by cultural landscape values and Quandamooka tradition. In 2017 QYAC entered into a MoU with the Queensland Reconstruction Authority to develop fire management strategies to better manage fuel loads and respond to fire events on Minjerribah. The strategies address risk mitigation, planned burning, hazard reduction and wildfire suppression for landscapes in and around each of the Island's townships. Critically, the strategies also complements the fire management strategy developed by QYAC in partnership with the QPWS for Naree Budjong Djara National Park. In combination, this Quandamooka driven approach aims to greatly reduce the risk of an island-wide bushfire and forms a comprehensive bushfire management and planning framework across all tenures on the island with support from all land management agencies and Queensland Fire and Emergency Services (QFES).

The Minjerribah Township Fire Management Strategies integrate modern disaster management techniques with the traditional burning and fuel load management practices of the Quandamooka People. Since their development, these fire management strategies have been recognised through the Resilient Australia Awards and by the Queensland Inspector-General of Emergency Management as an outstanding example of a cooperative, locally-led approach to fire management (10).

The Minjerribah community now has approximately 25 Quandamooka rangers qualified in best practice fire management and response working for QYAC, Minjerribah Camping, and the QPWS. This has been complemented by an expansion of rural firefighters trained in wildfire response to assist local QFES crews, Redland City Council responders and staff employed by mining company Sibelco. QYAC has worked to source resources to ensure Ranger units are well equipped with firefighting equipment. The ranger team now includes a fleet of four-wheel-drives fitted out with fire units to emergency services standards; All Terrain Vehicles equipped with tanks and hoses to enable access to some of Minjerribah's most difficult to reach landscapes; and heavy equipment including tractors, loaders, and mulching machinery to enable tracks to be prepared and fire breaks to be cut.

On 28 November 2018, as bushfires once again threatened Minjerribah with extreme weather conditions present throughout eastern Queensland, QYAC were represented 24 hours a day at the Incident Control Centre (ICC) coordinating the event on the Island, and were heavily involved in decisions about managing the bushfire response. The ICC's planning and response was heavily informed by QYAC's mapping and geographic information system (GIS) capabilities and QYAC's knowledge informed agencies of the cultural and ecological values, unique landscape and access points. QYAC's involvement highlighted methods to contain the fire, and cultural advice was sought on critical matters by all agencies. The Quandamooka People led the front line on the ground and ensured cultural values were recognised for their irreplaceable nature and considered as assets worthy of proper protection consideration. The fire response was directed with these values in mind and Queensland Fire and Emergency Services directed water bombing aircraft and helicopter firefighting units to protect cultural landscapes containing sacred features including scar trees, bora grounds, artefacts, and ancient trees in the south of the Island.

The Queensland Inspector-General of Emergency Management in the 2018 Queensland Bushfires Review recognised that the involvement of the Quandamooka People through QYAC was a critical success factor in the response to the 2018 bushfire (Fig. 5), and ensured that the response protected cultural and ecological values in line with the QYAC designed fire management strategies (10). The Inspector General's report also recognised the response to the 2018 fire event on Minjerribah as "an example of effective interoperability between different agencies with different structures working towards a common outcome, informed by traditional Aboriginal practices" (10).

Figure 5. QYAC Rangers undertaking regular controlled burn activities at night to make use of optimal climatic conditions (Source: QYAC).

Case Study 3: ***Traditional Owners leading the assessment of sustainable fisheries values – beche-de-mer***

Through the Indigenous Business Development Fund supported through the ETS, an expert study was commissioned by QYAC to provide information to assess a developmental fishery for beche-de-mer (sea cucumbers) in the Bay. Beche-de-mer were historically fished by Quandamooka People through Indigenous Owned businesses in the early 2000s, but this ceased in 2007, and there has been no approved commercial fishing activity since then. It was proposed that the reintroduction of this fishery could build additional fishing and fisheries management capability for the Quandamooka people as well as a new source of income.

However, acknowledging the fundamental principle of caring for country and that Quandamooka Country would be first recognised as the Quandamooka People's sanctuary, it was concluded that a thorough assessment of the current state of the fishery needed to be conducted. This work led to new insights showing concerning declines of some elements of the beche-de-mer population that demonstrated key issues in the Bay require further investigation. The 2018 survey and assessment, led by beche-de-mer fishery experts (11), established that major changes in beche-de-mer populations have occurred between 2007 and 2018. The two most concerning changes were the disappearance of sandfish (*Holothuria scabra*) from the area adjacent to southern Moreton Island and the complete disappearance of peanutfish (*Stichopus naso*) from all surveyed areas.

These changes are difficult to explain given that the Bay, and eastern Bay in particular, have been given 'B+' or 'A' report card ratings (https://hlw.org.au/report-card/) in recent years. There is also a general lack of parallel biophysical data on the drivers that could be in play, especially those that could affect the distribution and abundance of beche-de-mer, including during recruitment and growth phases of their life cycle. However, data on the relevant biophysical drivers of beche-de-mer populations can be difficult to obtain or may not have been collected. Furthermore, the sensitivities of beche-de-mer to a range of biophysical factors is not well understood. For example, the relationships between beche-de-mer health, distribution and abundance, and factors such as water temperature, abiotic seasonal shifts and indirect impacts of habitat change are not well established.

This complex management issue demonstrates the challenges that occur in complex marine systems, and that are potentially becoming more acute as the impacts of climate change continue to affect marine environments. Such challenges will continue to highlight the need to support further growth in QYAC's capacity to manage complex issues in the Bay in collaboration with research and monitoring agencies, as well as the interaction with organisations that have a key stake in the Bay's ecological health (e.g. HL&W, QPWS and the Qld Department of Forestry and Fisheries).

Case Study 4: *Working in partnership with community and not-for-profit groups to care for Quandamooka Sea Country*

Despite the disruption of European settlement, the Quandamooka people have maintained a special connection with Moreton Bay's land & sea country that saw them play a role in industries such as the dugong oil trade, oyster farming, whaling, and commercial fishing. Natural resource management and the protection of land & sea country is a relatively new industry in comparison, with many of Moreton Bay's National Parks and Marine Parks only established or expanded during recent decades.

On March 11, 2009, the "Pacific Adventurer" spilt 270 tonnes of oil into the Pacific Ocean in proximity of Moreton Island after Cyclone Hamish contributed to extreme weather in the region. The resultant oil slick impacted beaches, rocky reefs, wetlands, mangrove systems, and saltmarsh intertidal environments between Bribie Island and Coolum on the Sunshine Coast with the most extensive impacts being on Moreton Island. In this instance the Quandamooka People played a key role in clean up and rehabilitation works in partnership with all levels of government and community. This also presented an opportunity to increase capacity through the development of a Quandamooka Ranger team supported by the Regional NRM Group SEQ Catchments (now Healthy Land & Water (HL&W)). Many of these rangers continue to be employed by QYAC and through partner agencies.

Since this time QYAC has continued to grow and demonstrate its capacity in Sea Country management. As part of a coordinated approach to demonstrating sea country management capacity, QYAC in partnership with community and not-for-profit groups developed a sea country management program involving monitoring and assessment of ecosystems throughout Moreton Bay as well as direct rehabilitation works in targeted locations that result in immediate benefits for some of Moreton Bay's most sensitive marine ecosystems (Fig. 6).

This approach to increased involvement of Quandamooka Rangers in the management and monitoring of Sea Country has seen Quandamooka People strengthen skills in undertaking seagrass assessments, coral reef monitoring, improve understanding of dugong & turtle populations, as well as assessing the health of mangrove fringed coastlines throughout the entirety of the Quandamooka Native Title area. Some of the assessments conducted of these natural values have been done for the very first time and have demonstrated QYAC's capacity to undertake assessments of marine ecosystems while contributing to the wider community's understanding and knowledge of Moreton Bay.

Figure 6. QYAC Sea Rangers in Moreton Bay: growing young Quandamooka People to be the future leaders in caring for country (Source: QYAC).

The partnerships formed with environment focused not-for-profit groups across Quandamooka Country as a result of this approach have proven to be ongoing with Quandamooka Rangers able to regularly draw on the knowledge of organisations such as Reef Check Australia, Wildlife Preservation Society of Queensland, James Cook University, Griffith University, State Government Departments, the University of Queensland, Seagrass-Watch, Queensland Turtle Research as well as through Healthy Land & Water. It is expected that a focus on Sea Country will form a cornerstone for a future MoU with the State Government for the management of the Moreton Bay Marine Park, which will further increase active management of Sea Country by the Quandamooka People.

The value of Quandamooka involvement in undertaking marine environmental rehabilitation and monitoring activities cannot be overstated. While community and not-for-profit groups often strive to protect and restore landscapes using an organisational capacity built up over years or decades, Quandamooka People are part of a society and culture that has an intrinsic knowledge, understanding, and connection to the landscape. Built up over thousands of years, it is seldom easily accessed through conventional research. These Sea Country initiatives delivered over the past decade have identified that community and not-for-profit groups working in partnerships with QYAC produce mutually beneficial land and sea country management outcomes whilst also building community capacity to enable active management of these ancient landscapes into the future.

Case Study 5: *Blockbuster filming activities considering first nations culture and country*

Aquaman, a Warner Brothers superhero blockbuster starring Jason Momoa in the title role along with Nicole Kidman, Amber Heard and Willem Dafoe, involved a number of scenes shot on Minjerribah during 2017. The film shoot involved 250-plus crew and actors conducting filming activities on some of Minjerribah's most significant coastal landscapes.

The makers of *Aquaman*, directed by Australian James Wan, spent about $100 million on physical production in Queensland. QYAC worked with Warner Bros Feature Productions for several months to prepare for the filming. This included providing Native Title and Cultural Heritage guidance, briefing Elders on the proposed filming activities to understand their level of cultural appropriateness, and scoping film locations for their potential cultural and environmental suitability and works requirements.

Logistically, the shoot was a major exercise. QYAC played a vital role, providing cultural heritage monitoring before and during filming and undertaking considerable earth works at South Gorge to install a temporary track onto the beach capable of transporting machinery and multi-million-dollar film equipment from Point Lookout headland onto the sands of South Gorge. Prior to earthworks Quandamooka rangers were involved in removing dune vegetation with the assistance of the local Bushcare group so that this same vegetation could be replanted at the completion of filming. Rangers also helped to construct the site and supported the film crew during filming, and were involved in undertaking rehabilitation activities at the site for several months post filming. The landscape today contains fewer weeds and has a dune formation consisting of endemic dune species (Fig. 7).

Figure 7. Quandamooka Rangers prepare vegetation for frontal dune rehabilitation at South Gorge, Point Lookout following filming of the blockbuster Warner Brothers film, *Aquaman* (Source: QYAC).

At the peak of the filming QYAC provided a cultural briefing and Welcome to Country for all film participants whilst Elders were introduced to the site and crews to observe activities. Cultural Heritage Monitors and Rangers ensured Quandamooka protocols were followed and throughout Warner Brothers responded to advice from the monitors and rangers to ensure minimal risk of cultural and environmental impact. The film makers employed more than 30 locals to do everything from undertaking security, performing lifeguard duties, and driving just about every crane and forklift on the island, with these outcomes supported through the guidance of Quandamooka Rangers on the ground. *Aquaman* has since become one of the highest grossing films in cinema history. Many Quandamooka People can feel proud of their contribution to making the film a reality in a way that protected and considered culture and Country. Importantly it must also be recognised that the filming team from Warner Brothers ensured that the Quandamooka People were treated with respect and appropriately recognised as the custodians of the landscapes where the filming was taking place.

A selected list of QALSMA land- and sea-focussed initiatives for the past three years has been assembled as Annex A. It demonstrates the range and diversity of activities that QALSMA and in particular its rangers, has been involved with in looking after Quandamooka Country.

Conclusion

The integration of Traditional Knowledge and Science and Western Science into the growing custodianship role being provided by the Quandamooka People provides a recipe for an effective and acceptable, long-term management approach for the Bay. The Native Title decision and the formation of QYAC were important steps towards accrediting this new approach and have resulted in a portfolio of new and old initiatives that are transforming management of the Bay and its resources.

QYAC's growing role in these areas provide new opportunities for the sustainable management of the Bay's resources, but also for new sources of economic development, such as ecotourism. QYAC's diverse ranger capability and growing links with research and government organisations is facilitating an expansion in new knowledge for the Bay.

This Chapter has shown how the Quandamooka People, the Traditional Owners of Moreton Bay, who have nurtured this region for the past 25,000 plus years, are now seeking to protect their sanctuary, through a philosophy of shared use that safeguards Quandamooka's values, interests and vision through Traditional Owner-led land and sea management.

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Annex A. Selected QALSMA Land & Sea-focussed Initiatives (2017 – 2019)*. Abbreviations: DES, Department of Environment and Science; DNRME, Department of Natural Resources, Mines and Energy; HLW, Healthy Land & Water; LGAQ, Local Government Association Queensland; NESP, National Environmental Science Program; QALSMA, Quandamooka Aboriginal Land Sea Management Agency; QPWS, Queensland Parks & Wildlife Service; RCC, Redland City Council.

Number	Project	Report
1	Feral Animal Management on North Stradbroke Island	HLW provided funding support for QALSMA to undertake feral animal control activities during 2017 and 2018, which has seen several hundred foxes controlled in partnership with other land managers and reduced the threat from foxes and feral cats to the islands precious
2	Stage 1 Kaboora (Blue Lake) Visitor Facilities Upgrade	QALSMA worked closely with the QPWS to upgrade the visitor facilities associated with Kaboora, which included walking trail upgrades, car parking facilities, and signage works.
3	Naree Budjong Djara NP Strategic Fire Trails	QALSMA delivered fire management trail upgrades for QPWS on identified Priority 1 Firelines across Naree Budjong Djara National Park complimented by cultural heritage monitoring.
4	Development of Cultural Health Indicators for Indigenous Joint Management Areas.	This project involves the development of indicators of cultural health and measures to assist in monitoring for the effective management of Naree Budjong Djara National Park.
5	Coastal Hazard Adaptation Consultancy for RCC	QYAC in partnership with David Brewer Consulting and HLW are providing consultancy services to RCC to progress Coastal Hazard Adaptation Planning across Redland City. This project is being delivered under the QCoast 2100 funding program, managed by the LGAQ aimed at assisting coastal Councils across Queensland to prepare their Coastal Hazard Adaptation Strategies.
6	Maintenance works on Reserves managed by RCC	RCC provided support to QYAC for Community Rangers to undertake weed control and land management maintenance activities on reserves that were formally managed by RCC but are now managed by QYAC.
7	North Stradbroke Island Fire Management Works Program	The DNRME engaged QYAC through QALSMA to undertake a number of land management activities to support fire management operations on land managed outside of Naree Budjong Djara National Park. This included the removal of hazardous trees overhanging trails, management of vegetation to reduce fuel hazard, the establishment of fire trails, and fire operational activities.
8	Indigenous Engagement Action Planning for HLWr	QYAC was engaged by HLW to support the development of an Indigenous Engagement Action Plan to assist the organisation better understand current and future mechanisms for engagement with Indigenous stakeholders.
9	One Mile Track Maintenance	QYAC through QALSMA worked with DNRME to undertake One Mile track maintenance activities utilising local contractors including the repair of existing tracks, improving drainage, and grading surfaces.
10	Increasing Quandamooka On-Ground Participation and Stakeholder Cultural	This project funded by HLW involved QYAC working to increase the participation of Quandamooka People in on-ground land management activities while improving Council and Community Group awareness of Quandamooka cultural values in the Lota and Manly area, which is known by the traditional name of Narlung.
11	Minjerribah Bushfire Management Planning	QYAC has been working closely with the Queensland Reconstruction Authority and other State Government Agencies to develop Bushfire Management Plans for the townships on Minjerribah to complement the fire management planning that has taken place for Naree Budjong Djara National Park. The Bushfire Fire Management Plans aim to Improve community safety and protect life and property; Realise the aspirations of the Quandamooka People; and protect and maintain natural and cultural heritage and cultural landscape values.
12	Trail maintenance activities for Naree Budjong Djara NP	Slashing services for QPWS to maintain existing fire trails within the Restricted Access Area of Naree Budjong Djara National Park.

13	Dunwich Seawall Temporary Repair	RCC engaged QYAC to undertake the temporary repair to the seawall located at the barge ramp loading facility following the formation of cavities in the side of the seawall.
14	Ecological Study of the Restricted Access Area of Naree Budjong Djara NP	This project being funded by the QPWS involves QYAC through QALSMA undertaking an assessment of the significant ecological values of the Restricted Access Area at the southern end of Minjerribah so that these values can be better understood and managed. This project is continuing during 2018-19.
15	Peel Island Planning Study	QYAC is working with the QPWS to better understand the future opportunities, constraints and potential operational needs to support effective management of the Island. This project is continuing during 2018-19.
16	Quandamooka Festival 2017 Temporary Public Art Banners	As part of the 2017 Festival QYAC with support from RCC established public art works from Quandamooka Artists at several locations throughout RCC.
17	Feral Animal Control Services in Naree Budjong Djara NP	QPWS sought the involvement of QALSMA in the coordination and delivery of feral animal control activities within the National Park with a particular focus on foxes and feral cats.
18	Filming and location support for Warner Brothers Limited	The blockbuster movie *Aquaman* was filmed on Minjerribah during 2017 and QYAC provided support in establishing the set at South Gorge, undertaking cultural heritage monitoring, and rehabilitating the site after the completion of works.
19	Fire Management Support Activities for RCC	QYAC through QALSMA undertook fire management services for RCC on a number of their reserves including the management of weeds, the reduction of fuel loads, and participation in fire management operations.
20	Coochiemudlo Island Weed Control Training	Thanks to support from Coochiemudlo Coastcare, Quandamooka Community Rangers participated in training and delivered weed control activities on the island using the innovative and cutting edge steam weeding technology. This project is continuing during 2018-19.
21	Mooloomba Artificial Reef	QYAC through QALSMA provided support to QPWS in the scoping and development of an artificial reef project for Quandamooka
22	Weed Control Works along East Coast Road	TMR identified priority weeds for control along areas of East Coast Rd with particular focus on *Leucena*. QALSMA Community Rangers undertook these works.
23	Assessment to support Pipe Removal works at Bradbury's Beach	Old pipe infrastructure associated with the UQ Research Station poses a safety hazard within the Bradbury's Beach Area. QYAC is working with UQ to assess how the removal works can be undertaken whilst protecting the environmental and cultural values of the site. This project is continuing during 2018-19.
24	South Gorge Fence Replacement	QYAC worked with Warner Bros and RCC to scope the replacement of the fencing at South Gorge following filming of *Aquaman*.
25	Native Bee Trial	QYAC works with Star Entertainment to trial native bee hives and production. This involves working with renowned entomologist Dr Tim Heard and including training to Quandamooka Rangers and Elders in how to look after and establish native bee populations.
26	Capembah Creek Boardwalk Maintenance	QYAC regularly undertakes maintenance activities on the Boardwalk at Capembah Creek for RCC including works to improve the longevity and sustainability of the decking.
27	Speedy's Lane Dangerous Tree Management	The DNRME engaged QYAC to remove dead and dangerous trees overhanging the Speedy's Lane fire trail that had the potential to impact upon the trails suitability for emergency vehicle access.
28	Amity Point Erosion Emergency Works	Significant coastal erosion events occurred at Amity Point during 2017-18 and QYAC worked closely with RCC to undertake repair works to protect property in the area. This included working with local subcontractors and the provision of cultural heritage advice and oversight.

29	Cleveland Library Mural Dabilbahnba – place of saltwater	As part of the 2017 Quandamooka Festival, a 9 m tall mural entitled Dabilbahnba – meaning place of saltwater – now adorns the Cleveland Library building in Middle Street. Prominent Quandamooka artists, mother and daughter team Sandra and Shara Delaney worked to bring the mural from conception to completion with artists Matthew Newkirk and Deb Mostert. The project was delivered by QYAC in partnership with Creativemove and support from RCC.
30	Develop and Improve Minjerribah Recreational Trails	QYAC worked closely with the department of State Development to scope up the Recreational Trails project which is to be delivered as part of the Economic Transition Strategy. This project is now underway.
31	Follow up filming support for Warner Bros.	The *Aquaman* team returned to Minjerribah in October 2017 to undertake additional filming activities and QYAC once again provided location support services and cultural heritage expertise to support the project.
32	Fire Trail Slashing Services	DNRME is responsible for an extensive fire trail network on Minjerribah, and QALSMA provides slashing services to support DNRME in the maintenance of this network.
33	Honey Bee Trial	QYAC is working with industry and research institutions to investigate the potential for more people working in the Minjerribah honey
34	Jeff Horn visits Minjerribah	In the lead up to his fight at Suncorp Stadium Jeff Horn visited Minjerribah to undertake filming for content in the lead up to the big fight. QYAC worked with the filming team to showcase Quandamooka Culture and Minjerribah's landscapes and welcome Jeff to Quandamooka
35	Embracing the Bay	RCC held their first ever Embracing the Bay event which was delivered at Raby Bay. Quandamooka Culture featured prominently with Quandamooka dancers revealing culture and delivering education activities.
36	Community Rangers delivering works for Naree Budjong Djara National Park	The Community Ranger Program being delivered by QYAC provides an employment and training pathway for Quandamooka people and a cost effective on-island culturally appropriate workforce for joint management activities. The Community Rangers are undertaking a range of activities to support operations in Naree Budjong Djara National Park including fire and cultural landscape management, weed
37	Landscaping support for Minjerribah Camping	QYAC works with Minjerribah Camping to supply suitable materials for landscaping and addressing land management issues as they arise.
38	Adder Rock Beach Access Maintenance	QYAC worked with RCC to undertake repair works at the Adder Rock beach access following erosion and storm events.
39	Koala Action Plan Partnership	RCC is implementing their Koala Action Plan across Redland City and QYAC is supporting the delivery of research and surveys to better understand Minjerribah's unique koala population.
40	Fire Commissioner and Emergency Services Minister visit to Minjerribah	Quandamooka welcomed the Emergency Services Minister and Fire Commissioner to the Island and showcased culture and projects that QYAC has been undertaking to improve disaster resilience on Minjerribah.
41	EcoMarines Care for Country Events	The EcoMarines team engage younger generations in activities that promote and educate the values of Quandamooka. Quandamooka Rangers have been involved in providing education activities at the events to improve education and understanding of Quandamooka Country.
42	Girls Got Grit Filming on Minjerribah	A 4-wheel drive (4-WD) show with a difference *Girls Got Grit* aims to empower women to discover the outdoors through 4-WD adventures. Quandamooka female rangers provided support and cultural education to ensure filming activities were conducted
43	National Environmental Science Program Involvement	QYAC was involved in working with research intuitions and organisations associated with the delivery of the NESP to review achievements and work on improvements to collaborative Indigenous research.
44	Welcome to country.	QYAC delivered a wide range of Welcome to Country activities throughout the year.
45	Moreton Island Wildfire Support	In 2018 a wildfire broke out on Moreton Island and the QALSMA team were called on by QPWS to provide operational support to aid in bringing the fire under control.

46	Deanbilla Bay Barracks Demolition	QYAC is working with the DNRME and Queensland Public Housing and Works to undertake the removal of asbestos and demolition of the Deanbilla Bay Barracks in preparation for the Cultural Heritage Centre.
47	Tidelands Filming for Netflix on Minjerribah	In an Australian first, QYAC supported the team putting together the new TV series called *Tidelands* which has had a number of scenes filmed on Minjerribah. QYAC services included ranger services while filming on beaches and cultural heritage advice and expertise.
48	Feral animal control on DNRME managed areas	QYAC supported DNRME to undertake feral animal control activities on their reserves with a particular focus on fox and feral cat control. This project is continuing.
49	2018 fire season burn preparation works	In preparation for the fire season, QYAC undertook preparation works on a number of reserves including the protection of culturally significant trees and landscapes and improving the condition of fire trails.
50	Beche-de-mer environmental assessment	QYAC is working to assess the condition of sea cucumber populations in Moreton Bay to help inform future management strategies for Quandamooka Sea Country.
51	Removing Bitou Bush from Minjerribah	In partnership with Land Management Agencies and Biosecurity Queensland QALSMA rangers worked to survey Minjerribah east coast beaches to identify potential locations for bitou bush and undertake control activities. This project is continuing.
52	Native Title Planning Assessments on Moreton	QALSMA rangers in partnership with the DNRME undertook assessments on Moreton Island to identify weed management and land management issues.
53	ANZAC – Commemorating Indigenous fallen heroes	QYAC participated in ANZAC day celebrations on Coochiemudlo Island and other locations with a particular emphasis on commemorating Indigenous Fallen Heroes.
54	Fisheries Joint Patrols	QALSMA is working with Fisheries Queensland to improve opportunities for Quandamooka People to be involved in the management of the Quandamooka Fishery. This has included inductions for QALSMA rangers so that they can participate in patrols and crew vessels.
55	Monitoring and Education of Quandamooka Sea Country	QALSMA is increasingly playing a lead role in the monitoring of values associated with Quandamooka Sea Country. This has included monitoring of coral reefs, shorebird populations, beach patrols, and participation in forums educating the community about dolphins, whales, dugongs and turtles. This project is continuing.
56	Hosting the South East Queensland Pest Advisory Forum	QYAC hosted State and Local Government biosecurity officers from across South East Queensland as part of the South East Queensland Pest Advisory Forum. Officers were introduced to Quandamooka Country and the broad range of biosecurity management activities being undertaken on Minjerribah.
57	World Heritage Listing	QYAC proposed and secured a State Government commitment to progress a World Heritage Listing for Quandamooka Country.
58	Dolphin Compliance and Education Program	In partnership with QPWS, QYAC has initiated and has led improved compliance on illegal dolphin feeding and education.
59	Minjerribah Fish Population Assessment	QYAC has collaborated with RCC and QPWS to deliver an island-wide survey of native and invasive fish within wetland communities of Minjerribah. This is the first time an island wide survey has been undertaken and is informing how wetlands are managed on the island.
60	Capembah Creek Repair Works	QYAC works with land managers to halt significant erosion, protect cultural values, and prevent ecosystem collapse on the RCC managed reserve at Capembah Creek. Includes installing a boardwalk to remove compaction of tree roots and vegetation, working with TMR to remove over 60 t of road-base material that was contaminating the creek, and progressing repairs to the culvert under East Coast Road
61	Blue Star Removal for TMR	Through QALSMA, rangers have been working hard to control an infestation of the invasive weed "Blue Star" and have been working with Transport and Main Roads to reduce the risk of spread and contamination to other areas of the island.
62	Supporting the uptake of Environmentally Friendly Moorings	QYAC has worked closely with HLW for a number of years in the delivery of the Environmentally Friendly Mooring Program for Moreton Bay to allow the recovery of seagrass communities across Quandamooka Sea Country.

63	National Park Expansion on Minjerribah	QYAC has negotiated and progressed a State Government commitment to expand the National Park Estate on Minjerribah from approximately 2% of the Island to 50% of the Island with planned further expansions resulting in up to 80% of the Island being recognised as protected area in one of the largest national park expansion initiatives in Queensland.
64	Minjerribah turtle nest monitoring and protection	QYAC works with the QPWS, Minjerribah Camping, and community volunteers to record, monitor, and protect turtle nesting sites across the Island.
65	2018 Minjerribah Wildfire Response	QYAC played a lead role alongside Queensland Fire and Emergency Services in the response to the 2018 fire event on Minjerribah, with Quandamooka Rangers leading the front line, inducting interstate staff, and playing a pivotal role in the incident control centre. Quandamooka Rangers were instrumental in guiding water bombing operations to maximise protection of country and irreplaceable
66	Upskilling of Rangers in Fire Response and Management	QYAC has contributed to a significant increase in the numbers of on-island fire response staff with large numbers of qualified personnel now available from across QYAC, Minjerribah Camping, QPWS.
67	Expansion of Island Fire Response Units	Through QALSMA operations QYAC has greatly increased the number of Island-based fire response units (firefighting-equipped vehicles that include fire pumps and hoses) and machinery available to respond to emergency and wildfire incidences. This includes heavy machinery used to support trail upgrades and cut fire breaks.
68	Return of Bummiera to Quandamooka Custodianship	QYAC successfully negotiated with the RCC for the return of Bummiera (Brown Lake) to the custodianship of the Quandamooka People; an area previously managed by RCC as a recreation reserve. QYAC has worked to support Bummiera becoming part of the protected areas on Minjerribah under the joint management of the QALSMA and QPWS with management planning underway for improved visitor facilities that protect the sites cultural and environmental significance.
69	Land Transfer to support Bummiera Catchment Protection	QYAC has successfully negotiated with Seqwater to better protect Bummiera by having Seqwater relinquish their surrounding water reserve containing much of the Bummiera (Brown Lake) catchment. This culturally and environmentally significant landscape is now being managed by the Quandamooka People through the QALSMA in partnership with QPWS.
70	Amity Shoreline Erosion Management Planning	QYAC has worked closely with landholders and agencies involved in the development of the RCC-initiated Shoreline Erosion Management Plan for Amity, ensuring delivery in a way that is sensitive to country and the Native Title rights and interests of the Quandamooka People.
71	Asbestos Training and Removal Works	QYAC have had a number of Quandamooka rangers trained in asbestos removal. These rangers have worked carefully to remove asbestos contamination from two reserves with long term contamination from illegal dumping. These reserves which are now being managed by QYAC are now much safer spaces within the Amity community as a result of the rangers hard work.
72	Deanbilla Bay Barracks Acquisition	QYAC successfully obtained the Deanbilla Bay Barracks following their relinquishment by the Royal Queensland Yacht Squadron so that the site can be utilised as a space to protect and showcase Quandamooka Culture and Country
73	2018 Wild Dog Response	QYAC initiated and successfully led the response to dog attacks on wildlife during early 2018, which included the establishment of an ongoing response plan involving all island land management agencies to aid in preventing future attacks on wildlife and people.
74	MangroveWatch	QYAC has been working with scientists from James Cook University to undertake the most comprehensive recording of mangroves on Minjerribah's coastlines and neighbouring islands through the MangroveWatch Program. This has involved Quandamooka rangers using the latest scientific monitoring techniques to determine mangrove health using video assessment technology.
75	Reef Check Australia	QYAC has established new sites on Quandamooka Country to monitor and record reef health in partnership with Reef Check Australia. This has included the skilling of Quandamooka Rangers with the latest techniques to identify coral species and undertake reef health
76	Seagrass-Watch	QYAC has been heavily involved in the long term monitoring of seagrass communities across Quandamooka Sea Country. Quandamooka rangers work with experts involved in the Seagrass-Watch program to record seagrass health and densities.

77	Minjerribah Camping Sustainability	QYAC, through Minjerribah Camping, is improving the management of campgrounds to reduce numbers and impacts at peak periods. This management has been effectively in spreading the occupancy more evenly during holiday periods and enabled better management of culturally and environmentally sensitive areas. Minjerribah camping is continuing a continuous improvement program across Minjerribah's campgrounds to reduce overcrowding and impacts upon the cultural and environmental values that underpin the business.
78	Beach Camping Compliance	QYAC has worked with Minjerribah Camping to increase numbers and presence of rangers on the ground to ensure campers and visitors to Minjerribah have a great experience that respects Minjerribah's values. This includes work and compliance activities aimed at reducing driving on dunes, reducing rubbish left at campsites, and preventing unnecessary damage to vegetation.
79	Peel Island Compliance	Through joint management arrangements involving the QALSMA and QPWS, QYAC has increased patrols on Peel Island with Quandamooka Rangers ensuring that campers have a greater respect for this special part of Quandamooka Country.
80	Whale Strike Awareness Raising	QYAC, as had the Quandamooka Land Council before it, leads advocacy to all levels of government threat-reduction to whales and marine life from vessel strike. Includes responding and caring for animals impacted and supporting changes to vessel propulsion for Bay ferries.
81	Ancient Tree Protection and Cultural Values Recording	QYAC has been recording and undertaking rehabilitation of ancient Cypress Pine cultural complexes, which hold unique cultural heritage values across many parts of Minjerribah. This has included researching the ancient trees on the island to understand their ages and is working with the Queensland Herbarium and researchers to ensure their protection.
82	Quandamooka Country Collaborative Research Initiatives	QYAC is participating in and contributing to extensive and world leading research on Quandamooka Country including but not limited to: determining the age of wetlands on Minjerribah; the significance of the ecological structure of Kaboora; recording the distribution and health of *Phaius* orchids; recording the nest locations and reducing impacts to *Xeromys myoides* (water mouse) populations; and, researching the long term rainfall on Minjerribah through analysis of leaf samples from sediments at Swallow Lagoon.
83	Littoral Rainforest Mapping and Conservation	QYAC is mapping and improving the recording and protection of critically endangered littoral rainforest communities on Minjerribah in consultation with the DES.
84	Risk Management to Protect Minjerribah's Koala	QYAC is working with DES to ensure the movement of koalas from Minjerribah appropriately considers disease risks and ensures the long term protection of the special Minjerribah population
85	Species recording on Minjerribah	Through QALSMA, QYAC is regularly identifying and recording new species on Minjerribah and ensuring that these values are protected and the information captured is stored and treated sensitively.
86	Return of land at Mooloomba for cultural and environmental awareness raising	QYAC successfully negotiated with the DNRM and RCC to have land at Point Lookout headland returned to the control of the Quandamooka People so that a derelict site containing waste material and weeds could be turned into a site that promotes and highlights the cultural and environmental values of Mooloomba.
87	Steam weeding to replace chemical control	QYAC has been skilling ranger teams and obtaining equipment to replace chemical weed control techniques with environmentally friendly steam weeding where possible. Includes work on Minjerribah and Coochiemudlo Is where steam weeding has replaced chemical control.
88	Shellfish Research	In partnership with James Cook University, HLW and The Nature Conservancy QALSMA has been investigating shellfish communities and understanding their health and possibilities for Traditional Owner-led restoration.
89	FRDC Marine Resources and Traditional Owner considerations	QYAC participates in the FRDC Indigenous Forum, which aims to understand the traditional take of marine resources of Indigenous people on a local & national scale. This information is being linked to the national index of marine resource take alongside commercial and recreational activities to support a holistic understanding of fisheries resources and their sustainability. This work is ongoing.

*Excludes projects led by the Cultural Heritage Unit within QALSMA, and culturally sensitive and commercial-in-confidence related projects.

A custodial ethic: Indigenous values towards water in Moreton Bay and catchments

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Abstract
Most Australian jurisdictions, including Queensland, have struggled to sufficiently incorporate Indigenous values into their institutional frameworks. As a result, opportunities for formal Indigenous participation in water governance remain scarce. This study sought to fill a gap in knowledge through a qualitative exploration of Aboriginal water values in South East Queensland (SEQ). It explored how Traditional Custodians value SEQ waterways and how understanding these values can assist managers to adequately integrate Indigenous interests into water management and policy. Twenty Traditional Custodians, from across the SEQ region, participated in either a focus group with others from their Custodial group, or an individual interview (a choice was offered). Analysis was according to Kellert's typology of values. The research shows that Traditional Custodians' values towards estuarine and marine waterways in SEQ are multi-dimensional. Indigenous cultural values of water encompass more than spiritual and customary objectives, and extend beyond cultural heritage paradigms. Aesthetic values were strongly associated with ecosystem health, a point of difference from studies of non-Indigenous values towards water. As expected, identity is closely associated with the values and so a strong sense of personal loss was associated with damaged waterways. Understanding people's connections with waterways will help managers to engage and partner more effectively with Indigenous people, and to integrate social dimensions in their future management of waterways.

Keywords: water, South East Queensland, Kellert

Introduction
Aboriginal water values have received increased attention in recent decades. Population growth, climate change and an expanding urban footprint have led to environmental decline, prompting calls for change within water planning policies to recognise and better involve

Aboriginal people in water management (see for example 1, 2). Most Australian jurisdictions, however, including Queensland, have struggled to sufficiently incorporate Aboriginal values into their institutional frameworks (3–5)[1]. Instead, Aboriginal interests in water management are defined by limited notions of 'cultural value', confined to descriptions of spirituality and custom. This restricted perception of Indigenous peoples' values towards water means opportunities for formal participation of Indigenous peoples in water management are limited.

Their ambiguous and complex nature, coupled with a lack of definition of what 'cultural values' *are*, provides little guidance for water planners and decision makers (7). Australian literature commonly refers to 'cultural values' to define Aboriginal water interests; however, few articulate the meaning or their interpretations of this term (see for example (8–12)). Indeed Lee (13 p358) warns against concepts of country being 'shoehorned into a contrived view of "cultural" values'. This leaves water managers and decision makers to rely on limited policy interpretations of 'cultural values' (14), 'cultural purpose' and 'traditional activities' as encompassing Aboriginal cultural heritage and 'tradition' or 'custom' (15). Maclean (16 claims that while Aboriginal water values, knowledge and interests are more than 'just culture' p143), existing planning approaches and paradigms continue to marginalise Aboriginal interests to static and pre-settlement stereotypes (17 pp123-124), helping to create a barrier between water planners and Aboriginal people. Better articulation of the idea of 'cultural values' is required to show that 'cultural affiliations to water are expressed in many different ways' (18 p138). This research aimed to expand understandings of Aboriginal water values as more than cultural, for the purposes of improved Aboriginal involvement in water management.

Process

The research was carried out in South East Queensland (SEQ), focusing on Moreton Bay Marine Park and the rivers and creeks that flow into the Bay. The study area extended from Ipswich in the west to Caloundra in the north, and included the Moreton Bay islands and the Gold Coast in the south (see Fig. 1).

The study was part of a larger ARC Linkage project (19–21, Ross *et al*. (22) and (23), this volume), in which Aboriginal Custodians of the region were full partners alongside the state government and two government-non-government collaborations involved with land and water. The original partner organisation, an Aboriginal organisation through which most Custodial groups of the region coordinated over shared issues, closed very early in the study.

Thereafter the Aboriginal partner role was coordinated through four workshops held between January 2013 and March 2015 with SEQ Traditional Custodians, covering design, monitoring work in progress, and interpretation. An Aboriginal person (former staff member of the closed organisation) represented the Aboriginal partners at project meetings and maintained regular

[1] In this paper, we specifically focus on Aboriginal *values* towards water. The research was undertaken in the interests of informing and enhancing management approaches, but a development of management implications is beyond the scope of this paper. What sits behind this work is a more complex political and legal issue of Aboriginal water *rights* and the incomplete recognition of Indigenous rights to water in Australian federal and state legislation (see (6)).

communication with the groups between meetings and workshops. The Aboriginal partners (and individual participants in the study) identified with Kombumerri, Nunukal, Gorenpul, Ngugi, Quandamooka, Gubbi Gubbi/Kabi Kabi, Jinibara, Mulinjarlie, Jagera, Yuggera and Ugarapul.[2]

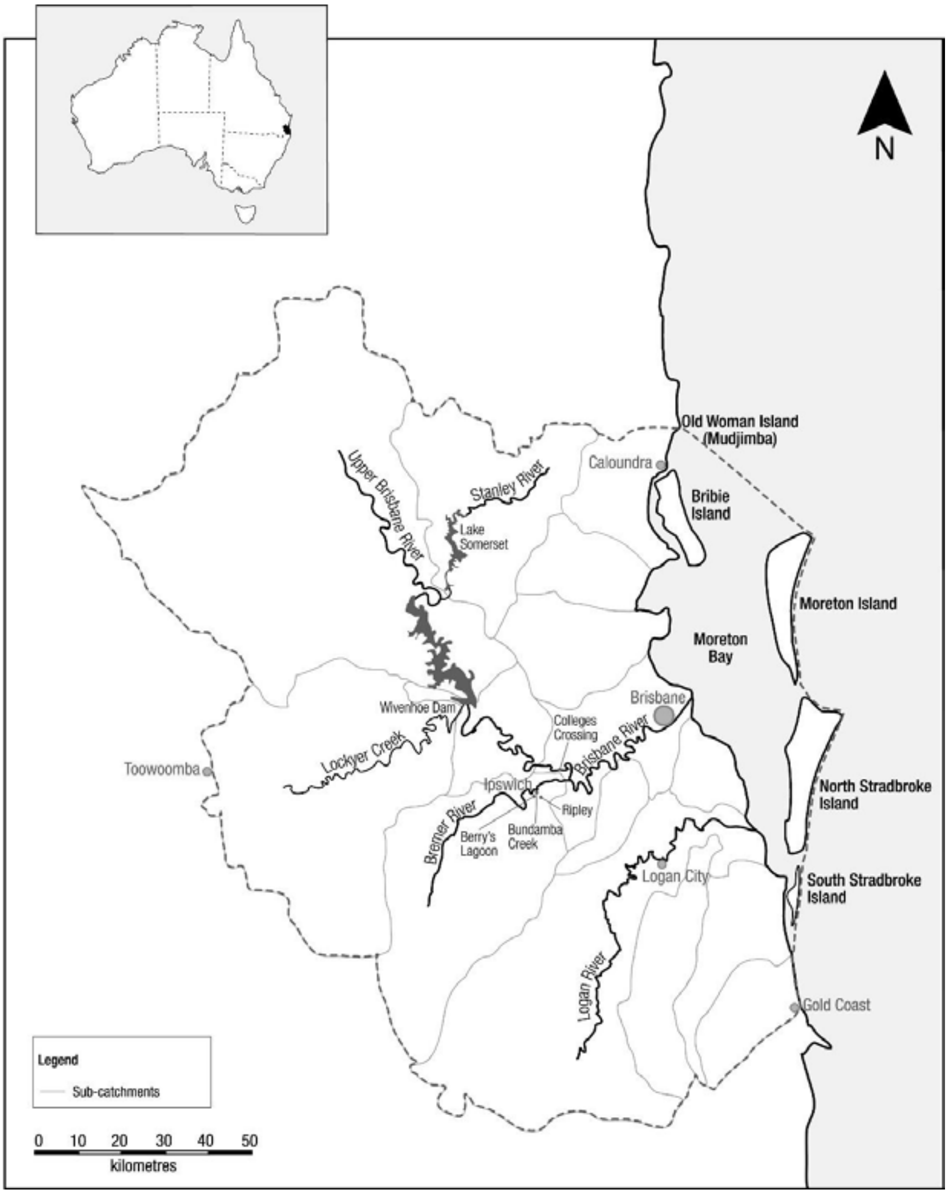

Figure 1. Study region from Caloundra in the north, Ipswich in the west and the Gold Coast in the south.

Custodians were offered a choice of methods (while the non-Indigenous participants had semi-structured interviews). They chose a mixed methods approach, with options of individual

[2] Traditional Custodians identified themselves in a number of ways according to language, clan or family groups, others according to larger social entities.

interviews or focus groups. Most people preferred individual interviews, because they provided an opportunity for confidential and in-depth conversations between the researcher and the interviewee, and it was often easier to schedule these around time constraints. Some felt a group discussion to be more appropriate for cultural or sensitive information, thereby allowing for group decisions on information disclosure and story sharing for inclusion in reports. Others simply expressed greater comfort in talking in a group setting.

Twelve semi-structured individual interviews and two focus groups were conducted with twenty Traditional Custodians between May and October 2014. All were conducted by the Aboriginal first author. In all cases permission was given for recording. The same questions were asked at each: participants were presented with a map of the study area and asked to mark the waterways important to them. These were used as a reference point to talk about how people interact with waterways, and why those waterways are meaningful to them.

The audio recordings from interviews and focus groups were fully transcribed and copies of the transcripts provided to participants. Analysis of the transcripts used a relational approach, based on Stephen Kellert's (24, 25) framework of ten nature-centred values, to explore Indigenous relationships with waterways and the values that emerge from those associations. The framework was derived from empirical research and has been tested repeatedly over many decades with respect to a wide range of environments, as well as animals, and in a number of different countries and cultures (26). To our knowledge it has not been used with Indigenous people. However, some literature on cultural values has elicited many of the same values for example Gould *et al.* (27) with respect to Indigenous Hawaiians, and Arias-Arevola *et al*. (28) in Colombia. A particular attraction is that this framework specifically links nature-related values with ethical behaviours for land and seascapes, and is relevant to environmental management and monitoring.

Kellert (29) argued that researchers and managers should seek to understand and engage with the values of all people interested in a given environment, in order to find approaches that respected a range of concerns. It is not sufficient to manage according to use values versus moralistic values to protect an area or species: there are many more values than these. Further, Kellert argued that this set of values has ancient origins related to humans' needs to survive, and achieve well-being in their environments (25).

In choosing Kellert's framework, we do not treat it as partitioning the ten types of value in ways that contradict Aboriginal holistic (and very relational) ways of thinking about people and nature. Rather, we see it as potentially illuminating facets of the holism. Kellert argued that individuals hold several values at once and that the sharing of some values across groups of people can help build consensus. We argue that Kellert's set of values is effective for an analytical consideration of an Aboriginal way of thinking that recognises that the well-being of people and environments are inseparable. We argue that the framework has the potential to examine the interconnecting parts in order to more effectively see the complex whole. We have taken a flexible application of Kellert's values typology to draw out some of the dimensions (and ambiguities) that underpin the overarching concept of Aboriginal cultural values.

Throughout the larger study with Aboriginal and non-Indigenous participants, Kellert's framework was used in a first round of coding, then open coding was used to allow other types of values, and variants to the Kellert framework, to emerge (30). The coding was entirely by one person, the Aboriginal first author, for sensitivity and consistency.

Interview and focus group transcripts were sent back to interviewees to ensure they were comfortable with how the information they had shared was rendered in written form. To ensure the views of Traditional Custodians had been correctly presented, multiple rounds of feedback were sought from participants through personal dialogue and the workshops to gain their opinions on the process and presentation of research findings.

The study received ethics clearance from the University of Queensland, based on design for strong Aboriginal participation in all aspects of the research, Aboriginal benefits from the research, informed consent by all individuals invited to participate in interviews and focus groups, and privacy and confidentiality provisions.

Humanistic values

Kellert defines humanistic values as those which encompass 'tender feelings of affection, solicitude, and caring for certain plants, animals, and places' (25 p67) that facilitate emotional attachments with the non-human world. Traditional Custodians expressed affection for certain waterways, explaining their emotional connections with waterways which were fostered through a range of experiences with waterways including work, recreation, and social or personal activities.

Many participants reminisced about childhood experiences shared with family and friends, often provoking strong emotional responses. Traditional Custodians recalled times *fishing* (TC2, TC5, TC9), *swimming* (TC2, TC5, TC12) or *playing* (TC14) in rivers and on beaches. One participant shared childhood memories about two rivers with which he maintains a close bond:

> *These two here, the Bremer and out at Ripley, Bundamba Creek there, that's where I spent my childhood, that was my background, that's where I played. I would go home, leave, have breakfast in the mornings, just take off, and that's where I'd spend my days* (TC8).

Childhood memories surrounding waterways were significant to people because of time spent with family. Generational connections to water places were echoed by others with one interviewee explaining that's *probably why I have such close affiliation with them, as I said, my grandmother was born here* (TC11). Waterways are important to the endurance of family traditions as explained by one Custodian who described having passed on their love of fishing and the river:

> *[I] mucked around all the time down there, but we used to fish there and all that sort of stuff. I still do I suppose, I still take [my son] and that down there, he's mad on fishing, but I still take him down there and he catches his dirty running catfish, but he doesn't care* (TC8).

Generational ties to waterways, such as these, are important for family and social relationships, and lend to maintaining ancestral connections and cultural practices.

Kellert claims that where feelings of love and attachment toward nature exist and that a particular animal or place disappear or become damaged, one may justifiably feel ‘a profound sense of loss and a sorrow akin to grief’ (25 p67). Grief and a great sense of loss was evident among many participants who felt their relationships to places were threatened or lost completely due to development processes; whereby various activities were now restricted due to the lack of access to waterways, loss of land (cleared for housing, for example), and degradation of waterways that limits peoples interactions with certain areas. Others expressed very strong emotional responses toward places they feel a connection to, as one participant explained *[t]hat's very close to me, that country there - they ripped my childhood out… you'll never see that again there, it's gone forever. It bugs me.* (TC8). A deep emotional connection between people and their environments is evident in this expression of sadness and anger. These expressions of emotion are very consistent with Turner *et al.’s* (31) discussion of ‘invisible losses’, including cultural and lifestyle losses, emotional and psychological losses, and lost opportunities.

The connections between SEQ Aboriginal groups and water places are unique to them as a sociocultural group in that these relationships represent ancestral connections that date back thousands of years and are deeply embedded in people’s cultural identity. Participants often referred to their cultural connections with various water bodies, identifying as either saltwater or freshwater people. Traditional Custodians described their *connection to land and water* (TC14), with some identifying themselves as *sea country people* (TC6) and explaining that *land and sea country… is what we are* (TC13). The ‘humanistic’ values for SEQ waterways are expressed as ancestral connections, as well as personal affection for places people visited in childhood and continue to visit today, and other places now lost to them.

Naturalistic values

Naturalistic values arise from direct experiences with the natural environment that can promote feelings of well-being. Values of the natural world emerged mostly through people’s childhood memories of their experiences with waterways. Participants explained that as children they used to go *swimming* (TC5, TC6, TC9, TC12, TC13, TC14) and would *play* (TC8, TC13) in and around waterways, as well as holidaying, camping and fishing which evoked positive memories of family and social interaction. Other naturalistic experiences occurred in recent memory and included direct interactions with nature such as walking along waterways, bird watching, exploring or immersion in nature by simply sitting near waterways and observing the environment. Some participants described visiting places that were *teeming with life* (TC4) where they would see *dugongs, dolphins and all kinds of tropical fish* (TC13).

Kellert claims that people gain a sense of satisfaction from contact with, or immersion in, the natural environment (32 p17). This sentiment was echoed closely by one Traditional Custodian who believes *it’s great for people to have natural things around them... [which] provide inner-self satisfaction* (TC12). Wildlife encounters were significant to some who described their experiences with estuarine and marine animals, which included observing the diversity of birds, marine and freshwater animals and in some cases direct contact with wildlife, as described by one participant:

> *I wandered out and I was fishing there, and the next minute this jolly stingray… came up to me. I saw it coming up and I said, "Hello… "What are you doing here?" He sniffed around me, I didn't worry about it. Next minute, it came up, put its head up out of the water... I touched it on the nose, and it went away. Next minute, a much bigger one, about three times the size… Came up to me, put its head out of the water, and I patted it on the head* (TC12).

The naturalistic experiences described convey the value people have for the natural elements of water places. Through direct exposure to waterways and wildlife, people build their appreciation, love and concern for nature.

Moralistic values

Kellert (25) describes moralistic values as ethical concern for nature, but what influences a person's ethical judgements? Throughout this research it was apparent that participant's moral concerns for nature were guided by their cultural perceptions and what they have been taught by generations before them. For example, many participants explained that Aboriginal people have an obligation to maintain a reciprocal relationship with the environment to preserve a natural balance. One participant explained this in terms of the intimate relationship between people and marine animals, stating *if all of a sudden, overnight, all the dugong up and die, I think a lot of [Aboriginal] people would die too* (TC4). Maintaining a caring relationship with the natural world was considered a cultural responsibility - *a custodial ethic, an ethic of looking after* (TC9). Caring for waterways was also considered a broader public obligation where *the waterways are everybody's responsibility* (TC14), *regardless of whether you're Aboriginal or non-Aboriginal* (TC13). Judgements about what is considered right and wrong were expressed in people's perceptions of harmful ecological impacts from human activities and development. One participant explained: *whichever way you look at it, healthy waterways are being severely damaged by the growth of industry and population* (TC11). Acting on their concerns for the environment, many participants expressed their desire to educate people and promote environmental sustainability.

Education was a key ethic amongst participants who expressed their desire to *protect* (TC13) and *look after* (TC5, TC9, TC10, TC12, TC13) the environment by *educating* younger generations *to make a difference* (TC1, TC5, TC11) in the broader community. Traditional Custodians also explained some small-scale management activities undertaken to mitigate impacts to waterways. These activities included informal observations and picking up rubbish to protect wildlife from harm and *ensure that [waterways are] better maintained [and] free of pollutants* (TC5). Concern about harmful impacts to waterways suggested a deeper appreciation of flow on effects to broader ecosystems.

Ecologistic values

Kellert infers ecologistic values to be values of function, process and relationships in nature (25). Traditional Custodians valued the natural processes and connections between nature and people, which were reflected in activities conducted to monitor the health and function of ecosystems. Custodian's holistic perceptions of ecosystem health and function were implied in people's comprehension of the natural elements and wildlife as indicators of waterway conditions. The natural processes of systems were described as *a beautiful chain of command by Mother Nature* (TC10) in which *nature's way to improve the water quality… would be to have oyster banks, and a lot of them. When you have oyster banks, you have seagrass, mud whelks, cockles, and you have fish* (TC3). Scientific methods including *monitoring* (TC4, TC14), observations and *water quality testing* (TC4, TC13) were undertaken by participants working with environmental management bodies, to better understand the natural functioning and health of ecosystems.

Participants spoke about their desire for the broader public to become more *in tune with [their] environment* (TC13) to understand the importance of maintaining balanced ecosystems, claiming *[y]ou've got to have a balance, otherwise if you don't look after it, it's the condition that it's in today* (TC1). The declining condition of local water bodies was a common topic of conversation and concern with many participants detailing the significant impacts to waterways that have occurred.

Ecological degradation of waterways was an important issue to most participants because of the effects upon the natural system as a whole. Knowledge of the natural function and process of waterways was implicit in most discussions where Traditional Custodians gave a comparison of the state of waterways in the past and the deteriorated condition of these today. One participant described the effect on a particular river in detail:

> *The trees way back in the older days… were firmly there and the grass was firmly there, [then] white man came and cut the trees down and loosened all the dirt up and then the rain would come and then wash it [away]… to make it so muddy, because when the floods come through… it's just like a big sheet of mud going over the bridge… That's what I think it is anyway, because… back in those days, it was muddy water but it was still-- you could put your hand [under water] and you could still see your hand. But now you pick it up it's like picking a big chunk of mud, watery mud. So I firmly believe that it's people building and chopping down trees* (TC1).

Perceptions such as this indicate that Custodians understand and are concerned with how poor waterway health impacts other natural elements and resources.

Utilitarian values

Utilitarian values represent practical and material use or 'exploitation of the natural world' (25 p63). Many participants expressed utilitarian values of the rivers, creeks and Bay in talking about how water bodies and their resources were used. Freshwater and saltwater bodies are fundamentally important to sustaining life:

> *It's probably the most important ingredient on the planet, aside from sunlight. So in that regard, water is very important, salt water or fresh water, because… it's a life force, it gives life, and it sustains life. It sustains me and my people because*

> *we can drink fresh water, or the resources that we depend on are supported by fresh or salt water, so when looked at in that perspective it's essential* (TC4).

Participants echoed the significance of water's life giving properties:

> *If we allow [waterways] to be degraded, our quality of life and the quality of life of those resources that we depend on becomes degraded. To what point are they degraded to such a point that life is not sustainable?* (TC4).

Practical use of water bodies was described by some participants who referred to previous generations and members of their family that would utilise the water for *washing, cooking* (TC14) and *food* (TC1, TC3, TC13), as well as some economic activities such as *oyster leases* (TC7). Today, waterways are used mostly for other recreational purposes such as *camping* (TC1, TC2) or *fishing* (TC3, TC4, TC5, TC12). Kellert argues that in modern society we value nature for its material goods and services and that the use of nature in this way reflects a common perception of nature as a 'natural resource' (25 p49). However, a distinction between natural and cultural resources was noted in the research.

Some Traditional Custodians referred to *cultural resources* (TC6) instead of the commonly used term 'natural resources'. More than just resources for consumption and exploitation, natural elements hold cultural significance for Aboriginal people. TC4 expressed the importance of resources in this way: *[i]t's the medicine that's there, it's the food, it's part of our essence, that's part of what makes us who we are* (TC4). Access and use of resources is important for the continuity of some aspects of cultural lifestyles and symbolise traditional knowledge of place.

Symbolic values

Kellert asserts that as humans we use 'symbols to represent reality', which occur in 'names, images, stories, decoration, and design… [and are] revealed in our metaphors, our myths, and our dreams' (25 pp108–109). SEQ Custodians conveyed symbolic values associated with Aboriginal place names in SEQ, which represent historical events, people, stories, animals or environmental features. One Traditional Custodian shared the story of how a place got its name:

> *Old Woman Island was Mudjimba, Mudjimba is the salt water crab, but Mudjimba Island, it was the Old Woman Island, we called it Old Woman Island because that's where the tribe put their older women when they couldn't go walking with the rest of them... there always was a couple of able bodied blokes there too... It was their duty to look after the old people. So that was how it got the name, Old Woman Island* (TC12).

This story is symbolic of the historical use associated with the island. Other place names were symbolic of abundant marine animals such as Bribie Island which is called *yurin or place of mud crabs* (TC3), or of totems; for example, *Ngarang-Wal translates into shovel-nosed shark, an Aboriginal totem* (TC13). Place names indicate a symbolic association with aspects of Aboriginal culture.

Kellert claims that symbols are integral to our capacity for 'language… as well as our capacity to imagine, create, and form culture' (25 p108). This point was reflected in stories where natural features inspired *folklore* (TC3) as told to me by a Traditional Custodian who translated particular Aboriginal place names that represent features of a dugong:

> *Tarangari, as leg or flipper, and it's part of their folklore, where they say that Bribie is a dugong because they call South Point 'Tumbah' and they have 'yippee' for round about where Bongaree is, and where Banksia they call that 'kuku', and here they call Tarangari, then up near Caloundra there was 'waarum' which is the tail… Well if you've got lips, neck or throat, abdomen, legs or flippers, and a tail, then you've got to be a dugong* (TC3).

The symbolic nature conveyed in place names and meanings connects Indigenous people to those places as an expression of their historical, cultural and spiritual belonging.

Negativistic values

Kellert defines negativistic values as fear of or aversion to aspects of nature critical to human well-being (25 p34). Traditional Custodian's negativistic values were twofold in that they related to the physical nature of waterways and to spiritual beliefs associated with particular water courses. Some participants expressed their caution around waterways attributed to the high presence of bull sharks rumoured to travel upstream in many SEQ rivers, meaning that people now avoid swimming in rivers: *[y]ou couldn't pay me enough money to jump in the canals anymore. Not enough fish, too many sharks* (TC13). Another Custodian commented on their fear of sharks saying *I worry too much about sharks and all that. We used to go out Colleges Crossing and all that, swimming at… Twin Bridges and all that sort of stuff but now with the bull sharks getting around, I'm a bit too, [scared]* (TC8). Caution around waterways also centred on concerns about pollution affecting water courses and associated resources:

> *when you see events like that where there's big floods and you start to see all the resources like fish and turtles, and dugongs come up with all these growths and things like that, you're not going to eat them. So it does impact hugely on our natural resources* (TC5).

Participants' responses suggest that fear of the contamination to SEQ waterways and resources affects people's interactions with waterways because they avoid particular places.

A culturally distinct aspect of negativistic values emerged from people's spiritual beliefs, which have been described as influencing people's interaction or lack of interaction with particular water courses. One participant explained that their caution and avoidance of certain waterways was a sign of respect to water spirits and their ancestors, stating:

> *My grandmother… She would always take me [out] there but we wouldn't ever go near that Berry's Lagoon. She'd go wide from that because she knew old matey was in there, that bugger was in there*[3] (TC1).

[3] 'old matey' refers to a spiritual eel believed to live in the river.

The same participant explained a deeper sense of fear associated with water spirits that has been passed on from previous generations where *generally our ancestors were scared of the river* and that people should always *be careful around the waterways in South East Queensland here* (TC1). Negativistic values reflect Custodian's spiritual beliefs and respect of waterways.

Spiritual values

Kellert explains that spiritualistic values encompass beliefs that all life in nature and humanity share a common underlying connection 'to a world beyond ourselves that seems coherent and even purposeful' (25 p94) and which encourages a 'reverence for life' (25 p99). Traditional Custodians expressed spiritualistic values of waterways in relation to Kellert's interpretation of feelings of awe, and also in distinct cultural ways. Some participants recalled a feeling of reverence for nature that proved difficult to articulate. One Custodian described how water places make them feel by saying:

> *Soon as I... get out of the car and get onto the boat or the ferry or the barge, there's something that ignites one's spirit. I can't explain it, especially when you smell the salt water too, beautiful* (TC10).

Custodians spoke about the ways in which visiting significant water places provoked feelings of awe and admiration. Another participant explained *[i]t's something that you can't quantify… this feeling... It's in you. It's part of you* (TC10). Most Custodians elaborated on the spiritual significance of these connections to country as guided by their cultural beliefs.

Traditional Custodians reiterated their spiritual values of SEQ waterways. Some Custodians made specific reference to a *spiritual connection* with the land and waters (TC1, TC3, TC11, TC13), in one case defined in the following way:

> *We don't separate land from the sea, and on the land we have the… sand island, fresh water, freshwater creek, runs into that sea, that's our whole spiritual connection, the two things that have come together* (TC11).

This comment indicates the ways in which Aboriginal Custodians draw together spiritual beliefs and connections to country. The same Custodian explained that *our spirituality is not based on a structured religion, it's based on our connection to land* (TC11). Custodians also sometimes referred to Dreamtime stories in the process of defining the broader cultural and spiritual significance of their connections to country.

Aboriginal cosmology is embedded in all aspects of the natural environment. A Traditional Custodian explained the interconnection of spiritual beliefs and country by saying *[a]ll the waterways are significant because… our dreamtime and creation stories are all encompassed around the waterways, the mountains, the coastal areas* (TC14). Others referred to their experiences in particular places within country with spiritual beings like the *moondagudda, junjadees* (TC1), and the *tall man* (TC14). Spirits such as these, that exist in (land and water) country, guide the behaviour and decisions of some participants who expressed a key principle in respecting those spirits. For example, certain practices must be conducted, including *talking* *to [the] ancestors* (TC7) when visiting the river, to show respect to those spirits. Another participant described a practice they undertake when fishing, associated with ancestor spirits:

> *After they'd caught their fish, they would have to rebury the bones back in the bank where they caught the fish. So that next time, there'd be more fish to catch for them to eat* (TC14).

Customary practices, such as mentioned above, convey respect for non-human beings in the country and indicate that spiritual beliefs are important to Custodians wanting to ensure the health of ecosystems.

Another culturally distinct aspect to spiritual values surfaced in the interviews as people explained the significance of marine and estuarine animals as totems for particular groups. For example: *[d]ugong, sea turtle, dolphin and whales, along with many other species are sacred Aboriginal totems for saltwater people in coastal areas* (TC13). One person explained the spiritual connection they feel with a river because of their cultural totem: *my personal totem is connected spiritually to the river because it's the eel* (TC1). Holistic perceptions of the connections between people, environment and animals, show that waterways are a spiritually important aspect of everyday life and an integral part of the cultural connection people have with the environment.

Aesthetic values

Aesthetic values are those of physical appeal and attraction to aspects of nature (25 p2). Traditional Custodians' aesthetic values of water often reflected perceptions of ecosystem health and were intertwined with ecologistic values. Interestingly, aesthetic values surfaced through juxtaposed descriptions of appeal and lack of appeal. Participants often recalled the *beautiful* (TC1, TC3, TC8, TC10, TC11, TC12, TC13, TC14) waterways from their childhood experiences as formally healthy environments. One interviewee described their perception of beauty as a thriving system explaining *it was beautiful country, fair dinkum. That creek there was fresh, there's lily pads and there's wildlife all around there* (TC8). Another described memories of a healthy river that *used to be big and wide. It was beautiful* (TC14).

From the interviews it is apparent that the *natural beauty* (TC4) of clear waterways is perceived to mean clean waterways and indicates pristine and healthy ecosystems. However, descriptions of beautiful waterways were often followed by a comparison of the *brown* (TC8, TC13) and *gross* (TC13) conditions of rivers today that indicate poor water quality. The comparison between past and present water aesthetics and quality was described by one Custodian stating *Look how dirty the water is. I remember that water used to be so clean and blue* (TC14). Most participants expressed sadness in their reflections on the health of waterways today, dominated by development. The lack of appeal attributed to waterways today, contributed to deeper themes of loss.

Dominionistic values

Kellert describes dominion as a human desire to master and control aspects of nature that 'contribute to character development and to the acquisition of various mastery skills' essential to our fitness and survival (25 p83). No dominionistic values were identified in this research.

However, it would be naïve to think that in an urban population such as SEQ, Aboriginal people do not undertake any activities that may be deemed dominionistic. On the other hand, explanations as to why such values did not emerge from the interviews may be found within Kellert's own reasoning that the 'inordinate desire to control nature is said to be a characteristic of Western society' (25 p81), whereas in societies where nature and the sacred are enmeshed, people cannot be separated from nature. It follows that 'people do not aspire to control or master their environments, rather they seek to work with them' (33 pp223-224). This view was reiterated by Traditional Custodians in the final workshop conducted as part of this research. They explained that Aboriginal philosophy does not seek to control nature, but rather works with it, perhaps through modest traditional management practices such as burning the landscape or building fish traps, as opposed to western philosophies that seek to drastically alter the environment through major physical change.

Values and cultural heritage

Values in relation to material cultural heritage emerged predominantly from interviews and focus groups with Custodians. This category of values does not fit within Kellert's framework. Nonetheless, the prevalence of cultural heritage values deserves some mention. Many Traditional Custodians referred to the significance of material cultural heritage along or near waterways as *cultural sites* (TC5) or more generally as *artefacts* (TC5, TC13). Sites included *bora ring[s]* (TC3, TC6, TC7, TC13), *middens* (TC3, TC5, TC6, TC9, TC13), *skeletal remains* (TC13), *fish traps* and *scar trees* (TC5). Each of these examples may be understood in terms of nature and culture entwined, since they contain material evidence of people's activity in specific places in the environment, people's ocean resource use, use of certain tree species, or the bodies of the deceased interred in the soil. These 'sites' are thus emplaced expressions of people's relation to country and how that relation may have changed and been maintained through time. The values for material heritage are also expressions of the future, since expressing value for such places is often linked to their legal protection (see (34)). One participant said that the *archaeology… that's laid claim to us as [saltwater] people* (TC13). For this Custodian, the material heritage investigated in archaeological research and representing prior use, belonging and knowledge of the place by Indigenous people represents tangible evidence of a cultural identity connected to a particular place in country. Thus tangible cultural sites referred to by participants were highly valued in terms of relationships to country. As such, we suggest that the inclusion of a 'cultural heritage' value may link Kellert's set of values about relationships with 'nature' to culture, but also to Indigenous *rights* in land and sea country.

Elaborating understandings of Indigenous values

In this paper, we have applied Kellert's framework as an analytical exercise to tease apart the ways in which Aboriginal Custodians in SEQ articulate their values towards water and sea country. We argue that doing so can highlight an expanded consideration of Indigenous values, their various dimensions and relative dominance through time, rather than suggesting an artificial separation of elements in value systems. For example, this analytical framework enables us to see how cosmological beings in waterscapes ('spiritualistic values') may be dangerous or cause harm to people ('negativistic values'); or how knowledge of processes within country ('ecologistic values') may inform the ways in which it can or should be used as a resource ('utilitarian values'). A second key tension in our approach to an analysis of values may be that it subsumes a discussion of the *rights* of Custodians to speak for and continue relationships with country. We suggest instead that the range of values identified using Kellert's framework demonstrates the complexity and relationships between different values. Furthermore, our additional consideration of values applying to cultural heritage illustrates the ways in which people and place are bound together, and how this relationship through time underlies the multiple dimensions of people's responsibility and right to waters and lands.

The participants in this study expressed all of Kellert's values, towards waterways, with the notable exception of dominionistic values.

Conclusions

This research builds on arguments put forward by Maclean & Bana Yarralji Bubu Inc. (16) and Jackson (35) that Indigenous values towards water encompass more than spiritual, customary and cultural heritage interests. Prior research suggests that there is inadequate recognition of Indigenous values towards water in management contexts due to a number of factors including poor understanding of Aboriginal world views, mismatch between Aboriginal and manager ontologies (36), a lack of guidance for willing managers to integrate Indigenous interests in water planning, and the relegation of Aboriginal cultural values to spiritual, customary and heritage domains. By focusing on Aboriginal relationships to water, the findings of this research expand appreciation of Aboriginal values towards water, which encompass interests in ecosystem health, biodiversity, resources, ancestral connections, spiritual beliefs, identity and cultural heritage among others – all within Aboriginal people's holistic views of culture and the indivisibility of people and country.

Non-Indigenous decision makers and Aboriginal Custodians alike should be able to draw from this research to enhance their perspectives of Aboriginal interests in water, and incorporate inclusive descriptions of water values into planning frameworks and management approaches. Ideally, both cultures could collaborate in this process, especially since there are many points of consensus – as well as some differences – between the Aboriginal and non-Indigenous people of Queensland in their expressions of values towards waterways. It is clear that the diverse water values that Traditional Custodians hold need to be recognised with broader acknowledgement in water management to effectively incorporate Indigenous interests. The range of specific values towards water identified in this research, within a holistic understanding of the interdependence of people and country, gives clearer bases for dialogue among Traditional Custodians, other environmental managers, and the general public, about how waterways can be managed and cared for more respectfully and inclusively.

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Chapter 2 - Communities and Values

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Queensland communities local knowledge about climate change adaptation (with Dr Sylvie Shaw and others); and the study featured at this Forum, an ARC Linkage study of Indigenous and non-Indigenous people's values towards waterways in South East Queensland. The team was Drs Sylvie Shaw, Natalie Jones, Kathy Witt, David Rissik and James Udy, Ms Breanna Pinner, Prof. David Trigger, and partner organisations state government, Healthy Waterways, SEQ Catchments, and Traditional Owners.

Values towards Moreton Bay and catchments

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Abstract

In environmental management, 'values' are often considered as inherent in the physical environment, rather than being recognised as human constructs: the most deeply held and stable of ways people think about environments. An understanding of how people value environments, beyond the well-recognised utilitarian and moralistic values on which most environmental management is founded, would offer greater opportunity to engage with the public and improve policy. A qualitative study of people's 'relational' values towards Moreton Bay and catchments shows the passion of people who are connected with waterways. We found that Traditional Custodians, and the non-Aboriginal residents of the upper catchments, and the lower catchments and Bay, share the same set of values, with some differences in foci and ways of combining them. Individuals hold several values each. The most commonly held are humanistic values, about emotional attachment to nature or landscapes; naturalistic values, about direct experience of nature; moralistic values, about ethical concerns to protect nature; and aesthetic values, focusing on beauty. Utilitarian values, about the practical use of natural resources, in this case waterways, were raised somewhat less frequently. Managers can explore how they can draw upon these values in designing and implementing management strategies, and in communication with the public. The passion towards the waterways highlights the importance of voluntary stewardship by Traditional Custodians, voluntary organisations and individuals, and suggests political support for managing waterways, a point important in making resourcing decisions.

Keywords: relational values, Kellert, South East Queensland, river

Introduction

People's values towards the environment, and especially waterways, are insufficiently studied (1), and incorporating them in management is relatively rare. Indeed, the term 'environmental values' is more often associated with environmental features as though these are divorced from the people attributing the high value to certain ecosystems and species. Values, as the most fundamental type of human cognition that underpins beliefs, attitudes, norms and behaviours (2), deserve far greater attention. The term 'values' is used and defined in many ways (3). In this paper, values 'represent important individual and collective judgements about what in this world and this life is truly important, worthwhile and meaningful' (4 p128).

This paper is based on a study of people's values towards the waterways of South East Queensland (SEQ). It was conducted in partnership with the state government, the former Healthy Waterways and SEQ Catchments (both collaborations of government and non-government organisations working to improve water quality and the management of natural resources, respectively[1]), and the Traditional Custodians of the region. It was designed to (a) contribute to the monitoring and evaluation of Moreton Bay Marine Park, as part of a suite of studies following rezoning in 2009; (b) inform Healthy Waterways about social dimensions that could assist its management strategies and communication, including its annual report card; and (c) provide Traditional Custodians an opportunity to document and seek recognition for the values they hold towards waterways and aspirations towards greater involvement in formal management. Through the study, the Traditional Custodians and the other parties also sought to build mutual understanding, relationships and opportunities. The study had two stages: content analyses of print and other media concerning Moreton Bay (5), and the rivers of the region; and semi-structured interviews with Traditional Custodians (two focus group interviews in addition to individual interviews), residents of the upper catchments, and residents of the lower catchments and the Bay. Here we report on the results from interviews and focus groups.

For the interviews, people from the upper catchments (n=30) to lower catchments, Moreton Bay coast and islands (n=30) were selected purposively to capture the widest possible range of relationships people have with waterways. This was done by creating a mind map of the uses of and interactions with the waterways of the upper and lower catchments, respectively. The categories included recreational users, working roles such as water transport, people who use river water in their enterprises (e.g. irrigators), and people in voluntary or formal management or advocacy roles. From these categories, typical organisations, businesses and community groups were identified. Individuals representing these organisations and groups were then recruited (1). In making these selections, we also aimed for geographical diversity throughout the catchments. Aboriginal Traditional Custodians participated in four workshops to coordinate their input as partners in the study, including design of their participation in the study and interpretation of the results. An Aboriginal team member conducted their interviews, and the Custodian groups were offered the choice of in-depth

[1] These organisations have since been merged as Healthy Land and Water.

interviews (n=12) and/or focus groups (n=8 people, in two groups) (Pinner *et al.* (6), this volume). The Traditional Custodians were from throughout the catchments.

Participants were presented with a map of the study area and asked to mark on it the waterways that they considered particularly relevant to them. Using a semi-structured interview technique, each participant was then asked why that waterway was important or meaningful to them and to explain their interactions with it, such as how often they visit the waterway and what they do there. They were also asked for comments on management (not reported here). Participants were encouraged to talk freely, with the interviewers probing as required to bring out depth. The analysis was guided by Kellert's (7–9) framework of 'relational' values between people and nature (3). This type of value contrasts with 'held' values, matters of principle, and 'assigned' values, where people attribute value to objects, such as particular species and locations (3).

The waterways considered in this study incorporate all catchments draining to Moreton Bay, from the upper catchments close to the Great Dividing Range, through creeks and rivers to Moreton Bay and its islands (Fig. 1). The coasts included Caloundra to the Gold Coast. This is a complex and rapidly developing region, incorporating rural, agricultural and forested areas, small rural towns, and the densly populated and growing urban areas of Ipswich, Brisbane, Logan, the Gold Coast and the southern part of the Sunshine Coast.

Values

This section compares the values expressed by Traditional Custodians (n=20) across the whole region, and non-Aboriginal people's values towards the upper catchments (n=30), the lower catchments and Bay (n=30), respectively. More detail is provided in Pinner *et al.* (6) this volume; Witt *et al.* (10), and Jones *et al.* (1).

Most of those interviewed expressed a passion for and deep sense of connection with the rivers, creeks and Bay. Table 1 explains Kellert's nature-based values, and summarises how they were expressed in relation to the waterways of SEQ. The values are widely shared. The Traditional Custodians and non-Aboriginal people held the types of values identified by Kellert in his extensive body of work, though with some minor variations (see below). Only one value was missing: the Custodians did not raise the dominionistic value as it contradicts their culture with respect to relationships with environments. Kellert, in developing the framework, does not appear to have worked with Indigenous peoples, and some of the values he lists reflect the extent of his work on people's relationships with animals. Traditional Custodians, upper catchment and lower catchment people, expressed some of the values a little differently (see below).

People hold several values each, and a number of them are held by over half of those interviewed. In Table 1, the values are listed in descending order, starting with those expressed by the most participants[2] to those expressed by the fewest (the counts exclude Traditional Custodians, since their interviews were not quantified).

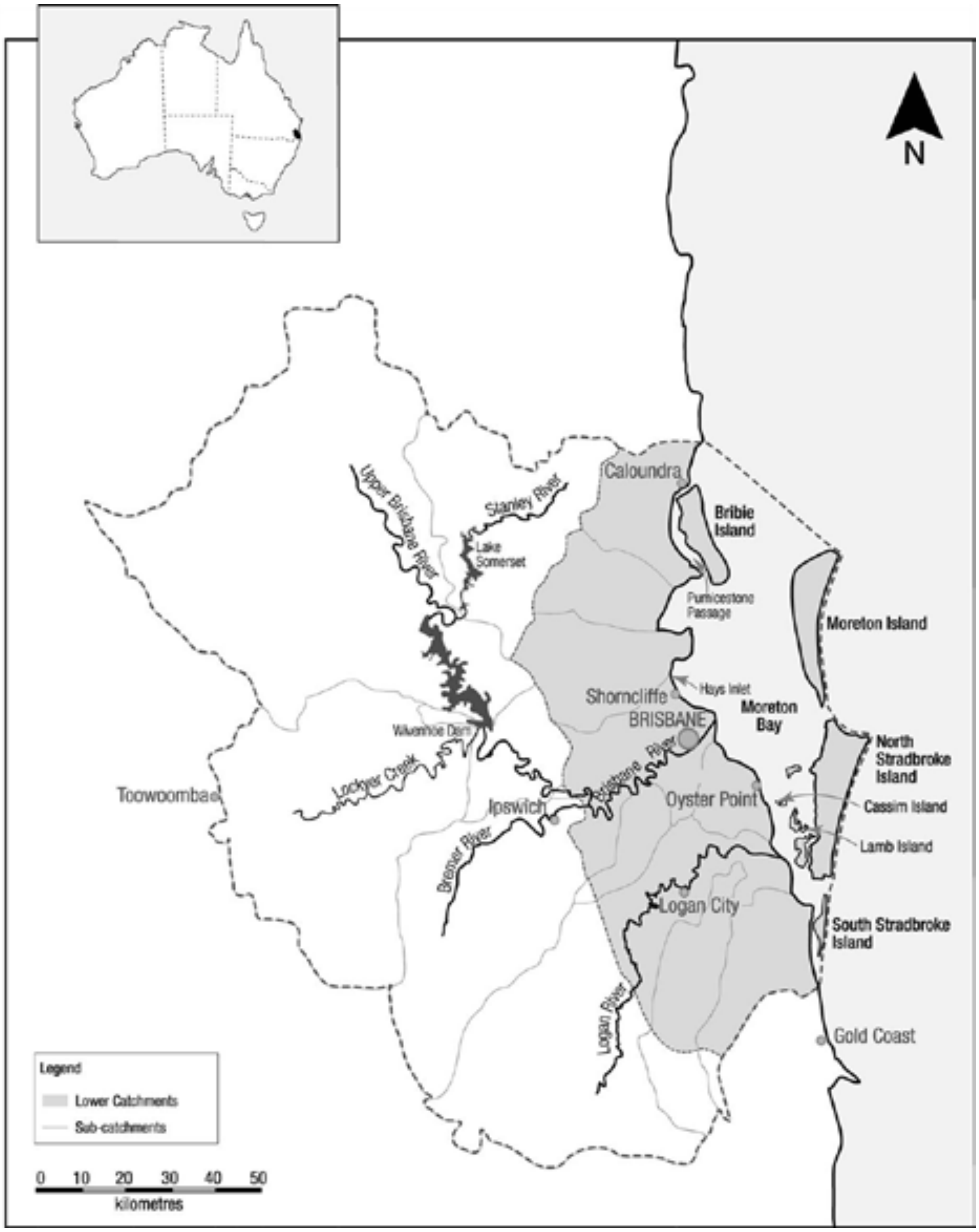

Figure 1. The study area, showing upper (white) and lower catchments, islands and Bay areas (shaded). Traditional Custodians' areas extended slightly north and south of the shaded areas. Fine lines show catchment boundaries.

[2] The count is according to at least one mention in an interview, regardless of the number of times it was repeated

Table 1. Summary of values expressed by non-Aboriginal people (percent who expressed each value). Because of the mix of focus groups and individual interviews with Traditional Custodians, frequencies cannot be calculated for those interviews.

Values definition	Percent	How values are expressed in relation to Moreton Bay and its catchment
Humanistic: emotional attachment	88%	People feel a deep emotional attachment—a '*love*', '*bond*' or an '*affinity*'—to the waterways. These emotional connections are developed through family heritage; living, working or socialising along a given waterway; or associating it with a significant or memorable life experience. ... a *personal experience and closeness...*
Naturalistic: direct experience of nature	83%	Waterways are places where people can connect with nature and explore the natural world. This is particularly important for those living in a highly urbanised environment. *…it's just bursting with life, everywhere you go…*
Moralistic: ethical concern for nature	75%	People expressed a need to protect the environment, which they acknowledge is under threat from urbanisation and development. *…Don't you look after something you find precious?*
Aesthetic: physical appeal and beauty	71%	An appreciation for the beauty of the waterways is valued by many. *…This is paradise, absolute paradise...*
Utilitarian: practical and material use of nature	68%	The waterways are valued for many practical and material purposes. For example, in the upper catchments, water from creeks is used for farming and in households. In the lower catchments, the deep channels within waterways are important to the boating and shipping industries. *…I think the water itself is a life blood for towns...*
Ecologistic: scientific appreciation for ecological functions	61%	People appreciate that the waterways in South East Queensland have important ecological functions. Some of the habitats and species found in the region are of international significance. *…there's all sorts of habitats, all sorts of diversity so we get groups, not just local ones but international ones that come to understand these areas and value them...*
Negativistic: fear and aversion from nature	42%	Participants talked about aspects of the waterways that need to be treated with caution and respect, particularly in times of flood in the upper catchments. *…understand the potentiality for it to completely envelop you and overpower you...*
Spiritual: feelings of transcendence; reverence for nature	25%	Waterways can invoke a sense of connection to life and the world around them, and feelings of transcendence. *…that feeling of belonging to a larger thing than just me…*

Dominionistic: mastery and control of nature	22%	Some people assert a need to control and manage water flows to mitigate the impacts of flooding. For others, waterways provide many physical and mental challenges, often in recreational pursuits, such as 'outwitting a fish' in upper catchments, and kayaking or boating on the Bay. *…it can be quite intense at times, and then there's the mental aspect of planning tactics, picking wind shifts…*
Symbolic: use of nature for language and thought	19%	Waterways symbolise important and meaningful aspects of life for people. An arts community on one of the Bay islands draws inspiration from the waterways in their artwork, which serves to heighten others' appreciation and love for the Bay. *…to use that island as their next muse…*

The ways in which people expressed these values, and the similarities and differences between non-Aboriginal people and Traditional Custodians, are expanded below.

Humanistic values: Emotional attachment
A significant majority of participants from throughout the study area, the Traditional Custodians and non-Aboriginal alike, espoused deep emotional attachment to the waterways, expressed as a love, a bond, or an affinity.

Traditional Custodians have a unique relationship with water places in that these relationships are deeply embedded in their cultural identities. They explained how their cultural identity is embedded in ancestral links to waterways. Traditional Custodians felt grief where their relationship to particular places was threatened or had been affected by development processes:

> *That's very close to me, that country there – they ripped my childhood out, part of my childhood, you'll never see that again there, it's gone forever. It bugs me.*

The other participants' connections with waterways also developed over time, through people having personal experience with a given waterway. These are highly personalised and include social relationships, developed through family heritage; living, working or socialising along a given waterway, or associating it with a significant life experience.

> *I value [these waterways] because I have such a longstanding and intrinsic relationship with this area...For me, I don't really care if I never leave this place, I am so happy here and in one sense I feel like an unofficial custodian...I get withdrawal symptoms if I don't access the water, even if it's to stand ankle deep, at Oyster Point.* (Moreton Bay participant)

Waterways convey cultural, community and personal identity. One participant speaking about the Sandgate area stated: '*it's our way of life down here, we're absolutely connected to the Bay*'. She described the strong collective attachment her community has to the Shorncliffe Pier, an iconic feature of the built environment in the area. This pier is historically important and provides a unique and accessible means to interact with the Bay, to fish, go walking, ride bikes and take wedding photos. An important aspect of the humanistic values is the extent to which they have a socially shared aspect. Many participants talked of developing their attachments to particular waterways through going there with others, particularly family and loved ones, and of enjoying those places with their significant others:

> *I think the first time that my wife took me to her little secret swimming hole was pretty special. I still remember that with a great deal of fondness. But as I say, there's just so many different memories that are tied to that particular waterway.* (upper catchment participant)

Naturalistic values: Direct experience of nature

The waterways are widely valued as important places for people to directly experience and interact with nature. Over 80% of the non-Aboriginal people interviewed immerse themselves in nature through activities such as swimming, diving, fishing, hiking or boating. Many described how they derive mental benefits—feeling relaxed, calm and peaceful—when being on and near the water. As a lower catchment participant stated:

> *You just feel relaxed, you need that escape. A connection to nature helps you deal with stress. I feel like spending all weekend out in nature.*

While the waterways provide many mental benefits on an individual level, they also provide important social benefits. Waterways are popular places where people choose to socialise with others. When people spoke about enjoying the natural qualities of the waterways, they often spoke of sharing those experiences with others. Waterway environments thus provide important backdrops for people to engage both with the natural world and with other people.

Many participants spoke of their joy in seeing wildlife within and around the waterways; experiences they described as incredible, stunning and amazing. In particular, people are excited by seeing the abundance and variety of marine life within Moreton Bay or a platypus in a stream in the upper catchments. One described the waters off North Stradbroke Island:

> *The amount of marine life that we have out here is so special and unique. A lot of South East Queensland just take it for granted that we have Moreton Bay on our doorstep here. We've got dugongs and six of the world's seven species of turtles. It's just a really special place.* (lower catchment participant)

Other sensory pleasures—the sounds and smells associated with waterway—were also appreciated: the sounds of a running creek, or cicadas.

People around the lower catchments and Bay explained that the opportunities the waterways provide for experiencing nature were particularly important when living in a highly urbanised area. Many appreciate that they can access beautiful, natural environments whilst still being in close proximity to a major city. They can feel a sense of remoteness away from people, as one participant described when on his houseboat on Pumicestone Passage: '*We're* *the only people there and you can't believe that you can be so close to human population yet so far*'.

For some Traditional Custodians, naturalistic values surfaced in memories, as they described how the natural qualities of certain waterways have diminished over time. Other Custodians expressed how they continue to enjoy nature within the waterways, particularly those that are teeming with life.

Moralistic values: Ethical concern for nature
Three-quarters of participants express a sense of ethical responsibility for habitats and species, especially species described as fragile and delicate ecosystems, under threat from population growth and development in the region. There is thus a strong desire to educate the public on the ecological significance of waterways and promote environmental awareness:

> *If the community doesn't know about it and understand the beauty and how it can be enjoyed for recreation, then should it ever be threatened, why should they fight to preserve it?* (lower catchment participant)

In the upper and mid catchments, moralistic values were aligned with utilitarian values and the need to look after the waterways to maintain a sustainable water resource: '*It's our lifeblood*'. In the lower catchments and around the Bay, moral concern was associated with ecologistic-scientific values (see below) and the recognition that waterways are unique ecosystems. For Traditional Custodians, moral concern was driven by cultural responsibility to look after the waterways: a custodial ethic.

Aesthetic values: Physical appeal and beauty
An appreciation of the beauty of the waterways, present or past, is widely shared among all participants (70% of the non-Aboriginal people). Non-Aboriginal participants throughout the study area value the beauty of the rivers and creeks and Bay including the scenic quality of the wider landscapes and seascapes of which they form part. The fundamental difference between non-Aboriginal participants and the Traditional Custodians is that the non-Aboriginal people see and appreciate current beauty, whereas the Traditional Custodians, while holding this value, recall the past beauty of waterways and regret their long-term deterioration.

Many aesthetic qualities are valued, such as the colours of waterway environments: the blues and beiges of the Bay, the flora and fauna, the unique perspective when looking back at land when out on the water, as well as the clarity of the water. One participant described Hays Inlet in the northern Bay:

> *When you look out from the bridge, depending of the tide, you might see the channels of sand. If the sun is setting, it will be all pink and silver and really beautiful. It's also green, you look out further and you see all the trees and mangroves, and no one's built there, so it's this natural patch of beauty.* (Moreton Bay area participant)

In the upper and mid catchments aesthetic values pertain, often but not always, to what are seen as more ‘pristine’ areas. One participant described their appreciation for creeks in the upper catchments, stating: ‘*its scenic value, I think it counts for a lot. I think it’s part and parcel of rural scenes, and there’s some beautiful waterways around*’.

Traditional Custodians feel despondent about the beauty that has been lost over time. Traditional Custodians expressed aesthetic values in contrast to their childhood memories of places; something of the past. They lamented how waterway environments in South East Queensland have been significantly degraded as a result of ongoing development, urbanisation and population growth within the region: ‘*it was beautiful country, fair dinkum*’. Traditional Custodians used the aesthetic qualities of the waterways as indicators of ecosystem health, relating them to their ecologistic values.

These differences in aesthetic appreciation reflect different temporal relationships with waterways. The Traditional Custodians spoke about their ongoing ancestral connections to waterways and the significance of water places to their dreaming stories, enhancing their rich social memory of the waterways. Non-Aboriginal participants spoke about their own experiences with the rivers, creeks and Bay—what they could personally remember from the past and how they see the waterways today.

Utilitarian values: Practical and material use of nature

Just over two-thirds of the non-Aboriginal participants interviewed derive utilitarian benefit from natural resources found in and around the waterways. In the upper and mid catchments, people depend on rural waterways for local irrigation, stock, domestic and town water use. As one participant stated: ‘*We can’t live without it*’. In the saltwater lower catchments and Bay, people spoke about the value they derive from aquatic species (fish, crabs, oysters) which are used for recreational enjoyment, commercial purposes and consumption. The naturally deep channels of Moreton Bay and the mouth of the Brisbane River are also valued for their uses. They are important to boat-building enterprises and support a shipping industry that transports people, goods and resources in and around SEQ. Physical features of all the waterways are also used in creative expression by artists and musicians, particularly on the Bay islands.

Traditional Custodians expressed utilitarian value of water by acknowledging its necessity in sustaining all life:

> *It’s probably the most important ingredient on the planet, aside from sunlight. So in that regard, water is very important, salt water or fresh water, because we know that it gives life. So that’s the immediate basis, that it’s a life force, it gives life, and it sustains life.*

Traditional Custodians also spoke of their family’s use of water resources in the past for day- to-day living (e.g. cooking and washing) and small-scale commercial activities. For Traditional Custodians, waterway resources also hold cultural significance and are important for continuity of cultural lifestyles and traditional knowledge, for example, the use of these resources for traditional medicine.

Ecologistic-scientific values: Appreciation of ecological functions
Ecologistic-scientific[3] values, held by around 60% of the non-Aboriginal participants, were expressed through people's recognition of the important ecological functions the waterways support, and through an appreciation of the varied and unique species and ecosystems found within the region, which provide important educational and research opportunities. For participants in the lower catchments and Bay, ecologistic-scientific values were often linked to moralistic values and a need to protect and effectively manage the waterways, particularly those under threat from development pressures. The unique species and ecosystems of Moreton Bay were recognised as providing important opportunities for scientific research and education:

> *There's so many habitats in Moreton Bay because Moreton Bay's an overlap of the tropical and the temperate regions and it's sheltered. It's fairly lagoonal, there's all sorts of habitats, all sorts of diversity, so we get groups, not just local ones but international ones that come to understand these areas and value them. They come to understand the habitats, the importance of the habitats.* (Moreton Bay participant)

Traditional Custodians also linked ecologistic-scientific values to moralistic values. They highlighted the benefit of enhancing knowledge of how local ecosystems function so that they can be cared for better. In the upper and mid catchments, the desire to understand ecological processes was linked to achieving management goals, and to achieving personal goals, such as improving one's fishing ability.

Negativistic values: Fear of and aversion to nature
Though negativistic values were mentioned infrequently (by fewer than half of the people interviewed, more in the upper than lower catchments), certain aspects of the waterways are avoided or may be feared, including the wildlife that live in and around the waterways (sharks and snakes). Traditional Custodians and those living in the lower catchments and around the Bay avoid interacting with water of poor quality, which could be harmful to one's health:

> *If they clean this area up, I'd enjoy it much more. But it's disgusting. When you get wet, if you've got an open cut, you then have to go home and put alcohol on it… there's a much higher risk of bacterial infection and things like that.* (Traditional Custodian)

When boating out on the Bay, people treat the treacherous conditions that can occur with caution and respect.

> *When people don't grow up having that kind of relationship with a place like Moreton Bay that they don't understand, the potentiality for it to completely envelop you and overpower you.* (Moreton Bay participant)

[3] Kellert's framework makes a distinction between the more reductionist scientific, and more integrative ecological, perspectives, though both emphasise understanding the natural world through study.

Similarly the power and strength of the waterways in times of flood are met with fear and awe, particularly by those living in the upper and mid catchments whose livelihoods depend on water and who are susceptible to the impacts of extreme weather events.

Traditional Custodians avoid certain waterways as a sign of respect to water spirits and ancestors. They also spoke sadly about avoiding much loved waterways which have significantly changed over time through development and environmental degradation: *I don't go out to the river anymore because I don't want to see what's out there... I just want to remember it the way it was.* (Traditional Custodian)

Spiritual values: Feelings of transcendence; reverence for nature

Spiritual values were raised as secular spiritualism, rather than in relation to a formal religion. Many participants described feeling a sense of belonging and connection to life and the wider world when interacting with certain waterways. One participant described this sentiment when taking in the view on North Stradbroke Island (Minjerribah):

> *I feel calmer, and my mind feels open and…that feeling of belonging to a larger thing than just me.* (lower catchment participant)

Traditional Custodians expressed a stronger, more holistic spiritual attachment than non-Aboriginal participants, with one Custodian stating:

> *All the waterways are significant because… our dreamtime and creation stories are all encompassed around the waterways, the mountains, the coastal areas.*

In addition to dreamtime stories, spiritual connections to waterways are carried through water spirits which guide people's interactions with waterways and sacred totems of marine and estuarine animals:

> *Dugong, sea turtle, dolphin and whales, along with many other species are sacred Aboriginal totems for saltwater people in coastal areas.*

Dominionistic values: Mastery and control of nature

Dominionistic values are about people's urge to master, control and have dominance over nature. This value was seldom expressed (around one-fifth of non-Aboriginal participants), and it was expressed in very different ways when it was raised. Participants in rural areas spoke about controlling waterways to protect people and their livelihoods from the impacts of flooding and droughts, whereas this was seldom raised by those living in more urbanised areas in the lower catchments and around the Bay. Rural participants thus value the ability to control waterways to utilise a resource whilst also guarding against the impacts of extreme climatic conditions. Within recent years, floods have devastated rural areas, which many participants in the upper and mid catchments experienced firsthand.

In the lower catchments and around the Bay, people expressed dominionistic values in a very different way, in relation to the physical and mental challenges they face personally in certain recreational pursuits and when interacting with the waterways. For example, they value the experience of acquiring and putting into practice the skills needed to sea kayak or sail on Moreton Bay: '*It's full of surprises and that's an essential to part of life I think. Just having surprises and having a place where surprises can happen*'.

Traditional Custodians did not express dominionistic values in relation to waterways. This issue was discussed during a workshop in the final stages of the project. They explained that their customary relationship with the natural environment involves working harmoniously with it, using their knowledge, rather than seeking to control it. They explained that the closest their people would come to a dominionistic value or behaviours is in traditional management practices, such as burning the landscape or building fish traps whereby Aboriginal people alter the environment for specific purposes. This is consistent with utilitarian, not dominionistic, values.

Symbolic values: Use of nature for language and thought
Although this was not widely expressed in the interviews (about one-fifth of non-Aboriginal participants), the waterways symbolise important and meaningful aspects of people's lives, both individually and as a community. On a personal level, particular waterways symbolise significant life experiences. Talking about these experiences brought up deep emotion within participants. Some spoke about scattering the ashes of loved ones within Moreton Bay, with one participant explaining that it seemed '*the right place, the right thing to do*'.

At a community level, the waterways carry symbolic meaning linked to community identity. For example, the Shorncliffe Pier is important to the identity of the local community: '*it's a huge, huge focal-point*'. Moreton Bay is also important to the identity of an arts community on one of the Bay's islands. This community draws inspiration from their relationship to the Bay to create art which in turn heightens the appreciation of others' for the Bay.

For Traditional Custodians, Aboriginal place names carry meanings that convey the importance and significance of those places. Some places were named after abundant animals of that area, Bribie Island for example, which is called 'Yurin' or 'place of mud crabs'. Other place names represent totems, for example 'Ngarang-Wal' translates as 'shovel-nosed shark', an Aboriginal totem.

Implications
Recognising this diverse set of values brings new insights for the social aspects of environmental management, which until now has focused on an apparent competition between resource use (utilitarian values) and conservation (involving moralistic and ecological values). While the waterways in SEQ support a wide range of behaviours, including cultural, commercial, recreational and stewardship activities, the ways in which people actually value these places turn out to be widely shared. Almost all of the people interviewed (88% of non-Aboriginal participants[4]) expressed a deep, emotional connection with a particular waterway (humanistic value). While these personal connections are unique,

[4] These figures are given indicatively to highlight approximate proportions of participants holding a value. Because the sampling was purposively capturing heterogeneity of types of participants within the catchments rather than being a random sample capable of representing the entire population of the region, modest reliance should be placed on these figures.

they all stem from people having, as one participant stated, a personal experience and closeness to a certain river, creek, dam or place within Moreton Bay or its catchments. These experiences may be gained through family associations, living or working close to a waterway, or associating it with a significant life experience. Another dominant value expressed (83%) concerned the importance and significance of the waterways as a place to directly experience and immerse oneself in nature (naturalistic value). People enjoy being in a natural environment and seeing the diversity of animal and plant species that live in certain places within the region. People also commonly voiced a moralistic concern (moralistic value, 75%) for the waterways and a need to care for and protect them. Many acknowledge that these natural places, which they love, use and recognise, provide important ecological functions (ecologistic or scientific values), are under threat from population growth and development in the region. In contrast with the earlier historical study of values based on media analysis (5), there was less emphasis placed upon utilitarian values (68%), and these were more often expressed in the upper catchments than in the lower catchments and Bay.

The degree of sharing, and the range of values held by the public, suggest new ways of enjoining public support for managing waterways, and new ways of managing the waterways to maintain people's very strong affiliation with them. Managers can explore how they can draw upon these values in designing and implementing management strategies, and in their communication with the public. For example, managers can build on expressed values to create localised management narratives that resonate with the deep connections people have with waterways in SEQ. Healthy Waterways began summarising social dimensions, including values, in its annual monitoring report card from 2015 (11–13).

Presumptions that people of the upper and lower catchments could be equally motivated to manage the rivers in the interests of Moreton Bay—an idea that has underpinned much of Healthy Land and Water's (and predecessor organisations) communication down the decades—are challenged by these results. People in the upper catchments associate closely with their local waterways, as evidenced by the waterways they described as important and meaningful to them. Compared to the lower catchment participants, fewer chose to describe Moreton Bay, located 80 to 150 km downstream, as a valued waterway. Upper catchment participants showed strong expectation that local waterways be managed towards local concerns such as drought, floods, erosion, weeds and access, and not primarily for downstream needs.

Further, the passion towards the waterways highlights the importance of and potential for further recognition of voluntary stewardship, by Traditional Custodians, voluntary organisations and individuals (14). It also shows latent political support for managing waterways, a point important in making resourcing decisions.

Notes

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Community knowledge about water and engagement in waterway protection in South East Queensland

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Abstract
Protecting waterway health requires active community support where individuals act to protect waterways and support new policies or investment. A critical first step in engaging with communities is to identify community knowledge about water. This study examined water-related knowledge using a survey of 807 residents of South East Queensland. This knowledge was assessed by 15 questions on the impact of household activities on waterways, the urban water cycle and water management. Engagement in waterway protection was assessed via household pollution-reduction behaviours, support for raingardens, and willingness to pay for waterway protection. Findings suggest that while most people know that household actions influence the health of waterways, less than one third understand that stormwater is not treated before entering waterways. Greater knowledge was associated with greater uptake of pollution-reduction behaviours, greater support for water sensitive urban design (raingardens) and greater willingness to pay for waterway protection. These findings highlight both the importance of water-related knowledge in the community and fostering that knowledge when planning community engagement that aims to change behaviour or build support for integrated water management initiatives.

Keywords: citizenship, behaviour, sustainable urban water management, policy support, water sensitive, community engagement, water quality, stormwater pollution

Introduction
Water quality in Moreton Bay is influenced by diverse land-use practices across its upper and lower catchments. Increasing urbanisation, and the accompanying increase in the area of impervious surfaces across urban catchments, increases flow of stormwater pollutants into waterways and coastal areas. This has adverse effects on water quality. Urban stormwater pollutants include heavy metals, nutrients, sediment, pathogens and gross pollutants such as plastics (1-4).

It is increasingly recognised that urban water management paradigms must address environmental outcomes. These approaches are variously referred to as 'integrated urban water management', 'sustainable urban water management', 'water-sensitive cities', or 'total water cycle management' (5, 6). Within these frameworks, water management goals extend beyond ensuring water supply and sanitation to include enhancing waterway health. To achieve positive environmental outcomes, stormwater pollutants that degrade waterways and coastal ecosystems must be managed effectively (2, 7).

Pursuing waterway health within sustainable urban water management requires diverse solutions that span new technologies, investment approaches and policies (5, 6, 8). For example, water sensitive urban design initiatives — also referred to as green infrastructure — involve installing biofiltration systems within urban environments. Biofiltration systems such as raingardens or wetlands can reduce stormwater flows and reduce stormwater pollutant loads (6, 7). In order to improve outcomes, some argue that new approaches to water management must also consider the sociocultural context in which these solutions are implemented (9). An important element of any strategy to manage stormwater pollution is building community support and acceptance of changes in policy, practice and technology (6, 9, 10). Therefore, a critical element of promoting waterway health is fostering an engaged citizenry. Engagement in water-related issues is multifaceted and incorporates (i) cognitive engagement – knowledge and awareness, (ii) emotional engagement – concern and supportive attitudes, and (iii) behavioural engagement – adoption of civic and household behaviours that promote sustainable water management (9). Within this framework, engaged citizens are those that understand, value and actively support the necessary changes in technology, investment and policies associated with sustainable water management.

Community actions have a significant impact on water demand, water quality, and potentially, the political will of governments to make significant changes to water policy and infrastructure (11). Community opposition to potable recycled water initiatives and the subsequent derailing of recycled water schemes (12) illustrates the importance of fostering community support for new water schemes. Much research has examined the determinants and importance of pro-environmental attitudes and behaviours in the community (13-15). Even though knowledge is considered a necessary precursor to environmentally friendly behaviour, there is relatively less research assessing that community knowledge. Therefore, the aim of this study was to assess water-related knowledge of South East Queensland residents, examine social factors associated with this knowledge, and explore the relationship between knowledge and support for sustainable urban water management initiatives relevant to water quality in Moreton Bay and the waterways of South East Queensland.

The role of water-related knowledge

Knowledge and understanding of water issues in the community are considered essential ingredients for solving water-related problems. There are several types of knowledge of particular relevance here: declarative knowledge, which refers to general awareness about an issue; procedural knowledge, which encompasses how to achieve a particular goal; and effectiveness knowledge, referring to understanding the relative effectiveness of different actions (16). Some researchers argue that knowledge is a core component of water-related engagement (9), environmental citizenship (17, 18) and environmental literacy (19). 'Water literacy' integrates knowledge about water with the capacity to apply this knowledge to decision making (20). The emerging emphasis on sustainable water management suggests that important areas of water knowledge for individuals should include the urban water cycle and impacts of urbanisation on waterway health via stormwater pollution, in addition to issues related to water demand, supply and treatment (6). Assessing community knowledge about water is important for a number of reasons. Community engagement initiatives are thought to be more effective when targeted to, and aligned with, existing knowledge within the community (21, 22). In addition, identifying strengths and weaknesses in community knowledge about water provides an important foundation for initiatives that aim to increase community knowledge.

Research about determinants of environmental behaviour highlights the importance of knowledge, suggesting that knowledge is a necessary, although not sufficient, ingredient to influence behaviour (16). Knowledge is one of many factors that can influence diverse pro-environmental behaviours (11, 23, 24); others include demographics, social context, psychological factors (e.g. environmental identity, social norms and values) and economic factors (e.g. pricing schemes) (11, 14, 25, 26). Research also highlights the importance of knowledge as a component of building community support for policies related to water conservation (27), waterway protection (28-30), water sensitive urban design (31) and alternative water sources (32).

The current study

Existing research suggests that community knowledge about water management may be poor, both among South East Queensland (SEQ) residents (33) and at a national level (34). Despite the important role that knowledge may play in driving water-related behaviour change or policy support, there is scant research focusing on water-related knowledge and its relationship with outcomes such as adopting individual behaviours or support for policies related to waterway health. A sample of adults residing in SEQ was surveyed to gauge community knowledge about water-related issues and assess support for water-related policies and adoption of behaviours related to water quality. Specifically, this chapter will address the following questions: (i) how does knowledge vary across different water-related issues, (ii) what characteristics are associated with water-related knowledge, and (iii) is water-related knowledge associated with individual behaviours and support for policies related to waterway health? Taken together, the findings will identify strengths and weaknesses in water-related knowledge, and enable water practitioners to more effectively design and target a range of engagement initiatives, from information campaigns to participatory initiatives.

Methods

Participants and procedure

A total of 807 adults in SEQ were recruited (as part of a larger study of Australian residents, N=5194) using an online panel provided by a social research company. All eligible panel members were invited to participate via email and offered the standard compensation (points and entry into a bimonthly cash prize draw). The 25-minute, online survey was administered during February–March 2014. Institutional ethical clearance was obtained prior to study commencement.

Measurement of water-related knowledge

Water-related knowledge was assessed using 15 items about the influence of household activities on water quality, catchments and the urban water cycle, and water treatment (Table 1). These items were adapted from a previous study (33) that included items based on what Australian water professionals identified as important for individuals to know about water. Fourteen items were rated on a 5-point Likert scale (1=*strongly disagree* to 5=*strongly agree*). A *don't know* option was also included. Eight items were framed such that the correct response was *agree*/*strongly agree*; six items were worded such that the correct response was *disagree*/*strongly disagree*. Neutral responses (*don't know* or *neither disagree nor agree*) were coded as incorrect. Finally, one item used a multiple-choice response: 'Which of the following options best represents your understanding of what a catchment is?' Response options were: (a) The area that retains water like a wetland or a marsh, (b) All of the land area that drains to a specific river or waterway (*correct*), (c) A reservoir that serves as a water source, (d) A small building where water is stored, (e) None of these, and (f) Don't know. A water knowledge index was calculated based on the number of correct responses (range 0–15).

Participant characteristics

The survey also measured the following factors (see full report for details (34)):

- socio-demographics, cultural background, and household characteristics
- information about water – recent sources of information about water (9 items)
- experience of water restrictions and whether behaviour had changed during restrictions (2 items)
- waterway use – frequency of local waterway use for diverse social activities (14 items)
- social capital – membership or participation in community organisations (11 items)
- household environmental identity – the degree to which the respondents see their household as environmentally sustainable (3 items).

The full methodology is reported elsewhere (34).

Measures of support for pollution-reduction behaviours and policies

Three variables were created that assessed respondents' engagement in pollution-reduction behaviours and support for policies related to water quality:

- *pollution-reduction behaviours* – mean frequency of performing seven pollution reduction behaviours (e.g. preventing animal waste from entering waterways, putting rubbish in the bin) (range 1–5, Cronbach's α=0.69)
- *support for raingardens* (definition provided) – willingness to install a raingarden on their property (yes/no), and support a raingarden in their street (yes/no)
- *willingness to pay for waterway protection* – amount willing to pay in their household rates to improve health of their local waterways such as creeks, rivers and bays (coded as willing yes/no).

Statistical analysis

Predictors of water-related knowledge and the relationship between water-related knowledge and pollution-related behaviours and policy support were identified using linear regression for continuous dependent variables (knowledge, pollution-reduction behaviours) and logistic regression models for dichotomous dependent variables (support for raingardens, willingness to pay for waterway protection). The initial stage of analysis examined determinants of water-related knowledge using linear regression analysis. All demographic, household and geographic characteristics, water information sources, life experience and psychosocial factors were included as independent variables. No interactions were examined. The second stage of analysis examined whether water-related knowledge was associated with the following: (i) uptake of pollution-reduction behaviours, (ii) support for raingardens, and (iii) willingness to pay for waterway protection. For each outcome a stepped regression analysis was conducted:

- Step 1 quantified the unadjusted influence of knowledge on each outcome
- Step 2 adjusted for socio-demographics (age, sex and education, income and home ownership)
- Step 3 adjusted for socio-demographics plus social capital, waterway use, environmental identity and information exposure.

Where analysis examined a binary outcome (i.e. for support for raingardens and willingness to pay for waterway protection), logistic regression was used. This generates an odds ratio as a measure of association between knowledge and the outcome of interest. All models were checked to ensure assumptions of normality and homogeneity were met.

Results

Participant characteristics

The mean age of respondents (N=807) was 48.7±16.2 years, and 55.1% were female. The majority of respondents lived in urban centres (90.1%), had qualifications beyond high school (65.2%) and were employed (50.6%). The most commonly cited sources of water-related information were water utility bills (25.0%) and television (25.0%). Approximately half the sample (50.7%) reported no exposure to water-related information in the previous six months.

Water-related knowledge

The mean number of questions answered correctly was 8.66 (SD=3.84, range 0–15, 8.66 is equivalent to a score of 58%). One in four respondents (n=202) scored 80% or above, and only 1.9% of respondents (n=15) answered all items correctly. More than three-quarters of respondents knew that household actions can reduce urban water use and influence the health of waterways, whereas only about one-third correctly identified that domestic wastewater is treated prior to entering waterways, that urban stormwater is not treated and that these are carried via different pipes (Table 1).

Factors associated with water-related knowledge

Regression analysis indicated that water-related knowledge was higher in males ($p<0.01$), older respondents ($p<0.001$) and in those currently studying ($p<0.01$) or with greater education ($p<0.01$) (Table 2). A northwest European ancestry ($p<0.05$) was associated with greater water-related knowledge, whereas speaking a language other than English at home ($p<0.001$) was associated with lower water-related knowledge. Those renting accommodation exhibited poorer water-related knowledge ($p<0.05$). Higher levels of water-related knowledge were associated with experience of water restrictions ($p<0.001$), social capital ($p<0.05$) and household environmental identity ($p<0.001$). Respondents reporting more sources of water-related information in the previous six months also reported greater water-related knowledge ($p<0.01$) (Table 2).

Table 1. South East Queensland residents were provided with the following statements about water management and asked to rate their agreement with each statement on a 5-point scale, as an indicator of water-related knowledge. Most items were worded such that the correct response was 'agree' or 'strongly agree'. Items 6, 9, 13, 14 and 15 were worded so that the correct response was 'disagree' or 'strongly disagree'. Item 10 was a multiple choice question.

Knowledge statements	% Correct (n)
1. Water conservation actions by householders can significantly reduce the amount of water used in urban areas	79.2% (639)
2. What individual residents do in their home and garden has consequences for the health of waterways and coastal bays	75.5% (609)
3. Planting native plants along a waterway's bank improves the health of waterways	73.1% (590)
4. The fertilisers that individual householders use in their garden can have a negative impact on the health of waterways	72.6% (586)
5. Waterways can be damaged by stormwater flows	71.6% (578)
6. Soil erosion from urban areas does not affect the health of waterways*	66.8% (539)
7. The pesticides that individual householders use in their garden have no negative impact on the health of waterways*	63.3% (511)
8. I know where my household drinking water comes from (e.g. dam, groundwater, desalinated water etc.)	61.8% (499)
9. Waterways can cope easily with large amounts of sediment (i.e. eroded soil suspended in the water) *	57.2% (462)
10. A catchment is the total land area draining to a specific waterway**	55.9% (451)
11. I know what catchment my household is part of	40.5% (327)
12. The amount of water available for use is finite	39.5% (319)
13. Stormwater from roofs and roads is treated to remove pollutants before entering the waterways*	36.1% (291)
14. Domestic wastewater and stormwater are carried through the same pipes*	34.0% (274)
15. Wastewater from domestic bathrooms and laundries receives little or no treatment before entering waterways*	27.6% (123)

* reverse scored items where the correct response is *disagree* or *strongly disagree*
** multiple-choice question

Table 2. Regression model examining what individual characteristics are significantly associated with water-related knowledge (R^2=0.33).

	Nonstandardised coefficient (B)±SE	95% confidence interval	t	Standardised coefficient
Age	0.85±0.16	0.54, 1.15	5.44	**0.22*****
Sex (male)	0.90±0.26	0.39, 1.41	3.49	**0.12****
Education	0.44±0.17	0.12, 0.77	2.68	**0.09****
Currently studying	–0.45±0.15	–0.75, –0.15	–2.93	**–0.10****
Unemployed	0.00±0.16	–0.25, 0.26	0.03	0.00
Household income	0.02±0.14	–0.26, 0.30	0.17	0.01
Language other than English at home	0.55±0.15	0.25, 0.85	3.59	**0.12*****
Northwest European ancestry	–0.33±0.13	–0.59, –0.06	–2.44	**–0.09***
Currently renting	–0.31±0.13	–0.57, –0.05	–2.38	**–0.09***
House with garden	0.11±0.13	–0.15, 0.36	0.81	0.03
Waterway use	0.10±0.1\5	–0.20, 0.40	0.65	0.02
Experienced water restrictions	–0.67±0.16	–0.96, –0.37	–4.45	**–0.15*****
Social capital	0.32±0.16	0.01, 0.63	2.01	**0.07***
Environmental identity	1.03±0.14	0.76, 1.30	7.52	**0.26*****
Information exposure	0.33±0.13	0.08, 0.58	2.63	**0.09****

$^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$. Significant findings are highlights in bold.

† For significant findings, a positive coefficient reflects a positive association between the ‘predictor’ variable and water-related knowledge. Conversely, a negative coefficient reflects a negative association between the ‘predictor’ variable and water-related knowledge

Pollution reduction behaviours

The most frequently endorsed pollution reduction behaviours were ‘putting rubbish in the bin’, 89% of respondents indicated they always did this, followed by keeping the car well maintained (58.1% responded ‘always’) and disposing of chemicals through council transfer stations (41.8% ‘always’). Water-related knowledge was significantly associated with uptake of pollution reduction behaviours (p<0.001), even after controlling for socio-demographics and psychosocial factors (Table 3).

Willingness to support raingardens

One-third of respondents (33.2%, 268/807) indicated that they would be willing to install a raingarden on their property, and more than half (56.6%, 457/807) indicated that they would support the installation of a raingarden on their street. Water-related knowledge was associated with a significant increase in the likelihood of supporting private (p<0.001) or public (p<0.001) raingardens (Table 3).

Willingness to pay for waterway protection
One-third of respondents (33.2%, 268/807) indicated that they would be willing to pay higher rates for waterway protection. Water-related knowledge was associated with a greater willingness to pay for waterway protection at all model steps (p<0.001) (Table 3).

Table 3. Association between water-related knowledge and key outcomes of interest (pollution-reduction behaviours and support for initiatives that promote water quality).

	Pollution-reduction behaviours		**Support for raingardens in home**		**Support for raingardens in street**		**Willing to pay for waterway protection**	
Step	**β**	R^2	**Odds ratio**	**95% CI**	**Odds ratio**	**95% CI**	**Odds ratio**	**95% CI**
1	0.24^{***}	0.06	1.13^{***}	1.08, 1.18	1.11^{***}	1.06, 1.15	1.10^{***}	1.05, 1.15
2	0.22^{***}	0.08	1.17^{***}	1.11, 1.23	1.13^{***}	1.08, 1.18	1.13^{***}	1.07, 1.19
3	0.12^{**}	0.21	1.15^{***}	1.09, 1.22	1.12^{***}	1.07, 1.17	1.12^{***}	1.04, 1.16

$^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$

Note: Step 1 = unadjusted effect of knowledge on outcome, Step 2 = adjusted for socio-demographics (age, sex, education, income, and homeownership), Step 3 = adjusted for socio-demographics plus social capital, waterway use, environmental identity and information exposure.
CI = confidence interval
An odds ratio greater than one indicates that the 'predictor' variable increases the odds of the outcome occurring. An odds ratio less than one indicates that the 'predictor' variable reduces the odds of the outcome occurring.

Discussion

The study describes the knowledge of SEQ residents about the region's water management and the urban water cycle, and identifies factors associated with this knowledge. The findings can inform community engagement campaigns that seek to improve knowledge about water management and waterway health. Importantly, water-related knowledge was associated with greater adoption of pollution-reduction behaviours, support for policies related to improving waterway health and reducing impact of urban stormwater pollution.

In general, the level of knowledge was low with only one-quarter of respondents correctly answering at least 80% of questions. While this is higher than the national average (34), our findings indicate that certain issues, particularly those that relate to managing urban stormwater pollution, are not well understood by the community. For example, almost two-thirds of respondents did not know that stormwater is not treated prior to entering waterways, and almost half could not correctly identify the definition for 'catchment'. Qualitative research indicates that most community members consider stormwater management to be an issue of flooding and management of excess water, rather than pollutants (35). Stormwater pollutants, especially non-visible pollutants, are not 'top of mind' for most community members (35). Engagement campaigns that seek to build community support for pollution-reduction should not assume understanding of the issue and should incorporate information about the problem and proposed solutions.

The general approach to building awareness and knowledge is through information and education campaigns. While such campaigns may generate modest increases in community awareness (36), it is important to emphasise that knowledge is not simply a result of exposure to information. Individuals with poor topic knowledge may also exhibit characteristics such as poor information-processing skills or low personal interest in the topic. These reduce the likelihood of information detection or retention. As such, engagement initiatives that provide information only and do not address the broader social context or actively target disengaged subgroups may not generate meaningful changes in behaviours or policy support (9, 37). Our findings indicate that knowledge is associated with a range of social and contextual factors. For example, participating in community organisations can generate new opportunities for information exposure or learning by observing others (referred to as 'social learning' in psychological theory) (38, 39). Information and education campaigns may be more effective if they can build on active community experience, or focus on values of the target audience (9, 40). The poor understanding of words such as 'catchment' is a reminder to minimise jargon and technical terms when engaging with communities.

Water-related knowledge was associated with a variety of behaviours and support for policies relevant to promoting waterway health. This is consistent with other research linking greater knowledge with adoption of behaviours and support for policies (11, 24, 27, 29). Knowledge has been conceptualised as a 'necessary but not sufficient' ingredient for behaviour change. Knowledge about how to act (procedural knowledge) or the effectiveness of actions (effectiveness knowledge) may have a stronger influence on environmental behaviour than general awareness (declarative knowledge) (16). In practice, environmental behaviours are influenced by many factors, not just issue awareness. These include: (i) costs and benefits, such as physical effort or financial impact; (ii) social factors such as values, or social norms – the accepted 'rules' of behaviour within a social group; (iii) emotional factors such as status; and, (iv) contextual factors such as availability of garbage bins or recycling facilities (41, 42). Effective behaviour change programs therefore should not solely rely on information, but also address the psychological factors that influence behaviour (41). Nonetheless, our findings reinforce the importance of knowledge as a component of building support for water management initiatives. In practice, when working with communities it is important to recognise that knowledge is not binary, but varies in depth and breadth across issues — individuals may be well informed on some water issues, but poorly informed on others. When planning engagement or education initiatives, it is important not to assume pre-existing knowledge, and to make information relevant for the target group.

Conclusions

Our findings indicate that community knowledge about water management is poor, especially in content areas related to management of stormwater and wastewater. Higher knowledge was strongly associated with greater uptake of pollution-reduction behaviours, support for raingardens and willingness to pay for waterway protection, even after adjusting for participant characteristics. These findings highlight both the importance of water-related knowledge in the community and fostering that knowledge when planning community engagement that aims to change behaviour or build support for integrated water management initiatives.

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Stewardship as a driver for environmental improvement in Moreton Bay

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Abstract
Individuals and communities care for South East Queensland's waterways in a wide variety of ways. Stewardship began with Indigenous peoples who have cared for lands, species and waterways for many thousands of years. In South East Queensland there are now more than 500 community groups which volunteer their time and effort to manage and protect our waterways. These include Traditional Owners, Landcare, Coastcare, Bushcare, catchment management organisations, citizen science monitoring groups, non-government organisations and environmental education groups. They are collectively coordinated through collaborative organisations such as Healthy Land and Water, and are supported by their state and local governments and other partners. They contribute enormous effort, passion and awareness-raising to restoring and improving waterway systems. Landholders and industry, applying best management practices in their production and land management systems, and individuals taking their own initiatives and offering leadership, are equally stewards of our waterways. This paper presents an overview of the development of stewardship activity in South East Queensland, and discusses enabling conditions, pressures and drivers, and the changing face of the many types of waterway stewardship across the region. Brief case studies illustrate the variety of initiatives and their achievements. The paper concludes with a summary of achievements in the face of declining environmental conditions, and canvasses the information needs, actions and directions put in place to meet the challenges the region faces in the future.

Keywords: community, community groups, landholders, industry, catchment management, Indigenous

Introduction
Moreton Bay (Quandamooka) has outstanding environmental and cultural values. As long as humans have inhabited Moreton Bay and its catchments it has been valued highly for its

resources and contribution to society and economy (1, 2). The Bay and its catchments have been managed beginning at least 20,000 years ago through Traditional Owner occupation and care (3). The original custodians of South East Queensland managed the Bay and its catchments to preserve their inherent resource value.

More recently however, the rapid and widespread urbanisation, together with commercial and recreational exploitation of the Bay and its catchments, have had serious negative impacts on the extent and quality of its resources. Therefore, land care groups, concerned community members, academic groups, Traditional Owners, government and industry have all played a part in the stewardship of Moreton Bay (4). Stewardship and its role in environmental management became more widely accepted with increasing public understanding that approaches to land management could not be guided by economics or science alone but should also be underpinned by the many other types of values which shape people's connections to place (2).

In assessing stewardship and its effectiveness, there has traditionally been a focus on achieving changes to environmental condition, including actions that lead to an improvement in environmental quality. In a complex system such as Moreton Bay, many interrelated drivers affect condition (5, 6). Measures of outcomes, while indicative, may not provide the only measure of effectiveness of stewardship actions. Continued population growth and urban expansion, coupled with sediment and nutrient addition, associated with erosion in upstream primary production landscapes due to historical land-clearing practices, continue to place pressure on the environmental condition and closely related social and economic values of Moreton Bay and its catchments.

The current management paradigm in Moreton Bay and catchments is collaborative, involving many partners with different responsibilities in land and water management (7). It attempts to balance differing interests and encourages development in ways that mitigate or minimise impacts on the rivers and Bay. As such, stewardship support systems in the region have, in the main, been designed to create conditions that foster and enable actions, policy and behaviour that results in the preservation, protection or enhancement of environmental condition and serve to mitigate negative outcomes for the Bay's natural assets and the communities that benefit from them.

What is Stewardship?

According to Myers *et al.* (8), stewardship refers to the values held by individuals, communities, corporations and government organisations, and the actions of those bodies to manage something in a way that ensures its functionality and existence into the future. Western concepts of stewardship are commonly understood as voluntary individual and community environmental activity, occurring within institutional, social and economic frameworks including legislated or government-led requirements of duty of care for environments (9, 10). Indigenous concepts of stewardship are holistic, and involve management of resources through culture, knowledge, and family connections to place, drawing from the wisdom and experience of ancestors and seeking to hand on to future generations (Pinner *et al.* this volume (11)). UNESCO, in the Convention for the Safeguarding of the Intangible Cultural Heritage also draws attention to less tangible aspects of stewardship of nature: oral traditions and expressions, including language; performing arts; social practices and rituals; knowledge and practices concerning nature and the universe; and traditional craftsmanship (12). Consideration of stewardship also includes activities and processes that facilitate behaviour change, such as uptake of new and innovative practices, and institutional environments that nurture capacity for stewardship and people's willingness to engage.

The region's Ecosystem Health Monitoring Program (13) definition of waterway stewardship combines many of these elements:

> the process by which individuals, organisations and industry actively manage and value waterways and associated environments to remove, avoid or minimise negative impacts on all relevant waterways and receiving waters and proactively restore or conserve ecological health of waterways, wetlands and aquatic and marine environments.

For the purposes of this paper the term stewardship is applied to the values (caring) and actions of the diverse range of individuals and groups who manage and care for Moreton Bay and its catchments. Our emphasis is on voluntary, non-government activity, while recognising the enabling roles that government policies and programs play. We recognise facilitating as well as direct actions.

The paper is built from the professional knowledge of the authors, all practitioners in facilitating stewardship in South East Queensland. Short case studies, from our working knowledge, are included to illustrate the many aspects of stewardship we highlight.

Stewardship in Moreton Bay and its catchments

The management of Moreton Bay has been recognised internationally for its strong collaboration and regional focus (7). This collaborative and regional focus has been a significant factor in stewardship of the Bay. It has been motivated by a number of factors. The spatial attributes of Moreton Bay and catchments involve a large catchment to bay ratio, environmental and climatic variability, and highly varied land use. Moreton Bay is considered as a system, with attention to upstream-downstream relationships, competing users, and the nature of the Bay as a receiving body. Added to this are competing influences of social, economic and environmental values and usage, needing to be incorporated within large scale policy and management interventions.

Within this collaborative, regional set of arrangements, stewardship actions take on a 'shared value' approach that focuses on management of public goods, such as oceans, waterways, forests and fisheries based on the premise that we are all accountable for the sustainable management of these resources (14).

Types of stewardship actions undertaken in and around Moreton Bay are diverse and range from grassroots community action through to policy and regulatory actions. Some of these have included:

- Actions taken by individuals, organisations or industry sectors to protect, maintain, restore or rehabilitate waterways, marine and aquatic condition and associated

terrestrial environments and natural processes (riparian revegetation, conservation easements, dune rehabilitation)(15);
- Adoption of practices that reduce or mitigate negative impacts associated with certain activities e.g.: best management practices (BMP) in agriculture; erosion and sediment control; Water Sensitive Urban Design; (16–18);
- Community engagement and education (19, 20);
- Investment that increases the capacity or willingness of individuals, organisations and industry sectors to manage waterways and associated terrestrial environments in a responsible and sustainable manner (including government initiatives, local government capacity building programs and education extension);
- Government policy and legislation, corporate policy and actions aimed at mitigating or regulating associated negative impacts of resource use impacting waterways and associated terrestrial systems (21);
- Monitoring and reporting on social, economic and environmental condition and linkages (15).

Stewardship in this region, as elsewhere (7), relies heavily on collaboration. The following five case studies illustrate different examples of stewardship through collaboration. The first case study, Healthy Land and Water, shows region-wide collaboration in waterway and natural resource management, while also supporting a wide variety of organisations and individuals in undertaking stewardship 'on ground' at more local levels. The second case study, the Healthy Country Program, illustrates how collaboration between scientists and practitioners can inform and guide successful, well targeted, stewardship efforts. The third case study, the Aura Community Stewardship Program, illustrates local collaboration, in this case stimulated by a private sector organisation. The fourth case study, Grazing Best Management Practice, illustrates the way institutional arrangements can support stewardship activity. The fifth and final case study, the Journey of QYAC, is that of the Quandamooka Yoolooburrabee Aboriginal Corporation, an Indigenous organisation with a long track record of effective stewardship of Moreton Bay and islands.

1. Healthy Land and Water

Healthy Land and Water was formed as a community-focused and science-based waterway and natural asset management organisation to continue to improve the coordination and implementation of best practice catchment management. It was formed through the merging of Healthy Waterways and SEQ Catchments, two collaborative organisations that have long supported and enabled stewardship actions to improve and protect Moreton Bay. It is one of Australia's 56 regional bodies for natural resource management. Healthy Land and Water is 50% owned by the South East Queensland Catchment Management Association, a collective with over 70,000 community members with a focus on all of the region's natural assets, with waterway and catchment health as key priorities – the remaining 50% of the organisation is equally owned by the South East Queensland Council of Mayors and the region's water utilities. Thus Healthy Land and Water has the capacity to engage with, and mobilise over 70,000 volunteers in South East Queensland to inform, support and deliver demonstrable community change and on-ground outcomes.

Healthy Land and Water takes a collaborative approach to preserving the region's natural assets, involving landholders, community groups, industry, Traditional Owners and government. These partners work to share understanding and knowledge, promote regional collaboration, and identify solutions across the catchments of South East Queensland. Researchers and policy-makers (including government representatives from China, Singapore, The Philippines and Indonesia) have extensively studied the organisation's collaborative style, and their work also attracts national attention with formal commendations from the Wentworth Group of Concerned Scientists and the Australian House of Representatives (22).

2. The Healthy Country Program

The Healthy Country Program was established in 2007 to support communities, farmers and scientists to improve the health of South East Queensland's waterways and Moreton Bay. It was set up as a "proof of concept" to share ideas and trial methods to reduce sediment and nutrients polluting local waterways and putting at risk the health of Moreton Bay.

Healthy Country is a science-based program that adopts a collaborative delivery model that combines the latest scientific knowledge with community priorities, to deliver innovative projects that improve water quality and landscape resilience. The focus to date has been on managing sediment and nutrient discharge from priority catchments. Modelling completed by SEQ Catchments, Healthy Waterways and the Australian Rivers Institute at Griffith University found that the Logan, Bremer, Lockyer and Pumicestone catchments contributed the greatest amount of sediment and nutrients flowing into our waterways (23). The on-ground initiatives included a mixture of well-established techniques such as managing eroding gullies, planting trees, and installing fencing to keep livestock out of creeks, as well as 'soft' engineering works such as rock chutes and sediment ponds and the trialling of newer methods such as engineered log jams. These initiatives have been focused around reducing erosion, improving livestock management and weed control, and providing expert advice to promote good practice and innovation across the catchment.

The key partnerships formed and developed during the Healthy Country Program were with: private landholders, the Department of Environment and Resource management (DERM); the Department of Employment Economic Development and Innovation (DEEDI); Griffith University; Healthy Waterways, and Indigenous Traditional Owners (Jagera, Yuggera and Ugarapul people). These partnerships operated through regional and local committee meetings, extension officers' and project managers' meetings/workshops, field trips and one-on-one interactions. The Healthy Country Program has been able to demonstrate that the original "proof of concept" works, i.e. using a science based approach to identify sediment sources and prioritise areas according to the highest sediment export loads combined with a local participative approach to engage landholders in the planning and implementation of sediment control works (24). The broad-scale rollout of the initial Healthy Country proof of concept has produced positive results for the environment in the past 10 years, including when floodwater caused by Cyclone Debbie inundated the Lockyer Valley in March 2017. Here sections of Laidley Creek previously rehabilitated as part of the Healthy Country program withstood the brunt of the floodwater and suffered only minor damage, and more mud and soil than expected was prevented from entering the waterway. Further, in early 2018 the Queensland Government announced it had allocated $1.4 million over three years to continue the program, a clear demonstration of confidence in the concept.

The Healthy Country Program has successful water quality outcomes due to the extensive engagement process with the local communities in priority catchments (24). This process allows the identification of local concerns and priorities and alignment with science driven support tools. Hence, the Healthy Country engagement process can see the formation of projects that meet the expectations of landholders and deliver strong environmental outcomes. Key to this was the long-term investment by Healthy Land and Water staff based in the catchments, building trust and facilitating the integration of community knowledge and science. This engagement resulted in extensive support from local communities in achieving enhanced landscape resilience and healthy waterways.

3. Aura Community Stewardship Program

In 2013, Stockland property group gained Australian and Queensland Government approval, with conditions, to develop a 2,310 hectare ex-pine plantation south of Caloundra, now known as the City of Aura. As part of the conditions under the *Environment Protection and Biodiversity Conservation Act 1999*, Stockland was required to establish an "environmental engagement strategy" to include a mechanism for ensuring community engagement with management practices required to protect 'Matters of National Environmental Significance'.

Since 2013, the Aura Community Stewardship Programme overseen by the Aura Community Advisory Group and facilitated by Healthy Land and Water staff has been achieving early outcomes for the ecological restoration and future sustainability of the development. The group has representation from over 16 community groups and government agencies, and meets quarterly to share information, plan and build knowledge.

The restoration work focusses on a peninsula of land between North and South Bells Creeks, known as "Little Italy" because of its boot shape. This area was previously grazing land. From 2014 it was fenced to exclude livestock, to create an Environment Protection Zone extending over 400 hectares. Two teams of participants from the Federal Government's Green Army employment program removed pine seedlings from 500 hectares of the 700 hectare future conservation zone. The Aura Community Stewardship Programme uses events, such as celebrating World Wetland Day and National Tree Day each year with the local Unity College and community groups, for building a frog pond, tree and other planting, as well as talks. The first cultural fire management training and burn has been undertaken, and the community Faunawatch programme has gathered two years of baseline data as the site regenerates. An Aura Flora nursery has been established initially for training purposes to collect and propagate seeds from the site. The community has had input in many of the sustainability initiatives on site, and into the development of the "welcome pack" offered to new residents. This program has been so successful that Stockland is using the Aura model to build community engagement and participation, achieve environmental outcomes, secure green star ratings and promote these credentials in future developments across Australia.

4. Grazing Best Management Practice (GBMP)

Grazing is a significant land use in South East Queensland. Best management practice guidelines help farmers to find sustainable ways of demonstrating good environmental stewardship, while also improving their economic outlook. Like elsewhere in Queensland, without careful management grazing land use can be a significant contributor of sediments and nutrients into waterways. GBMP is delivered in South East Queensland by Healthy Land and Water, the Department of Agriculture and Fisheries, and AgForce.

The GBMP program is a voluntary, industry-led process that assists graziers to identify improved practices to enhance the long-term profitability of their business and improve catchment water quality. An online, self-assessment tool, GBMP (www.bmpgrazing.com.au), allows participants to benchmark their current practice against an industry-developed set of standards, which have been verified by a producer reference group and are based on industry experience and science (through the Department of Agriculture and Fisheries). By participating in the program, graziers assess how they currently measure up in their industry and identify opportunities for improvement. It also provides an indication of current practices in the industry across the state.

In South East Queensland, 166 businesses covering 107,367 hectares have completed a GBMP module (16).

To illustrate the unique work of voluntary organisations, we highlight an Indigenous organisation, the Quandamooka Yoolooburrabee Aboriginal Corporation (QYAC), as example number 5.

5. The journey of QYAC

The Quandamooka Yoolooburrabee Aboriginal Corporation, formed in 2011, is the Native Title holder body for the Traditional owners of 24,903 hectares of land and 29,525 hectares of water on and surrounding North Stradbroke Island (Minjerribah). It includes areas of national parks and reserves, state land and other leases. Legal recognition of native title followed successful negotiation with the State of Queensland, the Commonwealth, two city councils, and a range of commercial interests and infrastructure providers.

Traditional Owners have cared for the waters, islands and mainland of Moreton Bay for at least 20,000 years (3). QYAC and its predecessor organisations set up formal capacity for stewardship activities in 1991, with the formation of the Quandamooka Land Council (later Quandamooka Aboriginal Land and Sea Management Agency, from 1998). Their stewardship includes: advocacy for their country (including a voice on development proposals); cooperation with other management organisations including the Queensland Parks and Wildlife Service in marine and terrestrial management, monitoring of marine and land conditions; and on-ground works, in conjunction with a wide range of partners which contribute policy, program, science and practical support. For example, Quandamooka elders and SEQ Catchments worked together to restore the culturally and ecologically significant Myora Springs wetland on North Stradbroke Island. QYAC has also worked with Queensland Parks and Wildlife Service to expand the protected area of Minjerribah from 2% in 2010 to currently 50%.

Following the Quandamooka people's native title settlement in 2011, QYAC has increasingly played a lead role in the management of Quandamooka Country and has secured a Queensland Government commitment to end sand mining in 2019, progress a UNESCO World Heritage listing for the area, as well as further expand the National Park to as much as 80% of Minjerribah.

QYAC's land and sea management capacity has grown significantly over recent years so that QYAC is now one of the largest land management employers in South East Queensland. It now employs over 100 staff and leads the management of reserves, the National Park, and the Camping Areas across Minjerribah. Priorities include: ecological assessment and landscape restoration following cessation of sand mining; development, training and employment for young people; protection of sacred areas; and management of groundwater.

QYAC also has the largest membership of any Native Title Body Corporate in Australia. It is playing a lead role in demonstrating how Traditional Owners are well placed to lead the stewardship of their country.

Institutional Arrangements

Any attempt to describe and explain stewardship in Moreton Bay should include the enabling conditions (institutional arrangements, plans, policies and programs) that support the on-ground aspects of the management system (25). Further, Snouder (26) suggests that for the most part, managing waterways and increasing uptake of stewardship activities have been enhanced by technical knowledge and agreement that behaviours and environmental conditions need improvement. Therefore, the stewardship activity is heavily influenced by either willingness or ability, or both. In Moreton Bay over the last 30 or more years that the following management components have influenced the degree to which stewardship actions have been successful:

- High levels of trust to enable partnering and certainty;
- Striving for cultural appropriateness or cultural 'fit' of planned activities;
- Social, political and economic context, including people's values, local and regional political priorities, the mix of enterprises in the region and variations in economic confidence or pressure;
- Willingness to pay for investment in the environment;
- Willingness to incorporate the true cost of production into value chains;
- Equitable funding arrangements for interventions that improve the quality of waterways;
- Correct information; the use of rigorous science to inform stewards;
- Stakeholder understanding of the impacts of behaviours (negative and positive), removing stakeholder doubt, that there are issues;
- Incorporation of risk management principles in program design and activities;
- Lack of availability or access to incentives to support landholders and organisations;
- Lack of resources, or undeveloped resource pathways, impacting on ability of stewards to undertake actions that improve environmental condition;
- Access to reliable and trusted sources of information;
- Availability of Natural Resource Management and Best Management Practice information;

- Regulations or conditions for operation that may be inappropriate or extremely difficult, or expensive, to implement; and
- Alignment of policy and regulation. Support by the broader community for environmental policy and regulation and the willingness of regulators to enforce non-compliance with environmental policy.

History and future of funding

Most funded projects in Moreton Bay and catchments are resourced collaboratively through federal, state, and local government, industry, water utilities and landholder/community resource pools. In many instances the projects rely heavily on in-kind support or volunteer works to achieve outcomes. Funding for stewardship has been driven, over time, by a series of national and national-state policies and programs:

1989: Federal funding for Landcare enables local Landcare bodies to be formed throughout Australia, and employ part-time facilitators. National and state coordinators were also employed;

1990: Land and Water Australia established, combining fragmented former research funding schemes under a single, more strategic body;

1990: Integrated Catchment Management was introduced formally in Queensland (27);

1991: Co-operative Research Centres established. These promoted research under collaboration between universities, CSIRO, industry and government partners;

1992: Federal Government's Decade of Landcare Plan developed and launched. The *Natural Resource Management (Financial Assistance) Act 1992* was established to manage and assign funding to natural resource management projects and programs (National funding of $320 million committed for the life of the program);

1992: Community grants become available, for projects with a limit of $15,000 and a requirement of 1:1 funding matching ratio from the community (this contribution could be in-kind);

1992: High level of partnering between states and federal government required under The *Natural Resource Management (Financial Assistance) Act 1992;*

1995: Waterwatch and Coastcare programs established;

1997: Natural Heritage Trust established. $1.25 billion made available nationally over five years. This expanded the national Landcare Program by providing large grants awarded on a competitive basis to community groups for on-ground works;

2002: $1.4 billion of funding over seven years through the National Action Plan for Salinity and Water Quality, a program to address these issues in designated catchments, and $1.032 billion over five years through the Natural Heritage Trust extension (NHT2). These Commonwealth-state programs established 56 regional bodies for natural resource management across Australia, scaling up the Landcare model into community-based organisations for planning, coordinating, leveraging partnerships and distributing funds. These organisations were recommended to have broad stakeholder bases in their membership and boards;

2008: Caring for our Country program, $2 Billion over five years. This replaced the National Action Plan for Salinity and Water Quality and NHT2, and reduced the level of funding to all regional bodies in favour of nationally competitive funding for specific purposes; and

2014: Green Army, a federal government funded initiative consisting of a combined employment and natural resource management program that aims to support local environment and heritage conservation projects across Australia whilst providing hands-on work experience for unemployed youth.

This evolving set of initiatives is internationally unique in its degree of focus on community-based action for stewardship. The time period covered above saw a focus on community-based action, shifting to a regional focus from the early 2000s which left the funding of Landcare groups to the discretion of regional bodies, at reduced levels. Thus, many Landcare and similar groups withered during this period, while others continued under their own resources and ability to attract funds (28). Meanwhile, the regional bodies for natural resource management received varied resourcing after 2008, depending on the extent to which national funding priorities applied in their areas (28).

This adaptation and innovation has stimulated collaboration, and increasing financial self-reliance. Industry, community groups, not-for-profit organisations involved in catchment management, governments and utilities are committed to working together in Moreton Bay and catchments to: increase cost-effectiveness through in-kind support for implementations; reduce 'silo-ing' and duplication of works; ensure correct information is used; partner to resource projects; and open up new or novel resource pools. Two regional collaborations led these processes, Healthy Waterways (from the late 1990s, self-started), and SEQ Catchments (from 2003, established under the National Action Plan for Salinity and Water Quality and NHT2 programs). The former specialised in water quality and the latter in all forms of natural resource management. These bodies merged in 2016 as Healthy Land and Water (see Case study 1: Healthy Land and Water).

Many organisations responsible for managing impacts on the waterways of South East Queensland and Moreton Bay have moved away from a reliance on government funding and have established self-funded business models – often relying on partnerships that allow greater autonomy and independence and deliver better funding security.

Self-reliance has also been realised through the establishment of social enterprises and commercial entities that feed profits back into the organisation through undertaking activities that achieve water-quality outcomes.

Stewardship organisations in South East Queensland

There are many types of stewardship organisation in South East Queensland, some originating spontaneously, others reflecting the types that developed nationally under stimulation from the national Landcare program, National Action Plan for Salinity and Water Quality, and other support programs listed above. One of the first advocacy groups, the Queensland Littoral Society (now Australian Marine Conservation Society), was formed by South East Queenslanders in 1965. The Moreton Island Protection Committee, and the Stradbroke Island Management Organisation, were formed in 1978. The first recognised citizen science program in SEQ was a Brisbane wildlife survey held in 1980.

There was a spurt in formation of voluntary organisations in the 1980s and 1990s.The first Bushcare group, Grange Forest Park Bushcare, was formed in 1984. The Gold Coast Environment Centre was established in 1989. Barung Landcare was founded in Maleny and the Blackall Range in 1989, just prior to the declaration of the Decade of Landcare. Other early Landcare groups were Noosa and District Landcare, and the precursor to Norman Creek Catchment Management Coordination Committee (both in 1991). When Queensland introduced Integrated Catchment Management (ICM) in 1991, as a voluntary system of groups based on the land care model, The Oxley Creek Catchment Association became the first urban ICM organisation, and the body that became Lockyer Catchment Association (building on the Lockyer Watershed Management Association of the late 1970s) was another of the first ICM bodies to form.

The Habitat Brisbane program was established by Brisbane City Council in the mid-1990s, and now has 78 participating groups. Karrawatha Forest Protection Society formed in 1991 to save an area of bushland, and establishment of Brisbane City Council's Bushland Levy enabled purchase of land. Similarly, Boondall Wetlands Management Committee, founded in 1992, arose from a community campaign to save these wetlands.

The Brisbane Catchments Network formed in 2012 to help the 11 catchment groups along the Brisbane River to coordinate, and represent themselves collectively. The state-wide organisation Queensland Water and Landcare, formed in 2004, provides another vital coordination medium for all voluntary groups in South East Queensland. As well as providing valuable resources, it is particularly important for providing public liability and accident insurance for its members and volunteers, solving an insurance crisis that had placed many voluntary groups in jeopardy during the 2000s.

Generational change

Nationally, the challenge of an ageing cohort of community stewards has been well documented (29, 30). The initial cohort of community members who engaged in environmental stewardship in the "Decade of Landcare" in the 1980s (31) are still in the field and remain the core of volunteers active in waterway stewardship. In the main, stewardship groups across South East Queensland report low-levels of renewal in catchment care groups associated with a failure to engage younger generations in environmental stewardship (32).

The ageing of the population is an opportunity for volunteering through which, collectively, volunteering organisations can 'turn grey into gold' (33). Living longer, in better health, and the active lifestyles of many senior Australians makes becoming involved in volunteering possible (34). Realising this opportunity to recruit further contributors to environmental management also relies on volunteer organisations being adaptable and able to offer flexible ways to volunteer (34). In Australia in general, stewardship is beginning to be recognised with a range of awards now existing at the regional, state and Commonwealth level to recognise the efforts and achievements of individual volunteers and stewards (34).

Alongside this trend in the ageing of the population, volunteering has become more common nationally among young people (34) offering a potential opportunity for an aging stewardship cohort to recruit younger people. The rate of volunteering by young people in Australia increased from 16% in 1995 to 27.1% in 2010 (34). Young people are engaging in volunteering in diverse ways. For example, volunteer tourism particularly during the student gap year is a growing area of involvement for young people and a start to engaging in lifelong experiences of volunteering. Through partnerships with young people, educational institutions, peak bodies and volunteer-involving organisations are developing new approaches to volunteering (34).

Environmental education research strongly suggests that learning experiences in the natural environment are extremely important in developing students' environmental knowledge, attitudes and responsible actions (35–43). Palmer's 1999 research (44) found that direct experiences with nature had far more impact on subsequent involvement in pro-environmental activities than did formal education.

Education Queensland has established 25 Outdoor and Environmental Education Centres (O&EECs) throughout the state, three of them in the Moreton Bay and catchments area. These centres are curriculum aligned and provide students with the opportunity to study aspects of environmental sustainability. O&EECs provide the personal nature-based experiences that have been identified as critical for the formation of pro-environmental attitudes, and are in a prime position to build positive and productive relationships between school students, the local community and the natural environment (45). O&EECs are significant contributors to building environmental stewardship within young learners through their use of experience-based learning (45).

The need for generational change in stewardship in the Bay and catchments is widely acknowledged (32), and the continuing need to engage younger generations or newcomers to act as stewards presents as an inherent problem for many stewardship groups. Community and catchment groups, governments, utilities and schools all understand the need to recruit the next generation of stewards to ensure the values of the waterways are sustained. By supporting, facilitating and designing programs aimed at engaging and raising the awareness of the broader community and the youth of South East Queensland, the important work of renewing the initial cohort of stewards is being undertaken.

Conclusions

Moreton Bay (Quandamooka) and its catchments are loved by their many stakeholders. The drive for improved water quality and ecosystem health has led to wide ranging and important stewardship activities by diverse individuals and groups. These include Traditional Owners, land care groups and catchment management bodies, the Brisbane Catchment Network, and the sustainable management efforts of individual landholders, and organisations such as urban utilities, local and state governments. Growing concern and awareness about the health of waterways has also resulted in greater community interest in monitoring, on-ground action and decision-making to support sustainable management of the region's natural resources.

The establishment of Natural Resource Management (NRM) organisations, the Healthy Waterways Partnership, SEQ Catchments, and now the integrated Healthy Land and Water, have helped to galvanise activities by state and local governments, business and industry and by stewardship groups, towards management of environmental conditions in the Bay. The extent and contribution of community stewardship has become better recognised in recent years (46), and is seen as a major driver that can lead to change.

Challenges remain. Stewardship activities need to be supported by funding, strategies, guidance, training and resources. Without these, participation and activities are likely to decline. Generational change may influence the availability of volunteers. While the interest and commitment of the younger generation to improved environmental outcomes in the Bay is clear, much needs to be done to recruit more young people into stewardship groups and activities. The outcomes associated with stewardship activities also need to be monitored and reported, which is critical for maintaining commitment and enthusiasm. These are critical components in supporting voluntary stewardship organisations and activities in delivering effective outcomes for Moreton Bay (Quandamooka) into the future.

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Managing the public health paradox: Benefits and risks associated with waterway use

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Abstract

Engaging with waterways affects our health and wellbeing. This engagement can be direct and intentional, such as when swimming, kayaking or engaging in conservation practices; indirect and intentional, such as when picnicking with water views; or incidental, such as when cycling on riverside bike paths. In the subtropical climate of the Moreton Bay catchment these activities are popular year-round. These forms of engagement can benefit our physical, mental and social wellbeing, and contribute to our cultural identity and sense of place. Conversely, there are health risks associated with waterway use, including exposure to waterborne pathogens, cyanobacterial toxins, dangerous aquatic animals and submerged objects. Whether our interactions with waterways enhance our health and wellbeing or constitute a health risk depends on a wide range of factors and management decisions. In the context of the waterways within Moreton Bay, this paper discusses ways of optimising opportunities for water users while managing public health risks, and how to evaluate the effectiveness of interventions through the use of environmental health indicators.

Keywords: recreational water, ecosystem health, wellbeing, DPSEEA, indicators

Introduction

'Healthy waterways, healthy people'— the connection is intuitive. Images of clear, blue rivers, lakes, waterfalls, beaches and oceans feature in tourism brochures as a backdrop to vibrant backpackers engaged in exciting water sports or families relaxing alongside tranquil water bodies. From the upper reaches of tributaries in sub-catchments of the Brisbane River through to Moreton Bay, this region provides a diverse range of water-based environments that impact on the health and wellbeing of individuals and communities. The state or condition of these aquatic environments and how we interact with them (directly and indirectly) are critical factors that determine whether health outcomes are positive or negative (1). Degraded, polluted waterways can result in adverse health outcomes due to direct exposure to pathogens or toxins or by providing habitats for disease vectors such as mosquitoes (2, 3). On the other hand, healthy waterways can be 'health-promoting' by providing locations suitable for swimming and other forms of physical activity, as well as spaces for stress relief, relaxation and social interaction (4). The aim of this paper is to consider the risks and health benefits associated with waterways in general, with a specific focus on the Moreton Bay region. It conceptualises the relationships between waterways and human health by drawing on trans-disciplinary constructs and international frameworks.

The complexity and richness of the relationships between waterway health and public health warrant a deeper analysis. The intrinsic and reciprocal relationships between human and ecosystem health were synthesised through the Millennium Ecosystem Assessment (MEA), framed around the construct of ecosystem services (5). The MEA describes ecosystem services as the benefits we acquire from ecosystems, which include our waterways. These services can be ‘provisional’ (e.g. providing fresh water and food), ‘regulatory’ (e.g. regulating water purification, climate and diseases), ‘cultural’ (e.g. being a medium for recreational, aesthetic, spiritual, cultural heritage and educational pursuits) or ‘supportive’ (e.g. cycling of nutrients). Human wellbeing is intrinsically linked to ecosystem health through the benefits arising from meeting our basic resource needs, social relations and access to resources that will mediate the security of health and sustained quality of life, including food and water security. Thus, protecting the health of waterways has both intrinsic value to these ecosystems and reciprocal value to public health.

Utilising ecosystem services at unsustainable rates will not translate to proportionately larger public health benefits. Similarly, when an ecosystem service is scarce, any small decrease ‘can substantially reduce human wellbeing’ (5 p.49). While better access to ecosystem services has provided human societies with the means to improve health and wellbeing, society may be forcing irreversible changes and damage to these ecosystems. For example, although societal factors such as changing demographics, economic policies, governance frameworks, scientific and technological developments, and cultural and religious choices can improve human health, they can also become indirect drivers of significant pressures on ecosystems. Detrimental changes to ecosystems have resulted from intensive land use, the introduction of exotic species or extinction of native species, inappropriate technologies, excessive use of chemicals, over-harvesting and over-consumption.

Human health cannot be isolated from the health of ecosystems. Nine categories of indicators of health outcomes related to wetland[1] ecosystem services have been identified by Horwitz and Finlayson (1): (i) contributors to hydration and safe water, (ii) contributors to nutrition, (iii) sites of exposure to pollution or toxicants, (iv) sites of exposure to infectious diseases, (v) settings for mental health and psychosocial wellbeing, (vi) places from which people derive their livelihood, (vii) places that enrich people’s lives, and enable them to cope and help others, (viii) sites of physical hazards, and (ix) sites from which medicinal and other products can be derived. It is, however, restrictive to consider that ecosystems deliver only a one-way service and that only humans benefit from a healthy ecosystem—this risks ignoring the reciprocity of the human–ecosystem relationship and the human contribution

[1] Wetlands are defined broadly by the Ramsar Convention on Wetlands to include rivers, lakes, marshes, rice fields and coastal areas (6).

(improvement, maintenance, degradation) to the health of the ecosystems described by Horwitz & Finlayson and Comberti *et al.* (1, 7).

The relationships between human health and the ecosystem services provided by waterways are not linear and can be paradoxical. Depending on how they are managed, wetlands can either enhance or diminish human health via effects on their ecological functioning and ability to provide the various ecosystem services from which we benefit (8). For example, trade-offs are made when engineering works carried out to regulate rivers for flood mitigation in order to protect lives and property in a way that may diminish some of their other intrinsic ecosystem services. On the other hand, river reaches could be managed in a way that enhances their aquatic ecosystem health by slowing down the water and creating habitats using large woody debris, but at the expense of safe swimming or boating. A framework for making these trade-offs and paradoxes explicit was first presented in Horwitz & Finlayson (1) and adapted slightly in Finlayson & Horwitz (6). This defined four possible relationships to consider when relating the condition of ecosystem services and human health:

- Double dividend – improved health outcomes and enhanced or maintained ecosystem services;
- Environmentalist's or Wetlands paradox – a degraded ecosystem which provides positive health outcomes (e.g. draining wetlands or applying pesticides to control disease vectors);
- Paradox of the health imperative or Health paradox – a maintained or enhanced ecosystem can pose negative human health consequences (e.g. protected wetlands providing ideal mosquito breeding sites); and,
- Unhealthy wetlands – a poor human health outcome associated with degraded wetlands.

These relationships are depicted in Figure 1.

Wise stewardship of places such as Moreton Bay and its catchment should aim for the double dividend of healthy people and healthy wetlands. This requires an understanding of how these complex relationships operate and change across the catchment and sub-catchments of Moreton Bay and over time. As a starting point, this would require multiple measures of both aquatic ecosystem health and human health and wellbeing so that these trade-offs could be made explicit.

Health benefits and risks associated with the use of waterways

The use of natural waterways provides health benefits yet presents potential health risks. The health benefits of water-based recreation are widely accepted (2, 4, 9). It is also well established that exposure to poor quality recreational waters can result in negative outcomes for human health (10, 11). These health risks and benefits derive from exposure to environmental health determinants that are physical, microbial, chemical, psychological or social. Table 1 summarises both the health risks and benefits associated with using waterways under these five categories of health determinants. In order to maximise their public health benefits, waterways must be managed such that human exposure to hazards is minimised without placing undue restrictions on waterway use (2).

Ecosystem services		Human health: Poor health outcomes	Human health: Improved health outcomes
	Enhanced or maintained	+ − Paradox of the health imperative	+ + Double dividend (healthy wetlands, healthy people)
	Degraded	− − Unhealthy wetlands	− + Analogous to the 'Environmentalist's paradox'

Figure 1. Four relationships possible when considering the condition of ecosystem services and human health (1 p684).

Physical hazards present the highest health risk to recreational water users (10, 12). Incidents of drowning, major impact injuries, and slip, trip and fall injuries can result in death or permanent disability. As a result, recreational water management programs should consider the physical characteristics of a beach or other water environment, including water depth and turbidity; swimming zone topography; presence of breaking waves, currents and rips; and local and foreign hazards such as coral reefs or floating debris (12). The risk of these hazards may be compounded by exposure to solar radiation, heat and cold (12). In addition to natural hazards, incidents of violence from other people may result in physical harm (e.g. muggings in remote or poorly lit areas).

The health benefits associated with physical aspects of waterways are probably the most intuitive. At the most basic 'sustenance' level, waterways provide food (via wild-caught and farmed seafood and crop irrigation) and sources of raw water for drinking. During extreme climatic events, such as the Brisbane flood of 2011, waterways can protect lives and property through peak discharge attenuation (22). Even small urban creeks within built environments can reduce the urban heat-island effect considerably (13, 23). The 'everyday health dividends', on the other hand, are the physical health gains derived through a wide range of recreational and sporting activities such as swimming, surfing, fishing, kayaking and walking along trails near waterways (4). In addition, these outdoor activities provide the co-benefit of vitamin D being synthesised in our bodies in sufficient amounts.

Table 1. Health risks and benefits associated with the use of waterways.

Type of health determinant	Health risks associated with waterways	Health benefits associated with waterways
Physical	Injuries sustained during recreational activities (e.g. jetski collisions, sunburn, trip hazards, drownings, and bites/stings from dangerous aquatic organisms) (12) High turbidity due to high sediment loads can increase the likelihood of physical injuries due to poor visibility, while also reducing the efficacy of UV disinfection of microbial contaminants (12) Personal security risks (e.g. muggings in poorly lit areas) Deterioration of water quality or water sites may impede participation in physical activities (8)	Improved physical health (e.g. through use of walking trails and water sports such as swimming, surfing, fishing and wading) (4) Buffering from extreme events (e.g. flooding) (6) Climatic regulation, mitigating the heat-island effect (13) Benefits of moderate sunlight exposure (e.g. vitamin D synthesis) (12) Provision of food and water (5)
Microbial	Ingestion of waterborne pathogens (e.g. *Cryptosporidium, Giardia, Campylobacter* spp.) and adenoviruses in water contaminated by sewage and/or stormwater (12, 14) Infection by water-based pathogens (e.g. Leptospires and *Naeglaria fowleri*) (12, 14) Infection by pathogens spread by insect vectors that breed or bite near water (e.g. Ross River virus infection) (12) Pathogens associated with engineered water systems including water parks (e.g. *Pseudomonas aeruginosa*) (15)	Bioregulation of pathogens via predation/competition (12) Sequestration of pathogens by natural vegetation (16) Protection against conditions fostering pathogen growth through intact riparian zones (e.g. increased sediment, temperature and nutrient levels) (12)
Chemical	Exposure to cyanobacterial toxins (e.g. *Lyngbya majuscula*)(17)	Reduced exposure due to pollutant filtration by wetlands (18)
Psychological	Loss of relaxing/stress-reducing aesthetics (6) Solastalgia – existential distress caused by environmental deterioration or loss (19)	Improved psychological health (2) Nature contact is associated with reduced mental ill-health (e.g. stress, anxiety and depression) and promotion of wellbeing (20).
Social	Loss of sense of place and/or cultural identity (2) Deterioration of water quality or water sites may impede opportunities for social interaction (2)	Improved community cohesion (21) Enhanced sense of place (21)

Microbial hazards, particularly pathogens, are of high public health concern. Pathogenic bacteria, viruses, protozoa and helminths have the potential to cause a wide range of acute, delayed, chronic and fatal health conditions (12). Major point-sources of such pathogens include faecal pollution from wastewater treatment plants, sewer overflows and industrial effluents (2). Non-point sources include water runoff from surrounding landscapes, defective sanitation systems (e.g. onsite septic systems), as well as agricultural run-off and faecal pollution from bathers, wildlife and domestic animals (14). Human faecal pollution is considered to pose substantially higher health risks than other animal wastewater (24, 25), particularly due to potential exposure to human enteric viruses (25). Globally, epidemiological evidence shows that gastroenteritis (with symptoms such as diarrhoea and vomiting) is one of the most common diseases caused by a range of human pathogens via exposure to contaminated waters (2, 14). Routine microbial water quality monitoring of recreational waters in Moreton Bay by local authorities is generally limited to faecal indicator bacteria (Enterococci). Regular exceedances of recreational water guidelines (e.g. where 200–499 Enterococci CFU/100 mL triggers additional investigation and ≥500 Enterococci CFU/100 mL triggers temporary site closure for recreation, CFU – colony forming units) occur particularly after heavy rainfall (26). While these data are not generally available to the public, the general advice provided on the Healthy Waterplay website is to avoid swimming during, and at least one day after, heavy rain in open waterways and beaches, and for at least three days within confined bays and estuaries (27). Brisbane City Council is one of the authorities that does publish its microbial water quality data (28). Despite these exceedances, epidemiological evidence of outbreaks of gastro-intestinal illness associated with recreational use of these sites is lacking.

Not all microbes in and around water are harmful. Recent developments in metagenomics have unveiled the importance of microbial biodiversity by allowing us to profile the bacterial communities associated with specific aquatic environments. Studies conducted by Beale et al (29) in variably polluted reaches of the Brisbane River have used metagenomics to better characterise the responses of bacterial communities to contaminants. Research in this emerging field suggests that diverse bacterial communities play a crucial role in ecosystem health resilience and the recovery of areas following pollution events (30, 31). This resilience and recovery may play a factor in regulating which water-based recreational activities can resume and when following pollution incidents.

Chemical hazards in our waterways can present health risks under certain exposure scenarios. Actual levels of health risk are determined by the characteristics of the chemical, exposure routes and pathways, the nature and magnitude of exposures, and the characteristics of the individuals and populations exposed (32). Chemical toxicants can enter waterways rapidly via a massive influx (chemical spill) or very slowly and imperceptibly over time via complex pathways. The former often triggers a public health response that minimises exposure and therefore the health risk, whereas the latter can lead to chronic, biomagnified exposures via the food chain (18). At commonly observed concentrations, chemical hazards in recreational waters typically pose a lesser threat to public health compared with the other types of hazards. This is because the health risks associated with chemical hazards (e.g. pesticides and polycyclic aromatic hydrocarbons) are often a result of chronic or high levels of exposure that are not likely to occur via recreational activities due to dilution and limited durations of exposure (12).

Toxins produced by cyanobacteria can adversely affect health through dermal contact or accidental ingestion or aspiration of water (12). In Moreton Bay, regular annual blooms of the nuisance and potentially harmful cyanobacterium *Lyngbya majuscula* have been studied extensively (17, 33). Several key toxins have been isolated and characterised from these blooms and anecdotal evidence of toxic incidents reported; however, only limited epidemiological data are available linking toxins and severe skin symptoms among exposed recreational users coming into contact with blooms (17). Most documented cases of human illness associated with cyanobacterial toxin exposures, however, have been associated with drinking water (12). Health risks from cyanobacterial toxins in recreational waters are likely to increase given the widespread nature of the hazards in combination with rising global temperatures, agricultural nutrient run-off and population growth (34–36).

Perceived health risks from chemicals in waterways need to be managed alongside actual health risks. This can present a challenge as illustrated by a recent, locally relevant example. Contamination of waterways (including several sites in Moreton Bay) by a particular group of persistent chemicals known as per- and poly-fluoroalkyl substances (PFAS) has recently triggered high levels of community concern and regulatory attention (37, 38). A recent accidental release of these chemicals via a spill of firefighting foam by an airline into Moreton Bay, along with historical, long-term industrial/commercial use of PFAS has led to potential exposure routes being identified and public health advisories being released (37). Factors such as involuntary, past exposures for particular affected communities via contaminated groundwater, high levels of ongoing media coverage, scientific complexity and uncertainty about long-term health effects have all contributed to elevated levels of perceived risk (38).

In contrast to the psychological risks posed by concerns generated by contaminants entering waterways, ‘blue’ environments can be a key contributor to people’s psychological wellbeing (9, 20). For example, research from New Zealand has shown that higher levels of blue space visibility within a person’s local urban area is associated with lower psychological distress (39). Further, non-coastal blue spaces, such as rivers, have also been shown to have health-enhancing aspects serving as therapeutic landscapes (20). Research investigating UK census data found that people living closer to the coast were more likely to report a good status of health (4). Given that approximately 85% of Australians live within 50 km of the coastline, these findings are especially interesting (40). With Brisbane, the Sunshine Coast and the Gold Coast being the major population hubs in South East Queensland (SEQ) (40, 41), coastal lifestyles are clearly valued by residents and research is beginning to emerge about how people interact with and what they value about these landscapes (3, 21). Furthermore, research from the UK also showed that the positive health effect can be more pronounced in deprived areas (4), indicating that blue environments may serve as an important instrument for tackling health inequalities. Urban blue environments may be of critical importance for buffering the stress- inducing characteristics of city living and living in areas of socio-economic disadvantage. Programs addressing place-based disadvantage in

SEQ, such as the 'Logan Together' partnership (42), could benefit in the future from more-explicitly nature-based interventions. Water environments such as riverside parks, lakeside trails and beaches provide important settings for people to come together with family, friends and neighbours or as part of larger organised community events. This is evident by the number of popular waterway themed festivals and events that occur in both SEQ (e.g. Riverfire in Brisbane, Lines in the Sand festival on North Stradbroke Island) and across Australia.

Degraded blue environments can negatively impact a person's sense of wellbeing by causing distress or creating a sense of loss (2, 6). This environmental distress, captured by the term solastalgia, is produced by environmental change impacting on people while they are directly connected to their home environment (19). As waterways face increasing pressures, signs of degradation can become more obvious and frequent, particularly under projected climate change scenarios. It is therefore likely that communities that witness algal blooms, fish kills, pollution of their local water environments or climate change impacts may be vulnerable to solastalgia. Similarly, communities may lament over the loss of coastal ecosystems to land reclamation works, canal estate developments and rising sea levels. As traditional custodians of the land, Indigenous communities in Moreton Bay are particularly vulnerable to experiencing a strong sense of personal loss in the face of environmental degradation (43). Once waterways become degraded it can also deter people from visiting and valuing them, decreasing their opportunities for social interaction.

Conceptual frameworks for managing waterways for health

Environmental health, as a discipline, recognises the importance of quality physical environments in protecting health and promoting wellbeing. Moreover, it recognises the complex, reciprocal relationships between human and ecosystem health and advocates for policies that aim to achieve the 'double dividend' of enhanced ecosystem services and improved health outcomes (1). The development of effective policies and interventions in this cross-sectoral domain, however, is often constrained by factors such as segregated governance structures and inadequate linkage across sectors of the abundant data being routinely collected about natural resources, planning, environmental management, health and social services. This 'Data Rich, Information Poor Syndrome' (DRIPS) was recognised by intergovernmental agencies around the time that the milestone United Nations Conference on Environment and Development was held in Rio de Janeiro in 1992. Two integrative frameworks were developed to evaluate and track environmental performance and to connect measured changes in environmental quality with their causes and consequences. The development and adoption of the DPSIR (Driver, Pressure, State, Impact, Response) framework was promulgated by the Organisation for Economic Cooperation and Development (OECD) (44), while the DPSEEA (Driving force, Pressure, State, Exposure, Effect, Action) framework, was developed jointly by the World Health Organization, The United Nations Environment Program and the United States Environmental Protection Agency to make the pathways between environmental changes and human health outcomes more explicit (45). Both frameworks are designed to facilitate decision-making that considers not only the 'higher order' or distal determinants of environmental quality, but pathways through which society is impacted by enhanced or degraded environments. Bowen et al. (46) present a thorough overview and comparison of the DPSIR and DPSEEA frameworks, using international case studies to highlight their differences. Scotland's Good Places, Better Health Policy initiative in 2008 is featured as the most wide-ranging and inclusive case that shows the value of the DPSEEA framework as an auditing and communication tool among a broad range of policy constituencies and stakeholder groups (46).

Metrics or scorecards can be useful to monitor and communicate the effectiveness of our investments in waterway management. An important caveat here is that rigour around what we are actually measuring with such metrics is critical, as any deficiencies can easily be carried through to oversimplified, but popular messaging. In SEQ, the ecological condition of waterways has been assessed and rated through the internationally acclaimed Ecosystem Health Monitoring Program (EHMP) coordinated by Healthy Land and Water since 2000 (47). An overall Environmental Condition Grade (A–F) is assigned to each of 18 catchments based on a synthesis of 25 indicators reflecting key freshwater and estuarine aspects of the waterways. In response to the need to develop additional metrics to capture the social and economic values associated with waterways, the 5-star Waterways Benefits Rating was developed by Healthy Land and Water and added to the annual report cards in 2015 (47). The 1–5 star rating is based on the following six components:

1. Community satisfaction with local waterways;
2. Appropriate access to local waterways;
3. Personal benefits residents derive from using local waterways;
4. Community motivation to use and protect waterways;
5. Economic benefits generated through recreation; and,
6. Contribution relevant catchments make to providing clean low-cost drinking water.

This Waterways Benefits Rating is designed to gather data that would help us better understand how social and economic benefits may be affected by changing environmental conditions; however, it has some shortcomings with respect to capturing the inherent and complex linkages between humans and ecosystems being discussed in this paper.

The DPSEEA framework offers an alternative, more robust approach to the development of metrics that link environmental conditions with human health and wellbeing within Moreton Bay. The first three elements (*Drivers, Pressures, State)* share perspectives with environmental protection and the protection of water-based ecosystems. This includes the large-scale social *Drivers* that lead to *Pressures* that can alter environmental *State* conditions. The framework then brings in the public health perspective by linking changes in the *State* of the waterways to *Exposure* routes and health *Effects*. The example illustrated in Figure 2 shows how the DPSEEA framework captures some of the links between environmental conditions and health in recreational waters that could be applied to Moreton Bay. Figure 2 also provides examples of metrics that could be monitored as indicators of changes over time. *Drivers* include population growth, changing land uses, as well as global patterns of energy use and climate change. For the *Driver* of population growth, another metric could be the proportion of Queensland's population growth that is concentrated in

SEQ (88.3% in 2016–17) (48). A significant amount of research has focused on both climate change impacts and adaptation strategies in southeast Queensland, including numerous projects under the auspices of the South East Queensland Climate Adaptation Research initiative (49). Metrics of *Pressures* could include sediment inputs due to bank erosion (influenced by land use) and sewage overflows triggered by extreme weather events within an undersized, aging sewerage infrastructure. To assess any changes to the condition of the recreational waterways, *State* indicators (i.e. observable and measurable measures of water quality such as those metrics incorporated into the EHMP and levels of faecal contamination) should be regularly monitored at the recreational water sites. The *Exposure* element of the DPSEEA framework is designed to capture how people are exposed to the '*State* of the environment' variables (e.g. water quality) that impact on their health and wellbeing status (*Effect*). Bowen *et al.* describe the *Exposure* attribute as one that reflects the 'vectors of risk exposure (either risk elevation or diminution) that emerge as a consequence of environmental change', and *Effect* as a measure 'of change in health resulting from changes in risk exposure' (46).

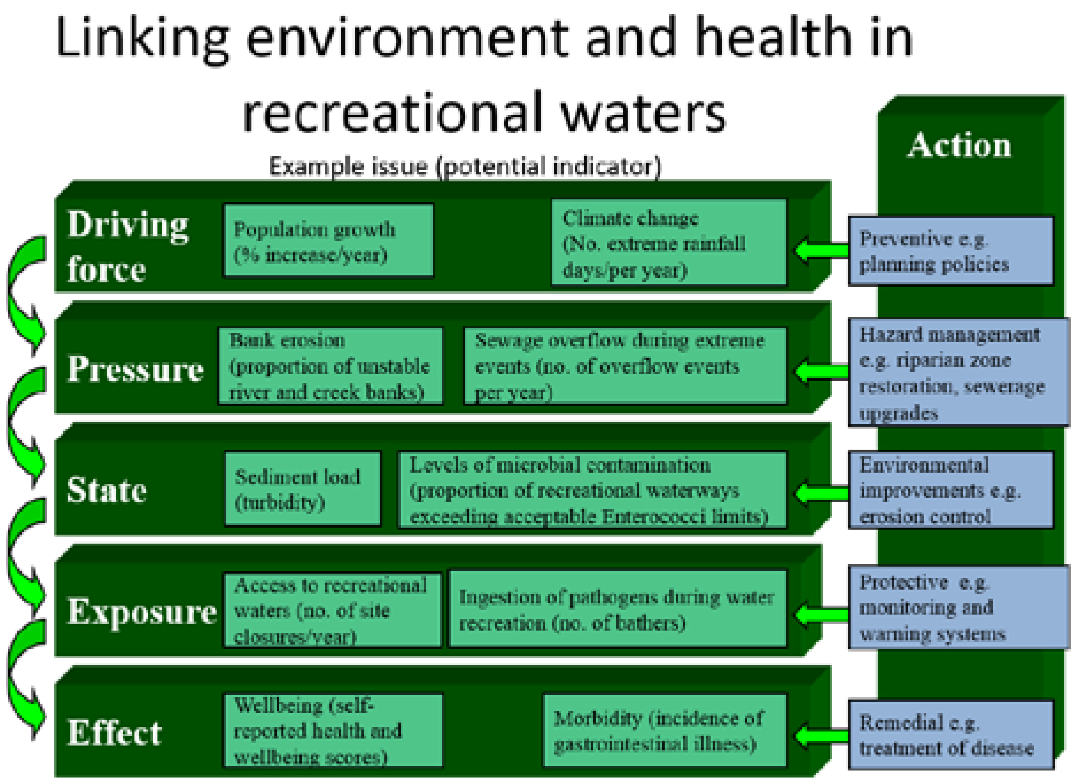

Figure 2. An illustration of how the Driving force, Pressure, State, Exposure, Effect, Action (DPSEEA) framework can be applied to the management of recreational waters.

While these definitions cater for both the positive and negative linkages between environmental quality and public health, in practice there is a paucity of routinely collected data that could be used for reliable *Exposure* or health *(Effect)* metrics. If we wanted to focus on health risks of recreational *Exposures*, biomarkers could be used to indicate exposure and models could be used to estimate likely numbers of pathogens ingested by recreational water users; however, these approaches are usually only applied in site-specific health risk investigations. On the other hand, focusing on the health-promoting exposures brings additional challenges, as reported benefits are typically narrative. To capture information on both health risks and benefits, it would therefore be best to combine metrics derived from measurements, where applicable, with stakeholder narratives to gain a more holistic understanding of the linkages. This approach is espoused by Waltner-Toews & Kay (50).

The 5-star Waterways Benefits Rating incorporated into the Healthy Land and Water annual report card brings us one step closer to capturing these positive benefits within Moreton Bay and its catchments. Unfortunately, neither the environmental *State* data relevant to public health (e.g. faecal indicator monitoring) nor the perceived benefits data (e.g. Waterways Benefits Rating) can be geo-referenced directly to EHMP monitoring sites. Using integrated frameworks such as DPSEEA could help us get the best value out of our ecosystem health monitoring and modelling efforts in Moreton Bay by shedding light on the structure of the complex interrelationships between human and ecosystem health.

The *Action* element of the DPSEEA framework captures the potential for multi-tiered management responses aimed at improving environmental and health conditions. A unique strength is that it shows how *Actions* can target multiple points in the DPSEEA pathway and be coordinated across policy sectors. It also facilitates the consideration and integration of more progressive, holistic management strategies such as health-based targets for drinking water management (51), water-sensitive urban design (52) and effects-based management (48, 53). The benefit of these strategies is that they shift environmental management from a regulator-driven, compliance approach to an environmental and community values-driven approach. This does not preclude using traditional tools such as zoning reviews, impact assessments, riparian zone restoration programs, environmental licensing regulations, health protection actions, and policy and clinical responses to the health outcomes. The merits and practicalities of using these approaches in Moreton Bay are currently being explored by a range of stakeholders, including water utilities, councils, researchers and consultants.

Integrative frameworks such as DPSEEA are designed to capture the complexity of the systems they represent. For example, a network of linkages is more likely to represent an issue of concern in Moreton Bay among a mixed group of stakeholders than a single cause–effect pathway. Importantly, DPSEEA can and should be applied flexibly and the stakeholders can begin to populate the elements of the framework from different starting points to promote a better, shared understanding of the integrity of the system as a whole.

Health effects too, are not limited to ill-health and an ongoing challenge when investing in ‘livability’ within catchments is how to capture the positive health and wellbeing contribution of our waterways. Several research projects in Moreton Bay are collecting valuable, in-depth empirical data that could populate parts of the DPSEEA framework. For example, several investigative approaches (microbial source tracking, epidemiological and quantitative microbial risk modelling) are being used by Kozak *et al*. to better characterise the potential health risks associated with exposure to diffuse and point-source polluted recreational waters (54, 55). Another project by Cleary *et al*. seeks to understand the role that ‘nature connection’ (the feelings, beliefs and behaviours that people have towards nature) plays in supporting mental health and wellbeing (56).

Variants of this particular conceptual model continue to evolve as our understanding grows. For example, the eDPSEEA ('ecosystem enriched DPSEEA') model, developed by Reis *et al*., extends the *State* element to incorporate the *State* of the ecosystem services, as well as positive and negative feedbacks between a wide range of the model's components. Using eDPSEEA facilitated better engagement with stakeholders and drew out the wider potential implications of reduced amenity on human wellbeing (57).

Conclusions

In striving for improved health outcomes and ecosystem services in Moreton Bay, we will inevitably come up against trade-offs or paradoxes. We need to better understand the science and social values behind these paradoxes to improve the alignment of environmental and public health strategies in order to maximise the gains from both public and private investment in them. Framing complex environmental health issues in Moreton Bay using models such as DPSEEA would provide the backbone of a more rigorous approach for linking existing data, identifying gaps and collecting relevant additional evidence to facilitate more effective actions at multiple levels and across several policy sectors. Combining emerging scientific tools and technologies with the narratives of stakeholders offers exciting new avenues to guide adaptive strategic management of Moreton Bay. The double-dividend of enhanced ecosystem services and improved human health outcomes is a worthwhile goal.

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Education in *Quandamooka* – A long and evolving tradition

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Abstract

The Traditional Custodians of this land, have a long history of education, and have been passing on their deep knowledge and love of this significant site for hundreds of generations. Quandamooka (Moreton Bay) is a rich and diverse resource for education. The complex interrelated system provides challenges that ignite the spark within students to conduct scientific and historical enquiry. It provides unique opportunities for critical thinking, which should be the goal of all modern education. Seven of the main education modes in Quandamooka are: (i) environmental education centres, (ii) schools (Marine Teachers Association of Queensland), (iii) universities and further education facilities (e.g. University of Queensland and Griffith University), (iv) local governments, (v) state government departments, (vi) not-for-profit organisations/industry, and (vii) ecotourism operators.

Three of the main ways to access Moreton Bay are the mainland foreshore, islands and by vessels travelling into the open Bay. Each of these access points has strengths and weaknesses for environmental education. The Department of Education and Training has invested in vessels that enable classes of students to become immersed in deeper learning in Moreton Bay. Research and infrastructure around Moreton Bay has been developed to capitalise on the unique learnings possible within the region. Future developments in environmental education may include improved access to the Bay and an emphasis on the health of catchments, waterways and wetlands supported by increasingly sophisticated technologies.

Keywords: environmental education, Moreton Bay, experiential learning, marine studies

The value of Moreton Bay to education

Here we describe the valuable contribution Moreton Bay makes to environmental education and also provides a brief educational history and an overview of the various education modes. These modes include both formal (e.g. schools and universities) and informal methods (e.g. recreation and ecotourism) designed for captive and non-captive audiences. While much of the discussion within this paper concerns educational opportunities for schools and children, we have also captured some of the opportunities and informal lessons available to the entire community. This information was gathered from multiple sources, including specific research into Moreton Bay, conversations with various educational stakeholders and information publicly available from relevant organisations. The paper goes on to discuss education access points within Moreton Bay, and then summarises and describes opportunities for future directions.

Goals of environmental education

Environmental education offers a holistic way of learning that is typically designed to enhance knowledge, attitudes, skills, values and motivation towards improving the environment and ultimately achieving an ecologically sustainable future (1). The goals for environmental education, as agreed in the 1977 Tbilisi Declaration and later modified to capture sustainability at UNESCO meetings in the Asia–Pacific region, are to:

- foster awareness and concern about social, political and economic interdependence;
- provide all people with opportunities to acquire the knowledge, values, attitudes, commitment and skills needed to protect and improve the environment; and
- develop and reinforce patterns of environmentally sensitive behaviour among individuals, groups and societies (1).

These goals link to the modern education goals outlined in the Melbourne Declaration on Education Goals for Young Australians 2008 (2). Environmental education encourages an active role in learning, the creative and productive use of technology, multidisciplinary real-world problem solving, collaboration and communication, and develops the abilities of learners to evaluate evidence and make sense of the world around them.

The exploration and study of Moreton Bay can assist in creating successful students who are aware of, and connected with, their environment. Using Moreton Bay as a context exposes students to complex scientific, historical and geographical problems that require multifaceted solutions. In learning about these aspects of Moreton Bay, students are required to both analyse problems and develop and evaluate possible solutions. In the various Moreton Bay education programs, students use a variety of traditional tools such as sediment grabs, plankton nets, beach seines and Secchi discs, as well as modern technology such as underwater video cameras, digital microscopes, iPad-based identification applications and satellite and drone-derived images. Students are required to use ICT skills to both analyse data and share their results with the wider community. Fieldwork framed with explicit objectives allows students to develop team and social skills, which have been shown to be an indicator of academic achievement (3), as well as the ability to plan and conduct investigations.

Moreton Bay's complexity and the impact of humans require students to be creative and resourceful in their deductions as students interpret the changing world. Information is drawn heavily from the disciplines of biology and physical geography, but also climate science, physics, chemistry and history. The extent of human impacts in the western Bay provides opportunities for students to address questions of sustainability, which is a cross-discipline priority within the Australian Curriculum. The Australian Curriculum recognises sustainability education as future-oriented, focusing on protecting environments and creating a more ecologically and socially just world through informed action (4).

Places such as Moreton Bay provide rich opportunities for environmental, place-based education. Ballantyne and Packer (5) conducted research examining the productive pedagogies used for learning in natural environments. Because of the rich opportunities available through place-based education, they proposed that experienced-based learning should be included as a fifth pedagogy to encompass those specific learning strategies (5). These strategies include hands-on exploration, using all five senses to experience and appreciate the natural environment, undertaking authentic tasks and investigating local real-life issues (5).

Educators working in Moreton Bay use these strategies to ensure students get the most from their experiences. It is a connection to place, authentic hands-on learning and the active participation of young people in decision-making that encourages students to care for the Bay. These approaches link back to the outcomes of the Melbourne Declaration and highlight the value of the learning that occurs when students operate outside the classroom in Moreton Bay.

Brief history and current state of education in Moreton Bay

Education in Moreton Bay began at least 20,000 years ago with the Quandamooka Peoples who still call the area home. They had an informal system of education that was both experiential and rigorous. Knowledge of their natural environment was passed to the next generation from their Elders partly to help sustain their livelihoods by taking advantage of cycles of food abundance, including fern roots, fruits, fish and shellfish. Environmental education in the Quandamooka culture also included the many sources and uses of various natural materials such as stone, wood, bone and shell and how to process them into effective tools.

Early Europeans visitors saw Moreton Bay as a gateway to the hinterland and a place to gather resources such as oysters for limestone and dugong oil for medicine. It was not until the 1880s that Reginald Heber Roe recognised it as an important education resource. He and his wife regularly took groups of students from the Brisbane Grammar School to a ‘Kamp’ on South Stradbroke Island near Southport to experience both communal life and explore southern Bay environments (6).

The Moreton Bay Research Station had its origin in 1949 as the Dunwich Marine Station (DMS), a joint venture between the Department of Harbours and Marine, CSIRO Fisheries division and The University of Queensland (UQ) (7). UQ’s formal education programs began in 1961 at the DMS. Following a complete rebuild using funds from UQ and gifts from Consolidated Rutile, the Port of Brisbane Corporation and the Royal Queensland Yacht Squadron, it was reopened in 2000 as the Moreton Bay Research Station and Study Centre. The station now serves as an important education facility for high schools, regional and international universities and community groups. Given its location, it offers a wide range of educational opportunities in fields from anthropology to zoology (7). An estimated

50,000 students passed through the station between 2000 and 2017 (pers. comm. Kevin Townsend).

State government departments have a long history of involvement in education activities within Moreton Bay. Their initial focus was community compliance with various regulations, but this has extended to more broadly educate the public about critical habitats and endangered species. Departments have undergone numerous name changes with changing governments and ministerial portfolios, but the departments that are currently most heavily engaged in education activities in Moreton Bay are the:

- Department of National Parks, Sport and Racing who manage the heritage parks of St Helena Island and Fort Lytton as well as Moreton Bay Marine Park and island parks such as Moreton Island, Peel Island and Bribie Island national parks (8);
- Department of Agriculture and Fisheries which includes the Fisheries and Forestry service area (9); and
- Department of Education and Training, responsible for the environmental education centres around Queensland (10).

In the 1980s, Education Queensland set up a state-wide network of environmental education centres (10). Three of those centres — Moreton Bay Environmental Education Centre, Nudgee Beach Environmental Education Centre and Jacobs Well Environmental Education Centre — have Moreton Bay as a primary focus (10).

The Queensland Museum, which opened in 1862, has had a long history of creating exhibitions that communicate information to visitors about the amazing animals and plants that reside in Moreton Bay. They have published very successful guides, such as *The Wild Guide to Moreton Bay*, that have enabled thousands of enthusiasts to identify creatures they find as they explore the Bay (11).

Local governments have also taken on the role of educators in Moreton Bay. Moreton Bay Regional Council runs Osprey House, first opened in 1996, as well as the Kumbartcho Centre and the Caboolture Region Environmental Education Centre, with a focus on educating the public on the value of the wetlands around Hays Inlet and the Pine River estuary (12). Redland City Council established the IndigiScapes Centre in 2000, with the aim of improving the environmental knowledge of its residents and increasing care for the local environment (13).

Ecotourism is a relatively new phenomenon in Moreton Bay, but has grown quickly in the past two decades. Operators such as Tangalooma Resort, SeaWorld, SEA LIFE Sunshine Coast (formerly UnderwaterWorld Mooloolaba) and whale-watching groups as well as numerous smaller operators offering boutique experiences are engaging with tens of thousands of individuals annually.

Modes of education within Moreton Bay

Modes of education delivered in Moreton Bay are varied and diverse. Below we describe many of the organisations, facilities and departments involved in education specific to Moreton Bay.

Environmental education centres

One of the most valuable modes of education within Moreton Bay is the continued use and development of environmental education centres (EECs), funded by the Queensland Department of Education and Training. With diverse settings in environments such as forests, estuarine and freshwater systems, EECs are able to provide specialised environmental learning for the education of students from Prep to Year 12 (10). The centres work within the Australian Curriculum for students up to Year 10 and senior student programs follow the Queensland Curriculum and Assessment Authority senior syllabi in subjects such as Senior Biology, Geography and Marine Science (10). Moreton Bay EEC, Nudgee Beach EEC and Jacobs Well EEC are the centres specifically located in the Moreton Bay area (10).

The main ideology powering the approach for teaching used by these EEC's is that of connecting people to place, inspiring them to care for animals and habitats, and developing an appreciation for ecosystem function and sustainability (10). The centres aim to foster this connection through student immersion in the environments of Moreton Bay and development of students' critical thinking skills in order to create a deeper understanding of the processes operating within the Bay (10). To achieve this, the centres have increasingly embraced data collection by students and the general public through citizen science as an educational model. This has the benefit of actively engaging students as well as providing useful data for environmental managers (14). According to their annual report, the three centres work with around 18,000 students each year which, with the present staffing, is operating at capacity (14–16).

These centres have land-based classrooms and other facilities but what makes them unique is their ability to directly access the Bay. Facilities that allow this access include Moreton Bay EEC's two aquatic vessels — *Inspiration*, a 12-m catamaran able to support 60 passengers or have 40 students actively working onboard, and *Janjari*, a 5.8-m rigid inflatable that can transport up to 11 passengers through the inshore areas of Moreton (14). Nudgee Beach EEC has canoes and an aluminium powerboat that is able to support 15 students (15). Jacobs Well EEC has *Educat*, a 12-m aluminium catamaran capable of supporting 40 students as well as canoes and two smaller outboard vessels (16).

Schools

Many schools, both primary and secondary, access education in Moreton Bay either independently or in partnership with commercial or not-for-profit providers. The vast majority access the western foreshore of Moreton Bay for studies of rocky shores, mud flats, seagrass and mangroves as these are the easiest places to access, typically just requiring a bus to transport students. Subjects in the Australian Curriculum that can leverage learning from interaction with Moreton Bay are Science, Geography, History, Biology and Marine Science in the senior Queensland syllabus.

Craig Reid, from the Marine Teachers Association of Queensland (MTAQ), estimated that around 20 schools regularly do fieldwork in Moreton Bay (17). From his perspective, MTAQ values students being able to do authentic scientific field work in the large number of accessible ecosystems within Moreton Bay, but it was often difficult to access the large datasets that students need to complete useful analysis (17). MTAQ is a not-for-profit organisation that supports marine education, coordinates activities and lobbies governments, industry and interested individuals (18). With over 400 members, MTAQ aims to foster curiosity, imagination, knowledge and enthusiasm for 'real world' science and vocational maritime studies for primary, middle and secondary school students (18).

Universities and further education

The University of Queensland, owner of the Moreton Bay Research Station, and Griffith University (Griffith) are the two major institutions that regularly conduct marine science education within Moreton Bay. By speaking to the relevant parties and contributors we found that all valued time spent in the field with students and agreed that the wide variety of accessible habitats and biodiversity in close proximity to a major population made Moreton Bay an exceptional educational resource (19-21). All of those we consulted would like to increase the time students spend out in the field but noted that the costs involved were quite high (19-21).

Griffith University

Griffith offers a Bachelor of Marine Science and a marine biology major in their Bachelor of Science course (22). Through their marine sciences course, students have access to the diverse wetlands and coastal biodiversity of Moreton Bay and other natural and artificial waterways (22). The course focuses on practical experience and ensuring marine industries prosper sustainably (22). Annually they take around 60 to 80 students out into Moreton Bay for fieldwork, which is generally land-based and includes studies of the mangroves, seagrass beds (South and North Stradbroke islands) and dune ecology studies out on the Southport Spit (19).

The University of Queensland

At UQ, a number of schools facilitate education that is directly involved in Moreton Bay. These include the School of Earth and Environmental Science, School of Biological Sciences, School of Agriculture and Forestry, and School of Veterinary Science, with an estimated 300 students and 30 academic staff involved each year (20). The Centre for Marine Science is based at the St Lucia campus of UQ (23). The Faculty of Science offers a major in marine science and an extended major in marine biology. Courses cover a range of disciplines from physical and molecular science through to nature conservation and global change science (23). It is a world-class environment for postgraduate and postdoctoral research in marine science currently including over 200 PhD candidates, 50 postdoctoral research scientists from around the world and 6 ARC Professorial Fellows (24).

Moreton Bay Research Station

UQ owns and operates the Moreton Bay Research Station (MBRS) which is used to advance science and to provide engaging learning opportunities for young scientists (24). MBRS is on North Stradbroke Island and has direct access to the waters of Moreton Bay and surrounding environments (24). MBRS hosts approximately 3000 high-school students and a similar number of undergraduate students each year (21). Year 11 and 12 student school groups and leaders of undergraduate student groups may either choose to administer their own curriculum or take advantage of the programs provided by MBRS (24). Higher level undergraduate and postgraduate groups also use MBRS facilities as an integral part of their degree programs (24). The station attracts local as well as international scientists and student groups, with excellent facilities including a range of accommodation from VIP to dorm, modern research laboratories, boating and diving facilities, a sub-branch of the UQ Library and AV-equipped teaching and lecture spaces (24).

Local government

Moreton Bay Regional Council and Redland City Council each have EECs that serve to educate citizens to care for the environment, including Moreton Bay and its catchments.

Redlands (IndigiScapes)

Redland City Council runs the IndigiScapes Centre with a particular focus on involving children and developing a sense of wonder and interest in the natural environment (13). The centre has a variety of environmental education programs, such as organic recycling and bush-tucker walks, which cater to a range of ages and learning abilities from early childhood and school groups to adult education (13). These programs target curriculum outcomes for primary and secondary schools and can be done by an excursion to the Centre or an activity at the school (13). IndigiScapes also provides free environmental education talks to local Redland's community groups either at the centre or at local meeting points (13).

Moreton Bay Regional Council

The Moreton Bay Regional Council ensures that school groups have access to pertinent education about the Moreton Bay Region. Environmental education is facilitated by lessons through the Council's EECs, with resources such as lesson plans, maps and photographs to aid in teaching about local history (12). The EECs are Osprey House on the Pine River, the Kumbartcho Centre, and the Caboolture Region EEC. The education goal of these centres is to motivate the community to value the natural environment, particularly through 'connecting to nature' and nature play (25). A mix of staff and volunteers deliver education programs that link to the Australian Curriculum (Prep to Year 7) while also highlighting the important ecosystems close to each centre (25).

State government departments

Many Queensland government departments have responsibilities that impact Moreton Bay, its ecological integrity and educational value. These include the Departments of Environment and Science; Education; and Agriculture and Fisheries. These departments, to varying degrees, serve to protect and preserve natural environments, make them accessible to the public and provide education about the importance of these places in our community (8, 9, 26, 27). Many of these departments provide resources and programs for schools and the wider community detailing facts about Moreton Bay environment, wildlife and the measures required to secure its ongoing importance as a natural resource for South East Queensland (SEQ) (8, 9, 26, 27).

Moreton Bay Marine Park

The Moreton Bay Marine Park, managed by the Department of National Parks, Sport and Racing, covers 3400 km^2 and is the only place in the world where significant populations of dugong (*Dugong dugon*) and sea turtles can still be found close to a major metropolitan centre (28). The goals of the Moreton Bay Marine Park are to increase environmental awareness, preserve the flora and fauna in the park for the enjoyment of the public, and to promote public access and use of the park (28). Most of the educational activities carried out by the marine park primarily involve disseminating information to users of the Bay so that they may readily comply with the regulations governing access to the park (29).

Not-for-profit organisations/industry

Provided here is a sample of the many industry and not-for-profit groups involved in education in the Moreton Bay area. Citizen science plays an ever-increasing role within these groups but will be discussed in the Citizen Science chapter in this volume.

Healthy Land and Water

Healthy Land and Water is an independent organisation that came about when experienced natural resource management groups Healthy Waterways and SEQ Catchments merged in June 2016 (30). Healthy Land and Water is dedicated to improving and protecting SEQ's environment and aims to inspire people with tools and action that will protect the natural environment and support the economy for future generations (30). The organisation provides assessments, advice, training, workshops and support services and responds to urgent community needs and natural disasters (30). Healthy Land and Water works with community, industry and governments at all levels to align policy and education planning (30). While striving to improve natural resources management, Healthy Land and Water recognises the difficulties in competing for people's attention. South East Queensland communities are highly fragmented and, apart from the Traditional Custodians, not as closely connected to the land as are more rural communities (31).

Australian Marine Environment Protection Association

The Australian Marine Environment Protection Association (AUSMEPA) is a not-for-profit organisation run mainly by volunteers with the main goal of promoting marine environmental education and awareness through school education programs and seafarer education (32). The school Marine Education Programs available through AUSMEPA are designed around core curriculum units for foundation years to Year 6 (32). Students learn about the marine environment and those who use it, both commercial and recreational, with the aim of becoming responsible users of marine resources and protectors of the marine environment for future generations (33). There is also a Junior Ranger program that gives children learning opportunities about respecting country and how Indigenous peoples care for country (33). Further, AUSMEPA aspires to instil in those it reaches an increased marine environmental consciousness and awareness. Indeed, AUSMEPA places a copy of an internationally recognised DVD 'Welcome to Australia: Protecting the Marine Environment' on every ship when it first arrives in Australia (33).

Port of Brisbane

The Port of Brisbane is located at the mouth of the Brisbane River, adjacent to the Moreton Bay Marine Park, and is Queensland's largest multi-cargo port and one of Australia's fastest growing container ports (34). It has many policies concerning respect for the environment that aim to minimise negative and enhance positive impacts on the surrounds by ensuring environmental management is considered in all decision-making processes (34). To reduce their ecological footprint, the Port is involved in energy efficient and waste-reduction projects and employee education programs (34). The Port of Brisbane provides a website for teachers and students offering educational resources for primary and secondary school groups and also operates port tours for school excursions (34).

Ecotourism operators

Ecotourism Australia defines ecotourism as 'ecologically sustainable tourism with a primary focus on experiencing natural areas that fosters environmental and cultural understanding, appreciation and conservation' (35). Operators identified within the sphere of Moreton Bay education are Tangalooma Marine Education and Conservation Centre, SeaWorld, SEA LIFE Sunshine Coast and whale-watching operators. These groups have access to the diverse flora and fauna of Moreton Bay and facilitate a range of educational programs for school groups that align to curriculum units (Prep to Year 12) as well as for tertiary students and community groups (36–39). They also provide specialised programs such as Tangalooma's EcoMarines, established to enable young children to participate in community engagement advocacy and action to protect waterways, rivers, oceans and wildlife (36) and SeaWorld's Rescue Ranger Program where children learn about threats to marine life and future protection strategies, supported with up-close animal experiences (37).

Education access points

There are few official data sources about the use of sites in and around the Moreton Bay area as they are often accessed by individuals and groups independently. The following overview was determined inductively and focuses on formal, school-based education. Informal education through recreation and tourism also plays an important role in Moreton Bay but is more difficult to characterise.

Mainland foreshores

The mainland foreshores are the most heavily visited as they offer the easiest access usually only requiring a bus for school, recreational and tourist groups. Students regularly use a number of sites, including Point Lookout for rocky shore studies, Nudgee Beach, Wynnum foreshore, Myora Springs, Jacobs Well, and around Paradise Point for mangroves.

Boardwalks at Nudgee Beach, Wynnum and Paradise Point draw larger numbers to these areas. Seagrass habitats are commonly accessed around Nudgee Beach and Wynnum foreshores as well as around Myora Springs.

Moreton Bay islands

The Bay islands that are commonly accessed for education include North Stradbroke, which is served by regular commercial ferry and barge services, and to a lesser extent Moreton Island, where access to the various ecosystems is more difficult. Some groups also access Coochiemudlo Island using the passenger ferry services. South Stradbroke Island is regularly accessed by Jacobs Well EEC and their vessel *Educat* and less often by Griffith University students using water taxis.

Open Bay

The open Bay waters are the most difficult for students to access as chartering a suitable vessel is challenging. Class groups are regularly taken into Moreton Bay by Moreton Bay EEC on their vessel *Inspiration* and by Jacobs Well EEC on their vessel *Educat*. A number of schools maintain their own smaller vessels as part of their marine studies. UQ's Moreton Bay Research Station has a number of aluminium-hulled vessels with a capacity of 5 people and several rigid-hull inflatable boats (RIBS) that carry up to 12 people. All are less than 6m in overall length and can be skippered by suitably experienced individuals with a Queensland Recreational boat driver's licence and a VHF radio operator's licence (less then 6m). UQ St Lucia campus also hosts a number of vessels from punts to RIBS and a 7.5m aluminium vessel. The Centre for Marine Science at UQ offers boat- handling courses specific to Moreton Bay conditions at introductory, intermediate (foul weather and night) and advanced (bar crossing) levels.

Conclusion

Summary of stakeholders

The focus on experiential learning and immersing students in authentic learning and the Bay environment has been a recurring theme in our conversations with stakeholders. These conversations helped identify the following three features as contributing most to the value of Moreton Bay education:

- Moreton Bay is easily accessible, close to a major city and possesses a wide range of biologically diverse habitats such as seagrass, mud flats, mangroves, coral reef, rocky shores and open beaches;
- There is significant human impact on these ecosystems in the western Bay and much less in the eastern Bay which can be seen as a benefit to educators focusing on human impacts and how to best manage them; and
- Iconic species in the Bay, such as turtles, dugongs, dolphins, sharks, whales and migratory shorebirds, increase student engagement.

The stakeholders identified some of the limits to education in Moreton Bay including:

- the price of such excursions, including transport and access costs;

- the time required to obtain a Moreton Bay Marine Park permit (currently ca 9 months);
- the restrictions imposed by OH&S standards limiting students opportunities to be in the water and snorkel; and
- a lack of suitable large vessels to explore the area.

Future directions

Education in Moreton Bay has been a longstanding priority among school groups and researchers with programs run since the 1880s to the present day. No doubt the future of education in Moreton Bay will likely see an increase in the sophistication and resolution of technologies used to monitor and assess its flora and fauna, such as satellites and drones. Citizen science will become increasingly easier and more available with phone and tablet apps available to the public. Other developments that may improve education in Moreton Bay include an increase in the number of vessels with which groups can directly access the Bay and improving accessibility to some of the Bay's diverse ecosystems, particularly through snorkelling. Learners can further develop their understanding of how the health and sustainability of the Bays' waterways, wetlands and catchments are connected with the availability of these new technologies and services.

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Chapter 3 - History and Change in Moreton Bay

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An environmental history of Moreton Bay hinterlands

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Abstract

Recent studies of local landscape and vegetation change have improved our understanding of the part Europeans have played in the evolution of subtropical Australia. Here, we focus on sedimentary and documentary evidence from the large, rural catchments draining to Moreton Bay. In the 1840s, the region underwent a transition from Aboriginal pastoralism to European grazing and agriculture. The first decades of European management brought changes to the floristic composition of the region's grasslands with only minor changes in the extent of forest and woodland. Changes in soil density in the catchment headwaters and valley floors associated with cattle and sheep grazing are linked to channel erosion in the middle and upper reaches of the river systems, accompanied by gullying in some headwater catchments. The erosion of waterways upstream is associated with a degraded riparian forest and the transport of muddy sediments into Moreton Bay. The timing of peaks in sedimentation, in the 1890s, 1950s and 2010s, was triggered by periods of enhanced rainfall and flooding. All of these factors are implicated in a tenfold increase in sediment loads into Moreton Bay since European settlement. Despite these impacts, changes to landscapes and soils in the region have been modest. In comparison with temperate south-eastern Australia, gully erosion has been limited in extent, the soils remain largely intact, and major changes in channel type have occurred on only a small proportion of rivers. This greater resilience in the Australian subtropics to the new European land uses is attributed to the naturally more variable climate and vigorous vegetation response to disturbance. However, sustainable management of these landscapes has not yet been achieved. The drainage network is presently unstable, leaving open the possibility of catastrophic system adjustment in the near future. This could produce dramatic increases in hill-slope and gully erosion and a metamorphosis of channel pattern in the trunk streams, similar to landscape responses documented in south-eastern Australia between 1850 and 1950.

Keywords: subtropics, land-use change, sediments, channels, gully, vegetation

Introduction

Recent studies of the shallow marine waters of Moreton Bay depict a landscape in crisis. Significant areas of clean sand within the Bay have been replaced by mud (1–4), the near-shore and estuarine waters are polluted by sediment, toxins and nutrients (5, 6), and seagrass and estuarine ecosystems are declining in both extent and health (7). Many of these changes point to unsustainable management of the hinterland. To address this through planning and adaptive management, an understanding of historical change, and the establishment of an environmental baseline are critical. We first need to know what the environment was like when Europeans arrived, how has it changed, and why? This is essential background information to an understanding of the responses and sensitivities of the catchments, rivers, and ecological systems that contribute to the health of Moreton Bay and its broader catchments.

Thanks to previous collaborative efforts to piece together the environment and history of Moreton Bay, parts of this complex landscape of islands, subtropical estuary and coastal plains are now well understood (8–10, Richards 2019 (11), this volume). The story of the hinterland has been slower to develop, and critical questions remain unanswered about the sensitivity or resilience of the largely rural catchment. The focus here is on the Logan River and Brisbane River catchment areas that lie outside suburban Brisbane and the Gold Coast, including their major tributaries, the Bremer, Lockyer, and the Stanley basins (Fig. 1). Together, the Brisbane

Figure 1. Map of Moreton Bay and major contributing river basins. The Brisbane and Logan basins occupy 82% of the total catchment area. Smaller contributing catchments drained by the Caboolture, North Pine, Coomera and Nerang rivers (shaded brown) have been extensively developed as suburban areas.

and Logan basins make up 82% of the total 21,200 km^2 catchment area for Moreton Bay. Today, similar proportions of native and plantation forest (50%), grazing pastures (40%), crop lands (6%) and urban areas (4%) occupy these catchments (12). At the time of the last compilation in 1998, the environmental history of the hinterland needed to be inferred from studies of landscape processes in temperate south-eastern Australia (13). Over the intervening 20 years, local data have been gathered from a number of Moreton Bay catchments, and their distinctive processes are beginning to be revealed. These catchments display some significant differences to their counterparts in eastern New South Wales and Victoria. This is hardly surprising considering that subtropical landscapes are hydrologically and geomorphologically distinct from those in the temperate zone. Rainfall is dominated by the summer monsoon and is highly variable, the vegetation response is rapid and vigorous, and the soils are conditioned by rapid chemical weathering. Here we review the land-use history, climate and floods, and changes in vegetation, landforms and erosion rates in the inland catchments of Moreton Bay, and compare their landscape responses to temperate areas of southern Australia.

European settlement

European settlers entered Moreton Bay in 1824 and have occupied its hinterland since 1841 when squatters established themselves on open grazing lands along the Brisbane River Valley. In many respects, the European settlement of Moreton Bay follows a parallel history to Port Jackson, but the subtropical environment yielded new challenges as Europeans expanded northward into the Torrid Zone. These new subtropical lands proved to be even more alien than their European homelands, described as 'more a new planet than a new continent' (14 p22). Apart from risks associated with remoteness and a widely dispersed population, the incidence of diseases was higher in the low latitudes, as were various 'fevers' including malaria, scrub typhus, dengue and leptospirosis (15). Mortality rates in the pioneering European population were high (16). The first penal settlement at Redcliffe failed within months owing to malaria and other health crises, failed crops, and to bloody clashes with the Aboriginal inhabitants (16 p64). Many of these problems persisted in the new establishment at Brisbane. The explorer and surveyor John Oxley's promises in 1823 of 'very fertile country…capable of producing the richest productions of the tropics' turned out to be the reverse of the truth (17 p116). Experiments with cotton, sugarcane, bananas and corn failed regularly, and the area of land under cultivation remained at negligible levels for the first generation of settlement (16).

After 1866, the area of cultivated land increased slowly from 8 km^2 to 120 km^2 in 1887, and reached a roughly stable area of 500 km^2 in 1920, still then a meagre 4% of the catchment (18). Pastoral expansion was delayed by the restrictions imposed by the penal settlement, as well as the rugged volcanic ranges that encircled the Moreton Bay catchments. In the eight years following the closure of the penal settlement in 1842, wealthy British pioneer families rapidly occupied the rich pasturelands on the tablelands west of the Great Dividing Range and the fertile valleys that drain into Moreton Bay. These areas had been carefully maintained by Aboriginal societies for the husbandry of kangaroos and wallabies, and were now readily exploited for grazing by horses and cattle following the extirpation of their native inhabitants.

In 1860, 95% of Queensland's wealth was generated from pastoralism, almost all of it owing to exploitation of Aboriginal grazing lands (16). The transition to European pastoralism was not without setbacks. Sheep grazing was introduced to Moreton Bay catchments in ~1844, but typically failed as the native pastures were depleted, usually within a decade (19, 20). In 1843 the explorer and scientist Ludwig Leichhardt reported that the kangaroo grasses in the region of Ipswich had lasted at least 12 years (21). Most sheep farms had reverted to cattle by 1880, but by the 1890s the large pastoral estates were deeply in debt to foreign interests, beset by economic depression (1891–1896), intense drought (1898–1905) and catastrophic floods (1890, 1893 and 1898) (16). Subsequently, livestock numbers declined dramatically in some sub-catchments of the Brisbane Valley and in others they remained static until 1905 (18). Attempts to encourage closer settlement and the break-up of the large pastoral runs through government legislation in 1884 (the *Land Act*) and 1887 (the *Repurchase Act*) resulted in a slow intensification of farming, particularly dairying and irrigated agriculture in areas such as the Lockyer Valley which possessed rich, basaltic soils (19, 22). The Lockyer has since become one of Australia's most productive agricultural valleys, but sediment transported out of this catchment by a flood in 2013 polluted the domestic water supply to one million people in Brisbane (23).

After forest land, grazed pastures remain the dominant land cover in the Moreton Bay hinterland (12), but much of the Moreton Bay catchment is in poor condition, with degraded waterways, channel erosion and gullying (19, 24–26). As in other parts of Australia, European Australians are still learning lessons from the country (27). After 180 years, sustainable land management of Moreton Bay seems to be still some way off.

Climate and floods

The vagaries of the climate in Moreton Bay's hinterland exceeded anything experienced by European settlers in southern Australia. Located at the southern limit of the Australian monsoon, intense downpours accompany tropical storms that stray south of their normal paths, some as fully developed tropical cyclones. More commonly these storms arrive as decayed tropical depressions, diminished only in the strength of the accompanying gales. Rainfalls of 500 mm over two or three days are not uncommon. The worst storm ever recorded occurred in 1893 when a series of tropical cyclones crossed the coast at Yeppoon, 460 km north of Brisbane, producing 77 inches (1956 mm) of rainfall over four days in the upper Stanley catchment. The 35.7 inches (907 mm) recorded at Crohamhurst on 2 February 1893 (28) remains the official Australian rainfall record for a 24-hr period (29). Climate variability in the region is enhanced by decadal cycles in rainfall superimposed on the erratic rhythms of the Southern Oscillation and other drivers of local climate (30, 31). The combined effect of these cycles, together with changing patterns in coastal circulation, make seasonal rainfall in South East Queensland (and its socio-economic impacts) difficult or impossible to forecast (30).

In the time since reliable observations began in the 1820s, Moreton Bay has experienced a number of extreme floods, even by Australian standards (18). South East Queensland is one of the few places where catastrophic floods need no aid to the imagination from palaeo-environmental archives or oral histories. Flood effects are well documented in the urban and rural environment while some, such as floods in 2011 and 1974, fall within the period of instrumental streamflow records. The physical legacy of these events in the floodplains upstream is visible from widespread stripping of confined floodplain areas, or may be dated from the beer bottles deposited in flood sediments (18, 32, 33). In 1893, floodwaters reached 32 m at the tidal limit of the Brisbane River, and peak discharge at Brisbane was estimated to be 16,000 m^3s^{-1} (18) The calamity destroyed all of Brisbane's bridges, washed away 150 houses and drowned 35 people (28, 34). Following the flood, detailed surveys of peak stages were conducted from the Bay to the upper reaches of the river (18). Eventually, these investigations led to the construction in 1984 of Wivenhoe Reservoir with a capacity of 1200 ML and a further 2000 ML of permanent flood storage to mitigate floods in the lower reaches (35).

This kind of hydrologic variability is difficult to imagine for those accustomed to the flooding patterns of Europe. A convenient way to evaluate flood severity in different regions is by comparing normalised flood growth curves, which show the relationship between flood size, given by the peak discharge, and its return period, as in Figure 2. Flood size is shown relative to the average flood in a region, in this case the conventional average mean annual flood ($Q_{2.33}$). The flood growth curve for tropical rivers (e.g. Guyana) that are supplied with predictably similar annual rainfall have 100-year floods that are similar in magnitude to their mean annual floods, while the ratio in moderately variable areas such as the U.K. is closer to four (36). In contrast, sub-catchments of the Brisbane River display ratios of 15 in some extra-coastal locations, diminishing to 3 in catchments such as the Bremer, which have their headwaters located closer to the coast (37). This implies that many parts of Moreton Bay's hinterland regularly experience catastrophic floods that would be rare events elsewhere in the world. Despite this, the inhabitants of Moreton Bay remain surprised at the severity of moderately severe floods such as occurred in 2011 (38). The largest events in the region's history occurred in ~1823, 1841 and 1893 (18), yet the 1974 flood remains the reference point for catastrophic floods in the popular consciousness.

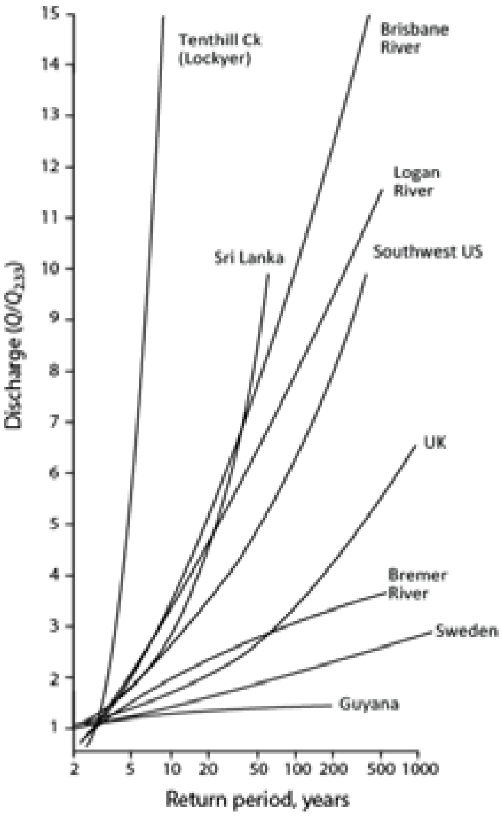

Figure 2. Flood growth curves for selected regions around the world compared to rivers in the Moreton Bay catchment (36, 37).

Vegetation cover and changing land management

The most obvious difference between the Moreton Bay landscape in the days of the pioneers and the landscape of later settlers is the change in vegetation. However, memories of the original vegetation cover have become distorted by rapacious clearing in recent decades, and by a long history of government support for forest removal (39, 40). There is a widespread perception of pre-European landscapes surrounding Moreton Bay as jungle and primeval forest, 'the result of some 60 millions of years of independent and unique evolution' (41 p1). This view tends to overlook, or at best to downplay, 50,000 years plus of human agency. The best evidence of pre-European landscapes in the Moreton Bay hinterland comes from the explorer and pioneer accounts between 1823 and 1834 (17). The first European explorers report mixed communities of forest and grassland: tall closed forests with a mix of sclerophyll and rainforest species on the steep slopes of the ranges, and open woodland, open forest and grassland on the plains. Patches of closed rainforest described as 'Araucaria scrubs' contrasted with the generally open country. The distribution of rainforest was observed by explorer Ludwig Leichhardt to reflect soil water availability (43), although the starkness of the boundary between the vegetation communities suggested, even to the pioneers, that Aborigines regularly burned the country (42). Much of the country inland from the coast was open. The surveyor James Burnett described

> *the whole of the country on the Brisbane…a very thinly wooded forest furnishing a rich and abundant pasturage, patches of scrub intervening in one or two places* (44 p28).

Explorer Edmund Lockyer in 1825 described the middle reaches of the Brisbane Valley as

> *very good on both sides… the country behind them having quite a park-like appearance. I saw Kangaroos in abundance… As far as I could see to the S and SW, the whole country appeared well timbered with forests of tall pines. And to the NW and NE. very few* (17 p191).

Four years later, explorer Alan Cunningham travelled to the north-west, where the Lockyer Valley appeared as a

> *fine plain, its larger portion stretched upward of three miles to the N.E., its length from north to south being not less than five miles (17 p317).* This was succeeded by *barren and frequently brushy country* and *grassy wooded hills…(17 p318) …Having rested…again encamped…on a spot so clear and open as not to allow the natives, whose hatchets we heard around, to surprise us in our tent* (17 p323).

Turning north towards the upper Brisbane River,

> *our whole stage was through an excellent tract of grassy country, sufficiently watered by small creeks …but indifferently wooded* (17 p326).

Leichhardt made similar observations on his travels through the newly settled country surrounding Moreton Bay in 1843. Along Laidley Creek were 'small plains without tree-growth … separated by light belts of forest' (21 p240). Towards Ipswich the party followed 'rough grass growth, park-like tree growth' (21 p240). The pattern continues to the north along the Stanley River: 'rich grassy vegetation' on the valley floors (21 p265) with moist depressions that contained a range of species including kangaroo and oat grasses (*Themeda* spp.), *Poa* tussocks, geranium and *Ajuga* (Austral bugle) and daisy species. (21 p265, 299, 300). Along Neurum Creek near Woodford 'beautiful flats are found, which would be very well suited to cultivation, dairies and paddocks' (21 p285). Stream banks were lined with 'scrubs' (21 p299) that included sclerophyllous casuarina and bottlebrush in drier areas such as Lockyer's Creek (21 p240). The higher hills were forested with hoop pine, *Angophora*, and tall gums (21 p240, 265).

These native pastures were captured by painter Conrad Martens in the first decade of European pastoralism during his tour of Moreton Bay, Darling Downs, and the Granite Belt in 1851–52. Sketches of the country at Coochin, near Boonah in the upper Logan catchment show valley slopes with grassy open eucalypt forest and grass trees opening onto grassed plains (Fig. 3a, 45). His depiction of Franklyn Vale, near Rosevale 40 km north-west of Boonah, shows sheep sheltering in the trees on an open plain (Fig. 3b). The wooded lower slopes of the ranges have a grassy understorey, and were sufficiently passable to allow Martens a view of the valley floor below Mount Beau Brummell and nearby hills. These ranges remain forested today although the trees have been cleared from the lowest foot slopes and lower hills.

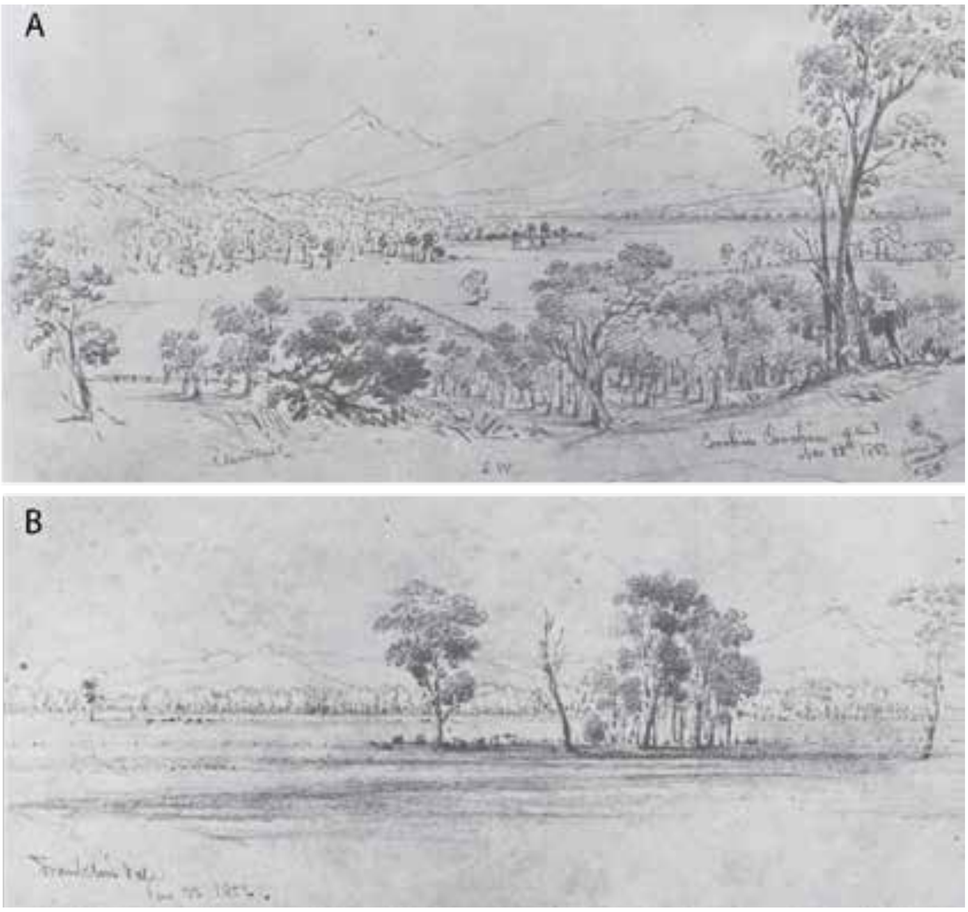

Figure 3. Impressions of the Moreton Bay hinterland in the first decade of European settlement. (a) Coochin Coochin, Qld, 28 Nov. 1851. The view is from the head station of Coochin near Boonah (Fig. 1) with Mount Moon and Mount Alford in the distance. The trees in the foreground follow the path of Teviot Brook (45) (b) Franklin Vale, 22 Jan. 1852. (Photographs courtesy C. Martens, Mitchell Library, Sydney).

These descriptions of open country, grassland or well-grassed open forest, the long-established paradigm of the Australian landscape under Aboriginal management, are easily applied to much of the Moreton Bay hinterland (14, 27, 46, 47). The open country provided easy access for explorers and was rapidly converted to sheep and cattle pastures. There is clear evidence of Aboriginal fire management from the explorer accounts (17), although the frequency of burning is difficult to determine owing to the use of fire as a weapon or deterrent against Europeans (48). In light of the pictorial and documentary evidence, it is strange that quantitative descriptions of vegetation change in South East Queensland are based on ‘a once continuous forest cover’ (41 p1), where ‘pre-clearing… generally equates to … pre-European’ (49 p13). The distinction may be a semantic one: very open forest is similar in structure to open savannah grassland, but ‘remnant vegetation’, has become synonymous for ‘forest’ in much recent literature. This implies that a 77% reduction in forest cover for the Moreton subregion (41) is an overestimate.

Some of the confusion about the extent of the pre-European ‘forest’ arises from geographical variations in the distribution of tall forest. Inland from the coast, rainfall declines from 1280 mm at Redcliffe on the coast (Station 40958: 2003–2017) to 770 mm at Gatton (Station 040082: 1897–2013, Fig. 1) (29). Further inland, forests and woodlands are typically open, with rainforest restricted to riparian zones and the better watered mountain ranges. Even in coastal areas, rainforest ‘brush’ or ‘scrubs’ were more common on the fertile, black, alluvial soils bordering the floodplains and river terraces, and this vegetation community features prominently in early accounts of the lower Brisbane River and explorations upriver by boat (17). Pollen records from the catchment inland from the coastal lagoons and lakes may eventually provide quantitative estimates of the magnitude of the regional changes in forest cover.

Some aspects of forest removal are well documented in the historical record from the 1850s, such as the selective extraction of prize timber species including red cedar, silky oak, blackbutt, hoop and kauri pine (50, 51). Private clearing of farmland outside the townships is less well recorded, but substantial rural clearing may not have begun until the 1880s, two generations after the introduction of European pastoralism. Mary Banks, whose father, David McConnell, established Cressbrook Station on the upper Brisbane River in 1842, noted the practice of ringbarking of large gum trees, associated with the transition to closely settled farms compared to the wild “Bush” of her youth, ~1865–75 (53 p79). Charles Cochrane-Baillie’s (Lord Lamington) memory of Cressbrook was that ‘the country is rugged near the hills and was heavily timbered…but the country was still Bush on the Brisbane River at this time’ (around 1900) (53 p8). Clearing had been encouraged by the changes in government legislation in the 1880s, but significant changes in agriculture were forestalled by drought and economic downturn in the 1880s and 1890s.

Changes in tree cover in the region have not been unidirectional. After the 1950s, there is some evidence of regrowth in areas that had been cleared for cropping, and a regional increase in forest density since the 1950s (54). In formerly cropped areas this may be owing to reduced agricultural intensity (19), but elsewhere in southern Queensland increases in woody vegetation have been attributed to a change in burning regimes (54) or to higher rainfall (55). Since 2013, clearing of rural lands has rapidly increased following the weakening of key statutory restrictions on land clearing (39). This has combined with suburban sprawl, in a region that now has the fastest growing population in Australia, and is consuming forest around already large urban centres (56).

Changing landforms and erosion rates

The impacts of European settlement wrought subtle changes on Moreton Bay's landforms and soils compared to catchments in southern Australia. This is not to understate the deleterious effects of soil erosion on water quality and ecological systems in riverine corridors and estuaries downstream. In a country naturally adjusted to low erosion rates, relatively small increases in erosion and sediment yield can have catastrophic and lasting consequences (4, 6, 7, 57). Yet, soils in the Moreton Bay hinterland catchments appear to have remained largely intact. Geochemical evidence from radionuclides in transported fluvial sediment indicates that erosion is focused along drainage lines and within existing river channels, with only a small contribution from hill-slope soils (12, 58). Grazing by European livestock did cause changes to soil structure and density. 'Virgin country' was known to be 'often boggy or "rotten", even on the ridges, owing to its loose formation', but 'when hardened by the trampling of stock it sheds a vast quantity of water that the subsoil previously absorbed' (59). The Government history provided a similar account of this change. 'On the spongy surface of virgin country, untrodden by any hoof, there was little "run" off the surface after rain, but when hardened by the tread of stock the creeks received a fairer share of the downpour' (51 p103). The consequences were flashier and ephemeral streams that dried in summer in places they had formerly flowed year-round (18). It remains unclear to what extent changes in the run-off regime influenced flood flows, and whether the destructiveness and frequency of catastrophic floods such as 1893 were at least partly the result of fundamental changes in catchment hydrology. The effect of changes in hydrology on flood flows to Moreton Bay remains a subject of ongoing investigation.

Changes to the drainage network in catchment headwaters occurred soon after European settlement. Initiation ages for the development of two gullies in the Bremer catchment have a weighted mean of 1840±9 AD (60). However, regionally the extent of gullying was small and mostly confined to highly erodible, sodic soils in the southern Brisbane and Logan catchments (24–26). Erosion along the larger river channels was relatively minor and was delayed until the 1890s, 50 years after European settlement of the hinterland. Early maps show that channel positions of the middle Brisbane and Lockyer rivers have largely been stable since 1885 implying that transport of sand and gravel along the major channels has not substantially increased (18, 61). Erosion has enlarged the channel cross-sections, mostly as a result of bank failures that are visible in early photographs on the Brisbane River from the 1890s. Many of the larger rivers display compound channels similar now in appearance to what was described by European explorers in the 1820s (18, 37). These were nested, channel-in-channel forms that are commonly found in regions with a naturally variable run-off regime. This channel form confers a high resilience to catastrophic floods, which can be accommodated by capacious channel dimensions. Despite this, bank failures occurred through the middle reaches of the Brisbane River during the flood-dominated decade of the 1890s, which saw large floods in 1890, 1893 (3 floods), 1896 and 1898. Since then, a cycle of bank erosion and infilling has recurred in major floods, most recently in 2011 and 2013 (18, 62–66).

The increased susceptibility of the Brisbane River to erosion may be explained by the progressive degradation of riparian forest along this and other major waterways in the region

(18). A comparison of riparian forest extent with sediment yield across South East Queensland suggested that erosion rates are enhanced up to 200 times along unforested streams (67). Degradation of riparian forest was also implicated in the catastrophic widening of one tributary in the upper Lockyer, where a well vegetated 10 m-wide stream with a clean sand and gravel bed transformed to a sparsely vegetated, 40 m-wide channel with a cobble bed (25). In the upper Logan, bed erosion and gullying has been such that the main channel is now deeply incised and is overtopped by floods with a recurrence interval of greater than 100 years (24). Sediment eroded from the upper Bremer River has been identified as sandy deposits in the lower tributary streams, with fine sediment being transported further downstream into Moreton Bay (26).

The bulk of sediments eroded from the Brisbane and Logan catchments are now stored within the fluvial floodplains and channels, with the remainder contributing to the infill of shallow embayed waters ~1500 km^2 in extent that make up Moreton Bay (2, 4). In the past decade, a number of sediment cores collected from the Bay have been used to reconstruct continuous records of catchment erosion. These suggest that sediment yields have increased by 3–9 times the pre-European rate in the Brisbane Basin (2, 6). The timing of the change is difficult to determine precisely with the available dating techniques, but sedimentation rates started to increase between 1840 and 1890 in the Brisbane River prodelta (2). This timing is also supported by ages determined by optically stimulated luminescence and radiocarbon for a shift in the ecology of the Bay between ~1842 and 1956, when increases in nutrients and sediments caused the replacement of sensitive branching corals with massive head corals (57).

Sedimentary records from intertidal areas around the perimeter of Moreton Bay indicate a further, dramatic increase in sedimentation rate after 1950 (5, 6). In 1949, mud was accumulating in the shipping channels of the Brisbane River 'faster than dredges could remove it' (68), and by 1951 there were calls for soil conservation in the upper watershed to reduce the rapid increase in silt levels over the previous decade (69). New gullies were also developing in the upper Logan and upper Brisbane catchments (60). The deluge of mud has been attributed to an increase in cropping in the Lockyer and Fassifern valleys (2), but the change has also been noted in the estuaries of the smaller catchments with different land-use histories (5). Shifts in climate may offer part of the explanation. Historical records suggest that episodes of channel erosion and gullying in both the 1890s and the 1950s coincided with periods of increased precipitation and flooding (18, 60, 70). The recent strong La Niña years, 2010–12, have produced the latest deluge of mud liberated by channel-bank erosion during floods in 2011 and 2013 (2, 4, 71).

The imprint of European land use in subtropical vs temperate regions

The transition from Aboriginal to European pastoralism with some cultivation induced a similar set of geomorphic adjustments across eastern Australia. In the Moreton Bay catchment area, the changes were relatively subtle compared with those reported in temperate south-eastern Australia. In the South East highlands of New South Wales and Victoria, gullying was the nearly ubiquitous consequence of European farming (72). Estimates from sediment infilling farm dams in the Southern Tablelands of New South Wales indicate that gullies contributed

80% of sediment eroded from small catchments (73). The proportion of gully sediments derived from Bromley Gully in the upper Avoca River in western Victoria was 80%, with the remainder derived from channel erosion (74). In some Moreton Bay catchments gullying of hillslopes is significant, such as in Knapp Creek and the upper Bremer River where it represents 89% and 76% of the sediment budget respectively, but in many catchments, such as the Lockyer, gullying is insignificant (Table 1). Sediment budgets for Moreton Bay catchments show that yields from all sources of erosion are two orders of magnitude lower than similar-sized basins in temperate south-eastern Australia (Table 1). This difference is all the greater considering that the peak of gully erosion occurred between 1850 and 1950 in south-eastern Australia while South East Queensland may be only now nearing its peak. Since 1950, natural gully revegetation and stabilisation in southern Australia have caused a slow reduction in sediment yields below the erosion peak of 200 times the pre-European rates (77). In contrast, gullies in South East Queensland remain active and are extending in some areas (60).

Table 1. Specific sediment yields and gully erosion for medium-sized catchments (10–100 km^2) in the Moreton Bay hinterland and south-eastern Australia.

Region/catchment	Catchment area (km^2)	Gully erosion (%)	Sediment yield ($t\ km^{-2}\ yr^{-1}$)
Moreton Bay hinterland			
Knapp Creek (24)	75	89	83
Bremer River (26)	123	76	43
Blackfellow Creek (25)	38	0	17
Temperate SE Australia			
Bromley Gully, Vic. (74)	16	90	2000
Southern uplands NSW and Vic. (131 catchments)(76)	50	-	1305
Jerrabombera Creek, NSW (75)	136	47	3255

Sheet-wash and rilling of hill-slopes are minor in both southern Australia and South East Queensland with most erosion concentrated on the stream lines. In the south, this has produced channelisation of small streams and metamorphosis of larger alluvial rivers from fine-textured stable channels that were sinuous or straight to coarse-textured, enlarged waterways that were braided in some cases (78, 79). In Moreton Bay, the larger rivers have developed wider channels through repeated cycles of bank erosion, but the single, compound channels have proved to be relatively resilient landforms in the face of larger and more frequent floods. In both subtropical and temperate zones, degradation of riparian forest has been an important factor influencing channel stability (79), but the more vigorous growth and recovery of vegetation in subtropical regions might be an additional aid to bank stability.

Conclusions

It should be encouraging to managers of Moreton Bay's catchments that, despite European settlement and agriculture, many aspects of the catchment's soils and vegetation have retained their pre-European characteristics. However, the drainage network presently shows the worst effects of land-use changes associated with settlement, with many of the headwater and middle reaches of the rivers showing erosion and instability, and sediment yields to Moreton Bay increasing towards the tipping point of ecological systems. It is worth noting that significant stores of floodplain and colluvial sediment exist throughout the catchment and could be released by catastrophic channel widening and gully erosion, further increasing the delivery of sediment to the Bay. The thresholds controlling channel metamorphosis and widespread gullying in this environment are largely unknown, and therefore the risks of unsustainable, irreversible change are palpable, even under the present climate regime. Future increases in climate variability raise the prospects for a major catchment readjustment, similar to that which occurred in much of south-eastern Australia a century earlier.

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Historical changes of the lower Brisbane River

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Abstract

The waterways and catchments of the Moreton Bay Region, including the Brisbane River, have changed significantly since non-Indigenous settlers first arrived in the 1820s. The choice of a river bank location for the initial convict settlement reflected transport and security logistics of the time, and influenced subsequent economic and historical expansion. This focus on the river also changed and degraded the surrounding environment. Increased use of the Pine, Brisbane, Albert, Logan and Coomera rivers, and development of their catchments and floodplains, coupled with widespread clearing, resulted in the loss of many native species and natural resources. Colonial activities and industry, especially river dredging, together with the impact of droughts and floods, modified river depths and flows, and dramatically increased run-off and pollution. Changing uses of landscape, including for transport, development, fishing and recreation, are illustrated in archival records, newspapers and secondary books and articles about Moreton Bay, the adjacent hinterland and coastal rivers. This paper discusses such changes as revealed in documents and historical accounts.

Keywords: archives, Brisbane River history, colonisation, dredging, flooding, bridges

Introduction

Moreton Bay, the coastal waters between the mainland of eastern Australia, the massive sand islands (Moreton and Stradbroke) to the east, and the connected estuaries and inlets were for many decades the primary gateway for migration to Brisbane and the rest of South East Queensland. Human impacts on the coastal waters and adjacent rivers have been steadily and significantly increasing since non-Indigenous colonists began arriving. This paper will focus on the historical changes observed in the coastal river systems and adjacent landscapes, and the impact of these transformations on the region's socio-economic use of the environment.

This paper discusses the changes revealed in documents and historical accounts (created by the incomers) using the interchangeable terms 'non-Indigenous', 'white' or 'European' in reference to the colonists of the nineteenth century. Some changes predating non-Indigenous colonisation (and broader transformations) are worth noting. For example, climate shifts and warming oceans affected the region's rivers and coastal waters. The long period of lower sea level reached its lowest point 21,000 years ago, pushing the coast eastwards of Moreton and Stradbroke Islands, and rejuvenated the lower reaches of the Brisbane River (1, 2). The increased velocity resulting from this invigoration meant the river transported more material and a deep channel, carved into the bedrock over successive intervals of low sea level, was re-occupied across the Moreton Bay coastal plain. When sea levels rose again, between about 21,000 and 7000 years ago, landscape changes caused major upheaval for ecological communities and human activity (3, 4). Aboriginal groups who had occupied the rich coastal plains, now the floor of Moreton Bay, were forced to relocate inland, increasing pressure on resources and territories (5).

Historical changes in catchments and rivers

The Brisbane River catchment, the dominant river basin in the Moreton Bay Region, occupies two- thirds of the total area and carries 40% of the region's total run-off. The Logan–Albert river system is the next largest. Other coastal watercourses, the Caboolture, Coomera, Nerang and Pine rivers, are relatively short. Alterations in the Brisbane River, such as the expansion of mangrove areas following bed dredging, reflect the patterns of change in the broader area. These clearly show how the catchment and environs of Moreton Bay have experienced significant disruption since non-Indigenous settlers arrived in the 1820s. According to marine scientists, 'little of the Moreton Bay catchment, apart from isolated areas such as the Southern Bay Islands, remains unaltered' (4, 6 p127).

The major climatic changes mentioned above had important consequences for Moreton Bay and the Brisbane River. Moreton Bay is a drowned river valley, and the river still flows in a shallow bedrock gorge through Brisbane city. Underwater investigations have shown that thick layers of debris carried from above the Bremer River junction have been deposited below Hamilton (7). According to one observer, at the time of European arrival the river from Hamilton to the Bremer closely resembled a flight of stairs - deep rapids separating still narrow deep beds (8). The explorer, Oxley, observed around the mouth of Breakfast Creek that 'the River is not fresh, but there is plenty of fresh water ... no obstacles exist with the Interior by the River itself' (9, p36). According to environmental scientists, the river's mouth at the time of European settlement was 'characterised by numerous "mangrove" islands and shallow channels with slow river flow' (6 p154).

Geologist Augustus Gregory observed that the lack of springs meant the upper reaches of the Brisbane River, above the Bremer River junction, during drought were mainly 'long reaches of stagnant water, with a small flow over the intervening banks of sand and gravel' (10 p3). Explorer and surveyor John Oxley observed that the river, at this point, was 'shoal and wide' (11 p137). Historical changes in the Upper Brisbane River are effectively illustrated by maps, historic paintings and photographs (12). For example, the map (Fig. 1) shows surveyed runs in the Moreton Bay district in 1872 and reveals how much land non-Indigenous graziers had selected. A surveyed run is pastoral land that a white settler has leased from the colonial government.

Explorers' journals and diaries offer useful descriptions of the coastal waterways and catchments at the arrival of non-Indigenous settlers, and sometimes offer insights into Aboriginal relationships with country. In 1823, John Oxley recorded his explorations in

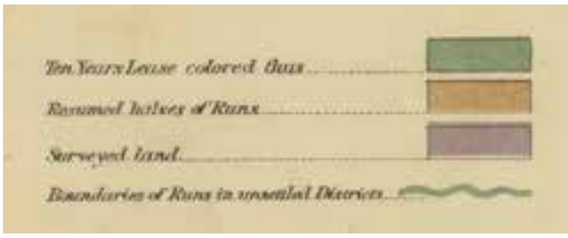

Figure 1. Map of surveyed runs 1872 (Reproduced from QSA item 634880).

Moreton Bay as he approached the mouth of the Brisbane River: 'The muddiness of the water and the abundance of fresh water mollusca convinced us we were entering a large river' (9 p36). He described the river thus. 'The slowness of the current and the depth of water induce me to conclude that the river will be found navigable for vessels of burden to a very considerable distance, probably at least fifty miles' (9 p36).

Early non-Indigenous explorers also noted freshwater levels and flood heights. Oxley's assistant, John Uniacke, wrote: 'The water became fresh after they had travelled eighteen miles up river, even at high tide' (11 p100). Oxley noted flood heights exceeding fifty feet (15 m) above the Bremer River junction (11 p136). Major Edmund Lockyer observed flood heights of one hundred feet (about 30m) at Mt Crosby (11 p189). Records show that major floods of the Brisbane River during 1825, 1841 and 1843, which were similar in height to 1893, inundated much of the riverine floodplain without causing widespread erosion or sedimentation (12).

Differing observations of the river's depth and character probably originated in varying local environmental conditions, from intermittent floods to extended droughts. In 1846 the steamer *Experiment* reached Ipswich one day after leaving Brisbane. The vessel ran aground near the crossing place at Woogooroo, but had an easy return voyage. Soon after, the steamer *Sovereign* travelled from Brisbane to Ipswich. The local newspaper described the river in 1846. 'The tide extends to the crossing-place at Canoe Creek [Oxley Creek]'. Seventeen Mile Rocks, about seven miles below Canoe Creek, 'form an insurmountable barrier to vessels drawing more than eight feet [about 2.5m] water'. 'There is but one channel, which is very narrow, and the tide rushes through it with great rapidity' (13 p3). Coal mining at Ipswich began at this time, and shipping traffic increased leading to early changes in the river and catchment (12).

During the 1850s, much of Brisbane's present-day inner city was subject to inundation from a combination of high tides and river flows, as revealed by Charles Melton (under the pen-name 'Nut Quad'). 'The whole length of Albert Street was a swamp, known in the early days as Frog's Hollow. On the occasion of high spring tides water from the river flowed up the creek and invaded backyards in Elizabeth, Charlotte, Mary and Margaret Streets. In flood time, Albert Street from the Gardens to Elizabeth street was submerged to a depth of several feet' (14 p12). At this stage, the river was still being regularly fished for eels, mullet, jewfish and codfish (15 p3). River (or bull) sharks were observed in the Bremer, and in the Brisbane River upstream of the Bremer junction (16 p8).

Dredging

The main navigational river hazards for white colonists were the bar at the mouth of the Brisbane River, Five Mile Rocks and Seventeen Mile Rocks, and extensive shoals at Lytton and Eagle Farm. Until 1839, the bar at the mouth of the Brisbane River restricted the size of ships entering the river to a nine feet (3m) draught at high tide. In 1856, a survey of the Brisbane and Bremer rivers 'to determine obstructions to navigation' was ordered (17). Galloway reported that 'banks of very large gravel and silt' near Redbank 'had a very great effect in keeping back the tide' and there was 'a very great current at certain times over the narrowest and shallowest parts' (17).

Queensland became a separate British colony in 1859, and the arrival of the steam dredge *Lytton* in 1862 heralded major changes to the river and nearby coastal waters (18 p90-91). Within four years, the bar at the river's mouth had been 'cut' and shipping began using the newly completed Francis Channel (19–20). Dredging progressively extended upriver, including at Seventeen Mile Rocks in 1863.

Dredging continued at Seventeen Mile Rocks in 1866, and a breakwater was built at the junction of the Bremer and Brisbane rivers. A turning basin constructed in the same year allowed Ipswich to briefly become the major transport hub for many inland pastoralists. River shipping reached a peak in 1866. By 1872, Brisbane displaced Ipswich as the most important shipping destination, and the river channel was dredged from the mouth to the Town Reach. “Reach” is a nautical term (recorded by marine surveyors) for a portion of a river between bends.

The construction of the dredge *Groper* in 1876 hastened work on the shipping channel. In 1877, a turning basin for newly constructed Brisbane wharves at Petrie Bight allowed ships to dock in the heart of the new municipality for the first time. A 6 m deep channel to the city was completed in 1892; as one historian noted, only an aspect of the further alteration to the River’s course which continued almost without interruption between 1894 and 1914 (18). Coal was carried from Ipswich to South Brisbane by rail or by river-barge and loaded at the South Brisbane coal wharves (Fig. 2) from the 1870s to the 1970s. These were eventually replaced by a new deepwater coal terminal at Fisherman Islands in 1983.

Figure 2. Dredges at South Brisbane coal wharves in 1964 (From author’s private collection)

About half of the material on the river bed was eventually removed, and significant changes to the river caused by dredging (for navigation, and to supply sand and gravel) became evident above the William Jolly Bridge after the 1930s. Coral dredged from the Bay was dumped in the river bed at Seventeen Mile Rocks for use at the Darra cement factory, causing an unknown impact on river flows (22). Dredging, which reached a peak in the 1940s, resulted in the extraction of 26 million cubic metres of aggregate by the mid-1980s; the end of dredging in the river's central city reaches subsequently caused increased siltation and reduced flows. River dredging in the lower and middle reaches stopped during the late 1990s, thus increasing potential flood levels in the river. By this stage, the tidal reach extended to College's Crossing, over 80 km upstream from the river's mouth. Compounding anthropogenic changes, droughts and floods had marked effects on river depths and flows (23).

Dredging for shipping and wharves also caused significant changes in parts of the Bay near the mouth of the Brisbane River. Dumping of large quantities of dredge spoil from the lower reaches of the river in the western Bay would have increased the availability of sediment, and dredging of the river facilitated the transport of suspended fine sediments from locations upstream (24).

Historical photographs from the 1930s show crowds of swimmers at places such as Indooroopilly, where the water was so clear that the bottom was easily visible (2, 18). One interviewee recalled changes in the river since the 1930s. 'When I first started [work on the river] the clarity was good…but once they started dredging it got dirty….It was dark green. You could see a depth of five to six feet [1.5-1.8 m] up until World War 2" (21 p47). Increasing pollution levels, including sediment, particularly in the river and on the Bay's western side, clearly demonstrate the major changes that have occurred since non-Indigenous colonisation began and development started (4, 12).

Scientists have noted that vegetation clearing and the introduction of exotic livestock associated with non-Indigenous settlement resulted in an increase in channel and hillslope erosion (7, 12, 25). Further downstream in the Bay, the loss of coral and seagrass owing to the increasingly turbid waters reduced the number and range of marine organisms (2). Parts of Moreton Bay are now classified as being in 'poor health' due to seasonal toxic algal blooms (26). All reaches of the Brisbane River are also judged to be 'poor' because of high sediment loads, and high nutrient concentrations; the Bremer and Lockyer catchments are described as 'in very poor health' (26). One problem was water hyacinth (*Eichhornia crassipes*), an invasive South American waterborne weed, which was washed from the Bremer into the Brisbane River in 1937 (Fig. 3).

Historical changes in the landscape

According to ecologists, about 80% of Queensland's land surface, including the catchments of the Moreton Bay rivers, supported forests, shrublands and heathlands until non-Indigenous settlement began (27). Valley bottoms and some areas of gentler topography were maintained as grasslands by Indigenous societies in much of the Moreton Bay hinterland (25). Before non-Indigenous settlers arrived, patches of rainforest known as 'scrubs' occurred on one or other bank of the river through most of what is now Brisbane and in a large area west from above

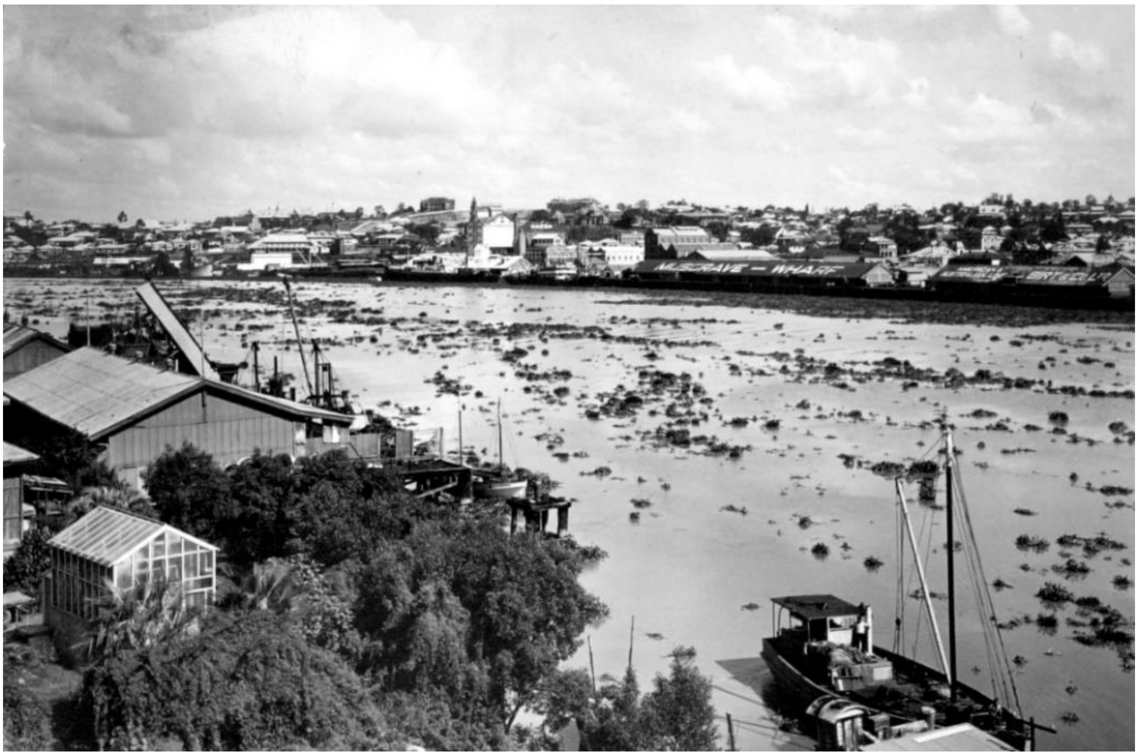

Figure 3. Invasive water hyacinth clumps floating down the Brisbane River 1937 (Reproduced from QSA item 1243115)

the junction of the Bremer River. Similar scrubs have been found on the North Pine River, and probably along Pumicestone Passage (28). There were also extensive scrubs further upstream on the Brisbane, on the Logan and its catchment, and in the Border Ranges. The area of scrubs within the region was widespread, and may have exceeded the better known “Big Scrub” of the Richmond River district in northern New South Wales (28).

European colonists attacked the powerful connection between Aboriginal people and country, disrupting their lives, access to food and participation in traditional laws. Indigenous tribes and nations were unused to coping with permanent invaders, and their greed for water and other resources. Government and settlers took part in forced relocations of Aboriginal people after violence, disease and starvation had massively reduced their population size. Development and increased use of the Pine, Brisbane, Albert and Logan rivers and their floodplains followed the arrival of non-Indigenous settlers. Changing uses of rivers and coastal waters, including transport, fishing and recreation, led to significant modifications that often spread to the adjacent landscape. Once again, the accounts of explorers and early surveyors offer us insights into the original vegetation and how it was altered.

In 1824, botanist and explorer Allan Cunningham described the land near Pumicestone Passage, declaring: ‘a somewhat shaded forest of stately timber trees, whose vast growth and present luxuriance indicated a depth of rich subsoil’ (29 p536). According to historian Judith Powell, ‘the association between stands of large timber and the lure of rich agricultural soil was to have a powerful effect on the future settlement of South East Queensland. Large trees suggested fertile soils and pressure from pastoralists and farmers for access to this soil through land clearing is a constant theme during the nineteenth century and the first half of the twentieth century' (30 pp6–7).

Oxley's 1825 map of the Brisbane River included descriptions of the landscape's economic potential. As he navigated up the river, he saw 'rich flats and land' at South Brisbane, Chelmer, Fig Tree Pocket and Moggill. 'Open country' was noted at Bulimba, Highgate Hill, Kenmore and Wacol, while useful stands of timber were seen at Bulimba and Fig Tree Pocket (31). Several years later, colonial botanist Charles Frazer described the landscape near 'a stream of fresh water' on the river's north side (present-day Eagle Farm); 'The high dry land next to the stream was well adapted to the growth of wheat. It is formed of undulating ridges of gentle height. The soil is a rich brown loam, covered with a luxuriant crop of Brome or kangaroo grass. The land on the banks of the river is extremely rich, and is covered with a species of panicum or panic grass, averaging from four and a half to five feet. The soil is evidently too rich for wheat but will produce enormous crops of maize. It is lightly timbered, averaging not more than twelve trees an acre. The timber is good blue gum' (32).

Frazer brought fruiting trees and bushes, grasses, roots, herbs and seeds from Sydney to Moreton Bay, and soon after, in the early 1840s, the first pastoral stations east of the Great Dividing Range were established. In 1844, surveyor Henry Wade mapped the 'Town of Brisbane and Environs' and noted economic possibilities: 'rich scrubby soil' at West End, 'good pasturage' and 'open forest' at Lutwyche, Enoggera Creek, Bowen Hills and New Farm. Mangrove swamps were observed at Eagle Farm and Enoggera Creek; 'poor' country was found at Clayfield, Wilston, Spring Hill, Kelvin Grove, Highgate Hill and East Brisbane (33). Although the area of wetland has massively decreased since that time, mangroves have colonised further upstream as a result of hydrological changes, particularly dredging and the resultant saltwater intrusion (6, 12).

Articles in the local newspaper in 1858 directed attention to the clearing of riverine vegetation: 'There is a sweeping destruction of trees and bushes lately growing there' [along the river] (34 p2); and 'If no care is taken of the few [trees] left on the river banks, etc., soon nothing in the shape of a native tree will be discoverable in the environs of Brisbane' (35 p2). One decade earlier, George Fairholme had sketched 'Kangaroo Point, 1845' clearly showing timbered hills behind the comparatively more open riverside settlement (Fig.4 (36)).

One local historian described the river as it would have appeared to the first Europeans who sighted it in 1823: banks 'fringed with foliage trees, and the upper reaches were lined with pine; the waters teemed with bird and fish' (37 p12). In 1893 a keen fishing and hunting enthusiast, in an article titled 'Shooting Spots', identified one remaining piece of original vegetation after the riparian forest was severely damaged by a series of large floods earlier that year: 'After reaching the Indooroopilly railway station, a fair-sized scrub lies about three miles along the river bank to the right of the bridge' (38 p494).

Local author and artist Jack Lindsay wrote of his childhood in Brisbane during the early decades of the twentieth century: 'I used to row up the river in our dinghy. The region was still

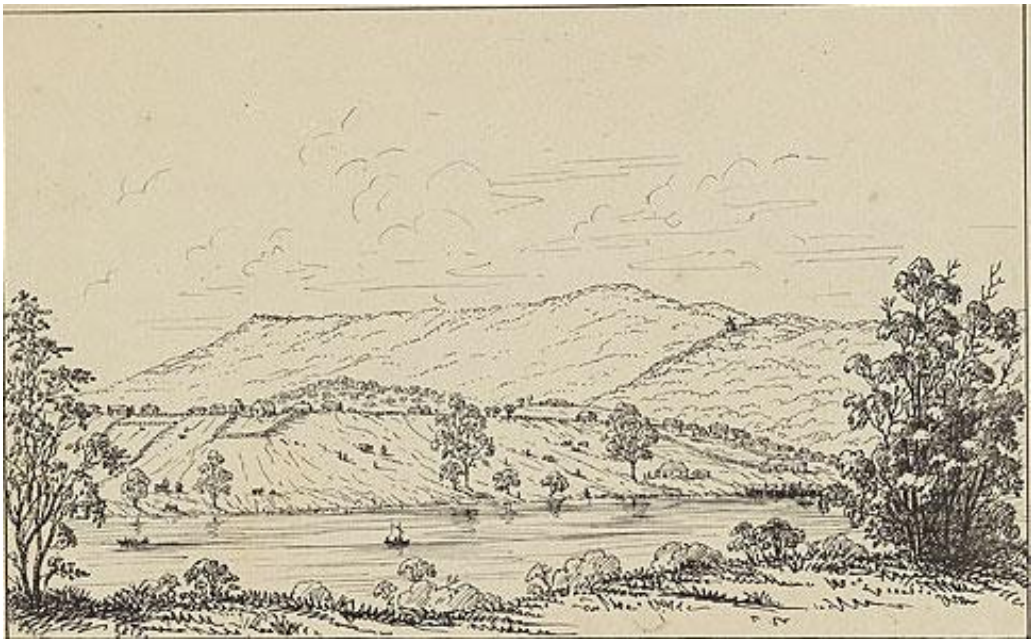

Figure 4. Fairholme G. drawing of Kangaroo Point 1845. NGA Accession no 2009.44.1

sparsely inhabited. Across the river were a few small farms and up past the reach [Graceville] where my uncle had built his house the country was wild. I landed in the more entangled parts, on slopes of fir trees, where I climbed by clinging to bushes and tree roots, into a thick resinous silence, or among clumps of lantana - that verbena introduced as an ornamental shrub from tropical America' (39 p68). Others recalled the river's past, and a wide range of artistic, literary and photographic references to the Brisbane River formed the basis of an exhibition, 'The River: A History of Brisbane', hosted by the Museum of Brisbane.

Tallowwood, ironbark and blue gum, which grew on the hills throughout Brisbane, were used for building construction. The timber-getting was followed by large-scale clearing on river flats, initially for farming and grazing, and later for industry or residential development (40). Until the 1940s, most suburban areas were restricted to a six-mile (10 km) radius of Brisbane's centre, reflecting the dependence on public transport and the rarity of private motor vehicles (41).

The Second World War changed many aspects of Brisbane, as new cars, roads and estates encouraged residents to build outside the old established districts. One emphatic expression of the motorcar's triumph, published during the 1960s, stated the Brisbane River 'tended to deter vehicular travel' but 'there should be a complete freedom in selection of travel mode for all individuals involved' and 'public transport will be hard pressed to maintain a favourable position with private motor car travel in the future' (42 pp171–72).

Extensive logging of hardwood in the D'Aguilar Range did not occur until immediately after the Second World War, and less fertile slopes were also not disturbed until the middle of the twentieth century (43). Intensive cropping and grazing, particularly in the Lockyer and

Fassifern valleys, increased sediment loads from the 1950s (7, 25). Since the 1970s, some of the greatest rates of forest clearing in Australia have occurred in South East Queensland (27). Increased sediment loads, particularly during floods, resulted from habitat clearing and modification (44).

Analysis of sediment deposits in Moreton Bay provides information on the source of eroded material. Fine sediments from the Lockyer Valley dominate (7). Studies show that the erosion of gullies connected to the rivers and streams is the dominant eroding process, but the extensive land clearing that began this erosion also inevitably led to the loss of species and resources (25, 45). At least two-thirds of the original woody vegetation in South East Queensland has been cleared to date, and this process continues (mainly for urban development).

Bridges and flooding

Stark changes in the region's economic uses began with the establishment of a penal colony in 1824 (46). The choice of a river bank location for convict settlement reflected logistics of maritime transport, penal containment and water supply. The first actions of colonial administrators were to provide law and order (judges and police), followed by funds for public works such as roads, bridges and wharves (47).

Navigation buoys were laid in the Moreton Bay channel during 1825, and the schooner *Talbot* was constructed at Brisbane in 1826. One year later, the first riverside landing stage was built (48). A second schooner, the *Letitia Bingham*, was constructed at Brisbane in 1829. The first steamship, the *James Watt*, arrived at Moreton Bay in 1837, and a second, the *Shamrock*, in 1842. Cross-river vehicular ferry services between Queen's Wharf and South Brisbane began in 1843.

A limekiln operated by convict labour was established at Ipswich in 1827, and riverboats connected the two settlements. Surveyors Robert Dixon, Granville Stapylton and James Warner started work in the Moreton Bay district from the late 1830s, and land sales (held in Sydney), initially for blocks in North and South Brisbane, began in 1842 (49). Land sales at Ipswich, which were at first more successful than land sales at Brisbane, began in 1843 (50). The 1846 census showed 483 Europeans residing at North Brisbane, with 346 at South Brisbane, and 103 living at Ipswich. At this time, land at North Brisbane sold for £100 per block and at South Brisbane for £1 per acre; Ipswich land was selling for £8 per block.

The establishment of the Acclimatisation Society Garden at Bowen Hills in 1862 led to a surge in the introduction of economic plant species (and weeds), and the resulting displacement of native plants (51). Society members 'played a key role in the importation and experimentation' of plants (52). Apart from introducing animal and bird species (such as sparrows and rabbits, now regarded as pests), the Society disseminated many commercial plants. The Society's work became 'consumed with economic botany', importing 'many plants that are now important agricultural crops in Queensland. These included sugar cane, bananas, cotton, apples, pineapples, pasture grasses, maize, olives, mangoes and macadamia nuts' (52). Native forests also attracted the Society's attention; in 1873, one member decried the 'wholesale work of destruction practised under the protection of Government by the licensed timber getters' (53 p3).

Constructing cross-river links was an important step in colonial development. These included the first Victoria Bridge (opened for traffic during 1865) and which collapsed owing to poor construction two years later in 1867. A second structure with the same name, opened in 1874, was partly destroyed in the 1893 flood. A temporary wooden bridge was used from 1893 to 1896 (Fig. 5), and a third Victoria Bridge opened in 1897. The first railway bridge at Indooroopilly, constructed in 1875, was also washed away in the 1893 flood. Most bridges over the river were overwhelmed by traffic as well as by floods. For example, in 1886, the Brisbane Town Council asked for the Victoria Bridge to be widened or an additional bridge to be erected 'adjacent thereto', saying: 'It is reasonable to suppose the increase of traffic between North and South Brisbane for the next five years will be equal to that of the last five years' (54).

Figure 5. Debris being cleared from the temporary wooden section of the Victoria Bridge in 1896 (From author's private collection).

Some developments did not last much longer than the timber bridges. In 1849, there was no wharf at North Brisbane so punts were used to unload ships anchored mid-river. Architect and builder Andrew Petrie constructed the town's first wharf ('Raff's' on the north bank): 'Over 100 tons of loose stone were thrown into the river, until the piles of stone reached high water mark. Stringers were then placed on the stone, and the wharf erected on the top. We came down one morning and there was no wharf left. It had disappeared in the fresh' (55 p7). The serpentine river's influence on suburban development, noticeably the lack of cross-river bridges and ferries except in the inner city, created ‘pockets’ of development interspersed with rural areas well into the twentieth century.

Urban water reticulation from the Enoggera Creek Dam commenced in 1866, and from the Gold Creek Dam in 1886. The Mt. Crosby Pumping Station was constructed on the river in 1893. A detailed 1907 report on Brisbane’s water supply and Brisbane River catchment stated: ‘the most obvious and important source of pollution is the cattle’(56 p4), and that ‘in general, it is a hilly region, and the hills are generally wooded. The population upon it is comparatively small. There are no considerable towns, and no sewage enters it’ (56 p8). Engineers recommended that water supply reservoirs be constructed on Cabbage Tree Creek and the Stanley River, and in 1916 Lake Manchester was built on Cabbage Tree Creek followed by the Somerset Dam on the Stanley River in 1954 (57, 58).

Flood mitigation

Flood mitigation was (and remains) a major concern, especially following the disastrous 1893 floods (59, 60). In 1896, the Government Engineer’s recommendation for cutting a deeper and wider channel at Gardens Point, Kangaroo Point and New Farm was accepted (61). A ‘Report on rivers and harbours of Queensland’, submitted in 1898, noted: ‘the effect on navigation of ordinary floods is to silt up the Hamilton Reach, Eagle Farm Flats and the Bar Cuttings first. Practically no deposits of material occur between Kangaroo Point and the lower end of Bulimba Reach’. The 1893 floods ‘raised all the shoals’ between the Victoria Bridge and the Bremer River, and the acquisition of a rock-removing dredge was recommended (62).

In 1899, one ‘Flood prevention’ proposal suggested cutting a canal from Milton to the mouth of Breakfast Creek (63 p6, 64). ‘The report on scheme for the abatement of floods in the Brisbane River’, prepared in 1899, stated that flooding could not be reduced except by a substantial reduction of the maximum quantity of water passing down the river at a given time, and this can only be done either by a diversion canal or a regulating reservoir (65). One engineer was ‘absolutely sceptical as to the value of increased waterway obtained by deep dredging’, saying that ‘this space being occupied by sea water which has to be pushed back before it can be available for the discharge of river water’. Instead, he recommended constructing a storage reservoir seventeen miles (30 km) below the junction of the Brisbane and Stanley rivers (65 p1050).

Somerset Dam, on the Brisbane River’s major tributary (the Stanley River), was completed in 1954, with more than half of the capacity reserved as flood mitigation (59). Yet, as experts warned, the dam’s construction would not totally prevent future floods (66 p2). Ten years later, similar questions were asked: ‘The heaviest rain so far recorded had always fallen on the 10 per cent of the catchment above the Somerset Dam’ (67 p1). The 1974 flood confirmed this fear. The completion of the Wivenhoe Dam in 1984 prompted a further round of anxious questions and government reassurances, many of which were acutely answered during the 2011 flood that submerged much of inner Brisbane (68).

Habitat clearing, increased erosion and massively increased sedimentation in Moreton Bay, caused by land clearing, began after the arrival of non-Indigenous colonists during the nineteenth century and increased during the twentieth century (25). Dredging of the Brisbane River, which reached a peak during the 1940s, continued. By 1941, when complaints were made about dredging noise, officials reported that 'the remaining deposits of sand and gravel are limited practically to the area between Indooroopilly Bridge and Oxley Creek' (69). In 1965, the obstruction at Seventeen Miles Rocks was fully removed, 100 years after major river modification began. Within three decades, dredging ceased altogether. Long-term significant effects of dredging included accelerated riverbank erosion, increased salinity and the extension of the tidal estuary upstream (23).

Conclusion

The Brisbane River, Moreton Bay, and the sheltered coastal waters between the mainland and sand islands to the east were for many decades the primary access routes for trade and movement to and from South East Queensland. The effects of human activities on the Bay and adjacent rivers have been increasing since non-Indigenous settlers arrived. The Brisbane River catchment, which occupies two-thirds of the total area and carries 40% of the region's total run-off, is the dominant geographical feature. Therefore, significant changes in the Brisbane River illustrate broader anthropogenic environmental modifications in the region. These clearly show that the catchment and environs of Moreton Bay have experienced significant disruption since non-Indigenous colonisation began in the 1820s. History, in the form of records, photographs and written descriptions, can tell us much about changes in Moreton Bay and adjacent catchments.

Acknowledgements

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Holocene history of Moreton Bay reef habitats

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Abstract
The history of marginal coral reef development in Moreton Bay is characterized by habitats with abundant coral communities. These habitats formed during discrete intervals over the past 7,000 years and their growth is tied to relatively subtle changes in sea level and climate, along with changes in circulation patterns. Mechanisms of reef growth include both episodic reef accretion and island spit progradation. Three episodes of reef initiation and growth occurred from 7,400 to 6,800, 4,900 to 3,000, and 2,100 to 400 years before present. Modern reef growth in the Bay has been suppressed because of increased sediment and nutrient runoff from anthropogenic land-use changes, which need to be reversed if the condition of Moreton Bay reefs is to improve.

Keywords: marginal reefs, reef growth, sea level history, climate change

Moreton Bay reef habitats
The growth of reef habitats and associated reef coral communities in Moreton Bay has been intermittent during discrete episodes over the past 7,000 years or so (1). Strong environmental gradients, including sea floor composition and variables affecting water quality (e.g. turbidity, total nitrogen, temperature and dissolved oxygen) exist in Moreton Bay, from the west through the central Bay to the eastern Bay. We follow Wallace *et al.*'s (2) geographic separation of Moreton Bay into an inner region composed of the body of water partly enclosed by North and South Stradbroke, Moreton, and Bribie Islands and an outer region composed of the rocky reefs immediately outside these large islands, including Flinders Reef near Moreton Island and Flat Rock, Shark Gutter and Shag Rock off the north-east corner of North Stradbroke Island (Fig. 1). The Bay's species and habitats are well documented, including coral assemblages that are, in many ways, unique for their latitude (i.e., presence of mainland fringing reefs, absence of *Porites* species, and persistence through large temperature extremes) (2–4), and are dominated by the Faviidae, especially the genus *Favia* in most parts of the inner Bay (2). The Moreton Bay reefal habitats fit every definition of a marginal reef (5, 6) and have done so throughout the Holocene (7).

Reef structure is typical of fringing reefs in low-energy environments (8, 9). Most reefs in Moreton Bay have a reef flat from approximately 0 m to -1 m LAT (lowest astronomical tide), an upper slope from -1 to -4 m, and a somewhat gentler deep slope from -4 m to the basement

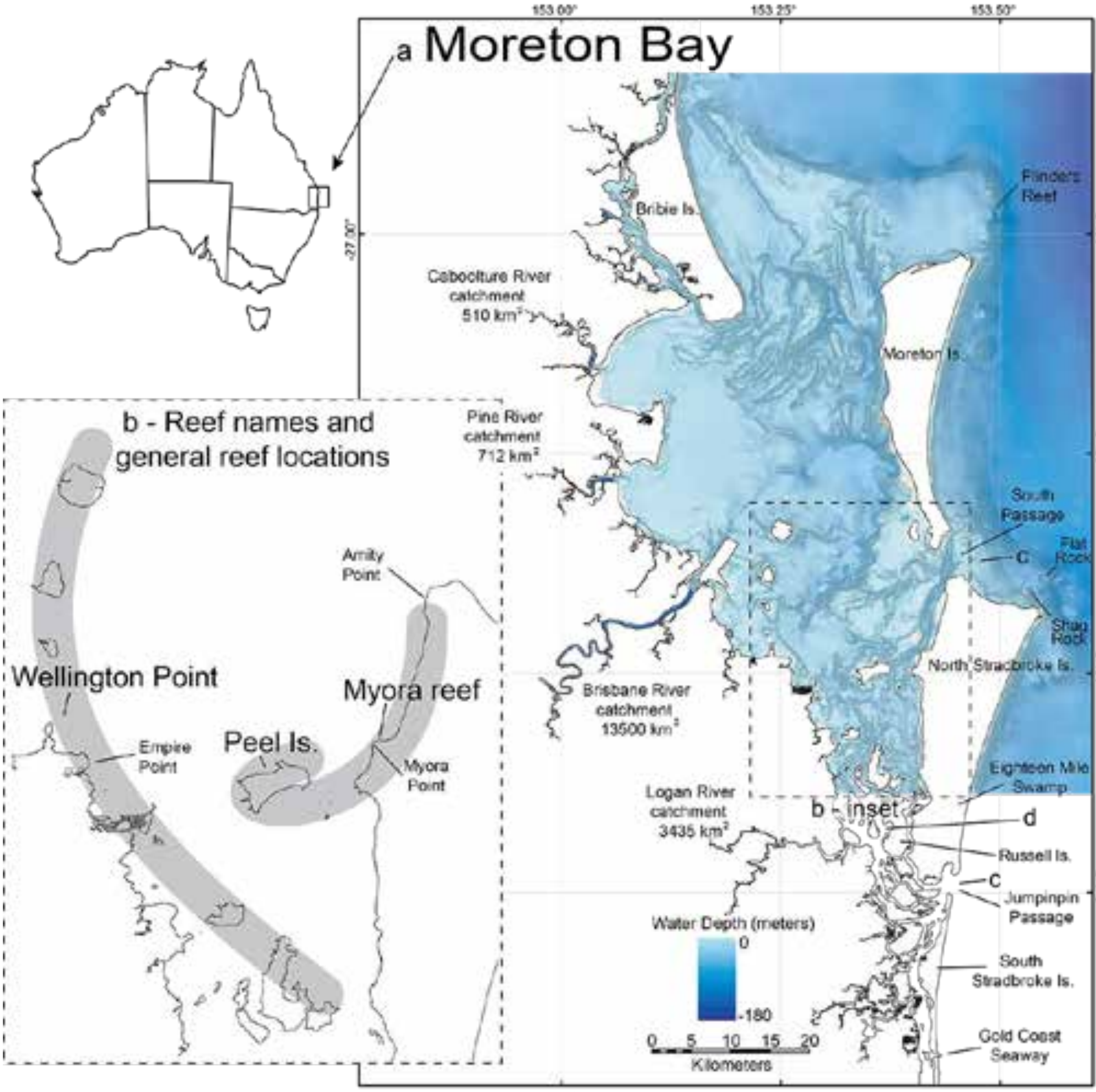

Figure 1. a - Overview of Moreton Bay with bathymetry depicting a network of tidal and river channels amidst generally shallow waters; b - Grey bands show the general areas of major Holocene reef growth; c - Historically ephemeral inlets; d - Modern tidal node.

substrate in the range of -5 to -8 m. The sediment underlying the reefs is usually composed of unconsolidated alluvial laterite sediments (clay); though also encountered is giant humus podzol (coffeerock) and kaolinite (bright white aluminium oxides). Crustose coralline algae and diagenetic cements are present on Moreton Bay's reefs, but their activity is reduced to the degree that reefs are generally unconsolidated. Reefs in inner Moreton Bay have initiated on substrate that is as deep as -8 m LAT (8, 10). There is no evidence that reefs have grown to reach sea level, either in modern or fossil reefs, though a submarine exposure at Myora Point suggests several metres of reef growth underlying living shallow water coral communities. Depth distribution of corals in Moreton Bay is restricted to approximately -0.5 to -8 m LAT, and the modern distribution of living corals is most dense in a very narrow range from -1 to -3 m LAT (11, 12). Vertical accretion does not extend into the intertidal zone as on many of the nearshore marginal reefs of the central Great Barrier Reef (GBR) (9, 13); but halts within the first metre of the subtidal zone.

Holocene Sea Level and Climate History

The Moreton Bay region was subject to changes in two major environmental factors since the mid-Holocene: (i) sea level and (ii) climatic regime, and these had primary control over reef accretion. Sea level rise following the last glacial maximum (LGM) ~18,000 years before present (ybp) began to flood proto-Moreton Bay around 9,000 ybp, and the basal elevations of the Bay's coral reefs in the range of -5 to -10 m were fully marine between 8,000 and 7,000 ybp. During the mid- Holocene, from ~ 8,000 to ~ 5,500 ybp sea level was rising to a stable level ~2 m higher than present (14, 15). This stability was followed by a drop in sea level to its present level from ~ 5,000 years ago to present (Fig. 2), which most likely occurred in a series of metre-scale oscillations (15–17). More recent data from subfossil corals in Moreton Bay show that sea level was at least 1.1 m above present from at least 6,600 ybp (18). The mid-Holocene highstand coincided with a period of climatic stability (warm and stable temperatures) and, for about 2,000 years, conditions were optimal for reefs to grow upwards to sea level. Resultant raised reefs are common features throughout much of the tropics, but are almost entirely absent from Moreton Bay. However, other features of the mid-Holocene highstand were preserved in the Bay (e.g., stranded dunes and beaches, wave-cut shorelines, and the geomorphology underlying the Eighteen Mile Swamp on North Stradbroke Island), so it is certain that sea level was approximately 2 m higher in the Bay at that time (15, 19–21). Sea level oscillations are produced by a combination of eustatic, isostatic, and climatic forcing with somewhat variable interpretations of how these drivers interact (15, 16, 18, 22, 23).

The first major climatic change following the post-glacial marine transgression was a destabilization of the mid-Holocene climatic regime. The mid-Holocene climate from 7,000 - 5,000 ybp was warmer by ~ 2°C and flooding was much less common than today despite rainfall 18-42% greater than today (24–27). Despite greater runoff, sedimentation to the nearshore reefs was an estimated 40% less than today because the enhanced vegetation cover, promoted by increased rainfall, reduced erosion (19, 28). The strength and frequency of El Niño–Southern Oscillation (ENSO) events in the early and mid-Holocene was substantially reduced relative to today (Fig. 2), and was scarcely detectable at the latitude of Moreton Bay (29). This period of stability, dubbed the "Holocene climatic optimum", ended abruptly ~ 5,500 to ~ 5,000 ybp when climatic conditions similar to today emerged. The region became about ~ 2°C cooler, precipitation declined, and cycles of extreme flood and drought associated with ENSO events became common (19, 30, 31). This climatic change caused erosion and sedimentation rates nearly double that of the Holocene climatic optimum (28).

Holocene Circulation Patterns

Dominant tidal flow and circulation in the Bay is through the northern entrance. General circulation is clockwise, tending south along Moreton Island and north along the landward margin of the Bay (4). Modern South Passage has some influence on circulation in the central and southern Bay, but modern Jumpinpin and Gold Coast Seaway have trivial influences on circulation (4, 17).

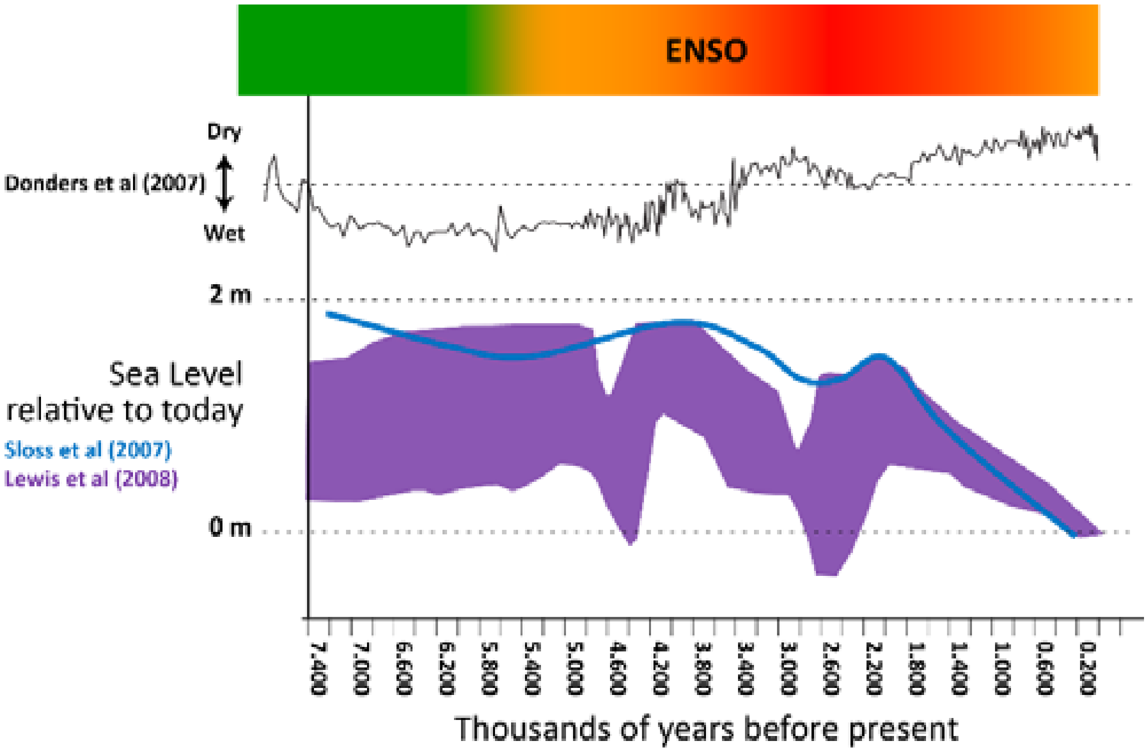

Figure 2. Composite of selected environmental data. The sea level curves of Lewis *et al.* (15) and Sloss *et al.* (14) were re-scaled to the same elevation datum. Lewis *et al.* (15) curve shows range of variability fitted between upper and lower means. Dry and wet contrasts are derived from PCA analysis of Bega Swamp (NSW, Australia) flora from peat profiles contrasting dry Asteraceae/Casuarina/Chenopodiaceae with moist Pomaderris/heath and fern taxa (27). ENSO intensity shown as a spectral colour gradient from low (green) to high (red).

Holocene changes in sea level likely had dramatic effects on circulation within the Bay in part because of changes in circulation efficiency (e.g., flushing) and in part because of the opening and restricting of tidal passages (32, 33). The modern tidal node where flushing is least efficient in Moreton Bay is near Russell Island in the southern Bay (Fig. 1) (34). At the mid-Holocene highstand, the tidal node would have been further north. Because tidal circulation was generally more efficient at higher sea levels during that time, the influence of the tidal node on water circulation was diminished relative to the present.

Shoaling of the Bay, restriction of channels, and restriction or closure of ocean passes by falling sea level reduces the efficiency of circulation, and increases the residence time of terrestrial inputs to the nearshore marine environment (19, 35). Jumpinpin passage in particular was likely much larger in the mid-Holocene as evidenced by its extensive flood tide delta (32), and South Stradbroke Island that presently blocks most of the passage is a more recent feature (19) (Fig. 1). Both South Passage and Jumpinpin are part of the dynamic beach and littoral drift system, and both should be considered ephemeral on timescales of the Holocene (17, 19, 32).

Holocene Reef Development

Two generalized representations of reef development patterns likely for Holocene reefs of Moreton Bay are episodic reef advance (Fig. 3A) and lateral progradation along island spits (Fig. 3B). Vertical accretion for Holocene reefs inside Moreton Bay approaches 8 m, and this is known primarily from reef mining practices (8, 10). Similarly, vertical accretion of the single Pleistocene reef found in Moreton Bay is approximately 6 m (36). Lateral progradation in tropical reefs throughout the Holocene can range from tens to hundreds of metres, and is dependent on the underlying substrate types, antecedent topography, and local environmental conditions (9, 37).

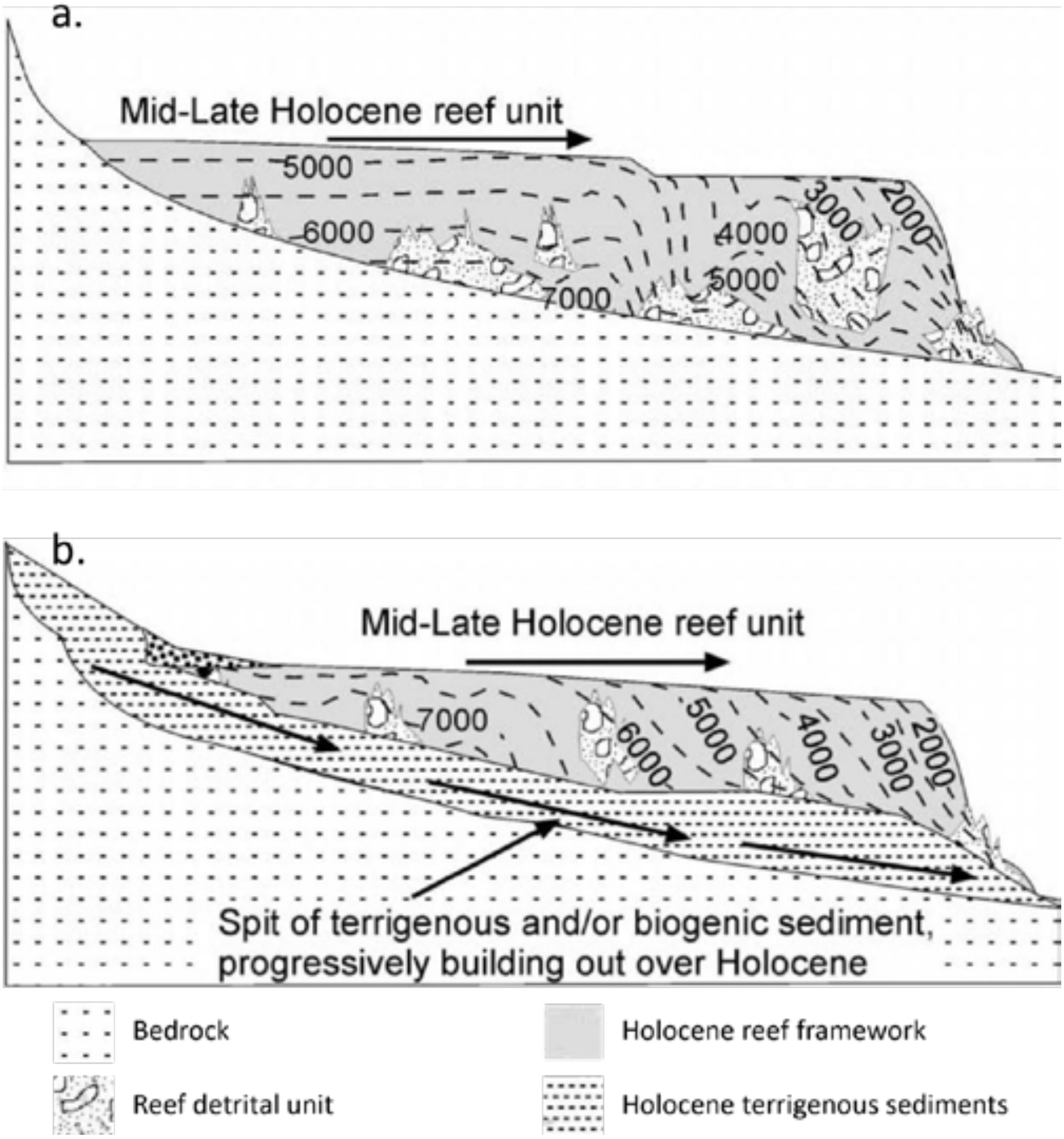

Figure 3. Conceptual schematics of nearshore reef development through the Holocene exemplifying the possible sequence of events for Moreton Bay reefs, from Smithers *et al*. (2006) (11). a) Episodic reef crest advance; b) lateral progradation along island spits.

An analysis of sediment cores from Wellington Point, Peel Island, and Myora Reef shows three clear episodes of reef development in Moreton Bay, separated by two clear episodes without coral reef growth (1). Reef initiation and growth in Moreton Bay occurred at 7,400 to 6,800, 4,900 to 3,000, and 2,100 to 400 ybp. The oldest section of Holocene reef in Moreton Bay initiated as an island spit ~ 7,400 ybp, which fits within the window of time when other marginal reefs initiated along the Queensland coast (9, 38). High-latitude marginal reefs tend to lag the tropical reef initiation window, which occurred ~ 9,000 to 7,000 ybp for the GBR (39) and as early as ~ 20,000 ybp in the central Pacific (37, 40). It is tempting to explain the older (~ 6,800 to 4,900 ybp) hiatus in Moreton Bay reef growth by a ~ 1.5 m sea level fall (14, 15, 18), combined with increased climatic instability (19, 30, 31). However, all of these factors occurred much later than the start of the hiatus, within a few centuries from ~ 5,500 to 5,000 ybp, so additional factors might also be responsible for Moreton Bay reef "turn-off" *sensu* Perry and Smithers (41).

The second episode of Bay reef growth diverges from the record of tropical nearshore GBR reefs with an intermediate reef initiation episode at 4,900 to 3,000 ybp. In the tropical nearshore GBR record this time period is a very clear hiatus in reef initiation (38) and a hiatus in reef growth for many reefs in the offshore GBR (9, 42). Either Moreton Bay was more favourable than the tropical nearshore GBR for reef initiation at this time, or this intermediate window remains undiscovered in the tropics. Regardless of the cause for this regional difference, it is clear that environmental conditions during the second episode were conducive to coral reef growth in Moreton Bay. The causes of the younger hiatus in Moreton Bay reef growth from ≈ 3,000 to 2,000 ybp is also less easily explained. There was another ~ 1.5 m sea level fall (14, 15), combined with a peak in ENSO intensity (31), but these factors cannot logically cause reef termination at ~ 3,000 ybp and also fail to prevent reef initiation at ~ 2,000 ybp.

The most recent episode of reef initiation in Moreton Bay is 2,100 to 400 ybp, which loosely fits the most recent episode defined for tropical marginal reefs of the GBR (38). Reef initiation during this recent episode is somewhat puzzling because environmental conditions do not satisfy the typical preconditions for reef growth. Environmental factors that promoted reef initiation during the Holocene climatic optimum were reversed for the youngest episode (9, 19). Sea level fell by 1 to 2 m (15), shifting the intertidal zone downward and reducing the amount of substrate available for corals. Sea level fall also shifted river mouths seaward, and the reduced volume of tidal circulation in the Bay increased the residence time of terrestrial inputs to the nearshore marine environment (35). However, a sea-level fall can also potentially allow enough light to reach the seafloor of some turbid areas, which could allow for renewed reef growth (43). The El-Niño Southern Oscillation (ENSO) reached its peak intensity at ~ 2,700 ybp, which included temperature extremes and a flooding regime more severe than today (4, 27, 31). This would have destabilized vegetation and increased sedimentation to the nearshore reefs along the tropical and sub-tropical east Australian coast. Nevertheless, reef initiation and relatively rapid reef accretion occurred in Moreton Bay and in other nearshore tropical marginal reefs as recently as ~ 900 to 300 years ago (41).

The marginal reefs of Moreton Bay exhibited robust growth in the mid-Holocene, and have grown episodically over 7,000 years with no significant change in community composition or accretion rate (7). Changes in temperature, sea level, ENSO intensity, and sedimentation led to natural reef declines sometime between 8,000 and 3,000 ybp (4), prior to major anthropogenic disturbance. However, the Bay's reefs have recently exhibited significant modern degradation due to overexploitation and water quality degradation associated with the beginning of European settlement of the Queensland coast in 1824 (4, 7, 19, 44). In the past 200 years, reefs have changed significantly, and for the first time in 7,000 years reefs of Moreton Bay persist in a degraded state caused by increased sediment and nutrient runoff from anthropogenic land-use changes (7). Branching *Acropora* corals dominated assemblages from 7,000 to 200 years ago, and since that time assemblages have been dominated by massive corals such as *Favia* (7). Reversal of this degraded state will require reduced sediment and nutrient loads onto the reefs.

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Trace metal contamination and distribution in sediments of Moreton Bay: An historical review

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Abstract

Trace metals identified as priority contaminants (Pb, Zn, Cu, Cd, Ni, Cr, As, Hg) in estuarine and coastal marine sediments represent a challenging issue because of their toxicity, persistence and their potential to become bioavailable to aquatic organisms. Estuarine embayments have provided the most favourable sites for the settlement of Europeans in Australia. Since the 1840s, following the rapid development of the Moreton Bay region, metal contaminants used in many human activities started to disperse into the Bay. Here we present a review of recent studies aimed at quantifying trace metal concentrations in the sediments of Moreton Bay and at describing sedimentation patterns. The effects of rapid catchment modifications are recorded in sediment cores from intertidal and subtidal areas where increasing concentrations of metals correlate with the history of development in the region. Also, metal concentrations in surficial sediments at many sites are above local natural background levels and above sediment quality guidelines used to assess the ecological effects of sediment contamination, implying ecosystem deterioration. Moreton Bay is recognised for its ecological significance and, with predicted increases in the frequency of extreme weather events, mobilisation of contaminated sediments represents the main pathway for trace metal dispersal. This paper highlights the importance of monitoring metal contaminants in the Bay's sediments together with water quality parameters, and provides an overview of areas where contamination occurred in the past and of areas most likely to be impacted by metal contamination in the future. The data reported in this review can play an important role in local and regional management strategies for the preservation of a healthy estuarine ecosystem in Moreton Bay.

Keywords: metal contaminants, metal distribution, intertidal sediments, subtidal sediments, sedimentation rates, sediment mixing, environmental monitoring

Introduction

Maintaining a healthy ecosystem is linked to natural and human-induced changes, and to its capacity to recover after perturbations (1). Human activities have modified the magnitude and composition of inputs from watersheds to estuaries, thereby putting pressure on the ecological health of the coasts. Major modifications of the Moreton Bay catchment after European settlement in the early 1830s (e.g. clearing of vegetated areas converted to croplands and cattle grazing, urbanisation) (2-4) led to increased erosion from channels and gullies, resulting in increased sediment yield into the Bay (5–9). The environmental impact in the region was particularly marked after 1960 when fertiliser use and the introduction of many new chemicals resulted in nutrients and pollutants entering the waterways when there was a lack of understanding of their toxicological consequences.

Among trace elements, trace metals (e.g. lead (Pb), zinc (Zn), cadmium (Cd), copper (Cu)) are an important source of pollution. Their non-biodegradability and inherent toxicity make them some of the most persistent pollutants (10). Introduced in the aquatic environment by atmospheric deposition, weathering or erosion, anthropogenic sources (e.g. ore mining, fossil-fuel combustion, industry, agriculture) are major contributors of metals in coastal areas. In sediments, their concentrations include the natural and anthropogenic components. The mineralogical or chemical form in which a metal occurs will greatly affect how readily it is released into the environment. Trace metals have high affinity for fine particles because of their high adsorption capabilities and are bound to sediments by particle surface absorption, ion exchange, co-precipitation, and complexation with organic matter (see example in (10)).

In coastal and estuarine regions, sediments play an important role in contaminant distribution by transporting and accumulating high concentrations of potentially toxic metals into low-energy areas. After deposition, disturbance of sediments induced by natural (e.g. storms, waves) or anthropogenic (e.g. dredging) factors may redistribute anthropogenic metals associated with previously deposited sediments into the environment (10). Additionally, changes in bio-geochemical conditions (redox potential, pH and salinity) at the water–sediment interface may affect the partitioning of sediment-bound metals, thus facilitating their mobility and controlling their potential toxicity (see example in (10)). Once remobilised, metals transported in the water column may become bioavailable and toxic to marine organisms via bioaccumulation processes (10). Thus, once deposited into the Bay, sediments could act as non-point pollution sources by releasing their toxic metal load, thus adversely affecting the ecosystem.

Today, the Moreton Bay catchment is one of the fastest growing regions of Australia and rapid population growth poses a significant threat to the environment and the quality of its waterways (2, 11). Increased suspended sediment load transported in the water column from the catchment together with the associated nutrients and contaminants is causing ecosystem health decline in various areas of the Bay (5, 12, 13). To address this problem, the regional management plan has set a target of reducing the suspended sediment input to the Bay by 50% (6).

This review integrates the available knowledge on sediment accumulation and metal concentrations in sediments deposited in Moreton Bay since the onset of industrialisation, providing a reference point for future works on trace metal contamination in Moreton Bay.

Assessing metal contamination in sediments

Metals' inherent toxicity can be used as an indicator to monitor the quality and ecologic health of estuarine environments. Assessment of trace metal contamination in sediments is made by comparison with the natural geochemical variability and/or by comparison with sediment quality guidelines (see examples in (14–16)). In order to quantify metal contamination, it is essential to distinguish between the anthropogenic and natural contribution of trace metals in sediments. Enrichment factors (EF=metal $concentrations_{(sample)}$/metal $concentrations_{(background\ sample)}$) (16) are commonly used as a means of quantifying anthropogenic contribution of metals by comparison with background concentrations, which represent concentrations of metals in pre-anthropogenic uncontaminated sediments (16). Based on EFs classification, EF = 1–1.5 indicates that metals are mostly sourced by crustal material, EF = 1.5–3 denotes moderate enrichment, EF = 3–5 implies moderate to severe enrichment and the need for further investigation, while EF = 10–25 represents severe enrichment and serious environmental contamination.

The environmental risk to the aquatic ecosystem associated with metals, organic chemicals or nutrients is defined by water and sediment quality guidelines that set acceptable levels for chemical substances. Sediment quality refers to the ability of sediments to support a healthy benthic ecosystem. For Australian sediments, it is assessed by applying the Australian and New Zealand Guidelines for Fresh and Marine Water Quality – ANZECC and ARMCANZ (Australian and New Zealand Environment and Conservation Council, and Agriculture and Resource Management Council of Australia and New Zealand) interim sediment quality guidelines (ISQGs) for fresh and marine water quality (1). Metal concentrations below ISQG-Low values (ISQG-L) are unlikely to have adverse effects on the environment or aquatic organisms, whereas concentrations higher than ISQG-High values (ISQG-H) indicate highly contaminated sediments, which are likely to have adverse biological impacts (17). Reference median ranges for metals occurring naturally in Queensland estuarine sediments (18) are also used as benchmark guidelines for comparison of metal contamination in sediments (Table 1).

Metal contamination in Moreton Bay

The ranges of concentrations (maximum and minimum) of trace metals (Cu, Pb, Zn, chromium (Cr), nickel (Ni), arsenic (As), and (Cd) found in intertidal and subtidal sediments of Moreton Bay are summarised in Table 1. Mercury (Hg) values were not listed in Table 1 because there were analysed in only very few studies (19–21) (Fig. 1). Details of the location of sampling sites, sediment characterisation, and concentrations of other metals are found in each cited work. Although results from these studies are difficult to compare because of the different analytical methodologies used, assessment of contamination was generally made against a) enrichment factors (EFs) and b) by comparison with sediment quality guidelines.

Background concentrations

To date, few studies have defined metal background concentrations to assess contamination in Moreton Bay sediments. Some studies have used as a reference, benchmark metal concentrations defined for sediments of Queensland freshwater

Table 1. Ranges of total metal concentrations (mg/kg) in Moreton Bay sediments (modified from (18)). ICP-MS: Inductively Coupled Plasma Mass Spectroscopy, ICP-OES: Inductively Coupled Plasma Optical Emission Spectroscopy, AAS: Atomic Absorption Spectroscopy, XRF: X-ray Fluorescence.

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Source	Location	Sample		Metals	Cu	Pb	Zn	Cr	Ni	As	Cd	sediment fraction (mm)	analytical method
[18]		RMR-median		mg/kg	17	5	5	60	10	n/a	0.5	< 0.063	
[17]		Australian ISQG-L			65	50	200	80	21	20	n/a		
		Australian ISQG-H			270	220	410	370	52	70	n/a		
[30,31]	Boggy Creek	surficial sediments	pre	min	3	8	41	8	2	n/a	n/a	bulk	aqua regia
		mangroves	2005	max	34	85	144	117	58	13	2		ICP-OES
[33]	Kedron Brook Floodplain	surficial sediments			117	118	184	n/a	n/a	n/a	0.3	bulk	seq.exctraction AAS
[28]	Whinnum	surficial sediments	pre	min	25	8	46	n/a	n/a	n/a	n/a	bulk	aqua regia AAS
			2005	max	134	27	211	n/a	n/a	n/a	0.15		
[32]	Bulimba Creek	sediment core	pre	min	20	10	30	33	18	ns	0.1	< 0.063	aqua regia
		intertidal	2005	max	50	62	96	69	30	ns	0.3		ICP-OES
[34]	Waterloo Bay	sediment core	pre	min	**20**	2	20	n/a	n/a	0.1	0.1	bulk	aqua regia
		intertidal	2005	max	42	20	52	n/a	n/a	2.4	0.8		ICP-OES
[36]	Logan River	surficial sediments	pre	min	15	2	45	23	23	n/a	0	< 0.063	aqua regia
		estuarine	2005	max	38	21	72	49	35	n/a	0		ICP-OES
[23]	Beachmere	sample 39	pre		2	n/a	35	19	7	5	n/a	bulk	aqua regia
		sample 40c clay	2005		2	5	53	20	9	9	n/a		ICP-OES
[37]	Gold Coast Broadwater	surface sediments		min	4	6	2	0.2	3	n/a	n/a	< 0.063	HNO3-H2O2-HCl
				max	2990	166	596	31	24	n/a	n/a		AAS
[35]	Waterloo Bay	surface /subsurface		min	2	3	4	n/a	3	n/a	0.5	< 0.063	HNO3-H2O2-HCl
		intertidal		max	61	56	117	n/a	27	n/a	2		AAS
[21]	Sandstone Point	surface	2005		4	4	14	3	1	n/a	0.02	bulk	aqua regia ICP-OES
	Beachmere	surface			1	3	8	6	2	1	0.04		
	Deception Bay	surface			14	5	11	4	1	1.4	0.03		
	Redcliffe	surface			5	6	10	18	2	3.6	0.11		
	Nudgee Beach	surface			6	6	34	14	9	2.2	0.10		
	Fishermann Island	surface			26	16	35	331	13	2.4	0.09		
	Wynnum	surface			11	27	58	23	10	n/a	0.04		
	Waterloo Bay	surface			4	4	13	6	3	2.9	n/a		
	Ormiston	surface			6	7	31	10	8	5.3	n/a		
	Point Halloran	surface			31	5	20	6	1	n/a	n/a		
	Point Talburpin	surface			18	13	89	26	20	5.5	0.01		
[15]	Moreton Bay	intertidal	2007-2009	min	3.2	4.5	9.3	15.5	3.7	5.9	0.02	< 1	HNO3, HF, HCl
		sediment cores		max	30	38	103	116	36	18	0.3		ICP-MS
[19]	Deception Bay	subtidal surface sediments	post-2011	min	4	3	9	123	9	3	0.02	< 0.10	3HNO3+1HCl ICP-MS
			Apr-12	max	26	17	118	358	36	13	0.08		
			post 2011	min	3	2	5	8	3	3	0.01		
			June2012	max	21	18	91	95	34	12	0.06		
			post-2011	min	2	3	5	8	2	3	0.01		
			Nov-12	max	23	19	99	111	37	17	0.09		
[14]	Deception Bay	subtidal	post-2011	Max	1.9	3.4	4.9	107	6.5	0.7	n/a	< 2	XRF
		surface sediments		Min	20.8	14.7	548	186	35.3	10.0	n/a		
	Moreton Bay	intertidal surface	2007-2009	min	3.1	3.2	11.3	11.5	3.5	2.7	0.02	< 1	HNO3, HF, HCl
		sediments		max	30.1	37.7	103.0	116	36.2	18.5	0.3		ICP-MS
[24]	Moreton Bay	intertidal	2007-2009	min	2.0	0.1	5.5	7.6	2.2	0.4	0.01	< 1	HNO3, HF, HCl
		sediment cores		max	45.6	21.2	117	116	51.7	24.0	3.7		ICP-MS
[22]	central Moreton Bay	surface subtidal	post-2011	min	6.0	10	17	13	10	n/a	n/a	bulk	3HNO3+1HCl
				max	40	26	140	257	54	n/a	n/a		ICP-OES

streams, estuaries and coastal waters calculated between 1975 and 1992 (18). In the central Moreton Bay mud-dominated zone, a geochemical background representing metal concentrations deposited before the onset of urban and industrial development was defined, based on the geochronology of two subtidal sediment cores (22). Metal concentrations prior to European development were also defined for intertidal areas in Deception Bay, Bramble Bay and in southern Moreton Bay (15). In Deception Bay, three sites were selected to define background concentrations (14), but a site near Rocksberg in the upper Caboolture River, the major contributor to sediments in Deception Bay (14, 19), was chosen to best represent the background geochemical composition of Deception Bay. Background values in the Pumicestone region were established for local bedrock, estuarine sediments and soils (23). Given the hydrodynamic variability of the Bay, contamination assessments should carefully select background concentration ranges

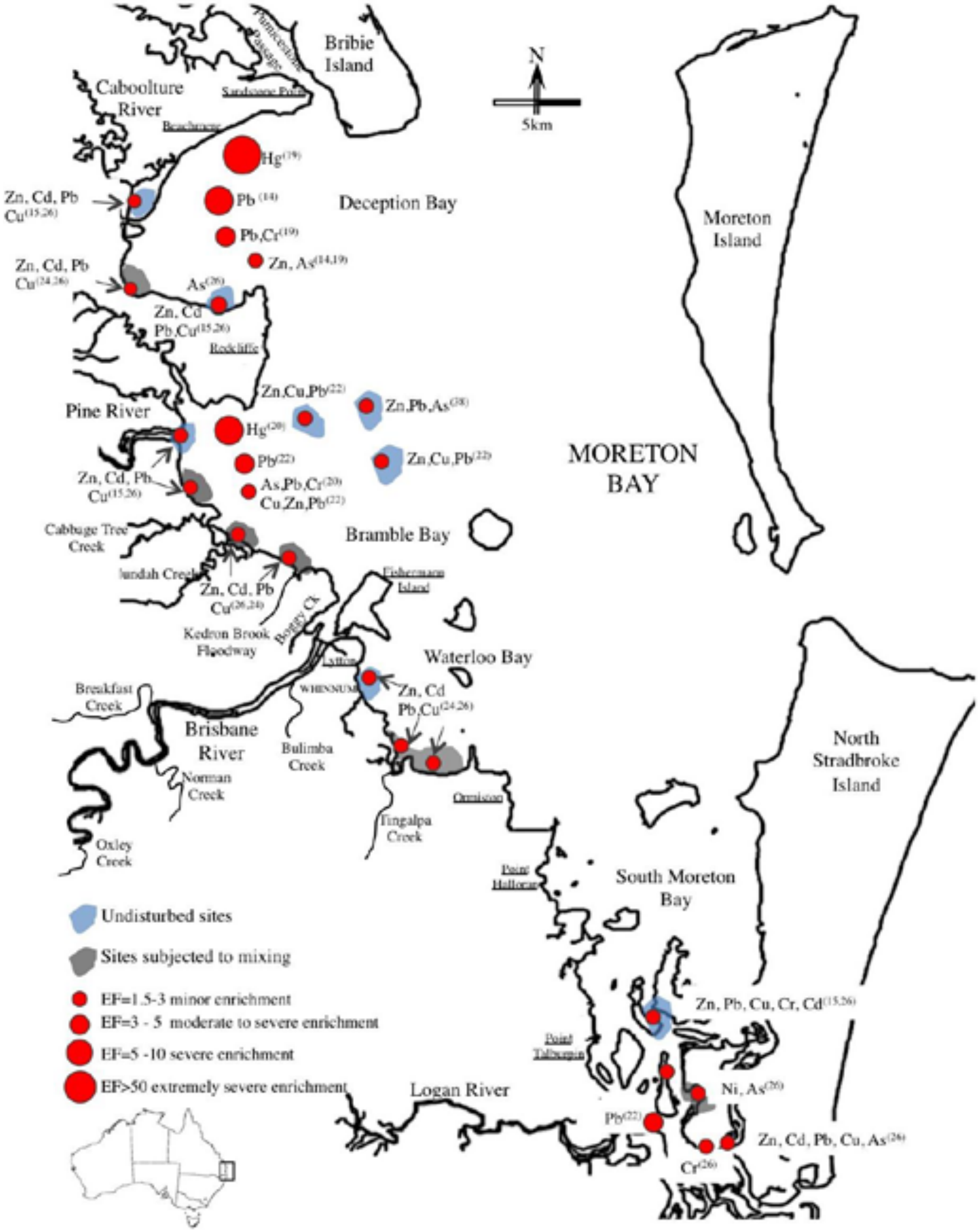

Figure 1. Distribution of trace metal enrichment factors (EF) in intertidal and subtidal sediments of Moreton Bay. Dots indicate ranges of enrichment factors for the metals listed. In the map only EFs>1.5 are included. Details of the sediment locations are found in each cited work (reference numbers in the map).

that best reflect the site-specific depositional environment of the area where contamination is assessed (16, 24). Most of the studies on sediment contamination in Moreton Bay are focused on small sampling areas or localised zones (e.g. 28, 29, 33, 40). Few studies (14, 19, 22, 25) have analysed sediments deposited in the period following the 2011 Brisbane River flood. Some large-scale investigations evaluated metal concentrations in sediments from the northern to the southern part of Moreton Bay (14, 19, 22, 25), while others provided a temporal record of metal contamination from sediment cores (21, 22, 24, 26, 27). An outline of the sites in Moreton Bay where sediments were found to be enriched in metals (EF>1.5) is shown in Figure 1.

Bay-wide studies

Pollution levels in surficial sediments across Moreton Bay were investigated in several studies. The regional distribution of metals within intertidal sediments along the western Moreton Bay shoreline was investigated in a 2005 study (21) integrating new results together with previously existing data. The most significant contaminants identified in this study were Ni, Pb, Hg, Zn, and occasionally Cd, As and Cr. The highest concentrations of metals were associated with fine estuarine sediments close to urban and industrial areas (maritime and port facilities, light industries) and concentrations were two to three times higher than in nearby sediments from sandy shorelines (21).

Another study has assessed contamination in 15 intertidal sites sampled between 2007 and 2009 (26). Chromium, Ni and Cu were found to be the main contributors to sediment pollution, with Cr and Ni exceeding the ISQG-L levels in Deception Bay, in the Pine River and in southern Moreton Bay (26). Sediments were also enriched in Zn, Cd and Pb by 1.5–3 times the background levels. A more recent work (unpublished thesis (27)) has analysed 43 intertidal surface sediments in mangrove areas from northern to southern Moreton Bay (27). Sediments in Deception Bay showed minor enrichment (EF<2) for most of the metals, while minor to severe enrichment (EF<10) was found in Waterloo Bay (EFs: As=2.25, Cr=3.56, Cu=2.55 and Zn=2.05) and southern Moreton Bay (EFs: Cr=2.93, Cu=7.74, Pb=2.26 and Zn=2.05). Average metal concentrations fell between the ‘high’ and ‘low’ range of ANZECC/ARMCANZ (17) and Queensland estuarine sediment (18) guidelines, while maximum values of As, Cr and Ni exceeded the ISQG-H at some sites (27). These results were not included in Figure 1 and Table 1 as they have not been published. Other investigations were aimed at assessing metal concentrations in restricted areas of the Bay.

Deception Bay

Thirteen subtidal sediment samples from Deception Bay were analysed three times over a period of seven months (4) and Hg was identified as the element of highest enrichment, posing moderate to severe risk to the local ecology of Deception Bay (19). Another study undertaken in the same area revealed severe Pb pollution (average EF=13) and minor to moderate enrichment of As, Zn and Cr (average EFs were 2.3, 2.7 and 3.7, respectively) (14). These concentrations reflect the rapid population growth and the expansion of industrial activities that has occurred in Deception Bay since the 1980s (4).

Bramble Bay

In Bramble Bay, fine estuarine intertidal muds were enriched in Cu, Zn, Cd and Pb close to the reclaimed landfill site in Wynnum, and concentrations decreased at increasing distance from the landfill (28). Significant concentrations of Cu, Zn, Pb and Ni were found in mangrove sediments in the same area. Analysis of the transfer processes of metals to mangrove sediments revealed that in a 15-year period around 46kg of Pb, 137kg of Cu, 941kg of Zn, 0.2kg of Hg, 1kg of Cr and 127kg of Ni moved from the landfill to the mangroves through surface run-off (29).

A recent work examined trace metal contamination in post-2011 flood surficial subtidal sediments of Bramble Bay and determined the spatial patterns of pollution and the temporal changes in metal concentrations in February, April, June and November 2012 (20). The overall sediment health of Bramble Bay was assessed as good, and only Cr and Ni maximum concentrations exceeded the low thresholds of the ISQGs (ISQG-L). Compared to the geochemical background, sediments across Bramble Bay were found to be slightly enriched in Zn (max EF=1.8) and Pb (max EF=2.9), moderately enriched in As (max EF=4.1) and at some sites severely enriched in Hg (max EF=73) (20).

Brisbane River estuary

The Brisbane River estuary is downstream of the most heavily urbanised area in the region. Breakfast, Norman, Oxley, Boggy and Bulimba creeks and Kedron Brook Floodway have been exposed to urban and industrial contamination. Reports by the Department of Environment (18) found levels of Zn, Cu, Ni and Pb exceeded the environmental guidelines in Breakfast, Norman and Oxley creeks (18). Surficial sediment analysis within mangroves along the Boggy Creek inlet showed high levels of nutrients (due to Luggage Point sewage) and metals (Cu, Pb, Zn, silver (Ag), Cr, Ni, As) at the seaward edge of the woodland, reflecting the industrial and urban history of the Brisbane River estuary (30, 31). In the lower sections of Bulimba Creek, close to the industrial zone near the junction with the Brisbane River, sediments were enriched in Cr and Pb (21, 32). In the Kedron Brook floodplain, a low-lying area drained by artificial canals, the estuarine channel bed sediments were more enriched in Cu, Zn and Pb than the floodplain sediments (33).

Waterloo Bay

High concentrations of Cu, Zn and Pb were found in intertidal muddy sand in Waterloo Bay close to a drainage creek near an industrial area (34). Also, along the intertidal areas in Waterloo Bay, data obtained from surface samples at 19 sites found contamination in sediments, with Cu, Zn, Pb, Ni and Cd above natural background levels for Queensland estuaries and exceeding the ISQG-L (Pb at three sites, Ni at two sites and Cd at one site) (35).

Southern Moreton Bay

Analyses of 20 surface samples of estuarine silts from the Logan River in southern Moreton Bay showed high levels of Pb and Zn in the vicinity of populated areas. Concentrations of Cu, Zn and Pb decreased downstream, whereas Cr increased (36). Sediments from the Pimpama River (15 km south of the Logan River) were enriched in trace metals despite the river catchment being characterised by low levels of anthropogenically introduced metals (23). Concentrations of Cu, Pb and Zn in sediments from residential canals and commercial marinas in the Southport Broadwater were found above Queensland natural background levels as well as Australian sediment quality guidelines in most of the sites. Those high concentrations were attributed to urban stormwater run-off, run-off from local industries, and to metals derived from maintenance of vessels (37).

Sediment cores

Sediment cores are excellent archives of past sediment deposition and vertical metal profiles in undisturbed sediments are used to reconstruct the history of pollution in coastal areas (see example in (15)). In the western side of Moreton Bay, analyses of nine sediment cores from intertidal flats that integrated sediment geochronology with vertical profiles of metal concentrations revealed the extent of trace metal contamination since European settlement (15). A consistent temporal increase in Pb, Zn, Cd, Cu and Ni concentrations was found in Deception Bay, Bramble Bay, Waterloo Bay and southern Moreton Bay. Compared to pre-European background levels, metal concentrations increased by up to two orders of magnitude (EF=2) after ~1923 and maximum metal input (EF=4) was recorded during the 1950s to 1970s. A similar trend was observed in sediment cores at two subtidal sites in central Moreton Bay (22). Enrichment in Zn, Pb and Cu in sediments deposited after 1959 corresponds to the period of increased population growth, and consequent intensification of metal inputs from industrial activities and urban run-off into the Bay. Similarly, temporal trends of increasing Zn, Pb, Cu and As concentrations in sediment cores in the northern part of Waterloo Bay were correlated with the expansion of the refinery in Lytton established in the 1960s, with run-off from the Brisbane Airport, and with the nearby wastewater treatment plants (24).

In the subtidal areas of Moreton Bay, an extensive study of sediment cores and surface sediments assessed the effects of the 2011 Brisbane River flood on trace metals deposition in Moreton Bay (22). Sediments deposited in central Moreton Bay after the flood, were highly enriched in Zn, Cu and Pb. The highest enrichment was recorded in Bramble Bay at the mouth of the Brisbane River, Cabbage Tree Creek and Kedron Brook, with Zn, Cu and Pb EFs as high as 2.7, 2.6 and of 3.4, respectively. Sediments in southern Moreton Bay were enriched in Pb (EF up to 5.3) close to the Logan River. The high metal concentrations found in the flood deposits were attributed to the remobilisation and redeposition of metal-rich sediments accumulated on the Brisbane River floodplain during the 10 to 40 years before 2011 (5, 22). Also, post-2011 flood sediments showed higher metal concentrations in subtidal areas in Bramble Bay and in central Moreton Bay (22) compared to concentrations found in pre-flood intertidal sediments along the western side of Moreton Bay (26).

Factors influencing metal distribution in Moreton Bay

Most of the reviewed studies found that sediments were enriched in metals in different areas throughout Moreton Bay. Among the main risks leading to ecosystem deterioration is the redistribution of metals associated with old contaminated sediments, induced by sediment mixing (10, 24). Identifying areas prone to sediment disturbance is thus of critical importance in Moreton Bay (24). A few studies have shown that deposited sediments remained undisturbed, thus providing a chronological record of metal input (15, 22, 38, 39). However, in some areas sediment deposition is mostly controlled by the local hydrodynamics of the Bay (24, 38) and vertical redistribution of metals may occur up to at least 80cm depth (24). For example, increasing concentrations of Pb, Zn and Cu towards surface sediments in Bramble Bay and Waterloo Bay correlate both with increased anthropogenic input in the last century and to post-depositional processes (e.g. bioturbation, sediment disturbance) (24).

Most importantly, in areas where sediment mixing occurs, changes in the environmental geochemical conditions may facilitate the desorption and remobilisation of sediment-bound metals (in particular the exchangeable or weak-bound metal fraction (10)), which may become bioavailable and toxic for aquatic organisms (10). For instance, high concentrations of As found at around 20cm depth in a sediment core from Waterloo Bay (24), following the resuspension of sediments, may represent a risk to biota. In Moreton Bay, the potential risk posed to the ecosystem by metals likely to become bioavailable (weakly bound metal fractions) was assessed only to a limited extent. Results of the available studies were not reported in Table 1 as they are difficult to compare because of the different analytical extraction methods used. Deception Bay and Bramble Bay were found to be the areas at higher risk (14, 26). Analyses of 15 surface intertidal sediments along the western side of the Bay found cobalt (Co), Zn and Cd falling into the medium risk category at almost all sites; Zn and Cd were found to pose high to very high risk to the aquatic biota at three sites in Deception, Bramble and southern Moreton Bay, while Ni, As, Cu, Pb and Cr may pose medium risk at all of the sites (26). Another study examined subtidal sediments in Deception Bay three times over a period of seven months, finding that the exchangeable fraction was relatively low compared to the guidelines for As, Cd, Cr, Cu and Pb, with the exception of Hg, which may pose some risk for the ecosystem (19).

Six sites (intertidal and subtidal) in Bramble Bay were analysed in four periods of the year to assess the temporal variability of the weak-bound metal fraction in sediments (20). The sediment guidelines were exceeded only for Ni and Cr, while Hg was found to be the most enriched metal with the highest Enrichment Factor in sediments collected in June. Also, Hg and Cd showed increasing trends over the entire sampling period, probably because of an ongoing pollution source in the area, while As concentrations were found to be more stable over the same period. Temporal variations in metal concentrations were also attributed to the occurrence of sequestration processes and to variation in sediment fluxes controlled by changes in water flow during the wet/dry season (see (20) for more details).

A study on Southport Broadwater sediments in southern Moreton Bay revealed that relatively small changes in the environmental conditions would cause the release of Cu, Pb and Zn associated with iron (Fe) and manganese (Mn) oxide minerals (7). The metal-exchangeable fraction was also quantified in 13 sediment cores from intertidal areas across Moreton Bay (41). Results showed that at least 20% of the total metal concentrations for Co, Cd and Zn in most of the sediments are potentially bioavailable. This study also correlated the temporal variability of the exchangeable fraction of Zn, Pb, Cr and Ni with the increase in metals usage since the beginning of the century. These data have not been reported here as they have not been published (41).

Major sources of metal contamination in Moreton Bay

Most of the studies reviewed in this paper show that the main contribution to the metal contaminants load in Moreton Bay derives from the urban development of the catchment area, from the associated sewage discharge, industrial run-off, urban stormwaters, and wash off from urban surfaces (e.g. roads). In Bramble Bay and especially close to the Brisbane River, contamination (Pb, Cd, Zn, As and Ni) is mainly associated with urban stormwater drainage from municipal solid waste landfill, and the industrial area of Lytton Point (20, 21, 26). Heavy marine traffic, recreational and industrial marinas, and vessel maintenance are identified as the major sources for Cu, Ni and Hg contamination in Deception Bay and southern Moreton bays (14, 40, 42), with relatively high Cu levels found around marinas and mooring facilities due to the usage of Cu-based antifouling paints (37, 40, 43, 44). Significant amounts of Cd, Cr and Cu also derive from agriculture and fertilisers, while Pb, Zn and Ni originate mainly from combustion of fossil fuel (22) and using leaded gasoline (Pb), similar to other sites around Australia (15, 23).

Variability of sediment deposition in Moreton Bay

Sediments are the main drivers of trace metal distribution in estuaries. Sedimentation in Moreton Bay is largely controlled by tidal currents and by major flood events. Some studies have characterised sediment accumulation rates in sediment cores, providing the geochronology of sedimentation in the last 150–200 years (Table 2).

Table 2. Sedimentation rates in Moreton Bay.

Source	Location	Dating method		dated material		Depth (cm)	Age (yBP)	Sedimentation rates (cm/yr)	Mass accumulation rates (g cm-2 yr-1)
[5]	central Moreton Bay	210Pb	137Cs	subtidal	core MB1	55	~59		0.66-0.82
	mud dominated region	210Pb	137Cs	subtidal	core MB2	59	~59		0.83-0.84
[15]	Deception Bay	210Pb	137Cs	intertidal	core G37	0-17		0.13-0.27	0.19-0.27
	Deception Bay	210Pb	137Cs	intertidal	core G34	0-12		0.12-0.23	0.16-0.23
	Pine River	210Pb	137Cs	intertidal	core G6	0-44		0.31-0.71	0.40-0.71
	south Moreton Bay	210Pb	137Cs	intertidal	core G31	0-40		0.63-0.72	0.67-0.72
[38]	central Moreton Bay	210Pb	137Cs	subtidal	core MBSC2	0-85	~ 42	0.62	
	mud dominated region	210Pb	137Cs		sediment core	0-60	~60	1.2	
[5]	central Moreton Bay	Optical dating	14C		core MB1		215 ± 50- 1440± 140		0.24 ± 0.02
	mud dominated region	Optical dating	14C		core MB2		2900±250 - 462±43		0.09 ± 0.01
[7]	Moreton Bay					500	6500	0.08	

Data on sedimentation rates in Moreton Bay are in agreement with studies suggesting that modern rates of erosion in Australia have increased by a factor of up to 145 compared to the natural rates before European settlement (3, 25). One of the first studies estimated a long-term bulk accumulation rate of 0.08cm/yr since about 6,500 years ago in central Moreton Bay (7). In the mud-dominated zone in central Moreton Bay two sediment cores recorded an increase in sedimentation from 1840 to 1890, following the start of European settlement (5). The same study showed that sedimentation rates increased by 3–9 times in the last 100 years compared to the 1,500 years before (5). The intensification of cropping and grazing practices accelerated in the 1950s, and the effects of greater erosion from the catchment are reflected by the increase in sedimentation rates recorded in central Moreton Bay between 1950 and 1967 (5). Similarly, an increase in sediment accumulation rates in intertidal areas was recorded in the same period in four sediment cores, which preserved the history of sediment deposition since approximately 1900 (15, 39). Average accumulation rates in the central part of the Bay were around ~0.83g cm^2/yr between 1959 and 2011 (5), while in intertidal areas rates varied from about 0.16 to 0.72g cm^2/yr in the last 70 years (15, 38). Comparison of sediment accumulation rates (Table 2) highlights the spatial variability of Moreton Bay sedimentation, which reflects the complex hydrodynamics of the Bay (24, 41), mostly controlled by the local hydrologic, physical and tidal conditions (15). Also, evidence of post-depositional diagenetic processes and sediment mixing at different sites (24, 38) shows that the sedimentary record may be disturbed up to a depth of at least 1m, as found in cores from Waterloo Bay (24).

The risk of metal redistribution induced by mixing of old deposited sediments is of concern, especially where fine particles are dominant. Fine sediments represent the dominant fraction in Moreton Bay, covering about 860 km^2 and more than 50% of the area of the Bay (45). Compared to the sediment distribution map completed in 1970 (46), the area covered by fine sediments has increased and other extensive particle size mapping exercises published in 1999 have shown that the area of mud-rich sediments had expanded significantly at that time (47). Tide-induced resuspension is the primary driver of turbidity regimes and sediment transport within Moreton Bay, while flood events are episodic determinants of sediment distribution in the Bay (5, 22, 45). For example, an estimated 5.4Mt of sediments were transported into the Brisbane River estuary during the 1974 flood, while ~10Mt of fine (<63mm) sediments were deposited in Moreton Bay during the November 2011 flood (22). After this event, a 10–20cm layer of recent fine sediments was found in sediment cores within the central mud-dominated zone north-east of the mouth of the Brisbane River, showing that after big floods sediments are transported and reworked from shallow coastal areas to deeper regions of the Bay where they gradually accumulate (5, 22). The dramatic increase in fine silt and clay that occurred in recent decades is cause for ecological concern as it may enhance the risk of dispersal of associated trace metals into still pristine areas (45).

Implications for management of contaminated sediments in Moreton Bay

Health assessments of estuarine ecosystems are based on indicators relevant to the type of estuary, pressures on the estuary and management objectives. Indicators should be selected considering existing problems, and likely future scenarios, such as those posed by changes in catchment land use or climate change. Existing studies have demonstrated that metal contamination in Moreton Bay is mainly caused by (i) current pollution from point sources e.g. wastewaters, industrial areas discharge, water treatment plants or urban run-off, (ii) transport of contaminated sediments, and (iii) remobilisation of old contaminated sediments buried below new sediments. The nature and distribution of metal enrichment in the Bay is controlled by local pollution sources and by hydrodynamic factors and it is not consistent across the different embayments (22, 24). This site-specific variability must be considered when performing contamination assessment monitoring. The complex interactions among meteorological, hydrodynamic, biological and geochemical factors result in a metal transport system with spatial and temporal variability. Post-deposition sediment remobilisation induced by natural (e.g. bioturbation) or by anthropogenic (e.g. dredging) processes increases the risk of metal redistribution (24). For example, strong tidal currents and large flood events transport fine particles into the central part of Moreton Bay, redistributing contaminated sediments from the western Bay (22). Hence, because of their inherent toxicity and the risk of becoming bioavailable (10), the monitoring of trace metal concentrations is needed to assess and thus preserve the quality and ecologic health of Moreton Bay.

Sediment contamination is complex to manage due to the tendency for metals to be retained within sediments for long periods, as shown by trace metal temporal trends recorded in sediment cores (15, 22, 24). Contaminated sediment can thus become a major obstacle to restoration efforts in degraded aquatic environments. Furthermore, climate change is increasing the frequency of extreme events (48) (e.g. storms, cyclones, floods) and it is expected to increase sediment loads, thus accelerating the redistribution of sediments and contaminants.

A regular environmental monitoring program is maintained in South East Queensland to support policy and planning decisions for the preservation of the natural ecosystem (49). The Healthy Land and Water (HLW) Report Card released each year delivers a measure of the pressures facing the Moreton Bay region and ranks its environmental condition grade from excellent (A) to fail (F) (49). Monitored indicators are freshwater communities, ecosystem processes, habitat, estuarine water quality, and sediment, nitrogen and phosphorus loads. However, the report card does not include metal contaminants as an indicator of environmental quality. Routine monitoring of trace metals in sediments could be added to the HLW program in Moreton Bay. Routine surveys would contribute to provide information for decision makers to take into account pollutant loads when restoring affected sites and/or preventing the disturbance of contaminated areas by, for example, improving management planning for dredging and maintenance of navigational channels preventing metal redistribution by sediment mixing.

Results summarised in this paper show that trace metals accumulated in sediments represent a risk to the Moreton Bay ecosystem. This review also identifies areas that are potentially more susceptible to metal deposition, and including these areas in future studies may contribute to future management strategies for Moreton Bay. The prevention of metal contamination will enhance the resistance and resilience of the ecosystems of the Bay and their ability to withstand the increased frequency and severity of disturbances caused by climate change. A more rigorous approach to managing contaminated sediments aimed at reducing the sources of metals into Moreton Bay should be embraced to preserve water quality and the health of the ecosystem.

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Chapter 4 - Water Quality, Land-Use and Land-Cover

Cluster Leader: Professor Stuart Phinn, Professor and Director, Remote Sensing Research Centre/Joint Remote Sensing Research Program, University of Queensland.

Stuart Phinn's research interests are in measuring and monitoring environmental changes using earth observation data and publishing/ sharing ecosystem data. A large part of this work has been in Moreton Bay and its associated catchments since the early 1990s. Stuart Phinn is a professor of Geography at the University of Queensland where he teaches remote sensing and directs the Remote Sensing Research Centre www.rsrc.org.au , which includes programs recognised as world's best practice, to support government agencies across Australia using EO data www.jrsrp.org.au. Stuart's research and teaching interests use airborne and satellite data sets for measuring and monitoring environmental changes and publishing/sharing ecosystem data. This work is done in collaboration with other environmental scientists, government environmental management agencies, NGO's and private companies. Most recently he chaired the Committee that produced Australia's first Earth Observation Community Plan – 2026 www.eoa.org.au . He publishes extensively with his collaborators, and currently has 190 papers in refereed international journals, 1 book, an on-line textbook, and 12 book chapters. A large part of this work also involves training the next generation of scientists and managers who effectively use remote sensing, and has graduated 42 PhD students.

Moreton Bay and catchment urban expansion and vegetation change

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Abstract
Here we describe changes in the Moreton Bay catchment via two remote sensing trajectory analysis methods, both of which are derived from Landsat satellite imagery. First, we describe changes in vegetation cover from a time-series of woody vegetation cover products. We focus on the absolute areas and spatial patterns in vegetation clearing across a time series between 1988 to 2015, focusing on the Brisbane, Pine, Logan and Caboolture River Catchments. We highlight several heavy clearing hotspots, as well as individual years in which clearing increased markedly. Second, we summarise the historical change from a time-series of categorical land cover and land use maps, with a focus on urban expansion. Our analysis shows a steady spread of urban areas outwards from highly developed areas, and a spread of lower density urban areas consistent with the increase in 'rural residential' and 'lifestyle block' developments.

Keywords: Landsat, remote sensing, time series, urbanisation, tree cover, satellite image

Introduction
As described in detail in the papers in this Chapter, South East Queensland's catchment has been significantly modified since the 1970s, including: extensive urbanisation; construction of dams and water impoundments; decreases in agricultural land use; and significant changes in vegetation cover. The availability of long term satellite image archives, along with modern computing resources, has seen a rapid growth in methods that utilise time-series analyses for studying and detecting changes in land use and land cover dynamics. Trajectory analysis (as these methods are commonly referred to) from landscape scale analysis from satellite imagery is generally divided into two main approaches: (i) those that detect either abrupt or long-term change that moves a system from one state to another, or (ii) those that explicitly aim to detect and monitor disturbance and recovery trends (1). We describe changes in the Moreton Bay catchment via two such trajectory analysis methods, both of which are derived from Landsat satellite imagery. First, we describe changes in vegetation cover from a time-series of woody extent and foliage projective cover (%), with a focus on land clearing. Second, we summarise the historical change from a time-series of categorical land cover and land use maps, with a focus on urban expansion.

Land clearing in South East Queensland (SEQ)

The Statewide Landcover and Trees Study (SLATS) is a vegetation monitoring program, coordinated by the Queensland Government's Department of Science, Information Technology and Innovation (2). The program maps and monitors the extent of woody vegetation, with a focus on determining the location, timing and extent of vegetation clearing. The methods include a combination of automated and manual mapping techniques, based on ancillary field data and Landsat satellite imagery. The backbone of the methodology is estimation of foliage projective cover (FPC), the fraction of ground covered by foliage from a 'birds eye view', in each Landsat pixel. Time-series of this information was then used to estimate the change in extent of woody vegetation (trees, shrubs and lianas) and the associated clearing rates. Danaher *et al*. (3) give background on the approach, and the SLATS website (2) describes current methodology, publications and products.

The FPC products are able to show the temporal trend in the intensity of woody vegetation clearing in SEQ between 1988 and 2015 (the years Landsat has been collecting imagery) for the Brisbane, Pine, Logan and Caboolture River Catchments (Fig. 1). Note the clusters of heavier clearing activity, corresponding to a mixture of the development of Brisbane's residential and commercial property, as well as clearing for agriculture and forestry. Examples include housing development at Springfield Lakes, development and clearing at Yarrabilba, Esk State Forest and the Mount Hallen rural developments, and agricultural and commercial development around the mouth of the Caboolture River. The FPC data can also be summarised to show the yearly clearing totals from 1988 to 2015 (Fig. 2). Note the peaks and troughs in clearing activity, some of which may correspond to changes in clearing legislation, but would need to be confirmed with more detailed study. The FPC mapping and clearing statistics process also provide a more detailed summary on the types of land use that replaces woody vegetation from 1988 to 2015 (Table 1).

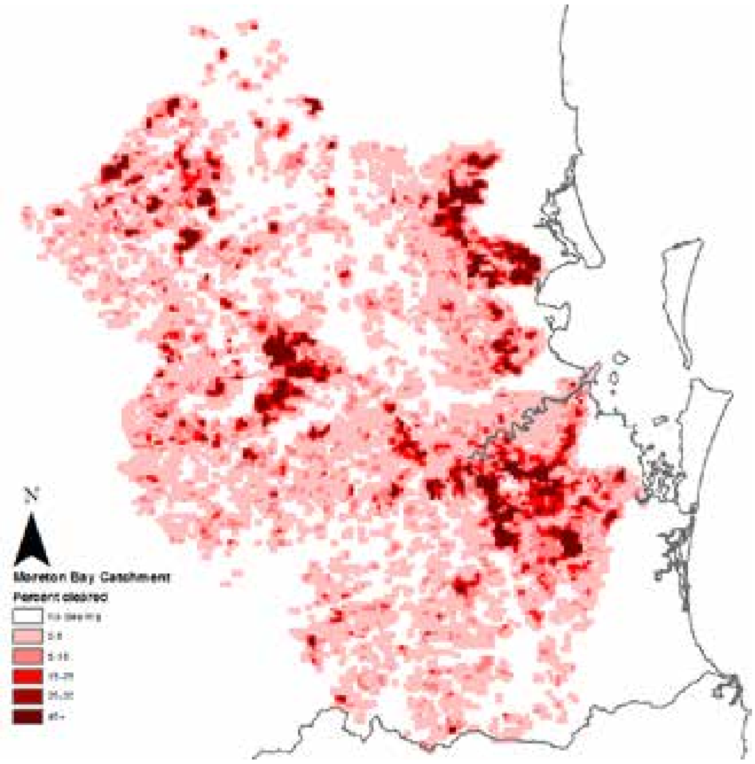

Figure 1. Woody vegetation clearing intensity in South East Queensland from 1988 to 2015, in the Brisbane, Pine, Logan and Caboolture River Catchments. Data come from the Queensland Government's Statewide Landcover and Tree Survey (SLATS)(3)

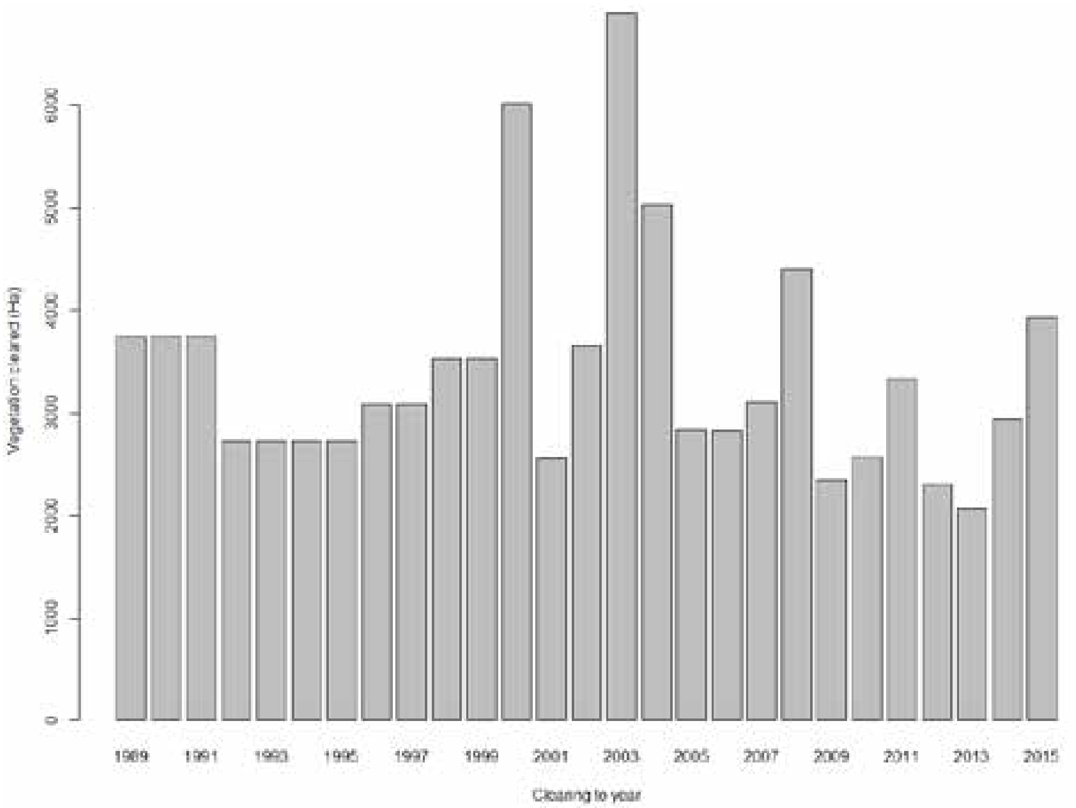

Figure 2. Woody vegetation clearing in South East Queensland from 1988 to 2015, in the Brisbane, Pine, Logan and Caboolture River Catchments. Data come from the Queensland Government's Statewide Landcover and Tree Survey (SLATS)

Urbanisation in South East Queensland

Using an archive of maps of South East Queensland from Lyons *et al*. (4) we examined the progressive change in the extent of urban areas over the past few decades. The maps were derived from Landsat satellite imagery using object-based image analysis. The maps summarised land cover and land use into the following categories: urban (urban or built area and urban-vegetation mixture); agricultural, non-persistent vegetation (grass, sparse/non-photosynthetic vegetation; bare sand, bare ground); and forest vegetation (closed canopy forest and other dense vegetation, and open canopy forest). Full details on the methods are given in Lyons *et al*. (4). This approach differs from the SLATS woody cover analysis because the urban cover classes were explicitly mapped as opposed to vegetation being the only parameter of interest.

South East Queensland has experienced rapid and wide spread population growth in the past few decades, and a very clear spatial trend of continued outward urban expansion was visible across the time-series (Fig. 3a). The trend showed that the later stages of development were encroaching on a larger spatial extent of the landscape, but the total area of new developed land was not increasing. That is, smaller individual developments or low density developments were built over relatively large areas. This is consistent with the increase of "rural residential" and "lifestyle block" type developments, where areas between developed sites are still mapped as vegetation proper. The corresponding map of vegetation clearing (Fig. 3b) showed that forest cover was the main vegetation type to be cleared for development. Note that the map of vegetation clearing does not necessarily match the chronology of urban development, since development does not always directly follow land clearing. For example, clearing rates were higher than average in 2003 (see Fig. 2) and trended downwards to 2013 whereas development did not reflect this trend.

Table 1. Woody vegetation clearing (in hectares) by replacement land cover (1988 to 2015) in the Brisbane, Pine, Logan and Caboolture River Catchments. Data come from the Queensland Government's Statewide Landcover and Tree Survey (SLATS).

epoch	pasture	settlement	mine	infrastructure	timber	thinning
1988-91	5883	3561	211	167	1203	0
1991-95	5001	3907	153	50	1640	0
1995-97	5877	1870	113	294	995	0
1997-99	3415	1411	174	370	1578	0
1999-00	3725	766	42	309	1091	59
2000-01	1538	329	26	69	596	0
2001-02	2192	632	17	111	691	1
2002-03	3413	2292	41	264	862	10
2003-04	2417	1494	40	166	609	269
2004-05	1767	685	7	81	258	25
2005-06	1646	496	43	65	537	0
2006-07	2023	239	34	331	370	101
2007-08	2045	1209	112	577	435	24
2008-09	1053	871	29	173	203	0
2009-10	958	577	46	430	394	140
2010-11	866	669	54	92	658	119
2011-12	1139	532	36	105	341	119
2012-13	803	457	22	86	294	294
2013-14	1072	646	17	120	430	575
2014-15	1866	976	63	24	728	189

Conclusion

Remote Sensing provides a powerful tool to examine historical changes and trends in land cover change. We have shown two remote sensing-based trajectory analysis methods that provide insight into the historical trends of vegetation clearing and the patterns of urbanisation in South East Queensland. The results from these analyses can be further interrogated and used to make explicit links between past actions, threatening processes and potential mitigation or palliative action. Key items of interest would be: (i) examining the spatial distribution of development and development types (e.g. low- vs high-density), and linking these analyses to biodiversity outcomes, and (ii) analysing the trends over time in clearing rates (e.g. the cyclical nature of the clearing totals) and how this potentially relates to changes in vegetation and biodiversity legislation as well as government cycles. Overall, it highlights the importance of continuing to invest in remote sensing-based methods as new imagery is acquired into the future.

(a) (b)

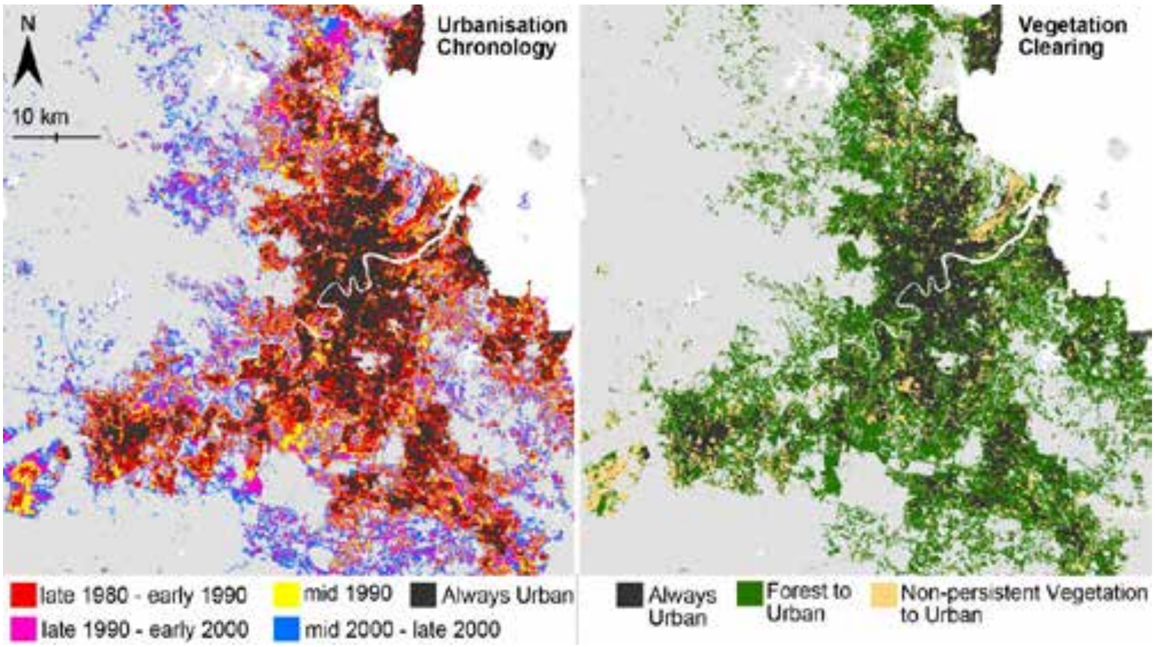

Figure 3. For South East Queensland, (a) the decadal patterns in urbanisation from date 1988 to 2013 and (b) the corresponding type of land cover clearing the urbanisation corresponded to over that period. Data derived from Lyons *et al.* (4).

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Water quality in Moreton Bay and its major estuaries: Change over two decades (2000–2018)

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Abstract

The catchment of Moreton Bay has been significantly modified since European settlement began in the 1820s, and these changes have not only changed the type of pollutants (nutrients and sediments) and the loading rates delivered to Moreton Bay, but also impacted on marine food webs and life cycles. This paper focuses on the major changes in water quality that have occurred in Moreton Bay during the past two decades (2000–2018). We analyse long-term water quality monitoring data and mud samples to determine the impact of catchment land-use changes and management efforts to reduce pollution over this period. While improvements in water quality have been observed in some parts of the Bay in response to management actions, water quality trends indicate that population growth and land development across the catchment is having a significant impact. Specifically, sediment and nitrogen loads threaten the health of Moreton Bay into the future and management of these pollutants is critical.

Keywords: nitrogen, turbidity, sediment, Brisbane River

Background

Good water quality critical for a healthy bay

Moreton Bay is one of the largest estuarine bays in Australia, supporting a wide variety of ecosystems from intertidal wetlands and seagrass beds through to coral reefs (1, 2, Maxwell *et al.* 2019, this volume (3); Lovelock *et al.* 2019, this volume (4); Pandolfi *et al*. 2019, this volume (5)). The environmental values associated with these ecosystems provide significant socio-economic and cultural benefit to the region (6). In 1993, Moreton Bay was declared a Marine Park to manage its many environmental, socio-economic and cultural values, with much of the Bay also declared as an internationally significant wetland for migratory shorebirds under the Ramsar Convention (7).

The health of these coastal ecosystems, and the value they represent to the community of South East Queensland, relies on good water quality. Water quality changes follow events, such as heavy rainfall and floods. These are short-term pulses and good water quality generally returns in the following weeks to months (8, 9). Changes in water quality over longer time periods can indicate a system is under pressure, with potential for loss of habitat, ecosystem resilience and overall value to the region. The interaction between the severity and extent of pulsed events combined with the background water quality prior to and after an event, will determine the ecosystem response and impact on community values and the benefits we receive from Moreton Bay.

The spatial extent and intensity of pressures on water quality can be monitored using a suite of indicators that includes nutrients and water clarity (10) Nutrients are important because estuaries and coastal areas, such as Moreton Bay, 'consume' nutrients, using them to stimulate primary productivity and to feed the Bay's food web (11–13). An excess of nutrients disturbs the equilibrium between nutrient supply and consumption, and often results in increased growth of phytoplankton and algae and unnaturally high productivity (14, 15). In extreme cases overgrowth of algae can lead to the loss of critical habitats, such as seagrass meadows, and to waterways becoming anoxic (16, 17).

Suspended sediment particles, phytoplankton and algae in the water result in the water looking cloudy or dirty. This is especially important for benthic habitats because it influences a range of things, including the amount of light reaching the bottom and sediment deposition and resuspension. As a result, key habitats like seagrass (9) and corals (18) are smothered and key processes such as reproduction and growth are inhibited.

Moreton Bay water quality is under pressure

Pollutant pressures on Moreton Bay from the catchments and estuaries along its western shoreline are considerable (Fig. 1), especially during the wet season. This is due to a dramatic increase in sediment export from the catchments, caused by land clearing that has occurred since European settlement. It is estimated that current sediment export rates are approximately 100 times greater than what would have occurred from natural catchments (19). In addition, there are over 30 sewage and industrial treatment plants discharging directly into Moreton Bay and its estuaries (20), and these are a significant anthropogenic source of nitrogen and phosphorus to the Bay.

The hydrology of Moreton Bay and associated water quality switches between two modes, either driven by freshwater input associated with high rainfall events or driven

Figure 1. Water quality monitoring sites from the Ecosystem Health Monitoring Program analysed in this study. The paper presents data for Caboolture, Pine, Brisbane and Logan estuaries (crosses) and for several Bay segments grouped based on similar water quality objectives, including: western (solid triangles), Waterloo Bay (open triangles), north central (closed diamonds), south central (open diamonds), north eastern (closed squares), South Eastern (open squares), Eastern Banks (open pentagon), southern (closed circles) and Jumpinpin (open circles) zones. Closed symbols represent areas of the Bay classified as 'moderately disturbed' by the Queensland Government (24) and are discussed in detail in the paper. The Bay zones with open symbols represent areas of the Bay classified as 'high ecological value' (or HEV), and data from these zones are presented separately in the electronic appendix as additional information (30).

by wave, wind and tidal action (20). There is a strong gradient in water quality from relatively high nutrient concentrations and low water clarity in the south-western portions of Moreton Bay, to low nutrient concentrations and high water clarity in the north and east (11, 21, 22). The north-eastern section of Moreton Bay, adjacent to Moreton Island, has the best water quality due to the fact that it receives minimal pollution from Moreton Island and is regularly flushed with clean oceanic water (23). The residence time of water in major Bay estuaries and throughout much of the Bay is 43–75 days, and the Brisbane River specifically can reach residence times of 189 days (11, 20). In contrast, the eastern and northern ocean boundaries have residence times as low as 3–5 days and are therefore well flushed and less impacted by catchment inputs. Consequently, water quality within the south-western Bay tends to exceed Queensland Water Quality Objectives (Table) more frequently and by a greater margin than it does in the north and east of the Bay, where water quality is generally very good (24).

When compared with the water quality of coastal systems alongside other large cities around the world, Moreton Bay water quality is relatively good (25). However, over the past 20 years Moreton Bay's catchment has been exposed to ongoing and increasing pressure from land clearing, urban development, population growth and several extreme flood events. Over the same period there has been significant investment in reducing nutrient loads from sewage treatment plant discharges.

Table 1. Queensland Water Quality Guidelines (2009) for the four sections of the Bay analysed in this study (24). The Queensland Government classifies these zones as 'moderately disturbed'.

	Zone			
	Western Bay	**Eastern Bay (north)**	**Central Bay (north)**	**Southern Bay**
Total nitrogen (mg/L)	0.2	0.16	0.16	0.2
Total phosphorus (mg/L)	0.03	0.016	0.02	0.024
Nitrates & nitrites (mg/L)	0.002	0.003	0.002	0.002
Ammonia (mg/L)	0.005	0.005	0.005	0.005
Filterable reactive phosphorus (mg/L)	0.014	0.005	0.008	0.008
Chlorophyll *a* (µg/L)	2	1	1	2
Turbidity (NTU)	6	1	5	7

NTU: nephelometric turbidity units

The Ecosystem Health Monitoring Program (EHMP) is a long-term monitoring program used to assess the ecological condition of waterways in South East Queensland. The program was originally designed to assist local government to plan and implement of sewage treatment plant upgrades. It was broadened in early 2000 to capture regional catchment issues from non-point sources of nutrients and sediments (11). The program is presently based on sampling at 142 estuarine sites and 41 Bay sites eight times per year (in February, March, May, August, September, October, November and December). Queensland Government Department of Environment and Science sample the water quality and details of the methodology is reported in (26) and (27).

Analysis of water quality trends from the EHMP long-term monitoring dataset allows us to identify the status of Moreton Bay, how it is responding to the increasing pressures, and if investment has had observable beneficial effects on water quality. In addition, catchment models have been used to predict future trends in water quality and identify where management can focus efforts to protect the health of Moreton Bay into the future (28).

This paper will focus on changes that have occurred in nutrient concentrations and water clarity within Moreton Bay during the past two decades (2000–2018) — since the publication of the last Moreton Bay book in 1998 (11, 29). Most of the data presented were collected as part of the EHMP (30). Changes in phytoplankton observed in Moreton Bay over a similar time period are discussed in Saeck *et al*. 2019, this volume (31).

Change in water quality over the past 20 years

Nutrients – nitrogen and phosphorus

The Bay – west, east and south

Phosphorus concentrations have not been a major focus for management over the past 20 years because Moreton Bay is considered nitrogen-limited (11, 21, 32). However, excess phosphorus in coastal systems can have implications such as increasing cyanobacteria growth, with negative consequences for food webs and ecosystem status (33). The major anthropogenic source of phosphorus to Moreton Bay is sewage treatment plant discharge, such as Luggage Point treatment plant at the mouth of the Brisbane river, which delivers around 300 tonnes per year (34).

Over the past 20 years, total phosphorus (TP) has frequently reached or exceeded guideline concentrations of 0.03, 0.02 and 0.024 mg/L in the western, central and southern areas of the Bay, respectively (Figs 2–4). However, data towards the end of this period suggests that TP concentrations may be decreasing in these areas, with concentrations for the past 5 years lower than those previously. It is difficult to say if this constitutes a decreasing trend given the high annual variation in TP. However, the more obvious reduction in filterable reactive phosphorus (FRP) concentrations over the same period would indicate an emerging pattern. In contrast, the eastern Bay has instead yielded TP concentrations consistently below the more stringent guideline of 0.016 mg/L (Fig. 5). Like other parts of the Bay, there are indications that TP is also lower in this eastern segment since 2013.

Nitrogen concentrations throughout the Bay have not improved (decreased) substantially over the past 18 years, and concentrations may even be increasing in some areas, most notably in the north-central and north-eastern Bay segments (Figs. 2-3). Over 30 sewage and industrial treatment plants discharge directly into Moreton Bay and its receiving waterways (20) and are a significant source of nitrogen to the Bay. Between 1998 and 2006 more than $300 million was invested in wastewater treatment plant improvements, improving their nitrogen removal capacity and reducing nutrient loads from the sewage treatment plant discharge by 44% (34, 35). As the population of South East Queensland and the Moreton Bay catchment has increased approximately two-fold over the past two decades (36), it is likely that this investment has played a major role in total nitrogen (TN) concentrations in Moreton Bay remaining at or below guideline concentrations across much of the Bay. However, the challenge remains to maintain or improve these concentrations in the face of increasing nutrient load, due to population growth and intensification of catchment land uses.

In the eastern and central Bay zones TN concentrations have exceeded Water Quality Objectives in some areas more frequently in the last 10 years than in the decade prior (Figs 3, 5). Similarly, since 2011 the dissolved inorganic nitrogen fractions (ammonia and nitrogen oxides (nitrite+nitrate)) have more frequently been measured at concentrations higher than the detection limit, where they previously were undetectable. At these concentrations they are approaching, and in some cases exceeding, Water Quality Objectives. The same pattern has also been observed in the western Bay (Fig. 2). The concern is that higher availability of dissolved inorganic nitrogen can increase benthic and pelagic productivity, which can cause shifts in ecosystem dynamics in these naturally oligotrophic waters (37, 38).

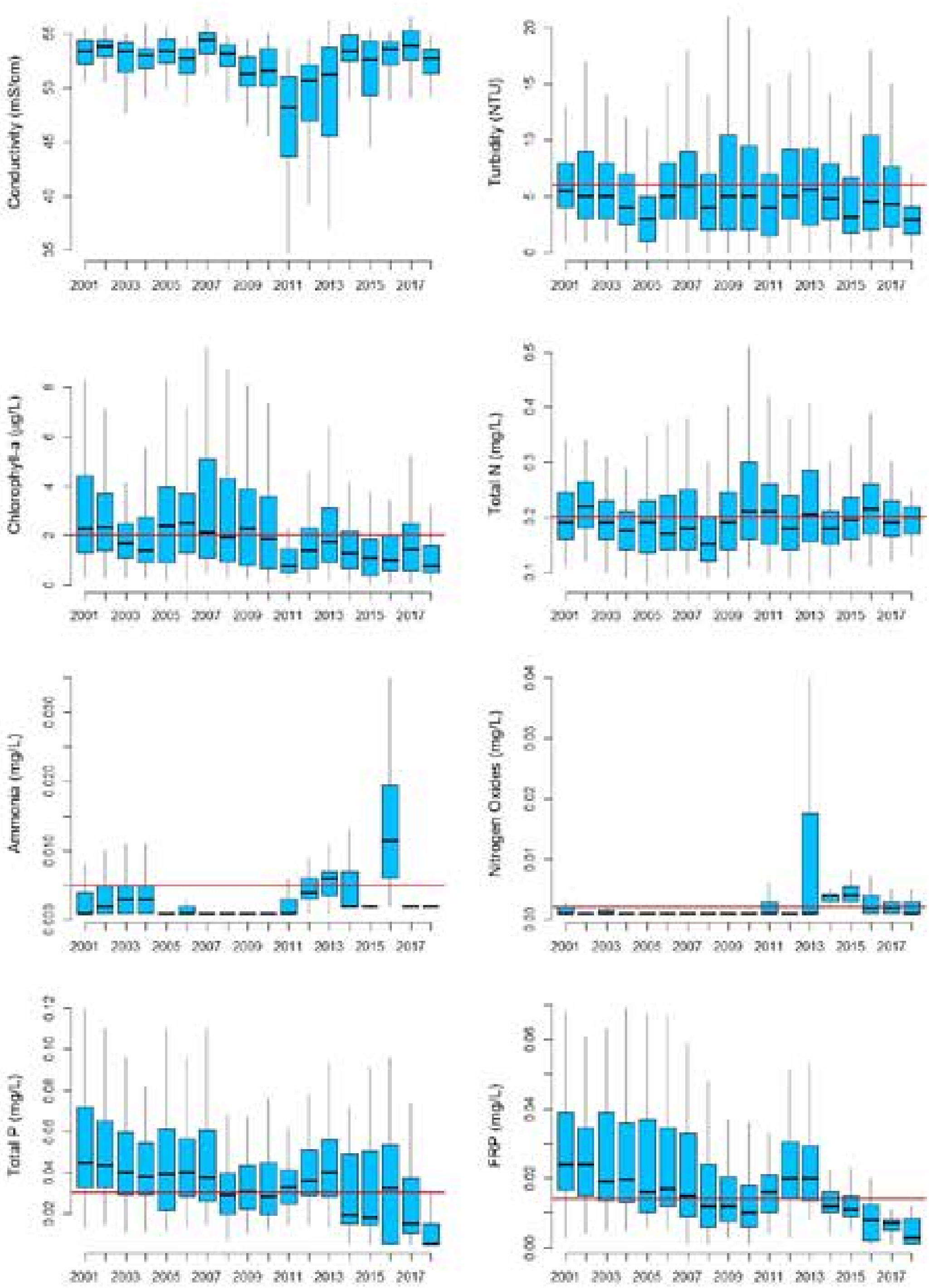

Figure 2. Results for 10 sites within the western Bay (Bramble and Deception bays) showing annual median, upper and lower quartiles for conductivity (mS/cm), turbidity (NTU), chlorophyll *a* (µg/L) total nitrogen (mg/L), ammonia (mg/L), nitrogen oxides (nitrates+nitrites) (mg/L), total phosphorus (mg/L), and filterable reactive phosphorus (FRP) (mg/L) for the financial years (July to June) 2001 to 2018. Red lines represents Queensland Government's water quality objectives as shown in Table 1.

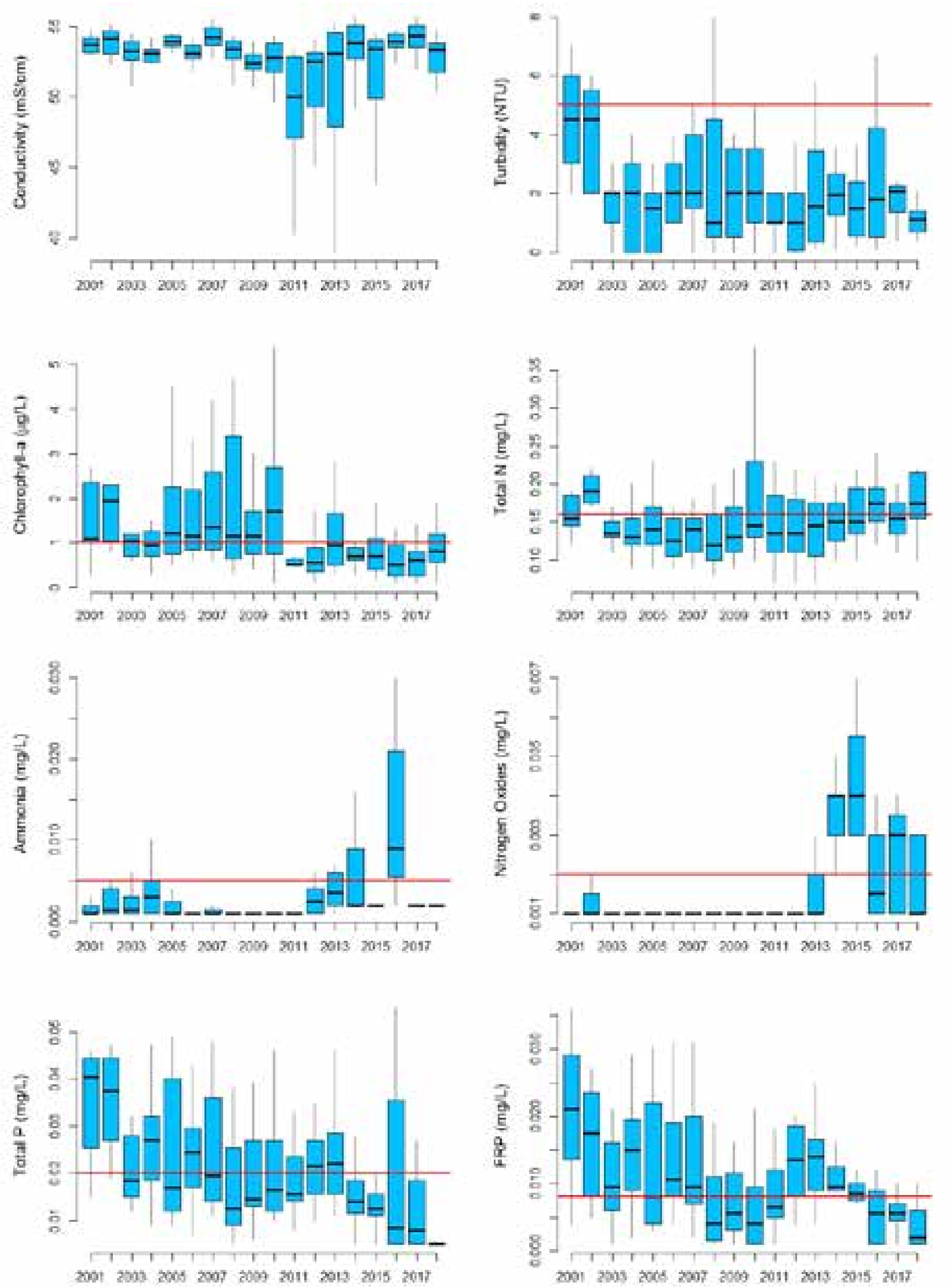

Figure 3. Box-and-whisker plots for two sites in north central Bay (See Fig. 2 caption for explanation).

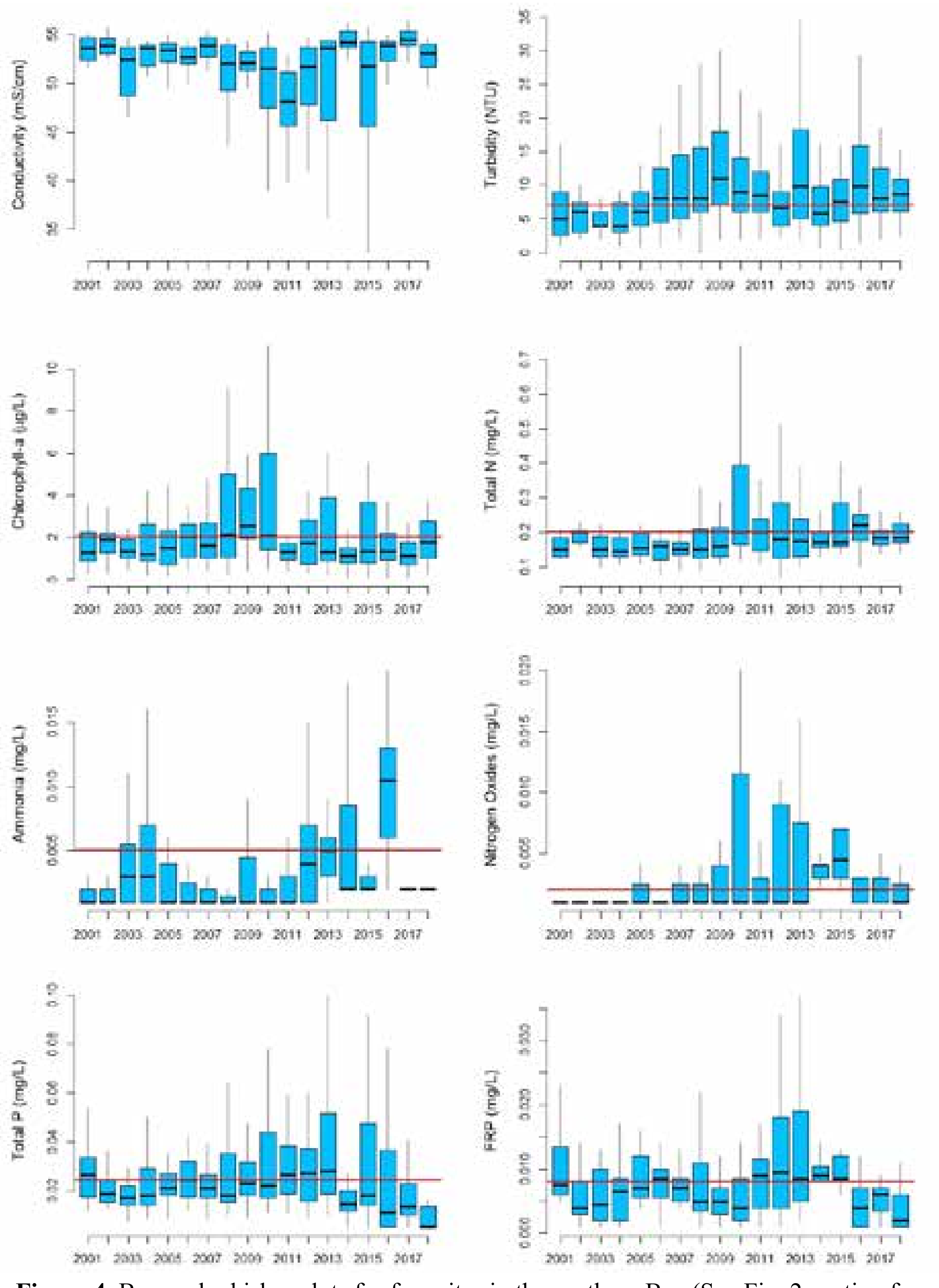

Figure 4. Box-and-whisker plots for four sites in the southern Bay (See Fig. 2 caption for explanation).

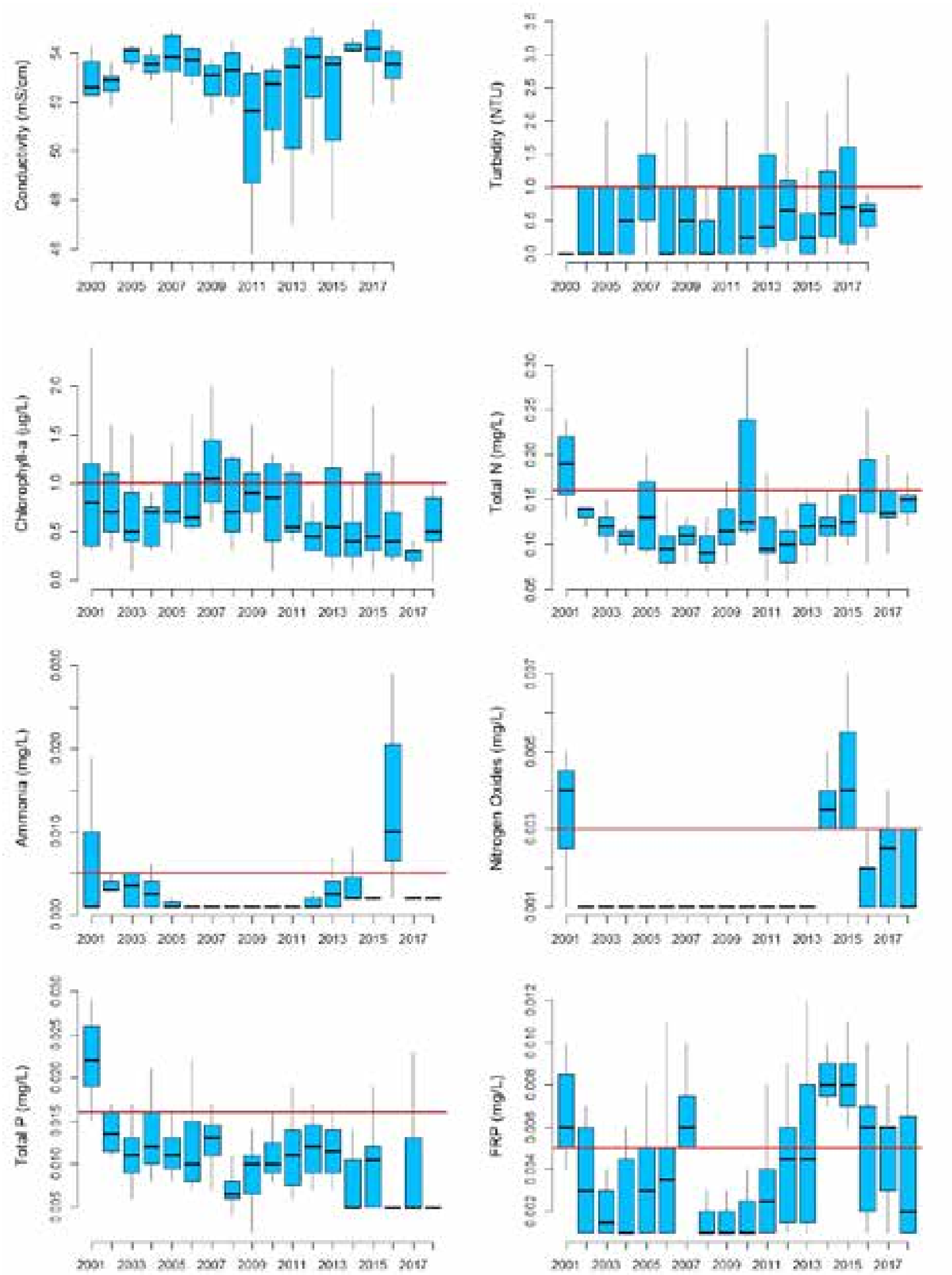

Figure 5. Box-and-whisker plots for two sites in north-eastern Bay (See Fig. 2 caption for explanation).

The specific cause of increased dissolved inorganic nitrogen across the Bay, particularly in the Eastern bay, requires further investigation. It is hypothesised that it may be linked to the deposition of catchment sediments during a couple of major floods. Sediment deposited by flood water can be a significant source of ammonium (NH_4^+), released in the period after the event as a result of microbial processing and benthic nutrient flux (38, 39). Given the timing of the increase in dissolved inorganic nitrogen (ammonia and nitrogen oxides; commencing after 2011), it is hypothesised that the catchment sediment deposited in Moreton Bay in association with the January 2011 and January 2013 flood events may be a source of dissolved inorganic nutrients. The January 2011 flood was a 1 in 100 year event for the Brisbane River catchment, and the largest since EHMP monitoring commenced (40). A total of almost 1700 mm of rain fell within the Moreton Bay catchment during the year of that flood (Fig. 6). While this hypothesis requires further investigation, the implications are that as flood frequency and intensity are predicted to increase with global warming, more such events could drive further increases in the availability of dissolved inorganic nutrients to Moreton Bay (41). Further supporting the need for catchment management of sediment loads from rural and urban areas in the face of increasing development. Such action will be critical if the ecosystem function (and nutrient assimilation capacity) of Moreton Bay is to be protected into the future.

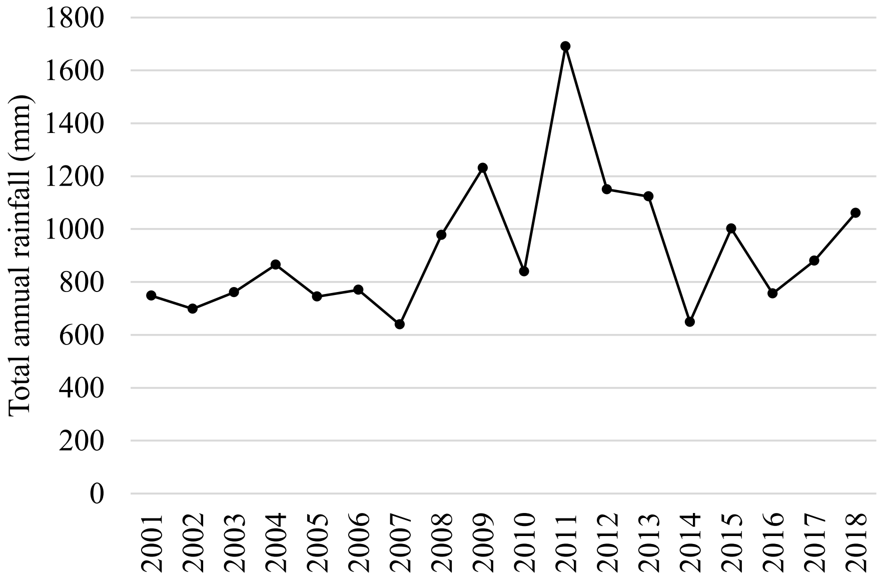

Figure 6. Total annual rainfall (mm) for the Moreton Bay Catchment between 2001 and 2018 (42)

The estuaries – Caboolture, North Pine, Brisbane, Logan

Changes in water quality and nutrient concentrations in Moreton Bay can be explained in part by processes and changes in the major rivers that drain into Moreton Bay—the Caboolture, Pine, Brisbane and Logan. The estuarine sections of all these rivers, except Caboolture, all show reductions in their total nitrogen (TN) and total phosphorus (TP) concentration since 2001 (Figs 7–10). These improvements in water quality are likely to be due to multiple changes in the extractive industry use and industrial and sewage discharges.

The largest management initiative, the reduction in nutrients discharged in wastewater, likely contributed to improvements observed in TN and TP in the Pine, Brisbane and

Logan estuaries (Figs 7–10). In addition, removal of other large industrial discharges, such as pulp from a recycling plant on the North Pine River and changes to sand and gravel extraction both in the Brisbane River and on the floodplain of the Pine River, likely reduced sediment and nutrient inputs. In contrast, nutrients remained relatively stable in the Caboolture River. The Caboolture River had similar nitrogen concentrations to the Pine River in 2000; however, it was not targeted for nutrient management to the same degree. Nitrogen concentrations in the Caboolture River are now double that of the Pine River immediately to its south. The Caboolture River experienced localised reductions in dissolved nutrients as a result of relocation of a wastewater discharge, but the lack of a reduction in total nutrients across the entire estuary suggests that the increase in diffuse nutrient loads from catchment development may have masked any improvements from reduced wastewater discharge (43).

The reduction in TP discharge from the rivers is the likely driver of the trend across Moreton Bay of declining TP (Figs 2–6). In contrast, the decline in TN concentrations in the Rivers appears to have had a smaller, if any, impact on TN concentrations across the Bay. Declines in TN concentrations in the rivers suggest that nitrogen loads to the Bay have also declined. This may not, however, manifest in observable declines in nitrogen concentrations due to substantial nitrogen recycling processes active within the Bay (12, 32, 44). For example, phytoplankton have the highest rates of productivity within the Bay, however their demand for dissolved inorganic nitrogen far exceeds dissolved inorganic nitrogen inputs delivered from the catchment (less than 1%) (38, 45). For this reason, bay productivity substantially relies on nutrient recycling, benthic nutrient fluxes and nitrogen fixation. In addition, catchment sediments deposited by previous events, particularly in the shallow western embayments, are a substantial source of nutrients that are made available by wind, and wave driven resuspension (Figure 11). The beneficial effect of declines in nitrogen load to the Bay may instead need to be measured using biological indicators, such as the observable decline of phytoplankton in parts of Bramble Bay over this 18 year period (Saeck *et al.* (31), this volume). Also, seagrass meadows have recently re-established in some areas of Bramble and Deception Bay (Maxwell *et al*. (3), this volume). These biological changes suggest improvement in Bay ecological condition, which is likely to have resulted from a reduction in nutrient loads to the Bay over an extended period.

Despite progress in reducing nitrogen and phosphorus from entering Moreton Bay over the past 20 years, notably from the Brisbane and Pine Rivers, there has been limited success in reducing the sediment load entering Moreton Bay. This is highlighted in the Caboolture, Brisbane and Logan Rivers where turbidity showed no net improvement over the past 18 years (Figs 9, 10).

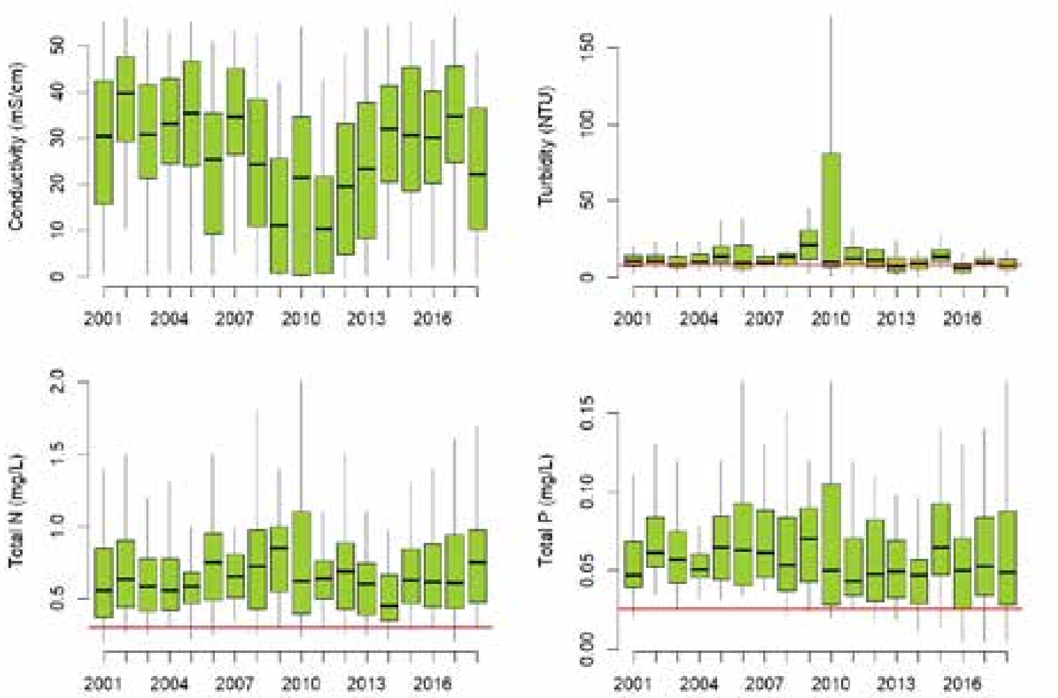

Figure 7. Box and whisker plots for 7 mid-estuary Caboolture River sites showing annual median, upper and lower quartile for conductivity (mS/cm), turbidity (NTU), total nitrogen (mg/L), total phosphorus (mg/L) for the financial years (July to June) 2001 to 2018. Red lines represents Queensland Government's water quality objectives as shown in Table 1.

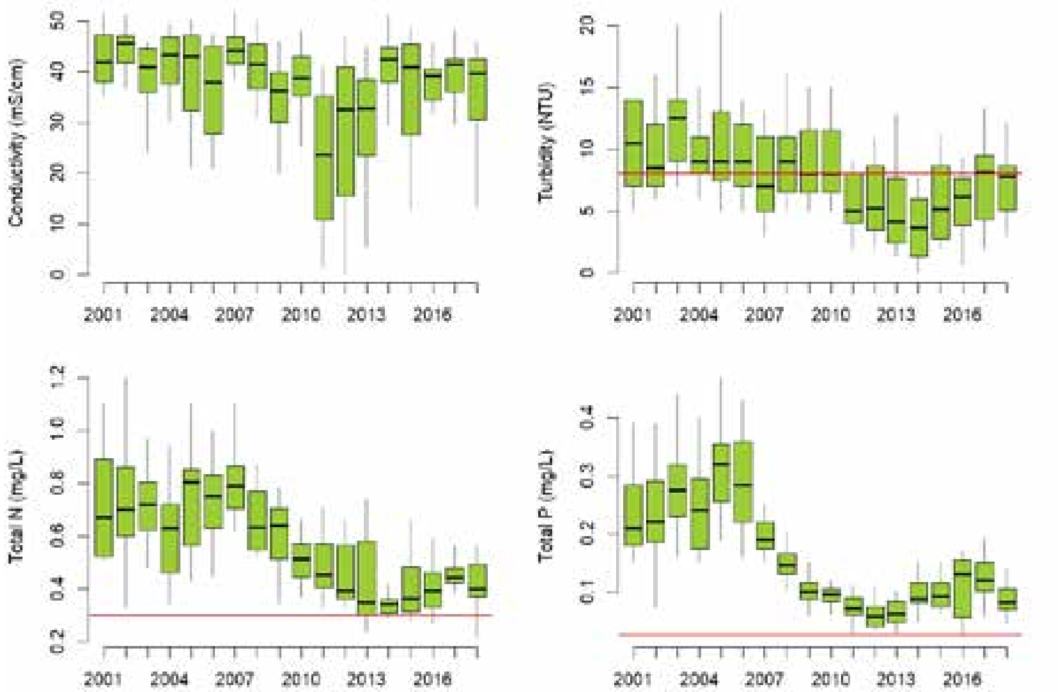

Figure 8. Box and whisker plots for 2 mid-estuary North Pine River sites as per Fig. 7.

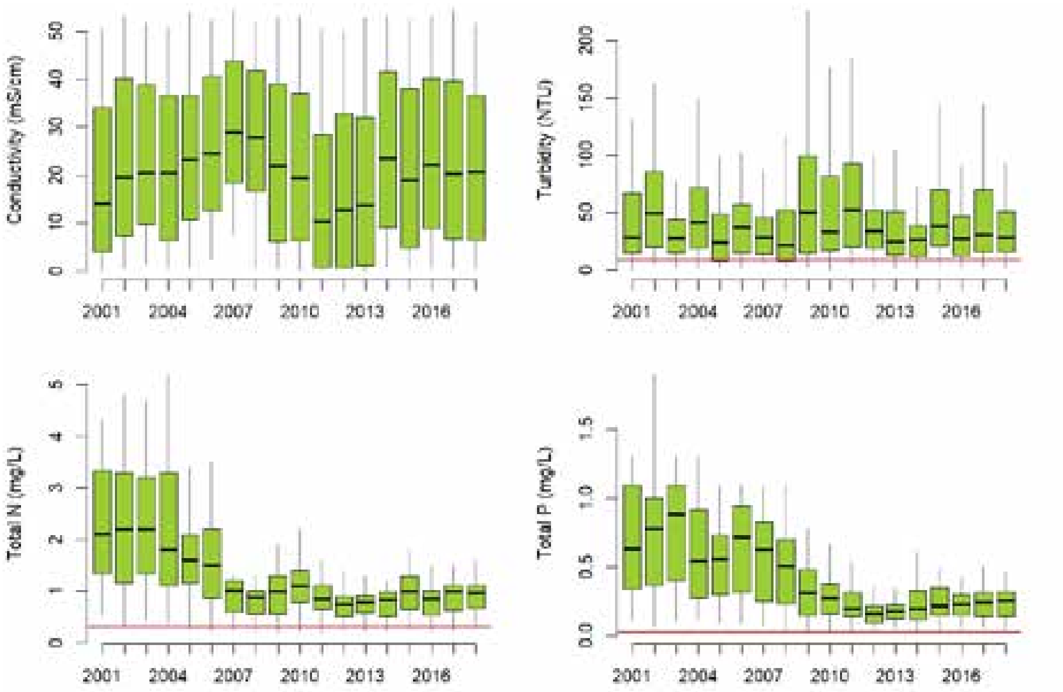

Figure 9. Box and whisker plots for 12 mid-estuary Brisbane River sites as per Fig 7.

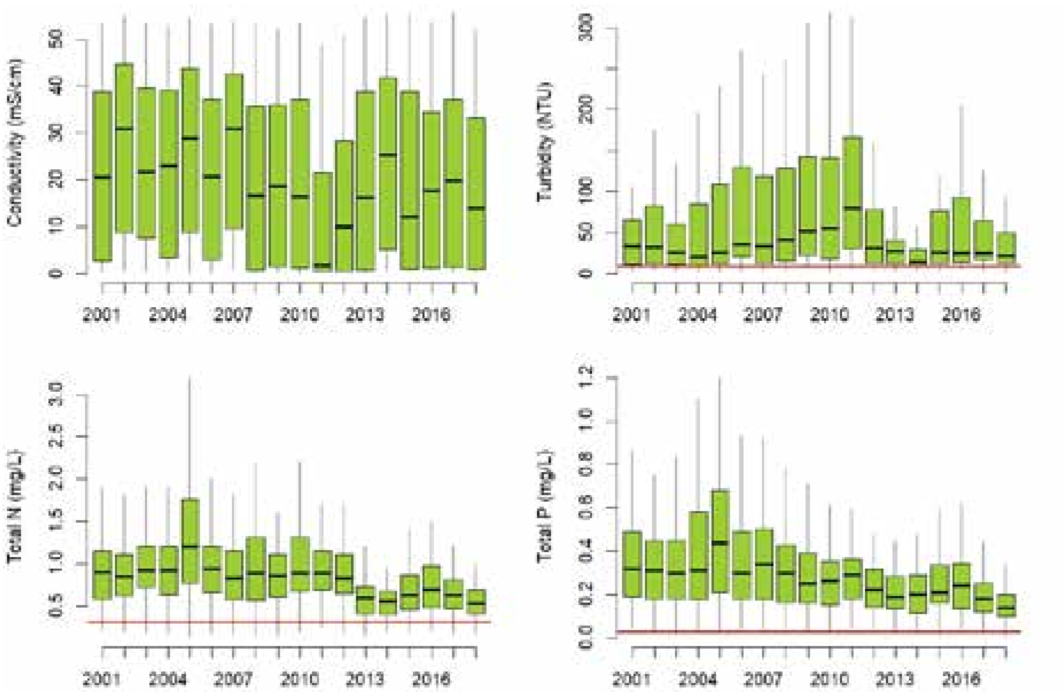

Figure 10. Box and whisker plots for 11 mid-estuary Logan River sites as per Fig 7.

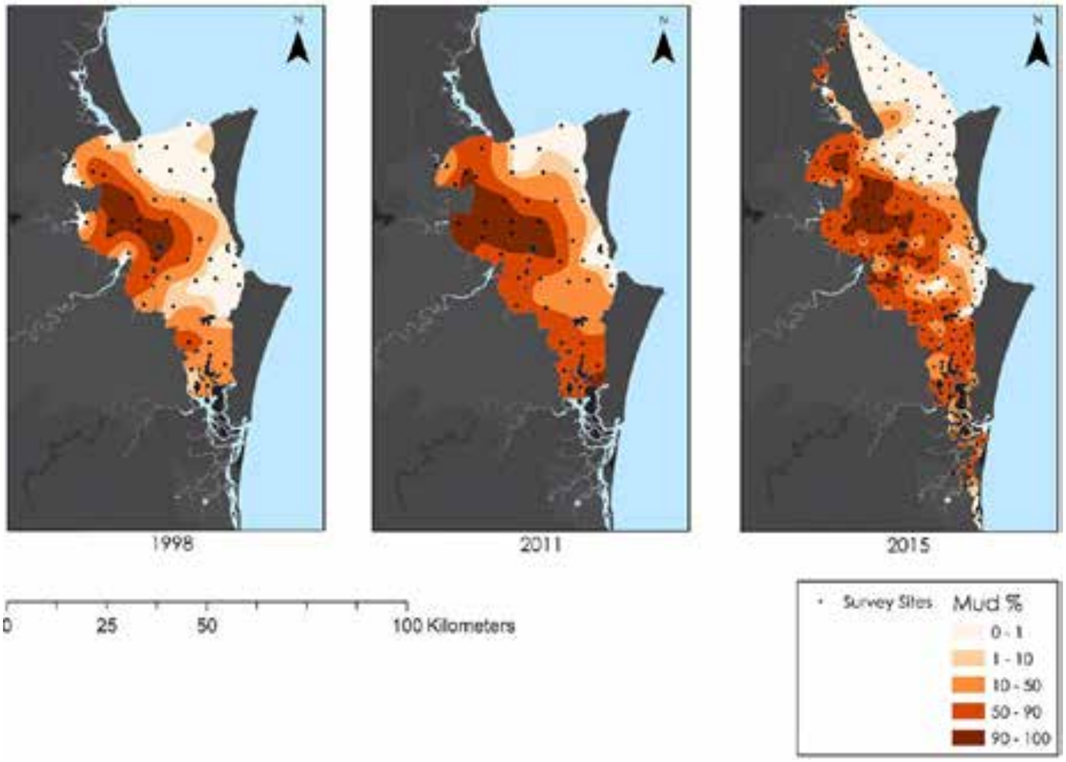

Figure 11. Estimates of mud deposited in Moreton Bay from its catchment during the past 70 years. Modified from Dennison and Abal (11), O'Brien *et al.* (61) and Lockington *et al.* (51).

Water clarity – sediment and mud

Water clarity typically declines during high rainfall and flood events due to the delivery of fine sediments from the catchment and the increased pelagic productivity (phytoplankton) stimulated by the pulse of new nutrients into the system (8, 46). Water clarity is also affected by resuspension events, driven by wind conditions, particularly in locations of sediment deposition in the Bay. Notable increases in turbidity have been observed in the western Bay when wind direction aligns with the direction of maximum fetch and wave energy is greatest (47, 48). On the western segments of the Bay, mean annual turbidity is significantly higher during years with higher than average north- or south-easterly winds (49).

Floods are the dominant source of catchment sediment entering Moreton Bay, as the major estuaries entering the Bay tend to retain river sediments under (non-flood) ambient conditions (50, 51). Between 1970 and 2015, mud cover more than doubled in area across Moreton Bay (51), much of it attributed to high rainfall events. An estimated 150 million tonnes of mud have been deposited in Moreton Bay during the last 70 years (51), where mud is defined as sediment in the finer fraction with particle diameter <63 μm.

Over 20 million tonnes of sediment were deposited in Moreton Bay during the 2011 and 2013 flood events (52). In 2015, a much larger area of the Bay had a mud contribution higher than 40% when compared with two decades prior (Fig. 11). This increase was most notable in the middle, eastern and southern Bay regions, where many areas previously had very little to no mud, suggesting a large increase in the spatial extent of mud across the Bay.

Increased muddy sediment deposition has caused a change in the benthic habitat, with muddy bottom habitats increasing from approximately 30% in 1998 to 70% in 2011 (51). While relocation of mud from shallow to deeper locations may continue and return some muddy areas to a more sandy bottom, Moreton Bay is clearly a sink for terrestrial sediment inputs (53). Given the scale of observed changes, it is hypothesised that the sediment delivered by the 2011 and 2013 floods will permanently alter many habitats of Moreton Bay from predominantly sandy to muddy. This shift in habitat is most likely to have the highest impact in the transition zones in the middle of Moreton Bay (Fig. 11). The change of bottom sediment type from sand to mud could also cause a long-term change of water quality, as mud is more easily resuspended by wind turbulence and tidal currents, reducing water clarity. Recent work around the Mud Island Dredge Placement Area highlights the persistence of the muddy bottom type despite being located in a relatively shallow area and experiencing strong tidal currents (54). Ongoing monitoring and research will be required to fully understand the long-term impacts of the expanding spatial extent of mud on water quality and benthic habitats across the Bay.

It is hypothesised that the more recent expansion in mud coverage across the Bay, and increased rates of vertical accretion, may be the result of the Bay receiving sediment at a rate that exceeds its natural capacity to move material offshore (19). Coates-Marnane *et al.* (19) suggest that infilling of deeper channels in the Bay with fine sediments has reduced the capacity of Moreton Bay to store sediments. Once the capacity of these deeper channels is exceeded, fine sediments entering the Bay will be subject to more frequent resuspension causing long-term changes in water clarity. This highlights that the negative effects of sediment are likely to increase in the future and the need for managing sediment loads is urgent.

The impact of reduced light availability in the water column and smothering of the benthos by fine sediments, creates a shift from benthic productivity to pelagic productivity, where sediment microbial nutrients are de-coupled from the benthic productivity and instead are released into the water column. Increased water column nutrient flux increases pelagic productivity, further reducing light availability and perpetuating these conditions (38, 55). The increase in dissolved inorganic nitrogen being measured across the Bay (Figs 2, 4, 6) suggests that the smothering of the benthos with fine sediments could be affecting nutrient processing, particularly in the eastern and central Bay.

The increase in mud is likely not because floods have become larger, but instead they now deliver proportionally more sediment compared with events in the past. Less than 25% of the Moreton Bay catchment remains as native vegetation (56) and more than 80,000 hectares of land has been cleared since 2001 (57). Loss of vegetation decreases interception and infiltration of rainfall run-off across the catchment and increases over-land flow. This shift to more over-land flow across the catchment results in increased erosion of catchments, particularly stream and river channels. In addition, the loss of riparian vegetation reduces channel protection by reducing channel roughness and exposing sediments. It has been estimated that catchments with no riparian vegetation export up to 200 times more sediment than catchments with intact riparian vegetation protecting the channel network (58).

In the last few decades there has been a rapid expansion of urban development (59), which poses a large risk of sediment export per hectare (Lyons *et al.* (59), this volume). The loss of sediment from recently cleared urban land during moderate to heavy rainfall events can be up to 1000 times greater than the sediment loss associated with the same area prior to disturbance, or after completion of the construction and landscaping (60). Land clearing and increasing urban developments over the past 200 years have increased sediment and nutrient loads delivered to the Bay, particularly in association with high rainfall events (19). The impact of these changes is manifested in declines in water quality within, and increased mud distribution across, the Bay.

Future pressures to Moreton Bay water quality

The population residing within the Moreton Bay catchments is predicted to reach four million by 2026. This and the associated increases in urban development and land-use change will place Moreton Bay under more pressure. Opportunities exist to reduce current sediment and nutrient loads and minimise future increases in loads, through improved management and innovative solutions. For example:

- protect, replant/regrow streambank vegetation
- best management practice in rural areas to manage fertiliser application rates and vegetation cover
- management of stormwater flow from new developments and construction sites
- innovative stormwater management designed into new developments
- innovative nutrient removal technology to upgrade sewage treatment plants.

Catchment modelling by Healthy Land and Water (28) was used to determine the benefits of applying such actions across Moreton Bay catchments, and how that would affect future sediment and nutrient loads. Current nutrient loads (baseline) were compared with predicted loads under the planned 2030 land use for two scenarios: 1) if no management techniques are changed (business as usual, or BAU); and, 2) if all currently available management techniques are applied to the urban and rural areas across the whole catchment (full investment, or FI) (Fig. 12 and Table 2).

If nothing changes (BAU), Moreton Bay will be exposed to higher sediment, nitrogen and phosphorus loads, and water quality will continue to decline; current trends indicate that this has already begun. Full investment (FI) across the whole region can halt any further increase in sediments and phosphorus from urban areas, and could reduce loads from rural areas by a factor of about 7. These investments would result in significant improvements in water clarity, and likely prevent further growth of the mud patch across Moreton Bay.

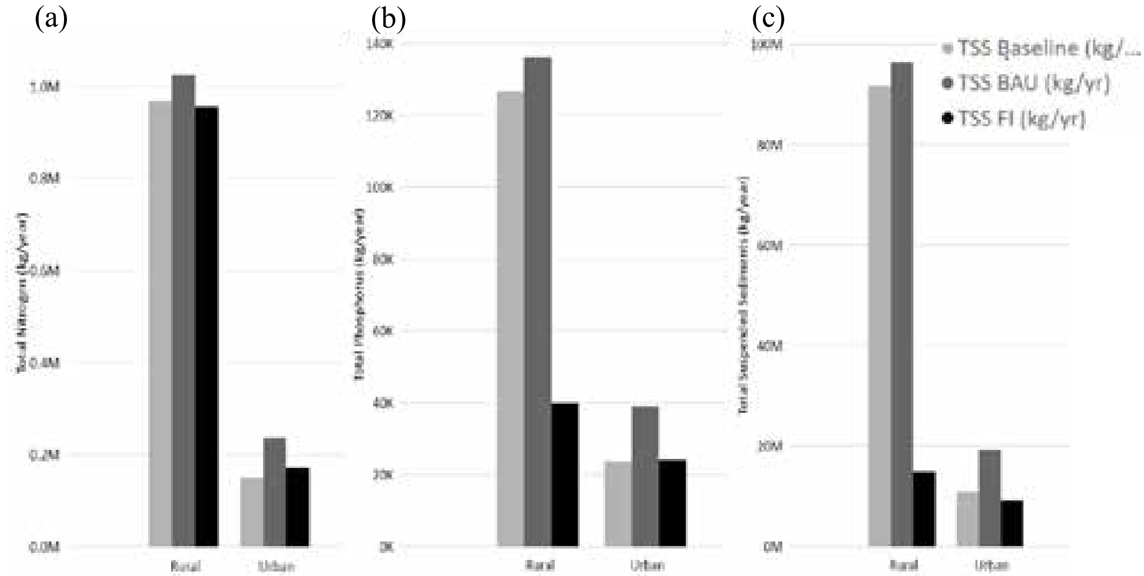

Figure 12. Pollutant loads (kg/year) under three management scenarios. Results of pollutant load generation modelling for the Moreton Bay catchment, recreated from Healthy Land and Water (28). Two future land-use management scenarios are compared with existing practices. Baseline 2015 (light grey bars) - current land management practices and existing land uses; Business-As-Usual (dark grey bar) – current land management practices, with increased population and expanded urban footprint at 2030; Full Investment (black bars) as per business-as-usual but with every land use type/management initiative undertaken to the fullest extent possible. Figures show the effect on (a) nitrogen, (b) phosphorus and (c) sediment loads generated within the catchment under each scenario. See Table 2 for details of each scenario.

Such reductions in sediment input could prevent further impacts on the benthos of the Eastern Banks and the nutrient processing in that region which appears to have started to manifest as increases in dissolved inorganic nutrients. In contrast, without better nitrogen management options, the simulation results suggest that nitrogen loads will increase slightly in the future, even under FI scenarios. This highlights that nitrogen may be a growing problem for Moreton Bay into the future.

There are a few limitations to this catchment modelling study that suggest investment in land and pollutant manage is likely to be more effective in reducing nitrogen loads to Moreton Bay than the results predict (Fig. 12). First, the model did not account for the latest engineering technology that can now further reduce the nutrient and sediment export from new urban developments. It is also anticipated that in the coming decade more progress will be made in this field. Second, targeted (and large-scale) investment in the upper catchments (e.g. riparian revegetation and increased ground cover) is likely to increase infiltration and reduce sediment and nutrient run-off during rainfall events. The effect of infiltration on nitrogen is not well understood, consequently the effect of increased riparian and ground cover on nitrogen export rates is likely to be an underestimate. Third, different land-use types generate different nutrient loads and in the model these were estimated from experimental data or derived from values in the literature. However, experimental information available for nitrogen generation from different land-uses in South East Queensland is poor, as a result, there is low confidence in the magnitude of nitrogen reductions predicted under each scenario. Our poor understanding of nitrogen behaviour and an underestimate of the effect of on-ground investment on catchment hydrology (see consideration 3) has limited the predictive capacity of this model in regard to the effectiveness of management on nitrogen load reduction to Moreton Bay. This consideration is most relevant for nitrogen, as there is a much better understanding of phosphorus dynamics from different land uses.

Total nitrogen loads were higher in the 1990s prior to the reductions in the early 2000s associated with sewage treatment plant upgrades (11, 62). During this period there were reports of very poor water quality, including high phytoplankton biomass (4–10 µg/L chlorophyll *a*) in the nearshore areas, and algal blooms that may have been implicated in fish kills and localised anoxia (23). Should TN loads increase in future, the likelihood of reversing the improvements observed is high. South East Queensland needs to invest in finding more innovative solutions to nitrogen management from both the rural and urban landscape. These solutions should include efforts to rehabilitate the stream network, particularly in the Upper Lockyer Catchment, which contributes most of sediment loading into Moreton Bay and has recently been shown to be a major source of nutrients during flood events (19, 63–65).

Table 2. Summary of the pollutant load management strategies applied to each land-use under the three catchment modelling scenarios in Fig. 12: baseline, business-as-usual and full investment. Modified from Healthy Land and Water (28).

	Baseline (2015)	**Business-as-usual (2030)**	**Full Investment (2030)**
Rainfall	1 Jul 2014–30 Jun 2015 (~long-term average)	1 Jul 2014–30 Jun 2015	1 Jul 2014–30 Jun 2015
Land-use layer	2012 (derived from Queensland Land Use Mapping Program (QLUMP)	2012 (QLUMP), with 2031 features based on the South East Queensland Regional Plan (2009-2031)	2012 (QLUMP), with 2031 features based on the South East Queensland Regional Plan (2009-2031)
Grazing			Riparian re-vegetation applied to all (90% reduction TSS & TP).
Rural-broadacre agriculture, intensive agriculture, grazing		No additional rural management practices	Riparian re-vegetation applied to all (90% reduction TSS & TP). Areas with intensive fertiliser (agriculture) (TN load reduction by 80%).
Rural - residential			Riparian re-vegetation applied to all (90% reduction TSS & TP).
Urban/dense urban		Water sensitive urban design (WSUD) features applied to new development – load reductions: 20%TSS, 15%TP, 11.25%TN; no retrofitting WSUD into existing urban;	50% of existing urban areas retro-fitted with WSUD features:WSUI to new development -load reductions: 80%TSS, 60%TP, 45%TN;

	perviousness of existing urban decrease to 0.5 (from 0.75); perviousness of new urban 0.3.	perviousness of all existing and new urban 0.5.
Construction	A portion (6.25%) of additional urban land classified as construction (bare earth for 1 year);construction site load reduction (through sediment control): 10% TSS, 10%TP & 5%TN	Construction site load reduction: 80% TSS, 80%TP & 40%TN
Wastewater treatment plants	Increased flow in proportion to population increase. No change in pollutant concentrations	Increased flow based on population increase. 50% re-use. Reduced pollutant concentrations (3mg/L TN and 1mg/L TP).

Conclusions and recommendations

To maintain the improvements in water quality (nitrogen and phosphorus) that have been achieved over the past 20 years, it is critical that we prioritise and fund management actions that reduce diffuse sediment loads, and seek-out and invest in innovations in nitrogen management from both rural and urban landscapes. Despite the dramatic reductions in dissolved nutrients discharged from the region's wastewater treatment plants two decades ago, water quality in most estuaries continues to be higher than the Queensland Government Water Quality Objectives. Water quality in the Bay indicates that the 800,000 additional people (approximately 50% increase in population) residing in the region in the last two decades has added additional nutrient loads to the catchments of Moreton Bay—replacing some of the nutrient load reductions achieved through upgrading wastewater treatment facilities. Changes in catchment land use (Lyons *et al.* (59), this volume) that have occurred and continue to occur in the catchment of Moreton Bay, are driving increases in mud and sediments across Moreton Bay. These increases are a cause of concern for water quality and ecosystem processes in the Bay. Catchment scale action is critical if we are to protect the habitats of Moreton Bay and their resilience into the future.

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Wetland and benthic cover changes in Moreton Bay

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Abstract
Wetlands are among the most productive ecosystems in the world, not only supporting a diversity of plants and animals, but improving water quality, and providing coastal protection against destructive impacts. Anthropogenic actions remain the greatest threat to these environments and in order to enable effective long term management of these areas, it is important to be aware of changes that have occurred to ecosystem distribution over time. This paper examines changes in the distribution of saltmarsh, mangrove, mudflat, seagrass and coral reef areas of the Moreton Bay wetlands, from historical records (circa 1950) to the most current mapping data available (circa 2015). Continued monitoring of the Bay's wetland communities through government organisations and community-science organisations such as MangroveWatch, Seagrass-Watch, CoralWatch and Reef Check Australia is vital in ensuring the management of these ecologically, socially and economically important wetlands remains effective into the future.

Keywords: wetlands, mangroves, saltmarsh, coral reefs, seagrass

Introduction
The wetlands of Moreton Bay comprise a diverse range of habitat types that include rocky shores, sand banks, mudflats, mangroves, saltmarshes, intertidal and subtidal seagrass meadows, and coral reefs (1). These distinct ecosystems include habitat and foraging grounds for a wide variety of organisms, some of which are International Union for the Conservation of Nature (IUCN) status "threatened" such as the green sea turtle, dugong and migratory wading birds (1). Additionally they deliver a number of critical services including coastal protection, water supply and purification (2). The significance of Moreton Bay's wetlands has led to their protection under the internationally binding Ramsar Convention (Ramsar Sites (3)).

Knowledge of how wetland areas respond to stressors is particularly important when considering climate change and its additive effect on wetland environments. To comprehend the degree and means by which stressors influence wetland communities, it is important to monitor their extent and composition over time. Specific chapters within this book detail the habitats within the wetland community. This chapter, however, will summarise the change in extent of Moreton Bay's wetland and benthic ecosystems including the intertidal flats, mangroves, saltmarshes, seagrass meadows, and coral reefs (Fig. 1).

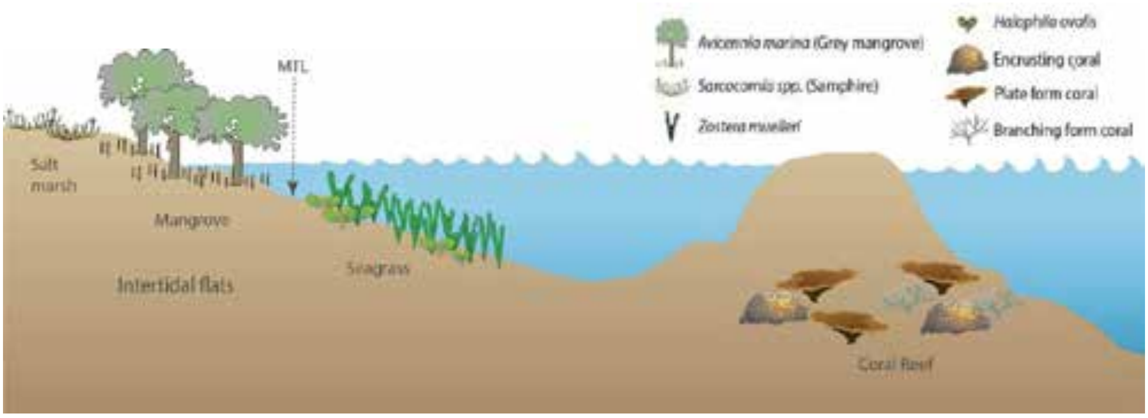

Figure 1. Moreton Bay wetland environments, a transition zone between the land and the ocean. These areas undergo periodic inundation and include all environments to a depth of 6 m. The intertidal zone is the most landward zone of the wetlands and is exposed to air at low tide, and submerged at high tide. The mid-intertidal zone indicated by the mean tide level (MTL) is regularly exposed and submerged. The intertidal zone encompasses saltmarsh, mangrove, seagrass and mudflat habitats. Wetland environments also include the inshore reefs found in shallow waters, atop a muddy substrate.

The Intertidal Zone

Moreton Bay's intertidal zone is comprised of numerous habitat types, including tidal flats (mud and sand), mangroves, seagrass and saltmarsh environments (4). The community structure, complexity and diversity of organisms within the intertidal zone reflect the range of environmental conditions within each sub-zone (supratidal, upper mid-littoral, lower mid-littoral and lower littoral) (5). As such, the organisms within each zone have specific behavioural, biological and physiological adaptations (osmoregulatory, metabolic) enabling them to withstand the diverse conditions that are unique to each zone (6).

Saltmarshes

Within the intertidal zone, landward of the mangrove communities, lie saltmarsh wetlands (Fig. 1). They exist on a marine-derived soil substrate on low gradient marine and estuarine plains (7). These areas are highly dynamic and provide a habitat for a vast array of vertebrate and invertebrate species, including migratory birds, fish, crabs, and molluscs (8). For a detailed description of saltmarsh habitat and ecology, refer to Lovelock *et al*. Ch 5, this volume.

Documented records of saltmarsh extent in Moreton Bay are limited. An initial study (9) reported that between 1955 and 2012, approximately 43% of saltmarsh communities in Moreton Bay were lost through invasion of mangroves (Table 1), a major threat for saltmarsh communities (10). An additional, 46% of saltmarsh communities were lost to anthropogenic activities, including grazing and urban development (Table 1) (9). Any saltmarsh gains arose from mangrove dieback or saltmarsh invasion of *Melaleuca* or *Eucalypt* spp. patches where the frequency of inundation had been altered. Collectively, this equated to a net loss of 5,700 hectares (ha) (with only 2,400 ha stable), or a net loss of 64% of the 1955 saltmarsh extent (9) (Table 2, Fig. 2), and the loss occurred across all major saltmarsh community types.

Table 1. Saltmarsh community expansion (+) and loss (die-back) (-) in Moreton Bay - the difference in aerial extent between 1955 and 1997, and 1997 and 2012 (9). Expansion/contraction rates are expressed in hectares per year in parentheses.

Saltmarsh Invasion into Mangrove and *Casuarina glauca* communities (ha)			
1955-1997		**1997-2012**	
661		180	
(+ 15.74 ha/yr)		(+ 12.00 ha/yr)	
Saltmarsh Die-back (ha)			
1955-1997		**1997-2012**	
Mangrove	**Anthropogenic**	**Mangrove**	**Anthropogenic**
3,077	2,170	670	618
(- 73.26 ha/yr)	(- 51.67 ha/yr)	(- 44.67 ha/yr)	(- 41.20 ha/yr)

Table 2. The total Moreton Bay saltmarsh area (ha) as recorded in the three mapping years (1955, 1997 and 2012) and the net change per study period (adapted from (9)).

	1955	**1997**	**2012**	**Decline 1955-2012**	**Decline 1997-2012**
Total Saltmarsh Community (ha)	8,901	4,135	3,171	**-64 %**	**-23 %**

In 2011, a program was developed by the Queensland Herbarium to monitor wetland communities within Moreton Bay (11), and in 2013, the saltmarsh community of Moreton Bay was listed as a vulnerable ecological community under the Commonwealth Environment Protection and Biodiversity Conservation Act (10) with greater than 50% loss estimated for the saltmarsh communities of Moreton Bay.

In 2015, utilising existing maps of saltmarsh distribution (11), a non-governmental organisation (12) undertook the South East Queensland Coastal Saltmarsh Value and Protection Mapping Project, the “Saltmarsh For Life” initiative. The study was designed to identify key locations of associated saltmarsh areas and assign coastal values to these areas to facilitate regional conservation outcomes for the saltmarsh areas of South East Queensland (13). Saltmarsh clusters were identified and prioritised based on a number of criteria including patch size, habitat, environmental significance and Ramsar designation. Areas with the highest score were labelled as priority areas and recommended for protection (Fig. 3a). Additionally, a study was initiated which collated data collected by citizen scientists to map saltmarsh areas of interest and areas suited to saltmarsh restoration, as well as potential threats to saltmarsh habitats (12, 14) (Fig. 3b). Further, potential saltmarsh areas were identified from a desktop study that overlaid the Queensland Government Regional Ecosystems map, aerial imagery and a Preclearing Ecosystems map (12, 14). Similarly, potential saltmarsh recovery areas were marked through identification of areas that were not developed or disturbed and historically had contained a coastal vegetation community (Fig. 3b). This mapping is ongoing but serves as a reservoir for detailed information about the current state of saltmarsh communities, how they are being used by the community, and provide a means by which to prioritise conservation actions (12, 14).

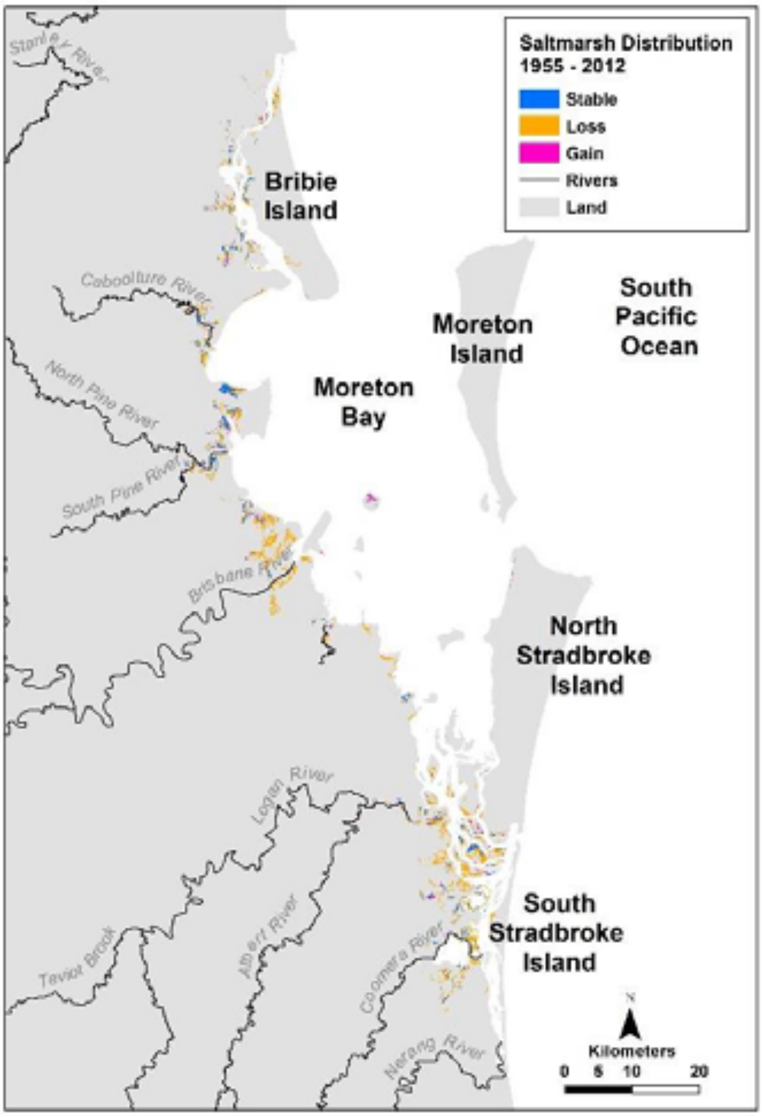

Figure 2. Loss and gain of saltmarsh communities in the Moreton Bay region. An assessment of saltmarsh areas from 1955 to 2012 (9, 11).

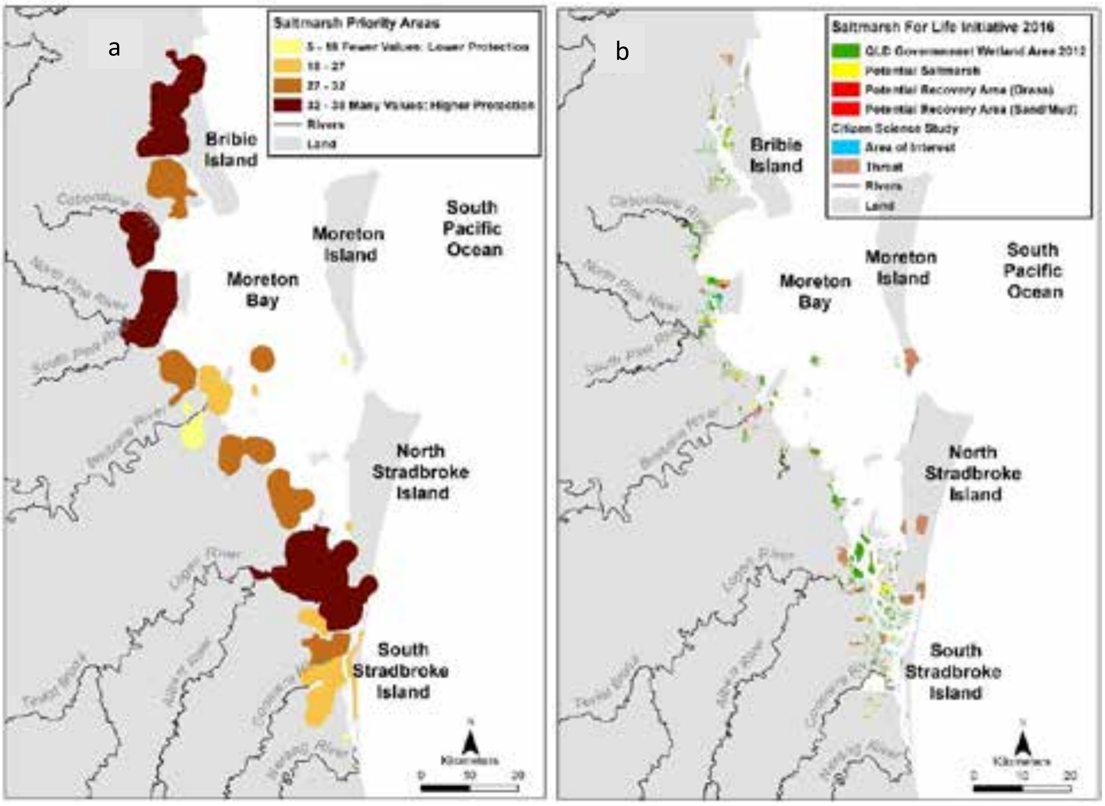

Figure 3. The saltmarsh communities of Moreton Bay. (a) Saltmarsh priority areas as mapped by (12, 13). (b) Potential saltmarsh recovery areas determined via a desktop study, and citizen science recorded threats to saltmarsh areas, and restoration opportunities (12, 14).

Mangroves

Mangroves are salt-tolerant vascular plants, constrained by mean sea and maximum tide levels, limiting them to the coastal intertidal zone, estuaries and riverine systems (Fig. 1) (15). Mangroves are important habitats for many organisms, as well as acting as barriers that filter pollutants, nutrients and sediment, and providing protection for the mainland against extreme weather events (1, 16, 17). For detailed information regarding mangrove communities in the Moreton Bay catchment refer to Lovelock *et al*. Ch 5 this volume.

Monitoring of the mangrove communities of the Bay has occurred at irregular intervals since it was first comprehensively mapped in 1955 (9). There have been recent site-specific mangrove community studies in the Bay (18), but the most comprehensive analysis of the Bay's mangrove environments was performed by the Queensland Herbarium in 2016. It compared mangrove distribution in 1955, 1997 and 2012, using historical aerial photographs and supporting maps (9). It was found that there was a net gain in mangrove communities of 958 ha between 1955 and 2012 (Table 3; Fig. 4).

Table 3. The total Moreton Bay mangrove community (ha) as recorded in the three mapping years (1955, 1997 and 2012) and the net change per study period (adapted from (9)).

	1955	1997	2012	Increase 1955-2012	Increase 1997-2012
Total Mangrove Community (ha)	14,273	14,896	15,231	**+4.4%**	**+2.2%**

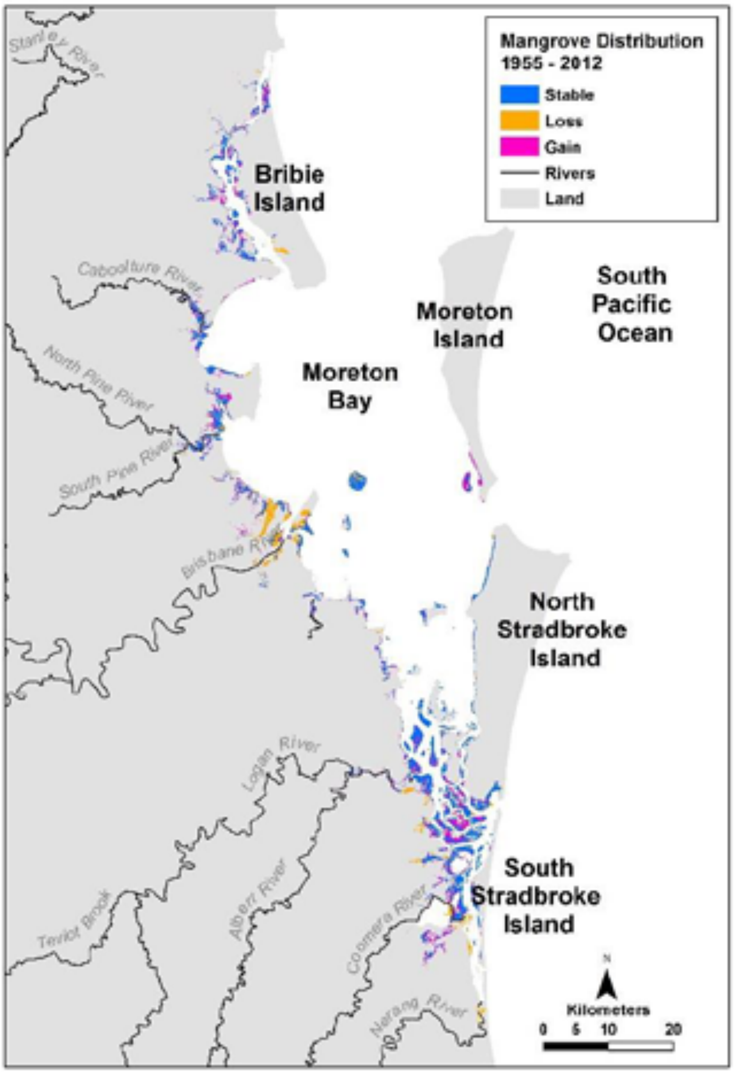

Figure 4. Loss and gain of mangrove communities in the Moreton Bay region. An assessment of mangrove areas from 1955 to 2012 (9, 11).

Of the original 1955 mangrove distribution 77% remained stable (9). The overall net expansion of mangrove areas was primarily attributed to mangrove encroachment into saltmarsh and *Casuarina glauca* communities (3,425 ha), as well as range expansion along the coastline and recruitment on newly formed islands (9). Interestingly, the net rate of mangrove community encroachment into saltmarsh and *Casuarina glauca* environments was greater for 1955-1997 than for 1997-2012 (Table 4) (9).

Table 4. Mangrove community expansion (+) and loss (-) in Moreton Bay – the difference in aerial extent between 1955 and 1997, and 1997 and 2012 (adapted from (9)). Expansion/contraction rates are expressed in hectares per year in parentheses.

Mangrove Expansion into Saltmarsh and *Casuarina glauca* communities (ha)			
1955 - 1997		**1997 - 2012**	
Saltmarsh	***Casuarina glauca***	**Saltmarsh**	***Casuarina glauca***
2,656	209	535	25
(+ 63.24 ha/yr)	(+ 4.98 ha/yr)	(+ 35.67 ha/yr)	(+ 1.67 ha/yr)

Mangrove Loss (ha)					
1955 - 1997			**1997 - 2012**		
Saltmarsh	***C. glauca***	**Anthropogenic**	**Saltmarsh**	***C. glauca***	**Anthropogenic**
426	132	1,839	133	17	103
(- 10.14 ha/yr)	(- 3.14 ha/yr)	(- 43.79 ha/yr)	(- 8.87 ha/yr)	(- 1.13 ha/yr)	(- 6.87 ha/yr)

Encouragingly, the rate of mangrove die-back attributed to anthropogenic causes decreased by 84% (Table 4). This marked decrease strongly correlates to the instigation of more rigorous environmental management practices with declaration of the Moreton Bay Marine Park as a Ramsar wetland in 1993 (19).

As well as changes in extent, marked changes were observed with respect to community structure and floristic composition, however, this was not specific to any one mangrove species. Of note, the area covered by *Avicennia marina* subsp. *australasica* increased during the entire period (1955 - 2012) for both of its 1B(i) and 1B(ii)b community types (1,524 ha and 636 ha respectively), whilst all other mangrove community types decreased (9).

Intertidal Flats

Intertidal sand and mud flats dominate the lower intertidal zones of the Bay, lying between the mean high and low tide levels (20). They provide important ecosystem services and have high conservation values. Predominantly devoid of vegetation, these flats support abundant micro-organisms, but also diverse crustaceans, worms and molluscs, important in the diet of wading birds (21). Additionally, they protect the coastline from erosion and the impact of storms, are important nursery habitats and fish feeding grounds, and act as connecting pathways between other environments (21, 22). This is particularly significant when considering the life cycle of numerous marine species, as spawning and juvenile nursery habitats often occur within estuaries and mangroves (4). Additionally, intertidal flats act as broader migratory pathways for ecologically important species such as dugongs, dolphins and turtles and are feeding grounds for migratory wading birds (4).

Environmental conditions within these regions fluctuate, affected by climatic events and anthropogenic factors (23–25). In fact, tidal currents, duration of aerial exposure, estuarine deposits, wave action and bedform migration result in increased exposure of intertidal flats to radiation, variable temperatures and desiccation, and are major drivers of spatial and temporal changes in the distribution and abundance of intertidal assemblages (20, 23, 26, 27). As such, the benthic assemblages within these environments are often complex communities dominated by deposit, suspension and detritus feeders and predators, with species diversity higher in low energy environments that have shorter periods of subaerial exposure (20, 21).

A 2017 study mapped the distribution of tidal flats within the Bay (25), and found sandflats and mudflats comprised of a variety of sediment classes with varying total areas: clean sand (569 km^2), sand (160 km^2), muddy sand (424 km^2), sandy mud (684 km^2) and mud (167 km^2) (Fig. 5). Sandflats within the Bay were largely concentrated to the east while mudflats were primarily concentrated to the west (25, 28). This distribution pattern was attributed to the land masses feeding terrigenous sediment into the Bay - those areas near the mainland were dominated by mud, whilst near barrier islands they were dominated by sand. Additionally, intertidal flat composition is influenced by the Bay's tidal currents, which are stronger on the eastern side, flushing out deposited sediment and creating tidal deltas at the Bay's ocean entrances (28).

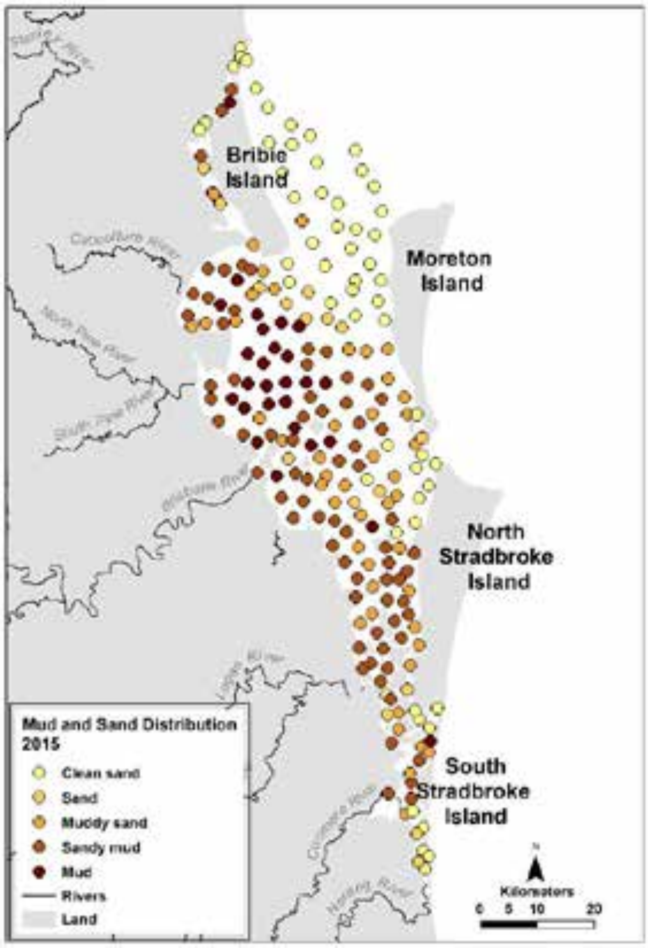

Figure 5. Sand and mud distribution throughout Moreton Bay. An intensive sediment sampling program (April to May 2015) examined the mud and sand distribution of Moreton Bay (25).

Historically, the distribution of mudflats within the Bay has been more restricted (28), however, the 2017 study contrasted the distribution of tidal flats within the Bay between 1970 and 2015, to determine the impact of extreme weather events on mud deposition and fine particle suspension (25). The study revealed an increase in mudflat extent of more than 50% in the past 30 years, with mudflats now covering 860 km^2 of the Bay (25, 28). This dramatic change in distribution can be largely attributed to major weather events, including the 1974, 2011 and 2013 floods (29, 30) increasing mud deposition and fine particle suspension. In addition to increased fluvial mud inputs, wind-driven wave formation is responsible for sediment suspension and distribution in shallow waters during such events (31). Thus, extreme weather events, in conjunction with historical and ongoing anthropogenic degradation of the quality of Moreton Bay's catchment, coastal and stream networks (32), have collectively increased sediment loading within the Bay.

Seagrass

Seagrasses are marine angiosperms that form meadows in inter- and sub-tidal areas of Moreton Bay. These meadows are important for biodiversity, fish and crustacean habitats, coastal protection, and carbon stocks (33). As is the case for mangroves and saltmarshes, these habitats are impacted by both anthropogenic activities and natural processes (34). For a detailed discussion on the seagrasses of Moreton Bay refer to Maxwell *et al*., this volume.

The extent of seagrass in Moreton Bay has been monitored via many ad-hoc surveying exercises since the mid-1970s, but it was not until the advent of remote sensing methods that the broad scale extent and composition of seagrass communities was studied in a systematic and repeatable manner (35). The Eastern Banks is the largest continuous seagrass community in the Bay, and sits nestled between Moreton and North Stradbroke Islands (Fig. 6). Here the seagrass meadows consist of six species: *Halophila ovalis, Halodule uninervis, Halophila spinulosa, Syringodium isoetifolium, Zostera muelleri* (dominant), and *Cymodocea rotundata* (36). Although these seagrass beds are dynamic, showing large changes in extent on both a monthly and annual time scale, from 1988 to 2010, the overall extent of the Eastern Banks seagrass meadows was shown to have been relatively stable (37). From a time-series of seagrass cover maps, it was shown that although the total area of seagrass meadows on the Eastern Banks remained mostly unchanged (not shown), seagrass cover trended towards lower cover levels (Fig. 7)(37).

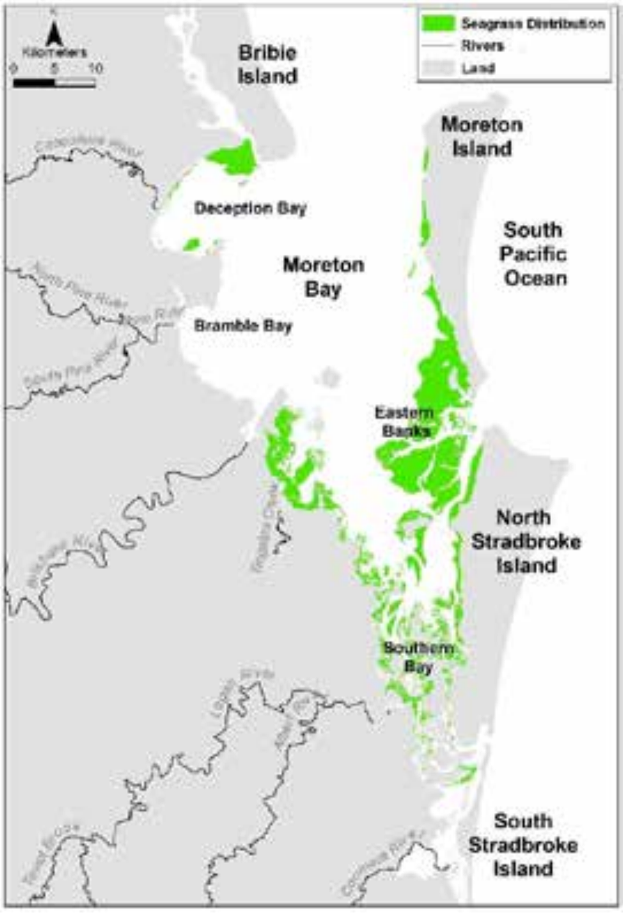

Figure 6. Moreton Bay's seagrass meadows (adapted from (35)).

The non-contiguous seagrass meadows of western Morton Bay are monitored at 28 sites by Wildlife Queensland Coastal Citizen Science (WQCCS). Here seagrass communities are less diverse than in the east, consisting of *Zostera muelleri* subsp. *capricorni* (dominant) (38, 39), *Halophila ovalis* and *Halophila spinulosa.*

Seagrass is absent to sparse in several western embayments, a result of seagrass loss that occurred in historical times. The undocumented total loss of seagrass in Bramble Bay (Fig. 6) is believed to have occurred prior to the 1980s (38), whilst a 2,000 ha loss was calculated from 1987 to 1998 for southern Deception Bay following a flood event (Fig. 6), and seagrass loss in the southern Bay islands has been estimated to be 800 ha (40, 41). Since then, however, there have been no recorded losses of large areas of seagrass in the western Bay, even following two major flood events (2011 and 2013). Baltais (39) has reported the overall cover of western Bay intertidal seagrass has been stable since 2001 (Fig. 8), which in Pumicestone Passage has been reported since the early 1970s (42). Seagrasses are impacted by many factors including changes in salinity (43), epiphyte cover (44), disease (45), pollution (46), and poor water clarity (40). However, in areas where water clarity has improved, such as Deception Bay (12), seagrass is recovering (39, 47).

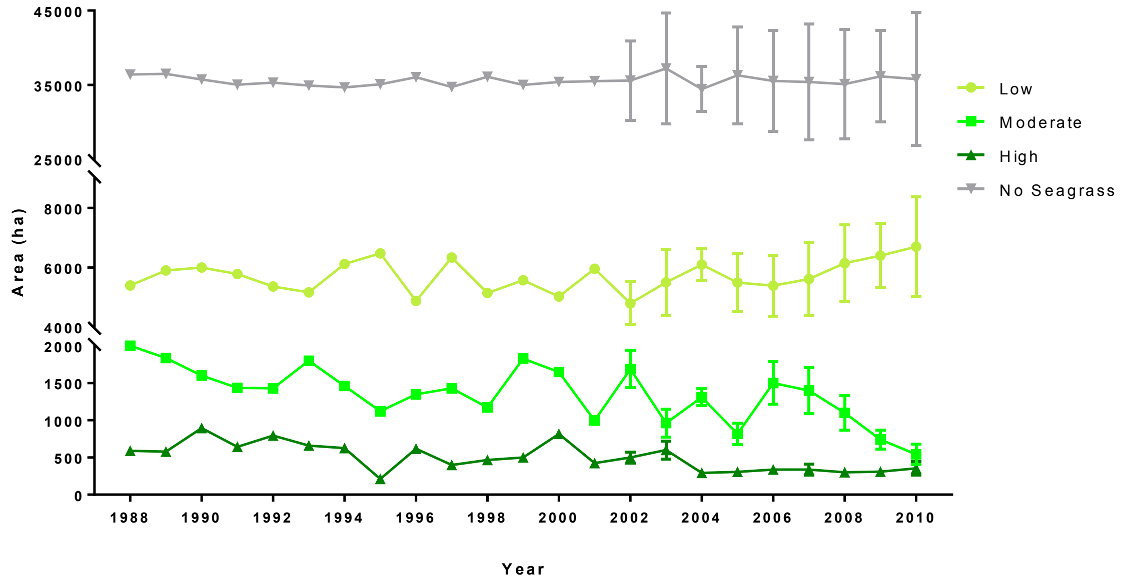

Figure 7. Change in area (ha) of seagrass across the Eastern Banks. A generally decreasing trend is observed for mid to high level seagrass cover (bright green and dark green respectively), whilst the extent of low or no cover remains relatively stable (light green and grey respectively) (reproduced from (37)).

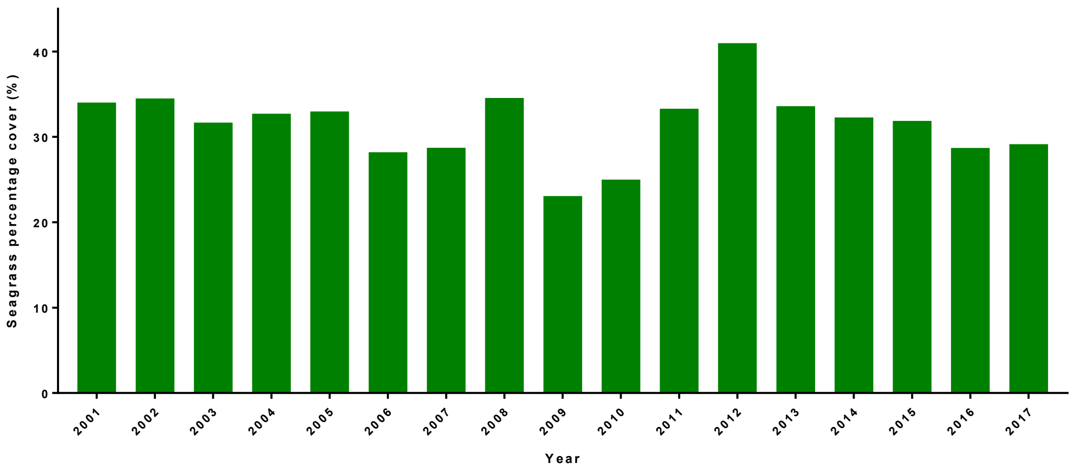

Figure 8. Total average intertidal seagrass percentage cover in the western region of Moreton Bay derived from data acquired at established survey sites. Seagrass recovery data at Deception Bay wer not included as those were determined through remote sensing studies (39).

Port development and bait worming are human impacts that either cause localised seagrass loss or a reduction in seagrass cover (48). The Seagrass Monitoring Program (SMP) concluded that there has been a trend of slight expansion of seagrass at the Fisherman Islands port development in Moreton Bay, driven by seagrass expansion into deeper waters (49). However, in contrast, WQCCS has reported a 45-54% decrease in seagrass cover in areas subject to bait worming (Table 5), an activity that has increased by 30.5 ha from 2009 to 2013.

Table 5. Bait worming activity in western Moreton Bay from 2009 to 2013 (39). Site increases and the overall increase are indicated (ha).

Bait Worming Activity (ha)			
Site	**2009/2010**	**2013**	**Increase**
Manly	0	0.9628	**100%**
Snipe Island	0	2.056	**100%**
Lota/Thornside	7.065	34.474	**488%**
Total	**7.065**	**37.492**	**30.427 ha**

Coral Reefs

The coral reefs of Moreton Bay encompass areas of inshore reefs in central Moreton Bay in shallow water with a muddy substrate (around Mud, St. Helena, Green, King, Goat, Macleay, Russell and Peel Islands as well as some fringing areas) (50). For a detailed review of the corals of Moreton Bay refer to Pandolfi *et al*. Ch 5, this volume; for a review of the importance of Citizen Science for monitoring of Moreton Bay reefs refer to Roelfsema *et al.* Ch 6, this volume.

Due to the sensitivity of coral to environmental parameters and its ecological importance, the extent and condition of hard coral is identified as one of the regional metrics for South East Queensland (SEQ) Natural Resource Management targets (51). Moreton Bay coral extent maps tend to be updated irregularly, therefore comparisons between data sets are seldom possible. The Queensland Government created a baseline map of coral in Moreton Bay for 2004, from Comboyuro Point to Jacobs Well, as part of the Ecosystem Health Monitoring Program (Fig. 9a; (52)). The next map published was produced in 2016 following implementation of a collaborative citizen science project to re-map key coral habitat areas in central Moreton Bay (Fig. 9b)(53).

The largest reef area was identified around Peel Island in both studies, with smaller fringing reefs occurring around the islands of inshore Moreton Bay, and the coastline between Wellington Point and Coochiemudlo Island. Unfortunately, as the refined habitat assessment of 2016 utilised high resolution satellite imagery, more advanced mapping software and increased field knowledge, no direct comparison of specific habitats can be made with the 2004 baseline map. However, an estimate of the extent of areas containing coral can be made from each of the maps (Table 6). In 2004, 1,724.7 ha of coral were mapped, whilst in 2015/2016, a total of 1,627.5 ha of areas containing hard coral and an additional 192.5 ha of areas containing soft coral were mapped (1,820 ha combined total).

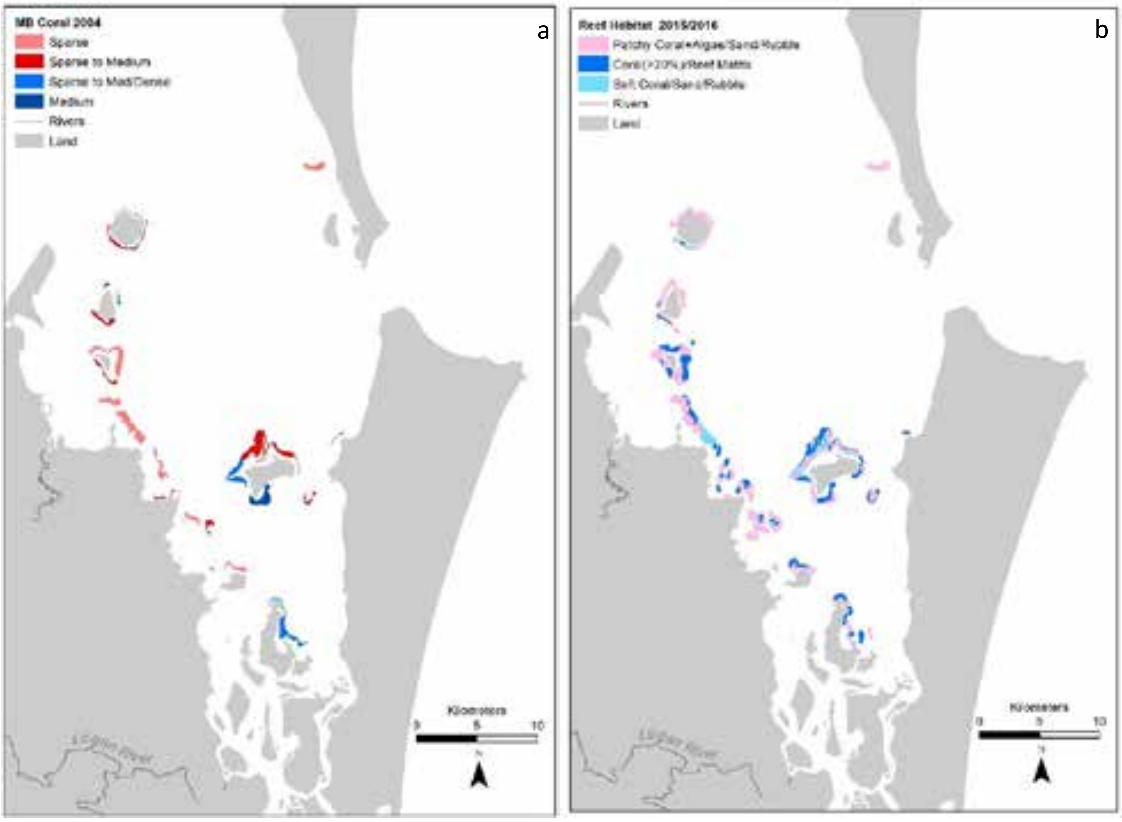

Figure 9. Coral habitat in Moreton Bay. (a) Location of coral in Moreton Bay mapped as part of the Ecosystem Health Monitoring Program, State of Queensland, 2004 (52). (b) Inshore Moreton Bay reef habitat areas, derived through manual digitisation guided by 2014 ZY-3 satellite imagery (5 m x 5 m pixel), overlaid with spot-check field data collected in 2015 and 2016 (53).

The 2016 study does not necessarily reflect an increase in coral cover in Moreton Bay as the higher resolution of the mapping product has provided more accurate identification of reef areas and as such should be viewed as a more accurate baseline quantification of the extent of coral cover.

Table 6: Extent of coral habitats mapped in 2004 (52) and in 2016 (53). For the 2004 study, coral was recorded as the density observed at each field site (52). Due to the availability of higher resolution satellite imagery for the 2016 study, more complex categories were used to record benthic cover at each field site. Each of these categories contained at least some coral (53).

Year	Coral Habitat	Area (ha)
2004	Sparse	742.4
	Sparse to Medium	555.5
	Medium	150.3
	Sparse to Med/Dense	276.4
2015/2016	Soft Coral/Sand/Rubble	192.5
	Patchy Coral + Algae/Sand/Rubble	1091.0
	Coral(>20%)/Reef Matrix	536.5

Conclusion

This analysis of the historical and current range of wetland communities highlights the threats that climate change, sea-level rise and anthropogenic stressors pose to wetland communities. Sadly, many of the wetland areas of Moreton Bay are in decline. Human activity has resulted in marked decreases in the areal extent of all wetland communities, reiterating the threat that these changes have and will continue to have, particularly on the more vulnerable wetland communities such as saltmarsh.

For instance, increasing sediment loading decreases ecosystem health by increasing siltation which decreases water clarity, restricting penetration of sunlight, and decreasing photosynthesis (54). This increased siltation smothers the benthos and creates a shift from benthic to pelagic productivity (55, 56, 57). Additionally, sediment loading is accompanied by phosphorus and nitrogen, which can lead to increased risk of cyanobacteria and algal blooms within the Bay (58, 59), thus exacerbating the decrease in water quality.

As the Bay's wetland areas are important socially, culturally, ecologically and economically, it is vital that we maintain a comprehensive understanding of the health of these systems, their ability to respond to disturbances, how their extent changes with time, and develop models to predict how they are likely to fare in the future under various management scenarios.

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The impact of marine pollutants and marine debris in Moreton Bay

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Abstract

Moreton Bay is affected by a wide range of persistent pollutants, including the following four broad groups: (i) persistent organic pollutants (POPs); (ii) trace elements (e.g. metals, metalloids and non-metals); (iii) perfluoroalkyl substances (PFAAs); and (iv) plastic-based marine debris. The pollutants discussed in this paper come from diverse chemical groups, and are similar in that they are persistent in the environment and impact the health of animals and/or humans. While most of these pollutants are banned and/or actively monitored by health organisations on a global scale, (e.g. PCBs and DDT) many are still entering our waterways daily (e.g. marine debris). We discuss how dioxins have impacted on the health, lifestyle, and culture of the region's Traditional Custodians. Case studies are presented, highlighting the impacts of the four pollutant groups on marine megafauna found in Moreton Bay including sea turtles, seabirds, and stingrays. In all cases, the authors recommend increased monitoring and the development of new strategies to reduce the four pollutant groups entering Moreton Bay.

Keywords: marine rubbish, polymer, PCB, DDT, PFAA, heavy metals, human impact

Introduction

The term marine pollution brings to mind many different images ranging from beaches covered in oil through to waterways filled with plastic bags. While the authors acknowledge that there are many types of pollution, including pharmaceuticals, petrochemicals, nutrients and sedimentation, this paper focuses on four persistent pollutant groups currently impacting Moreton Bay (Quandamooka): persistent organic pollutants (POPs), trace elements, perfluoroalkyl substances (PFAAs) and marine debris.

Moreton Bay (Quandamooka) is situated off the coast of one of the largest cities in Australia, Brisbane. Colonised in 1824 as a penal colony (1) and with a current population of over one million (2), managing man-made waste has long been a challenge. Prior to European colonisation, pollution was primarily organic-based, including items such as food scraps, stormwater, human and animal waste. However, the pollutants being introduced to Moreton Bay changed as Brisbane grew as a city. For example, pharmaceuticals, sediment and nutrient inputs have all increased as the population has grown. The four persistent pollutant groups reviewed in this paper have one thing in common—they are all highly resistant to degradation/decay processes. As such, all of these compounds bioaccumulate in aquatic organisms and many can biomagnify up the food chain, further exacerbating their long-term environmental impact. We review how they have changed over time and discuss how POPs have impacted on the health, lifestyle, and culture of the region's Traditional Custodians. We present case studies highlighting the impacts of these key pollutants on marine megafauna including sea turtles, seabirds and stingrays found in Moreton Bay. We discuss the role that government agencies, non-government organisations and volunteer organisations have in monitoring and cataloguing marine pollution within the region. Although progress has been made in reducing marine pollution there are still many challenges to address. The paper concludes by suggesting strategies for improving pollutant management in Moreton Bay.

Persistent organic pollutants

Persistent organic pollutants (POPs) are hazardous to humans and wildlife and encompass a wide variety of chemicals with various structures and applications (3). The most toxic POPs are subject to the Stockholm Convention, which aims to reduce or eliminate the release of these pollutants on an international scale (4). They include chemicals that are now banned or restricted (e.g. PCBs, DDT), some that are released unintentionally (e.g. dioxins), and emerging new compounds that are still being used (e.g. chlorinated paraffins). These chemicals are highly lipophilic and persistent, so even banned POPs are still present in the environment and can be stored in soil, sediments and biota for decades to centuries (5). From these environmental sources, the chemicals can bioaccumulate to elevated levels, particularly in fatty tissues, and can biomagnify through the food chain, which explains why higher trophic organisms typically contain the highest levels of POPs (3, 6). Studies have shown that even low-level chronic exposure can lead to a wide range of adverse effects including cancer, reproductive and developmental effects, disruption to the immune system and damage to the nervous system for both humans (7) and marine species (6, 8, 9).

Several studies have investigated the sources, transport and levels of POPs in the Moreton Bay region (e.g. 10–13). Based on initial findings, dioxins (a chemical subset of POPs) were the focus of further investigations due to their ubiquitous and elevated levels in soils, sediments, seafood and other marine wildlife. In addition, PCBs and DDTs were found to be elevated in localised hotspots, especially in western Bay areas and in species frequenting these waters such as the humpback dolphin, *Sousa sahulensis* (Fig. 1) (14).

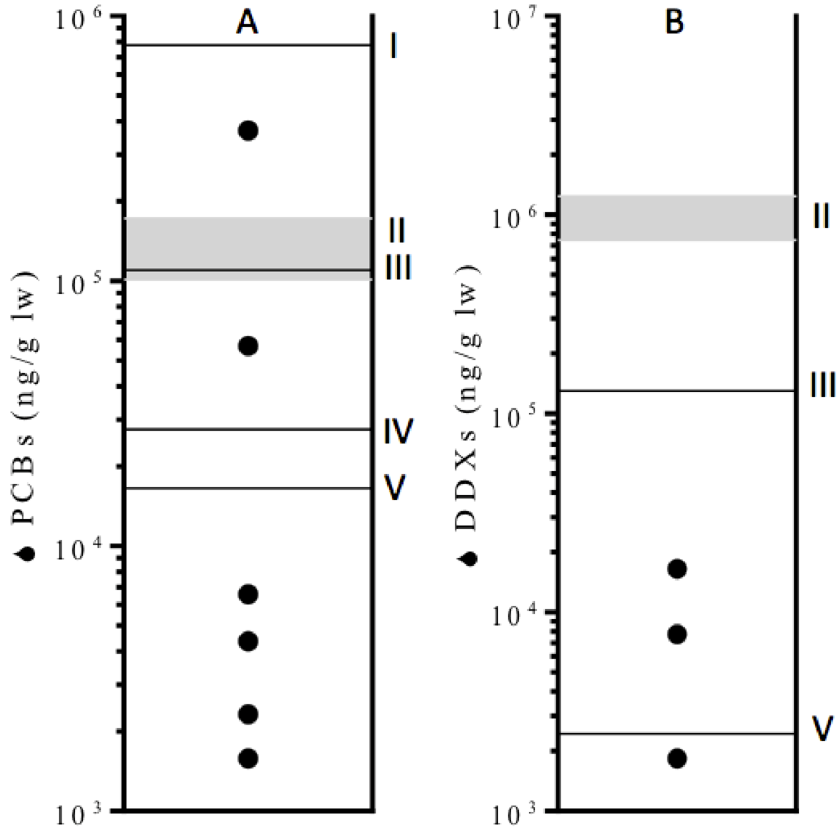

Figure 1. Toxicity endpoints in humpback dolphins (*Sousa sahulensis*) (n=6, individuals marked by ●) with respect to ∑ PCB exposure (A) and ∑ DDX exposure (B). All endpoints are based on concentrations in blubber: **I** – Epizootic, diseased striped dolphins (85) (PCBs not specified) **II** – Premature pupping in California sea lions (86) (based on sum of *p,p'*-isomers in (B), PCBs not specified for (A)) **III** – Pathological changes in the uterus leading to low reproduction rate in ringed seals (87) (DDXs or PCBs not specified) **IV** – Harbour porpoises that died because of infectious diseases (88) (sum of 25 PCBs) **V** – Immunotoxicity in harbour seals (89) (based on *p,p'*-DDT in (B), PCBs not specified for (A)). Figure sourced from (14).

Case study 1: POPs and the Quandamooka people

Approximately 90% of the total exposure of humans to POPs occurs through intake of contaminated food, particularly lipid-rich products, including seafood. As a signatory to the Stockholm Convention, Australia funded a four-year National Dioxins Program in 2001 to increase knowledge of levels in the environment and determine the risk posed to the health of the population. As part of this assessment, toxic equivalent (or TEQ) levels in a number of retail products (including seafood) were analysed and human consumption levels were estimated from national surveys. The study reported that the TEQ levels of POPs in Moreton Bay seafood were 9 times higher in wild caught Australian marine/estuarine fish and 25 fold higher in retail fish compared to background levels measured for the National Dioxins Program (12). However, the TEQ levels of most seafood analysed were below the European Union (EU) guideline limits (11). The study concluded that the levels were found to be comparable to those measured in other urban areas, which similarly received historical discharges of agricultural, municipal and industrial wastewater. The conclusion from the program was that the risk to the general Australian population from dioxins was low (15).

However, the National Dioxins Program did not take into account population groups who may consume more self-caught seafood compared to the general population. Unique subsistence patterns of coastal and Indigenous populations may place them at greater risk of exposure to dioxins due to reliance on contaminated food sources (16, 17). The Quandamooka people of Moreton Bay have cared for the local environment for thousands of years (18). Their cultural practices ensured a sustainable abundant supply of seafood and other resources. Like other Indigenous communities, Quandamooka people would utilise most aspects of the catch, including lipid-rich organs such as roe and testes (melts). Dugong (*Dugong dugon*) was hunted for both its flesh and oil. Hunting practices played an important role in social cohesion as every part would be shared amongst families (18). Fishing and traditional hunting are an important affirmation of cultural identity and continue to be an essential aspect of Quandamooka life. These food sources have also been assumed to be a healthy and affordable dietary source.

Given the higher contamination levels in Moreton Bay seafood compared to retail food and the subsistence patterns of local communities, a health risk assessment was conducted for the Quandamooka and broader North Stradbroke Island community (19). Surveys showed this community consumed on average two to six times more seafood than the general Australian population. Depending on the level of seafood consumption, the exposure assessment found that the average monthly dioxin intake for the community ranged between 34 to 107 picogram TEQ/kg body weight/month—an order of magnitude higher than that estimated for the general population. Between 11 and 44% of the community may be exceeding the WHO safe intake guideline (70 picogram TEQ/kg body weight/month) at chronic exposure levels.

A delicate balance is required between educating the Quandamooka community about risks from consuming seafood compared to the nutritional and economic benefits, as well as the cultural benefits of maintaining consumption levels. Risk management strategies have been suggested that can effectively reduce contaminant intake, while having a low impact on beneficial aspects of seafood consumption (19). Some strategies include removing skin (and associated fat layers) from fish before cooking and eating more of the leaner fish species, such as snapper, whiting and flathead. The current study showed that local seafood consumption in coastal communities can result in high exposure to dioxins. It highlights the importance of considering local economic, cultural, and environmental conditions and information on contaminant fate processes when conducting human exposure evaluations.

Trace elements

Trace elements enter the marine environment in several ways including, weathering and erosion of rocks, atmospheric deposition and through industrial and domestic activities in the water and adjacent catchments. Trace elements can bind to both mineral particles and organic matter in the water column and settle out to accumulate in the sediment (20). When disturbed, or if water quality is altered, sediment-bound trace elements can be liberated and become bioavailable (21). Rainfall and flooding events can result in short-term enrichment and bioavailability (22, 23). Excessive accumulation of trace elements, even those essential for life, can be toxic to marine flora and fauna (24, 25).

Trace elements have been well documented in the waters (22, 26), sediments (27–29), flora (30) and fauna (14, 31, 32) of Moreton Bay. They are generally highest in the western Bay (31, 32), and are closely linked to point sources such as shipping/boating (22, 28) and refuse tips (33), as well as more generally to catchment land use (26, 27, 29). Sediment coring within the Bay shows an increasing concentration trend since the 1920s, likely due to industrial, agricultural and urban development in the adjacent catchments (34). Recently reported concentrations of several trace elements in western Bay surface sediments exceeded background reference ranges with arsenic (As), cadmium (Cd), cobalt (Co), copper (Cu), nickel (Ni), lead (Pb), and zinc (Zn) posing a medium to high risk to benthic biota (27).

Water quality guidelines, values and objectives for managing trace elements in Moreton Bay are outlined by the Queensland Government (35). However, these guideline levels are not consistent across the Bay, with some regions considered to be of 'high ecological value' (HEV), receiving 99% protection values in the ANZECC, while others, such as the western part of the Bay, are considered to be so impacted that they are no longer considered to be of HEV, and will only then be protected under the 95% guideline value (35, 36). It is important that researchers communicate with managers to regularly review the levels of protection and their trigger values to determine if they are adequate for protecting the Bay and its marine inhabitants.

Case study 2: Trace elements and sea turtles

Sea turtles are exposed to trace elements when they consume contaminated food sources such as seagrass, macroalgae, benthic crustaceans, soft sponges/corals and jellyfish, as well as when they incidentally ingest contaminated sediments during benthic feeding. Various trace elements were identified within tissues of stranded Moreton Bay sea turtles (*Chelonia mydas*, *Caretta caretta*, *Eretmochelys imbricata,* and *Lepidochelys olivacea* from 1990–91) at lower concentrations relative to other reported populations outside of the Bay, with the exception of cadmium (37). A subsequent investigation of stranded Moreton Bay green sea turtles (*C. mydas)* from 2006–07 described much higher cadmium and arsenic tissue concentrations than previously reported, causing the authors to raise concerns about the impact of these increases (38).

Interpreting the consequences of elevated trace element concentrations in sea turtles is difficult in the absence of any baseline data that tell us what a healthy population, subject to minimal anthropogenic disturbance, should look like. Until recently, the only comparable trace element data for sea turtles came from stranded or free-ranging animals from other urban and industrially impacted regions of the world (39–41). Now, trace element baselines (for 20 elements) have been developed for green turtle blood using what is considered to be a healthy population from the Great Barrier Reef, a region that has historically been free from high levels of industrialisation (42). These baselines can be used to evaluate and monitor trace element trends in free-ranging green turtles, those in rehabilitation, or during mass stranding investigations. They also allow us to retrospectively evaluate trace element exposure from previously reported blood concentrations.

For example, by comparing the trace element concentrations reported in stranded green sea turtles (*C. mydas*) collected from Moreton Bay between 2006 and 2007 (38) to the recently developed baselines (42), the study showed that van de Merwe *et al.*'s concerns regarding high arsenic and cadmium were valid, being 10x and 4x the upper baseline limits, respectively. In addition, we also discovered that copper and particularly selenium were also elevated (1.4x and 6x, respectively) (Fig. 2). Due to a lack of relevant toxicological information for sea turtles (43), the overall health risks posed by elevated trace elements cannot be accurately predicted, particularly considering the complex mixtures of trace elements and other chemicals that sea turtles are exposed to in Moreton Bay (see also Case study 1).

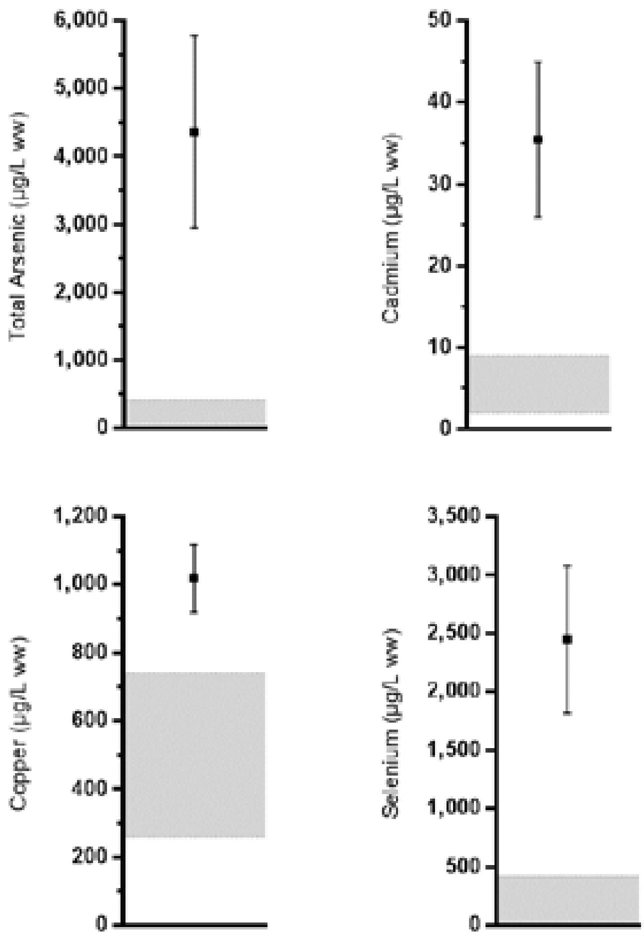

Figure 2. Blood concentrations (µg/L ww ± standard error about the mean) for stranded 2006–2007 Moreton Bay green sea turtles (38). Shaded region indicates blood reference interval (normal range) specific to green turtles (42).

Trace element biomonitoring of populations of sea turtles and other marine megafauna that forage within Moreton Bay is important given the complex mixture of chemicals that the animals are exposed to and the dynamic physical and chemical fluctuations that occur. Additional baseline data, similar to those recently established for green turtles (42) is also required for other species, in order to better interpret biomonitoring data from free-ranging populations or as part of investigations into mass stranding. Finally, as recommended for POPs above, species-specific information on the toxic effects of trace element exposure in sea turtles and other species must be investigated to assess the impacts of trace elements accumulating in the Bay. Managers could then use this information when developing ecosystem indicators and local water quality guidelines.

Perfluoroalkyl substances

Perfluoroalkyl sulfonic acids (PFSAs) and perfluoroalkyl carboxylic acids (PFCAs) are an anthropogenic class of chemicals that have been used in numerous consumer products and industrial application since the 1950s. Sources of PFAAs include Teflon pans, outdoor clothing, firefighting foams, food packaging, carpets and pesticides. Some PFSAs and PFCAs bioaccumulate in biota and biomagnify along the food chain. They can present toxic effects, with some evidence suggesting that PFAAs could alter thyroid hormones levels in infants and pregnant women (44, 45). PFAAs are highly resistant to degradation, making them environmentally persistent. These chemicals have been detected worldwide, including remote areas such as Antarctica and lakes in the Himalayas (46). Their widespread distribution occurs through atmospheric transport, via surface water currents and via degradation of volatile precursors (47). Despite recent media attention (48), long-term monitoring data on PFAAs available within Australia are scant. Seven selected PFCAs and three selected PFSAs were detected in 100% of samples taken from the Parramatta River, the main tributary of Sydney Harbour, with a mean concentration ranging between 0.0002–0.014 µg/L (49), which is well within the current Recreational Water Quality Guidelines of 0.7 to 5.6 µg/L outlined by the Commonwealth Department of Health (50). Sampling of the Brisbane River system following major flooding in 2011 also found PFAAs in water from Somerset Dam to Moreton Bay (51). No manufacture of PFCAs or PFSAs has ever been recorded in Australia (52). Therefore, the presence of PFAAs in the Australian environment is due to the use and disposal of consumer articles (53) and the environmental degradation of other per- and poly-fluorinated chemicals. The impact of PFAAs on Moreton Bay's flora and fauna is not yet fully understood. In the meantime, the use and disposal of PFAA-generating consumer articles must be closely regulated.

Case study 3: Perfluoroalkyl substances and mass stingray stranding

PFSAs and PFCAs have been detected in the tissues of a wide range of aquatic species worldwide, particularly in liver tissue where they bioaccumulate (54). The stranding of 49 stingrays on North Stradbroke Island (Minjerribah) provided an opportunity to conduct tissue sampling (55). The concentrations of PFSAs and PFCAs were investigated in the liver tissues of six species of stingray (*Aetobatus narinari, Dasyatis fluviorum*, *Himantura astra*, *Himantura toshi*, *Himantura uarnak,* and *Neotrygon kuhlii*) with the aim of providing more information on the exposure level in Australia environment and assessing whether differences in concentrations could be explained as a function of the age/size of the individuals (55).

Perfluoroalkyl substances (PFAAs) were detectable in all liver samples, with total concentrations ranging from 1.2 to 152 ng·g^{-1} wet weight. The concentrations of total PFCAs and total PFSAs were significantly higher in blue-spotted rays (*N. kuhlii)* than in any other group of rays for all age/size categories (Fig. 3). PFAAs come in many forms and similar to previous studies on aquatic biota, perfluorooctane sulfonate (PFOS) was found to be the major contributor to total PFAAs in each population group.

In the case of rays, there is a positive relationship between the age and size, with larger rays being older (56). Interestingly there was a negative size-concentration relationship found for total PFAS levels in the blue-spotted rays (*N. kuhlii)*, with larger rays having lower overall concentrations (55). This does appear to be counterintuitive, however, previous studies have shown that the uptake rates of PFAAs are faster and elimination rates slower in smaller fish (57). The rays were collected 20 months after the 2011 flood, when the Brisbane River delivered up to 17 kg of PFOS and 3.7 kg PFOA into Moreton Bay and showed a persistence of high concentration levels for many months post-flooding event (51). Therefore, the negative relationship between PFAAs concentration and size/age could be related to differing uptake kinetics of the chemicals as a response to an sudden increase in these substances 20 months prior, caused by the flooding of the Brisbane River. Hence, smaller rays take up the chemicals more quickly and eliminate them more slowly, leaving those rays with an overall larger body burden. This study highlighted the complexity around the uptake of PFAAs and the importance of including biological measurements such as size and age, in order to adequately study and understand the exposure of marine animals to these complex chemicals.

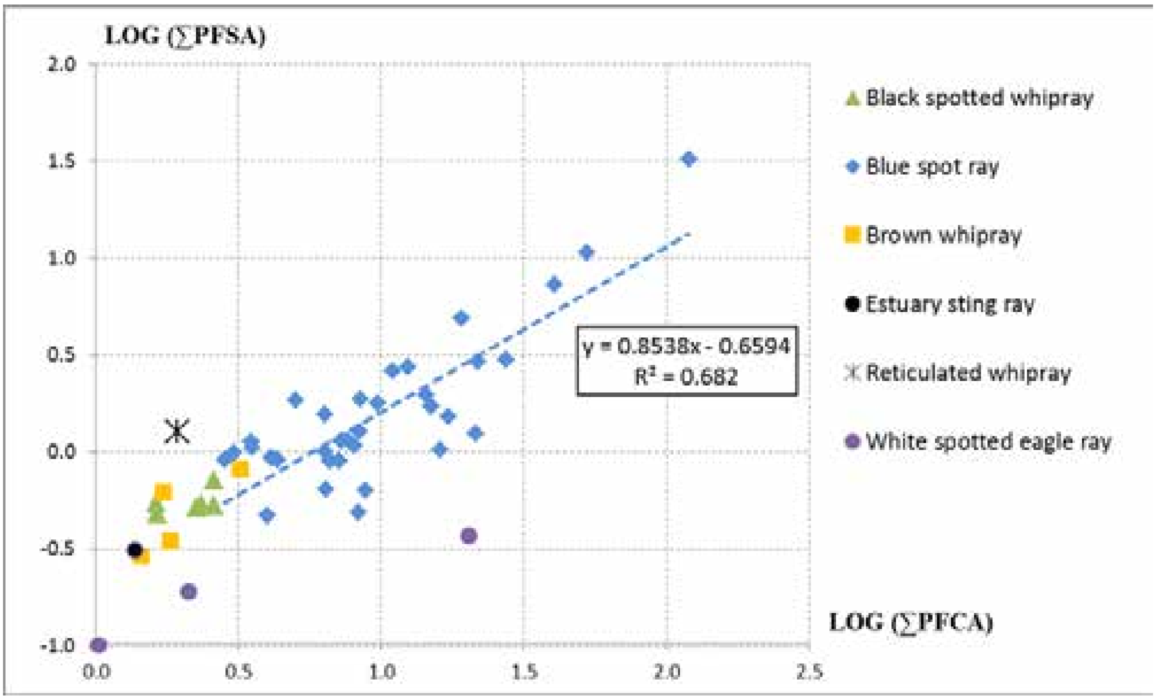

Figure 3. Log-transformed concentration of ∑ PFCAs and ∑ PFSAs found in the liver of rays stranded on North Stradbroke Island. The equation on the chart and the correlation coefficient are given for the blue-spotted rays' dataset, which were significantly higher than any other group of rays. Figure sourced from (55).

Marine debris

Marine debris is defined as any man-made product entering the marine environment, whether by accidental loss or damage, or wilful disposal. It is generally thought that about 20% of marine debris enters the water by being discarded or lost at sea, while about 80% originates from land-based sources (58). Land-based sources include littering and inadequate waste disposal facilities, with an estimated 33% of rubbish being lost from landfills into the environment every year (59). It is estimated that there are 150 billion tonnes of plastics in the world's oceans as of 2017, with an estimated additional 4 to 12 million tonnes entering the world's oceans every year (59). While the composition of this debris varies regionally and spatially, between 60 and 80% is plastic (60).

Global mass production of plastic commenced around 1950 at relatively low production levels of two million tonnes per year (59). However, it did not take long for these first plastic products to interact with marine life. The first scientific record of plastics being ingested was by seabirds in New Zealand during the late 1950s (61). This was less than 10 years after global mass production of plastics had started. Over the next couple of decades, plastic polymer production grew rapidly, with a compound annual growth rate of 8.4% a year (59). Today plastic debris production is estimated at 400 million tonnes per year and can be found in all of the oceans of the world (59, 62). Despite this rapid growth, the earliest recorded evidence of marine debris surveys in the Bay are from 1993 (63), by which time the global plastic production had increased to over 100 million tonnes per year (59).

In terms of threats to wildlife and potentially to human health, plastic debris is both persistent and pervasive (64). In different forms, it can be lethal through both ingestion and entanglement. Similarly, lost or discarded fishing gear such as nets, fishing line, and crab pots can entangle and drown marine life, while ingested hooks are lethal to both sea turtles and seabirds (65). A potential threat comes from microplastics, which are tiny pieces of plastic usually resulting from the deterioration of larger pieces of plastic or from clothing fibres (66). Microplastics can also adsorb chemicals from the environment and transfer them to the tissues of organisms that ingest them (8).

Case study 4: Marine debris, sea turtles and seabirds

The impacts to marine life from marine debris have been well catalogued (67), and include both lethal and sublethal impacts from entanglement and ingestion. Entangled animals can drown immediately, or can suffer from increased drag from entangled objects, impairing feeding and normal movement (68). Ingested objects can pierce the gut wall, causing septicaemia, or can block the gastrointestinal system (67). Recent research indicates that chemicals leached into body tissues from ingested plastics can cause hepatic stress, and even affect the endocrine system (8, 69).

A 2009 meta-analysis into the impacts of marine debris on wildlife in Australia found that 77 marine species had ingested or been entangled by plastic debris (70), but that number has certainly risen in the ensuing decade (e.g. (71)). In the Bay, the majority of scientific research on marine debris and wildlife to date has focused on sea turtles and seabirds (71-75). Whilst the population and ecosystem level effects of debris are more challenging to measure, there are several studies that have documented the effects of marine debris on a species level.

A survey of 115 sea turtles that died between 2006 and 2011 in Moreton Bay and nearby beaches found that 33% of all animals had ingested marine debris at the rate of anywhere between 1 and 329 pieces per turtle (73). Note, that these finding contrasts with Flint *et al*. (75) who found that only 4% (n=7) of necropsied sea turtles died from ingesting foreign bodies. However, the mean size of turtles in this study was much larger relative to Schuyler *et al.* (73). Interestingly, Schuyler *et al.* (73) noted that young, juvenile turtles, which had likely been foraging in pelagic offshore waters as opposed to inside of the Bay, were more likely to ingest debris (54.5%) than their elder counterparts (25%).

Schuyler *et al.* (73) also found differences between the type and colour of debris ingested by each group. Pelagic-feeding turtles preferred white, hard plastics, while the older, benthic-feeding turtles were more likely to eat soft, clear plastics (Fig. 4). The authors attributed this pattern to the ubiquity of white plastics in the environment and the relatively non-selective feeding style of post-hatchling turtles. In contrast, the preference of adult turtles may be due to the visual similarity of ingested plastic bags to a preferred prey taxa, jellyfish (73, 74). A quantitative analysis was made based on information obtained from the Queensland Government's StrandNet and necropsies. This indicated that 14 pieces of marine debris were required to kill 50% of juvenile sea turtles investigated, many of which came from the Bay (76).

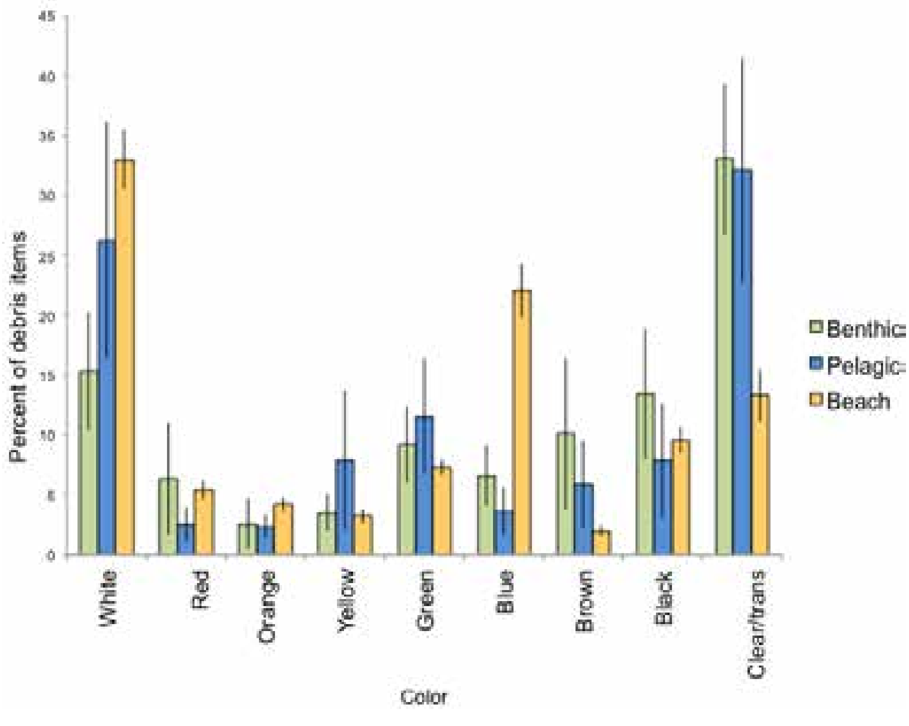

Figure 4. Colours of marine debris found during beach surveys and in the gastrointestinal system of stranded sea turtles, reported as an average of the percentage of each category found within each animal (benthic n=22, pelagic n=11), and during each beach survey (n=25). Error bars indicate standard error. Figure sourced from (73).

Similarly, a study of 139 short-tail shearwaters (*Puffinus tenuirostris*) stranded on the beaches of North Stradbroke Island found that 66% of all animals had ingested marine debris (72). Here again, juveniles were more likely to ingest debris (85%) than adults (63%). The birds appeared to select hard plastics, rubber and balloons. This selectivity may be due to a similarity in appearance (including position within the water column) between balloons and squid, a common prey item of shearwaters.

Although the animals were found on North Stradbroke Island, short-tail shearwaters (*P. tenuirostris*) migrate for thousands of kilometres, and the debris may have been ingested many kilometres from the Bay. However, this case study and that of the turtles indicate that wildlife frequenting the Bay and surrounds experience significant impacts from marine debris, whether the debris is local or regional in origin. It is critical to implement plans that reduce debris at its source across all levels of government, local, state and national.

Methods and bodies responsible for monitoring and cataloguing marine debris in Moreton Bay

Numerous organisations contribute to actions that deal with marine debris within the Bay by conducting community clean-ups and education. Three not-for-profit organisations—Healthy Land and Water, Reef Check Australia and Tangaroa Blue Foundation—are active leaders in monitoring and cataloguing debris with the goal to target debris sources in the Bay. These organisations collaborate with the Queensland Government's Litter and Illegal Dumping Program to drive the adoption of best practices in waste management and education (77). Queensland's Litter and Illegal Dumping Action Plan sets the agenda for managing the problem statewide. It is made up of a suite of programs that positively influence community attitudes and behaviours around waste disposal. Actions range from compliance and enforcement to community-based social-marketing campaigns, informed by rigorous research.

A better understanding of the sources of marine debris in the Bay is beginning to emerge from the data collected through standardised clean-ups conducted by Reef Check Australia, Healthy Land and Water Clean Up program, and Tangaroa Blue Foundation monitoring surveys and clean-ups (78). Reef Check Australia engages the community using a citizen science approach. They gather data that monitors and reports on reef health within the Moreton Bay Marine Park, including data on marine debris. The Healthy Land and Water Clean Up Program has run for over 16 years in South East Queensland and employs a crew to collect floating and bank-bound litter. Tangaroa Blue Foundation supports community clean-up events through an on-ground network of community volunteers and organisations, which contribute data on marine debris to the Australian Marine Debris Initiative database. It also provides educational resources and support programs, and collaborates with industry and government to create behavioural and legislative change at a state and national scale.

An important component of these programs is the systematic collection and analysis of data, which is used by the three organisations to educate and inform local communities and to drive local source reduction plans in collaboration with local and state governments. Within South East Queensland source reduction plans are being implemented to target specific waterway litter items. A source reduction plan serves the dual purpose of identifying regionally and temporally specific sources of litter and engaging the community, industry and local governments in a plan to reduce litter. The success of a source reduction plan can be evaluated using the data collected from community clean-up events. Through an iterative process of assessment, future reduction plans can evolve to address new issues as they arise.

In 2018, the Queensland Government banned single-use plastic bags (79) and mass balloon releases (80). During that same year, a container refund scheme for bottles, cans and cartons was also put into place (81). With ongoing beach/river clean-ups and data collection and analysis, source reduction plans can be measured for both success or failure, enabling them to be modified if needed, and providing case studies that can be used by communities across the country who may be trying to find similar solutions.

Conclusions

For all of the persistent pollutant groups discussed in this chapter, there is a recognised need to increase monitoring of these potentially toxic compounds, while simultaneously providing strategies to reduce their inputs into the Bay. These strategies require local, state and Australian government buy-in. Much progress has been made in the area of marine debris, however, many of the pollutants do not have coordinated monitoring programs, making it difficult to understand the impact of major weather events, such as flooding, into the Moreton Bay catchment.

The authors recognise that a coordinated monitoring program is not simple, as the number of industrial chemicals in use far exceeds the number of chemicals for which toxicological data are available (82). A proactive approach to developing baselines is complicated as it is difficult to predict what will be an issue and it is impractical to make baselines for all potentially toxic chemicals in the short term. One way to address this issue is to generate an environmental specimen bank that contains tissue samples that can be accessed by researchers and government agencies to go 'back in time' to make comparisons.

Queensland lacks a well-established or coordinated system for necropsies/sampling of stranded animals. It is highly recommended that the Queensland Government, in conjunction with a relevant tertiary institution, such as the University of Queensland's 'Queensland Alliance for Environmental Health Science', look towards establishing a well- maintained and well-funded tissue bank, such as the National Oceanic and Atmospheric Administration's marine mammal tissue bank (83) or the South Australian Museum tissue bank (84). It is also recommended that researchers consider the practical applications of their work by working with, or developing tools for, traditional owners, frontline conservation, and monitoring agencies. It is time to move on from monitoring problems and actively concentrate our energy on solution-based approaches.

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Moreton Bay and catchment: Projected changes to population, climate, sea level and ecosystems

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Abstract

By 2050 Moreton Bay region will be impacted by significant changes in environment and population size and distribution. The human population of the Moreton Bay catchment is expected to increase from 3.2 million in 2015 to 4.8 million in 2036, with migration the likely primary driver of this growth. Mean annual air temperature is expected to rise between 1.2 and 1.7ºC relative to 1986-2005 values, by 2050 depending on the emissions scenario. Mean annual rainfall will likely decrease by 4–7% over the same period, depending on the emissions scenario, although significant multi-model variability in this estimate means changes of +13% to –23% are possible. Rainfall in summer will change little, whereas rainfall in winter, spring and autumn will likely decrease. Sea level will likely rise 0.21–0.27 m by 2050 relative to 1986–2005, and will impact coastal marine ecosystems. Seagrass area is expected to decline by 6% relative to year 2000 values and saltmarsh by up to 13% relative to year 2013 values by 2050. Mangrove habitats could potentially almost double their current extent, if they are able to establish in presently dryland areas.

Keywords: population, climate change, temperature, precipitation, sea-level rise, seagrass, mangrove, saltmarsh

Overview

Substantial changes in climate and population are expected to occur in the Moreton Bay region by 2050. This will affect people and natural ecosystems in the region. This paper examines how human population, climate, sea level and the distribution of coastal ecosystems may change by 2050. Projections are not available for 2050 for some variables; in this instance, the projections for the latest year that are available are presented. Estimates of future human population in the region have been made by analysing historic trends in population and projecting to 2036. Population data are based on Statistical Areas Level 2 (SA2) in 2011 and Geosciences Australia's *Australia's River Basins 1997* (93rd edition 2004) (1) for the catchments of Brisbane River, Logan-Albert Rivers, Maroochy River, Pine River, South Coast and Stradbroke Island. Projections of changes in climate, including temperature and rainfall, have been derived from climate projections developed to support the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) released in 2013. Estimates of sea-level rise rates have been obtained from regional projections, which closely follow IPCC projections based on Representative Concentration Pathways (RCPs). Projections of the redistribution of coastal ecosystems, including saltmarsh, mangrove and seagrass meadows, have been made using the Sea-Level Affecting Marshes Model (SLAMM) and a seagrass distribution model parameterised for Moreton Bay. The projected redistribution of coastal ecosystems is presented for subset areas of Moreton Bay under a number of different sea-level rise scenarios. These estimates do not include changes in the distribution of coastal ecosystems resulting from changes in precipitation or temperature, nor from changes in land-use policies such as clearing and development.

We acknowledge that other environmental changes will also influence the system (e.g. ocean acidification) as will other human developments (e.g. the potential expansion of the blue economy and marine industries in the region). However, as reliable projections of these changes and the influences on the area do not yet exist, we have chosen to omit them here and focus on those changes that have been most fully assessed to date.

Population

The Moreton Bay catchment sits within South East Queensland, which is one of the most populated and rapidly growing areas in Australia, home to around 3.2 million people in 2015 (Table 1) or close to 15 % of the total population of Australia. There are six sub-catchments draining into Moreton Bay – The Brisbane, Logan-Albert, Maroochy, and Pine Rivers, South Coast, and Stradbroke. Four sub-catchments drain entirely into the Bay, whereas, the Maroochy and South Coast catchments drain only in part into Moreton Bay. The majority of the population of South East Queensland is located in the Brisbane catchment (1.2 million), followed by the Pine River (0.7 million) and the South Coast (0.6 million) catchments. The Stradbroke catchment is the least populated, with a population of just 9,500 in 2015. Since 1991, the Moreton Bay catchment population has grown by more than a million people, an annualised growth rate of 2.3%. This is much higher than the 1.3% per annum Australia-wide over the same period. High levels of growth are projected to continue over the next two decades, with the population of Southeast Queensland catchments expected to reach 4.8 million by 2036 (2). The majority of this growth to 2036 is projected to occur in the Brisbane River sub-catchment.

The growth between 1991 and 2015 has not been distributed uniformly across the catchment area (Fig. 1). The most dramatic population growth occurred on the peri-urban fringe of the Brisbane metropolitan area, the northern Gold Coast and hinterland, Caboolture and the Sunshine Coast. The pattern of growth is a product of urban extensification, with greenfield

Table 1. Observed and predicted population of the Moreton Bay catchment and its sub-catchments, 1971–2036. (Source: Australian Bureau of Statistics unpublished data and Queensland Government Statistician's Office unpublished data)

Catchment	1991	1996–2015 (% per year)	2015	2015–2036 (%)	2036
Brisbane River	744,923	1.9	1,166,838	1.9	1,730,739
Logan-Albert River	314,251	2.3	538,404	1.8	790,718
Maroochy River	145,259	3.2	310,461	2.1	480,045
Pine River	393,370	2.2	662,343	1.4	886,466
South Coast	257,841	3.2	550724	2.1	857,317
Stradbroke	4,078	3.6	9,472	1.4	12,644
Moreton Bay	1,859,722	2.3	3,238,242	1.8	4,757,929
Queensland	2,960,951	2.0	4,778,854	1.7	6,763,153

Note: the Moreton Bay catchment is defined here as the sum of the sub-catchments listed above.

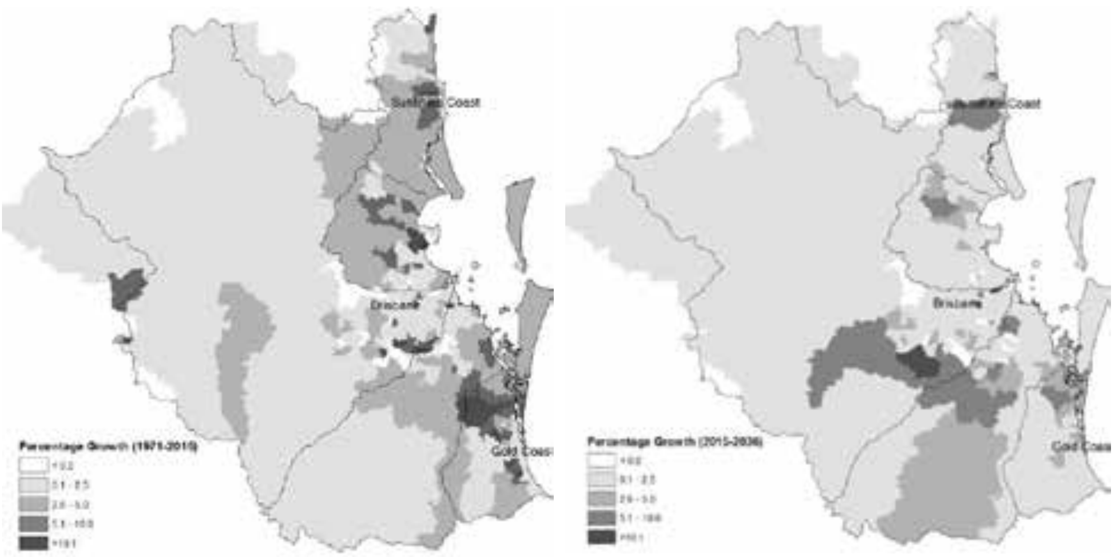

Figure 1. Population growth, Moreton Bay Catchment 1991–2015 and 2015–36 (Source: Australian Bureau of Statistics unpublished data and Queensland Government Statistician's Office unpublished data)

development transforming agricultural land and other land types for urban development. The growth in Brisbane's urban core is the exception, and reflects a process of urban consolidation, much of which is occurring within a couple of kilometres of the Brisbane River.

Natural increase (births – deaths) increased between 2001 and 2008 but has been relatively stable since 2009, contributing around 21,000 people per annum (Fig. 2). Net migration, both internal and international, has been much more variable, ranging from 27,000 to 57,000 people per annum. Migration accounted for more than three-quarters of the growth at the start of the period and was primarily comprised of moves from other parts of Australia. In recent years, the contribution of migration to overall growth has declined, accounting for just over half of the annual growth in 2014. There is some evidence that the composition of migrants has changed, with international migrants making up an increasing share. Migration is expected to continue to an important driver of population growth in the Moreton Catchment to 2036.

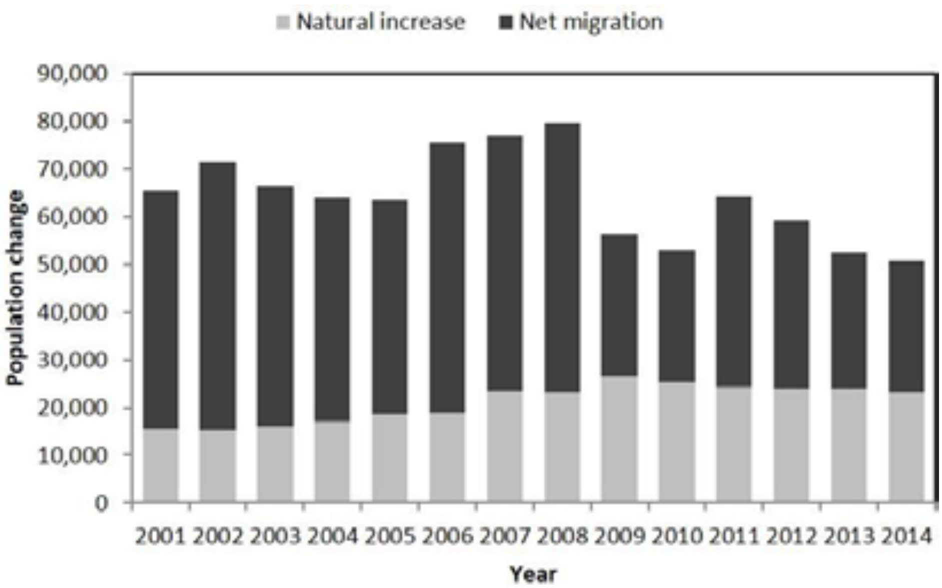

Figure 2. Components of change in population for Moreton Bay Catchment 2001–2014 (Source: Australian Bureau of Statistics unpublished data and Queensland Government Statistician's Office unpublished data)

Climate

The South East Queensland region has a subtropical climate, with warm to hot weather for most of the year. The average annual surface temperature (1986–2005) in the South East Queensland region was 19ºC. The rainfall in the region has strong inter-annual variability influenced by El Niño–Southern Oscillation (3). The average (1986–2005) annual total rainfall over the region was 996mm.

Climate-change projections to 2050 are presented for two RCPs. The high emissions future (RCP8.5) assumes no curbing of greenhouse gas emissions, where a carbon dioxide (CO_2) concentration reaches 940ppm by 2100. A lower emissions future (RCP4.5) assumes emissions peak around 2040, with CO_2 concentrations at 540ppm by 2100. While the Paris Agreement aspires to substantially reduce global emissions to limit global warming to below 2ºC by 2100, the global greenhouse gas emissions currently track close to the RCP8.5 pathway, so RCP4.5 is a more realistic lower emission scenario. Climate projection information presented herein is based on data from the CSIRO and Bureau of Meteorology Climate Change in Australia (4). Figure 3 shows the patterns of projected changes in mean annual temperature and rainfall in Queensland at 2050 for two emission scenarios (5).

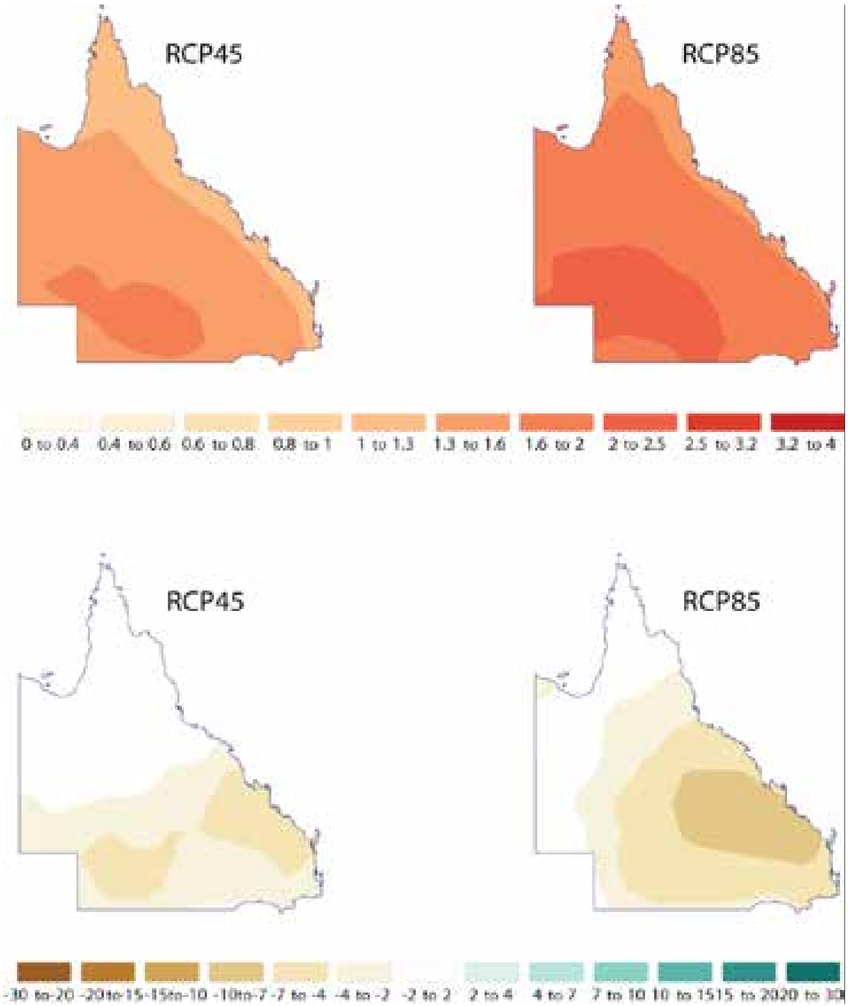

Figure 3. Projected changes in mean annual temperature (°C, upper panel) and the per cent change in annual precipitation (lower panel) by 2050 for the low (RCP4.5) and high (RCP8.5) emissions scenarios. Changes are relative to the 1986–2005 period. Source: http://qgsp.maps.arcgis.com/apps/MapJournal/index.html?appid=1f3c05235c6a44dcb1a6faebad4683fc

Projected temperature changes

Climate change projections show that by 2050, the median annual temperature is likely to increase by 1.2°C under RCP4.5 and 1.7°C under RCP8.5 relative to the 1986–2005 base period. The projected range of annual temperature change derived from multi-model projections is 0.9°C to 1.6°C for lower emissions and 1.2°C to 2.1°C for high emissions. Projected changes at seasonal scales are qualitatively similar to the projected changes in annual temperature.

Projected precipitation changes

Projections show that by 2050, the mean total annual rainfall is likely to decrease by 4% under RCP4.5 and 7% under RCP8.5. However, projections show a large range of changes simulated by multi-model ensemble ranging from an annual increase of 13% to a decrease of 23%. Projections show little change in median rainfall during the summer season, but a significant rainfall decrease is projected for median rainfall during the winter, spring and autumn. The median rainfall decrease is around 6% for lower emissions and 6–15% under high emissions, with winter season rainfall projected to decrease the most (Table 2).

Table 2: Projected changes in seasonal rainfall in South East Queensland region at 2050 for lower (RCP4.5) and high (RCP8.5) emission scenarios. Projected changes are shown for median and range (5th and 95th percentile) of model projections. Projections are shown as % change from the 1986-2005 period. Source:https://www.Qld.gov.au/environment/climate/climate-change/resources/-science.

	Annual	Summer	Autumn	Winter	Spring
RCP4.5	**-5** (-15 to 9)	**-1** (-21 to 23)	**-6** (-26 to 29)	**-6** (-26 to 8)	**-5** (-27 to 19)
RCP8.5	**-7** (-23 to 13)	**0** (-27 to 21)	**-6** (-28 to 29)	**-15** (-33 to 9)	**-9** (-32 to 15)

Sea-level change

Global mean sea level is driven by changes in water temperature (i.e. thermal expansion/contraction) and ocean mass (e.g. contributions from melting ice caps). Regional changes in sea level are additionally influenced by ocean dynamics and land motion. Around Australia, tide-gauge records show an average trend of relative sea-level rise of around 2.1 mm yr^{-1} for the period 1966–2009, which is closely correlated to the global-mean trends. A slightly lower trend of 1.8 mm yr^{-1} was recorded at Mackay tidal-gauges, the closest station to Moreton Bay (6).

Regional sea-level rise projections for the Australian coastline are very similar to the global RCPs projections for 2050 (7). As for the global levels, the projected rises under the different RCP scenarios diverge considerably after 2050. Based on projections from nearby sites (Newcastle and Mackay), sea-level in South East Queensland will rise between 0.21–0.27 m for 2050 relative to 1986–2005. Under RCP2.6 the predicted rise is around 0.21, and under RCP8.5 the rise is at the upper end of the range. By 2090, trends in sea-level rise are expected to accelerate and reach values between 0.43–0.86 m relative to 1986–2005 (with the lower end of the range likely under RCP2.6, and the higher values the more likely outcome under RCP8.5) (8).

Rapidly increasing sea levels will combine with astronomical tides, storm surges and waves, particularly from tropical cyclones and east coast lows, resulting in accelerated coastal erosion and increased inundation of some low-lying areas. In South East Queensland, rates of coastal erosion can be expected to increase with storm tides and changes in sediment transport along exposed sandy shorelines, such as those on the Gold Coast, Sunshine Coast, and Stradbroke and Moreton islands. Low-lying, sheltered areas such as sectors of the coastline along Moreton Bay can expect higher frequencies of both temporary and permanent coastal inundation.

Assessing the impacts of projected sea-level rise on ecosystems or infrastructure is very challenging given the uncertainties inherent in sea-level projections, particularly at the regional and local scales, and the complex interactions with atmospheric forcing and uncertainties in spatial data. Recently, case studies along Moreton Bay and the Sunshine Coast have implemented probabilistic approaches that explicitly incorporate such uncertainties when assessing coastal vulnerability (9, 10) and modelling impacts to ecosystems (9). This approach can be used in a risk-averse decision-making process by planning for scenarios with different probabilities and providing visually intuitive maps that convey uncertainties inherent in spatial data and analysis (Fig. 4).

For a subset of the Moreton Bay coastline, probability of inundation at each location was calculated for 1 m SLR during a 100 average recurrence interval (ARI) storm surge event, with the probability of inundation indicated by the colour gradient (Fig. 4). Our expectation of whether a property will be inundated varies depending on whether a bathtub model or a probabilistic model is used to quantify inundation risk. Areas with a probability of inundation greater than 1% are indicated by the thin solid line, and areas indicated as inundated by a bathtub model are shown by the thick black line. Examples of low-lying areas (zone I) and houses surrounded by vegetation (zone II) are mapped as inundated based on the deterministic bathtub map (wide solid black line) but appear as uncertain areas with lower probability (30%) of becoming inundated based on the probabilistic mapping. Conversely, areas with a complex terrain (zone III) that appear safe from inundation based on the deterministic mapping can have a large probability (60–90%) of getting inundated (from Leon *et a*l. (10)).

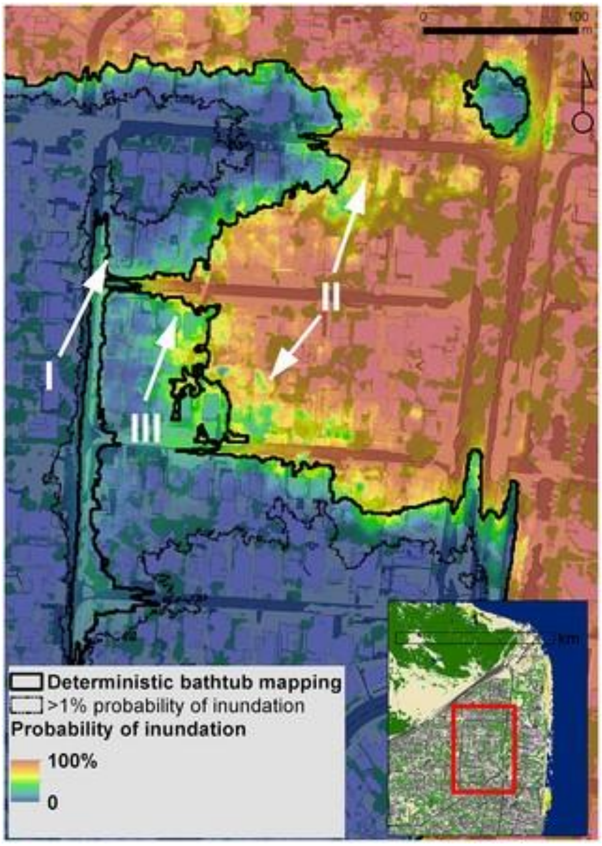

Figure 4. Example of a probability inundation map for a scenario combining a 2.9 m 100yr average recurrence interval storm surge event over a 1 m sea level rise (From Leon *et al.* (10); See adjacent text for further explanation.)

Ecosystems

Research examining the potential future distribution and abundance of wetlands in Moreton Bay, including seagrass, mangroves and saltmarsh, has focused on the impacts of sea-level rise on those habitats. Warming temperatures, ocean acidification, and changes in precipitation will also affect marine wetlands, but to date have not been assessed in detail for the region. Taxa other than habitat-forming species will also be affected by environmental and human driven change in the region; however, projections are not readily available for these other species so we focus on the habitats to give a sense of the scale of the issue.

Rising seas cause a redistribution of the plants and animals that live near sea level. This is because deepening water causes changes in the distribution of environmental conditions influencing the distribution and extent of suitable habitat for coastal marine species. Coastal marine habitat-forming species can respond to rising seas by (i) moving shorewards; (ii) building the seafloor upwards by trapping sediments and biological materials (vertical accretion); (iii) adapting to new environmental conditions, such as diminished light or longer periods of immersion; or (iv) ceasing to occupy areas that are no longer suitable. The combination of these responses results in altered (increased or decreased) distribution and abundance. For instance, mangroves and saltmarsh are terrestrial plants that can tolerate periodic immersion in seawater. Therefore, rising seas cause increased immersion at the deep edge of the habitat extent, and encroachment into terrestrial habitats at the landward edge because of inundation.

Seagrass and corals are marine organisms that live in shallow coastal water due to high light requirements. Increased water level reduces the light intensity at the seafloor, but increases the accommodation space for growth at the shallow edge. Seagrass habitats across Moreton Bay are expected to decline by ~6% by 2050 as a consequence of sea-level rise due to (i) reduced light intensity at the deep edge, and (ii) limited opportunity to expand shoreward (11). Losses are expected to increase to about ~15% by 2100 as sea-level rise accelerates (11), but these could be minimized by policies aimed at coastal retreat, which help ecosystems migrate inland unimpeded by sea-walls, levees or other infrastructure (11). Larger relative impacts are expected in the western Bay where water clarity is murkier and the seagrass depth range is contracted compared to the eastern Bay. Policies aimed at improving water clarity could help seagrass adapt to rising seas (11).

Impacts on mangroves and saltmarsh have been assessed for two areas within Moreton Bay; specifically, the southern Bay islands (12–14) and the Moreton Bay Regional Council area (9). Mangrove habitat is expected to expand with sea-level rise, but this comes at the expense of salt marsh and previously dryland areas, which are expected to contract (Fig. 5, Table 3). However, this expansion is only possible if land currently used for agriculture is allowed to transition to wetlands, and there is no further urban development in the region. Given the projections for population growth in the Moreton Bay region, urban development is likely to continue and reduce the area available for coastal wetland migration. This is concerning, as the majority of the coastal wetland expansion is projected to occur outside the current reserve

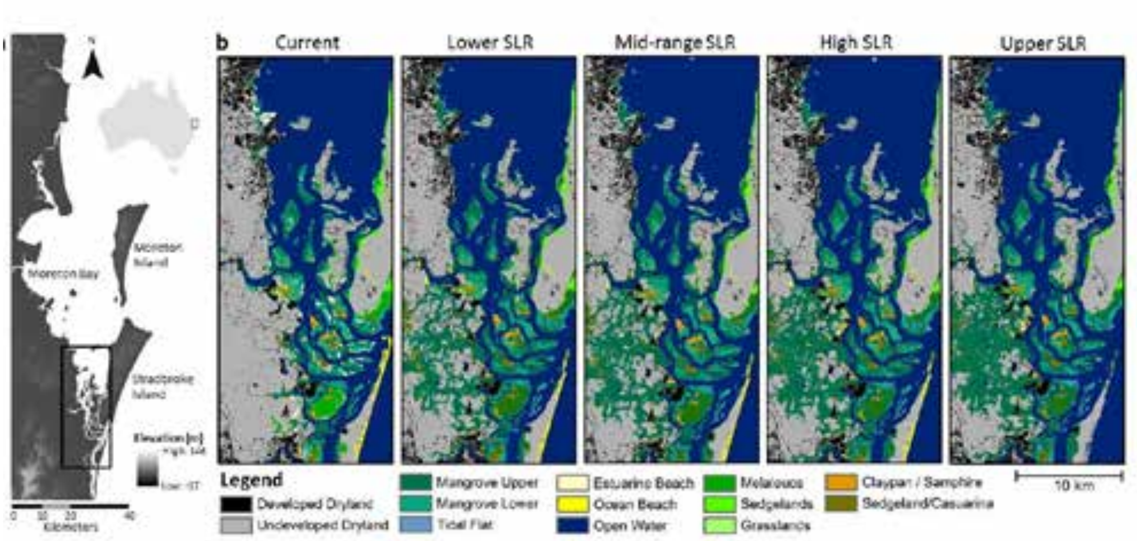

Figure 5. The change in coastal wetland distribution in 2050 under sea-level rise. Panel (a) indicates the location of the study site. Panel (b) shows the impact of different sea-level rise projection on the distribution of coastal wetlands in 2050, and how these compare to the current distribution (lower=10.3 cm, mid-range=20.2cm, high=36 cm, upper=47 cm). All scenarios assume no further urban development.

Table 3. Total area of mangroves and salt marsh protected and unprotected based on different projections of sea-level rise by 2050 (low=10.3 cm, mid =20.2 cm, high=36 cm, upper=47 cm). All values are in hectares and calculated based on modelling reported in Runting *et al.* (13).

		Current	*Low*	*Mid*	*High*	*Upper*
Mangroves	*Protected*	1,015	1,492 (+47%)	1,595 (+57%)	1,787 (+76%)	1,856 (+83%)
	Unprotected	6,193	10,235 (+65%)	10,922 (+76%)	11,944 (+93%)	11,860 (+92%)
	Total	*7,208*	*11,727 (+63%)*	*12,517 (+74%)*	*13,731 (+90%)*	*13,716 (+90%)*
Salt marsh	*Protected*	493	481 (-2.4%)	461 (-6.5%)	428 (-13%)	371 (-25%)
	Unprotected	1,158	1,480 (+28%)	1,408 (+22%)	1,245 (+7.5%)	1,092 (-5.7%)
	Total	*1,651*	*1,961 (+19%)*	*1,869 (+13%)*	*1,673 (+1.3%)*	*1,463 (-11%)*

network. This highlights the importance of expanding the reserve network (or rezoning land) to accommodate the potential landward movement of coastal wetlands subject to sea-level rise.

Historic changes in sea level have impacted coral reefs in Moreton Bay in the past (15) as have human activities such as land-clearing causing increased sedimentation and turbidity. It is unclear how corals will respond to future sea-level change as future impacts of sea-level rise (and other drivers) on coral reefs in Moreton Bay have not been assessed. In general, increasing water level over reefs that are currently constrained by water level increases accommodation space, allowing corals to resume upwards growth (e.g. Saunders *et al.* (16)). However, the increasing temperatures in the Bay have implications for exposure to temperatures that could cause bleaching. In combination with the effects of ocean acidification on the capacity for calcification and growth (17), the future for corals becomes more uncertain.

Conclusions

The Moreton Bay region is likely to see significant population growth and climatic changes in the coming decades. By 2050, under the high RCP8.5 emission scenario, mean annual air temperature could be 1.7ºC higher, rainfall could decrease by 7%, and sea levels could be up to 27 cm higher. The human population is likely to increase by 1.8% yr^{-1} over the coming decades, leading to an overall population increase to 4.8 million by 2036 These changes will undoubtedly affect both human and natural systems, as we have illustrated here, with substantial shifts in the distribution of coastal ecosystems in the region by 2050. These impacts should be considered conservative projections, and the cumulative impacts of growing human populations and the full range of climate change phenomena could lead to more extreme changes throughout the Moreton Bay region.

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Chapter 5 - Habitats, Biodiversity and Ecosystem Function

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Primary producers in Moreton Bay: Phytoplankton, benthic microalgae and filamentous cyanobacteria

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Abstract

Phytoplankton and benthic microalgae are critical to the ecosystem productivity of Moreton Bay. The Bay is oligotrophic for most of the year, with acute nutrient pulses delivered by high rainfall events. These nutrient pulses are important drivers of primary production leading to phytoplankton growth and shifts in species composition. Consistent with many coastal areas of the world, the phytoplankton community is dominated by diatoms and a range of pico- and nanoplankton. A west to east gradient of phytoplankton standing stocks across the Bay reflects the influence of river and groundwater discharges. In the past, sewage discharge has also been a significant driver of phytoplankton growth in the western region of the Bay, particularly prior to 2000 when a sewage treatment plant at the mouth of the Brisbane River was upgraded to reduce nutrient discharges. The management of sewage successfully reduced phytoplankton standing stocks, and appears to have improved resilience to acute rainfall events. Acute rainfall events also deliver pulses of sediments, particularly from catchments cleared of vegetation, which affects Moreton Bay light conditions in the water column and silt content of the sediments. The species composition of benthic microalgae (BMA) in the Bay is dominated by diatoms and is driven by the silt content of the sediment. It is hypothesised that low light conditions limit benthic algae and phytoplankton productivity during and following events, in the same way that light limitation affects seagrass productivity; however, research in this area is limited. The exception to diatom dominance in the shallow sediments is in locations where the toxic benthic cyanobacterium *Lyngbya majuscula* occurs. *L. majuscula* blooms have become regular in occurrence, especially in the north western Bay. Anthropogenic influences including changes in nutrient inputs likely led to these increased occurrences. Overall the phytoplankton and BMA biomass and species composition of the Bay reflect a relatively healthy system that has improved in response to management intervention. Despite this, persistent chronic pressure from catchment-derived sediment and nutrients has potential to erode this resilience.

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Keywords: microphytobenthos, diatoms, flood, cyanobacteria, productivity, sewage, *Lyngbya*, nutrient limitation

Background

Phytoplankton and benthic microalgae (BMA) are critical for the productivity, water quality, habitat condition and biodiversity in Moreton Bay (the Bay). In the Bay it is estimated that phytoplankton contribute 74% to Bay productivity and BMA 9% (5). In coastal systems globally, these primary producers are under pressure from increasing sediment and nutrient enrichment caused by human development. Nutrient enrichment can cause persistent phytoplankton blooms and shifts in phytoplankton community composition, which in extreme cases leads to harmful algal blooms (HABs) and hypoxic dead zones (6, 7, 8). Such conditions in turn affect light and oxygen at the benthic interface, leading to species shifts and growth limitation of the benthic microalgae (BMA). Changes in and loss of BMA affect nutrient cycling and increases nutrient availability for pelagic productivity, furthering degrading water quality and habitat conditions (5, 9).

Moreton Bay is naturally oligotrophic—low nutrients, low productivity (<100 g C m^{-2} y^{-1} following the Nixon (10) classification)—and on a global scale it is a relatively undisturbed system (11–13). However southeast Queensland is one of the fastest growing regions in Australia, with a current human population of 3.5 million (14) and over the years there have been indications of anthropogenic impacts, specifically eutrophication, in some regions of the Bay. This chapter synthesises the existing understanding of phytoplankton and BMA communities of the Bay, and highlights human pressures that may impact growth and species composition of these primary producers.

Phytoplankton

Community characteristics

Abundance and distribution

Moreton Bay is oligotrophic for most of the year with acute nutrient pulses delivered by high rainfall events that stimulate productivity (15–18). These nutrient pulses are important drivers of primary production leading to phytoplankton growth (19–21). A west to east gradient of phytoplankton standing stocks across the Bay reflects the influence of river discharges (Fig. 1). Overall the mean annual chlorophyll (Chl *a*) concentration in the Bay is 2.09±0.5 µg L^{-1}, based on monthly samples between 2006-2016 at 67 long-term monitoring sites (2) (Table 1). In the western and southern regions of the Bay, there is a significant riverine influence, with mean annual Chl a concentration of 2.20 ±0.7 and 2.36 ±0.8 µg L-1 respectively. The range of annual maximum Chl a for these regions is 6.2-37.4 and 7.3-44 µg L-1 respectively. In the eastern bay Chl a levels are relatively low, as this region is least influenced by river discharges and has the strongest oceanic influence (0.87±0.28 µg L-1). Chl a concentrations are highest during the wet summer months when rainfall and runoff is highest (approximately September-April), and lowest in the dry winter months (approximately May to August) (12, 22, 23).

Queensland Government policy sets water quality objectives for maintaining the environmental value of the Bay, which include objectives for Chl *a* concentrations. The mean annual Chl *a* concentrations in the western and southern regions for the period 2006 – 2016 reached or slightly exceeded these guideline values. In contrast, the eastern regions more frequently fall below guideline maximum values (Saeck *et al.* this volume (25)) (Table 1).

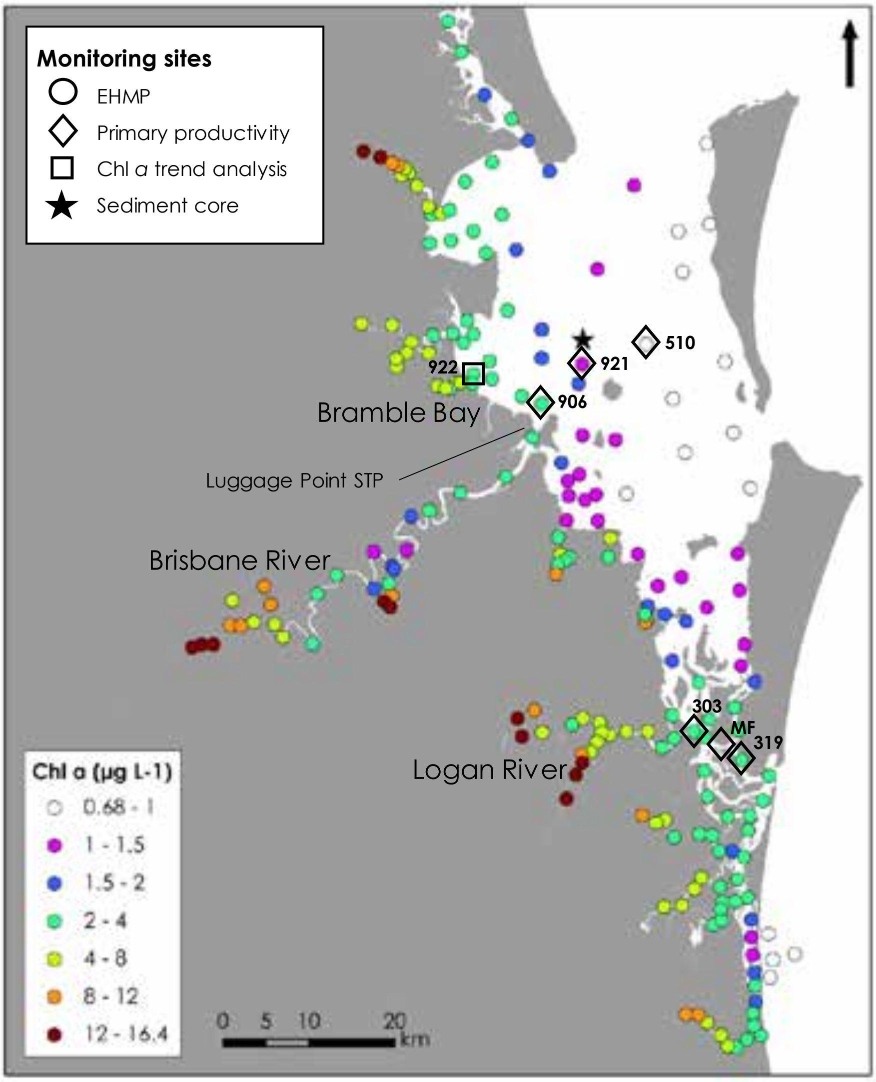

Figure 1. Mean chlorophyll *a* concentrations (μg L^{-1}) at long-term monitoring sites (Ecosystem Health Monitoring Program (EHMP)) throughout Moreton Bay based on monthly sampling for the period 2006-2016 (n = approx. 120 per site) (2).

Productivity rates

In 1997 O'Donohue & Dennison (26) concluded that Moreton Bay has overall low areal phytoplankton productivity (<25 mg C m^{-2} h^{-1}) due to light and nitrogen limitation during summer and temperature limitation during winter (26, 27). Peaks in phytoplankton productivity occur following rainfall events. The system is slightly net autotrophic, with an estimated 3% of carbon being exported to the ocean. It is hypothesised that rapid recycling of the nitrogen pool in the water column supports these rates of primary productivity within the Bay (5, 28).

Table 1. The Mean chlorophyll *a* concentrations (µg L^{-1}) in Moreton Bay based on long-term monitoring sites, compared against the Queensland Government (2009) water quality objectives for different regions of the Bay (Ecosystem Health Monitoring Program (EHMP)) sampled monthly for the period 2006-2016 (n = approx. 120 per site) (2, 24).

Region	Mean annual Chl *a* (µg L^{-1}) (±SD)	Min (µg Chl *a* L^{-1})	Max (µg Chl *a* L^{-1})	Queensland Govt water quality objectives (2009) (µg Chl *a* L^{-1}) (24)
Moreton Bay overall	2.09±0.5	<0.10	44.0	
Western Bay	2.20 ±0.7	<0.10	37.4	<2.0
Southern Bay	2.36 ±0.8	<0.10	44.0	<2.0
Eastern Bay	0.87±0.28	<0.10	11.1	<1.0

Few studies have measured phytoplankton productivity rates in Moreton Bay since 2000 (5, 23, 29). Saeck (unpublished data) measured productivity rates across the Bay in 2009 and 2010 using ^{13}C uptake incubations as per Burford *et al.* (30). The study found areal productivity rates significantly higher in the delta region of southern Moreton Bay compared with the central region (Fig. 2). Cloern (13) reviewed phytoplankton productivity rates across natural and modified coastal systems globally and reported that 29 mg C m^{-2} h^{-1} is the median rate, with maximum rates of 215 mg C m^{-2} h^{-1}. As such, in a global context, measured Moreton Bay rates fall below global medians, especially during dry conditions (noting that methods to measure productivity differs between studies and can cause significant variation in rates) (Fig. 2) (13).

Community composition

The Moreton Bay phytoplankton community includes species most typical of the *temperate neritic* assemblage, as described by Jeffrey & Hallegraeff (31), with an abundance of chain-forming diatoms (Fig. 3, A-D) and a low proportion of nano- and picoplankton (1, 32, 33). The community responds to highly variable and episodic intrusion of land-derived nutrients, following which the ever-present diatom populations form peaks in biomass (1). However, there is spatial variation across the Bay, with relatively more oceanic and dinoflagellate species in the northern regions compared with the south (29, 32, 34).

Nutrient status

Moreton Bay phytoplankton growth rates are typically limited by nitrogen, meaning that when nitrogen availability increases growth is stimulated. This observation is based on: coupled physical and biogeochemical modelling of Moreton Bay (35, 36); phytoplankton bioassay experiments (23, 26, 29, 37); and trend analyses of water quality monitoring data (22). Nutrient budgets calculated for Moreton Bay have found the rivers and catchment only contribute 1% of phytoplankton demand for dissolved inorganic nitrogen, suggesting significant reliance on nitrogen recycling, benthic fluxes and N fixation to meet nitrogen demands (5).

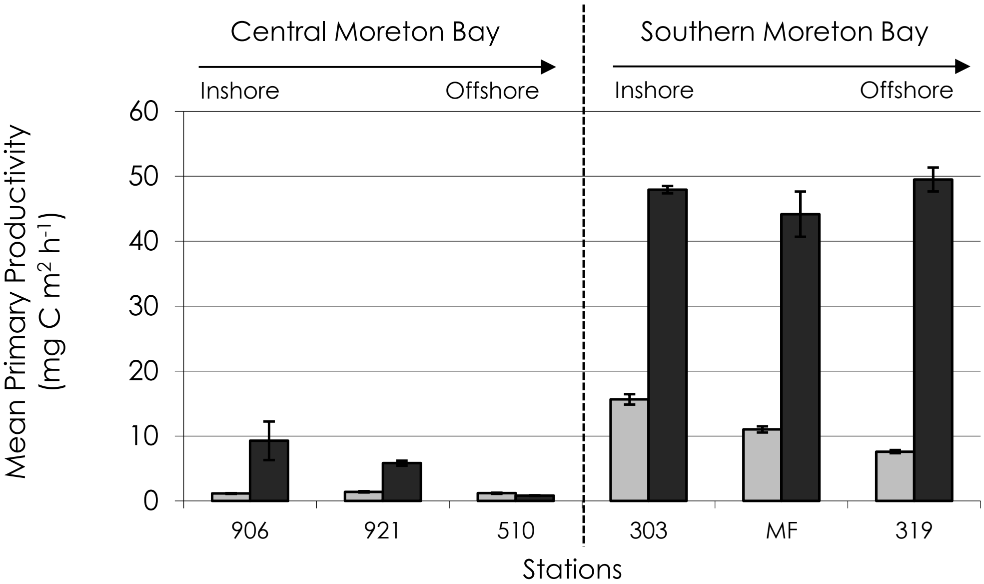

Figure 2. Spring/dry condition (grey bars) and summer/wet condition (black bars) primary productivity rates (mg C m-2 h-1) measured (using 13C uptake methods) in central (906, 921, 510) and southern (303, MF, 319) Moreton Bay (Saeck, unpublished data). Spring samples were collected under dry conditions (November 2009) and summer samples were collected during high rainfall inflow conditions (February 2010). Error bars represent standard error of three replicate samples. Refer to Figure 1 for map of station locations. Error bars represent standard error of three replicate samples. Refer to Figure 1 for map of station locations.

The degree of nitrogen limitation varies across the Bay, reflecting the west to east nutrient gradient and the influence of river discharges and groundwater input (38). Specifically, studies have found low or no phytoplankton response (measured as growth, carbon uptake and/or photosynthetic yield, F_v/F_m) to nitrogen in samples collected from the nearshore areas at the mouths of Brisbane and Logan River, whereas samples from the central to eastern Bay consistently responded to nitrogen addition (29, 37, 39).

Furthermore, Saeck *et al.* (37) found that when ambient dissolved inorganic nitrogen concentrations were higher than 2 µm L^{-1}, phytoplankton photo-synthetic yield (F_v/F_m) in bioassays of Moreton Bay water samples did not respond to additions of dissolved nitrogen (N). This suggests an ecological threshold above which Moreton Bay phytoplankton consistently have a high potential for growth and subsequent blooms, unless limited by other factors such as light, Phosphorus (P), silica (S), iron (Fe) or residence times.

In terms of nutrients other than N, Glibert *et al.* (23), O'Donohue *et al.* (26) and Quigg *et al.* (29) found little to no increase in growth response with P additions. Phytoplankton may respond to P by increased P storage, rather than growth. However, the lack of an increased response to N and P together suggests that there is no co-limitation of these two nutrients. Glibert *et al.* (23) similarly found minimal response to Si, and concluded that Si is unlikely to limit phytoplankton biomass in the Bay.

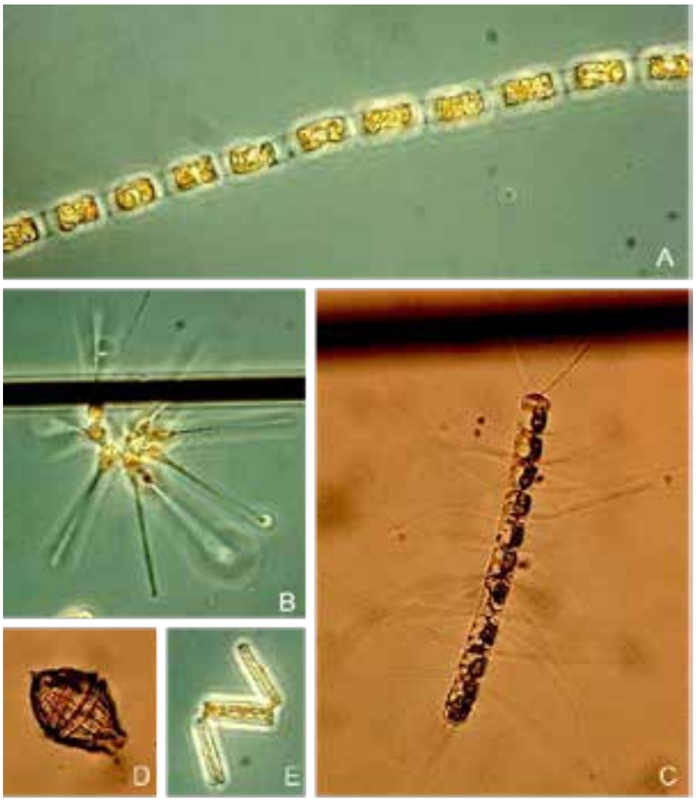

Figure 3: Images of phytoplankton sampled from Moreton Bay (1): A) Skeletonema costatum; B) *Asterionellopsis* sp.; C) Chaetoceros sp.; D) *Protoperidinium* sp., and E) *Thalassionema* sp.

Pressures

Vulnerability to acute nutrient inputs from high inflow events

Increased phytoplankton abundance following high rainfall and river inflow events is a pattern broadly found in coastal studies (e.g. Burford *et al.* (40); Valdes-Weaver *et al.* (41)). Runoff events deliver new dissolved inorganic nitrogen and Moreton Bay phytoplankton respond by increasing productivity, growth rates and photosynthetic yields (1, 23, 26). Typically, there are increased abundance of phytoplankton in the western and southern regions of Moreton Bay following events, irrespective of season (1, 29, 32).

Phytoplankton community composition varies when comparing different high inflow events, with no consistent pattern of response. This is because the conditions associated with each event are unique, as every flood varies in nutrient, turbidity and flow characteristics. Previous studies of coastal systems have reported significant variability in species response patterns to new nutrient inputs, not only between locations but also between events (42, 43). In Bramble Bay, Saeck (1) found diatoms consistently dominated the initial peak — typically large chain-forming species — but the proportion of these species varied. In the 1996 Brisbane River flood event the community was dominated by Bacillariaceae and Rhizosoleniaceae; the 2009 event was diverse with significant contributions from Chaetocerotaceae, Thalassiosiraceae, Fragilariaceae and Leptocylindraceae; while the 2011 event was dominated by Skeletonemaceae and Chaetocerotaceae (1, 44).

Phytoplankton blooms off the east coast of Australia have been described by Hallegraeff and Jeffrey (45) to follow a predictable succession pattern from dominance by small chain-forming species to large centric species and eventually to large dinoflagellates. Most studies of the Bay have not detected a consistent diatom to dinoflagellate succession pattern following high flow events (1, 44), but this may be due to the limited sampling frequency following events.

In addition to nutrients, high flow events introduce suspended particulates that strongly increase light attenuation and would be expected to influence pelagic primary productivity. Light limitation affects BMA and seagrass productivity in the Bay (46, 47, 48). As such, by extension, it is hypothesised that light limitation would act on phytoplankton productivity following events. However, research in this area is limited.

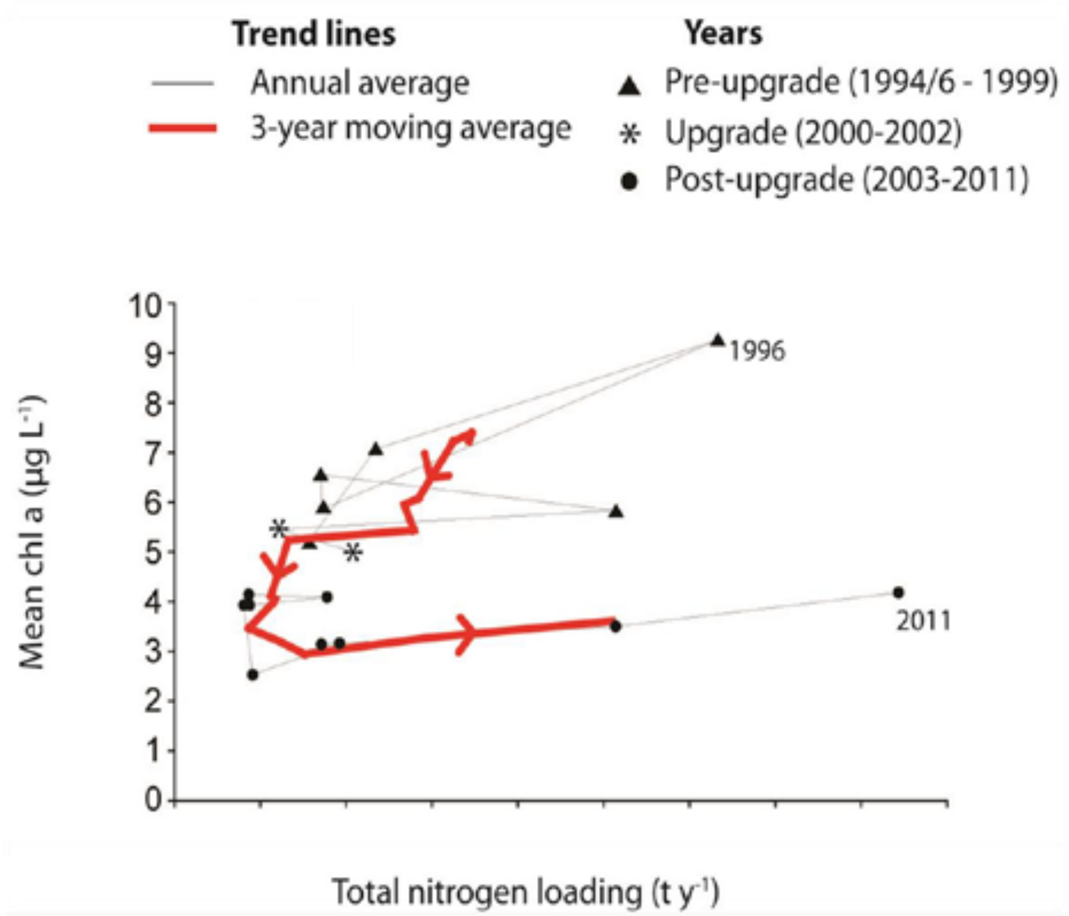

Figure 4. Trajectory of annual mean Chl a concentration (µg L^{-1}) at a station influenced by the Brisbane River Plume and sewage treatment plant outfall (Station 922, refer to Figure 1 for map). Redrawn from Saeck *et al*. (22).

Vulnerability to chronic sewage nutrient inputs

Studies have shown that discharged sewage loads discharged can impact the phytoplankton community dynamics, including increasing standing stocks and extending the duration of blooms resulting from catchment flow events (9, 49, 50). Historically (prior to 2000) Bramble Bay, in western Moreton Bay, was characterised by elevated nitrogen concentrations (4 - 8 µmol L^{-1} dissolved inorganic nitrogen (DIN)) and phytoplankton biomass (4 - 10 µg L^{-1} Chl *a*) (22). This eutrophication was found to result from sewage related nitrogen (22, 35, 36, 51) and prompted major investments to improve the nitrogen removal capacity of sewage-treatment plants in the region. The reductions in chronic sewage nitrogen loads resulted in reduced mean monthly Chl *a* concentrations. Following sewage reductions (post 2003) Chl *a* concentrations were consistently lower at inshore sites, compared with years prior to the sewage treatment plant upgrades (mean below 2.0 and 4.5 µgL-1 for Stations 921 and 906 respectively) (2, 22) Saeck *et al.,* this volume (25).

Comparison of the response of phytoplankton to the high flow events of 1996 (prior to sewage N reductions) and 2011 (decade after sewage N reductions), found that the two events were associated with a total annual nitrogen load of similar size. However, the phytoplankton response to these events was significantly different (Fig. 4) (22). A single runoff event can deliver a nutrient load larger than the total annual sewage treatment plant (STP) load. Notably, the bloom associated with the 2011 flood peaked and fell within two weeks of event, compared with the 1996 flood when high phytoplankton abundance persisted throughout the year (Fig. 4). This suggests that reduction of chronic nutrient loads to Moreton Bay may have been successful in improving system resilience to these large nutrient loading events.

Moreton Bay, like other sub-tropical and tropical coastal ecosystems, is particularly vulnerable to shifts in nutrient delivery patterns (i.e. from acute events to chronic loading) across all seasons. This is because temperature infrequently falls low enough between seasons to limit growth (39). In comparison, in temperate estuaries, sewage nutrients have been found to affect phytoplankton Chl-a only during the warmer summer months (50).

Benthic microalgae (BMA)

Community characteristics

Role in sediment nutrient flux to surface waters

Benthic microalgae (BMA) are found at the sediment water interface (52). Their community composition largely mirrors that of phytoplankton with all major algal groups represented including cyanobacteria, diatoms, dinoflagellates and chlorophytes (53, 54). BMA play a key role in nutrient cycling, occupying the zone between anoxic sediment porewaters and oxic surface waters (5, 55). Sediment porewaters in the Bay generally have two to three orders of magnitude higher of DIN and P concentrations compared to overlying surface waters (36). Oxygenation of sediment surface layers through BMA photosynthesis controls the flux of available N and P to the surface waters (56, 57). However, blooms of N-fixing benthic cyanobacteria can fix significant amounts of N and increase N availability to surface waters (58, 59). The relative importance of N fixation to the overall nutrient budget is dependent upon the frequency and magnitude of these blooms (60).

Abundance and distribution

Udy *et al.* (3) studied the biomass and distribution of BMA at 55 sites across the Bay and found significant patchiness across the Bay, reporting high variability within and between sites. The highest densities were found on the intertidal banks and at depths shallower than 5 m (Fig. 5). Biomass, as indicated by Chl *a* concentration, ranged from 0 to 195 mg Chl *a* m^{-2}. Seasonal patterns in Chl *a* appear to differ between the western and eastern Bay. Specifically, during the cool dry season BMA Chl *a* increases in the western Bay and this is hypothesised to be the result of improved water quality conditions during this period. In contrast, in the eastern Bay, where water quality is higher year round, BMA Chl *a* declines during winter.

Productivity rates

Studies show that the productivity of BMA in the Bay is strongly seasonal, with significant influence of temperature and light availability. Grinham *et al.* (47) reported that BMA productivity across the Bay was typically higher in summer than winter. During summer, when temperatures were highly suitable for growth, productivity was primarily influenced by light and, consequently, by water clarity.

In shallow coastal systems, BMA can contribute up to 50% of the total primary productivity (61), although in Moreton Bay, BMA productivity is estimated to be 9% of total carbon inputs (5). The overall productivity of BMA across the Bay has been estimated in several studies and these range from 50 to 350 mg C m^{-2} d^{-1} (5, 28, 36, 47). As such, BMA and phytoplankton represents the smallest biomass in the Bay compared with seagrass and mangrove (i.e. <1% of the total carbon). However, they contribute the highest productivity (producing 81% of total C y^{-1}) (3, 5, 36). This supports the theory that they have significant influences on nutrient and sediment processes across the Bay.

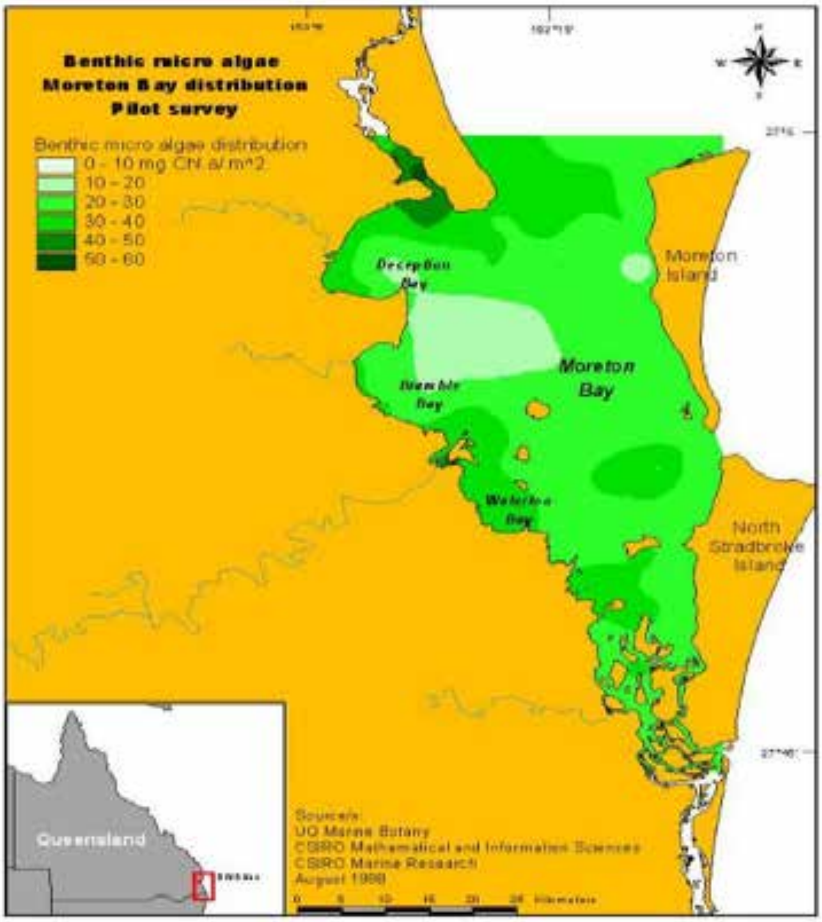

Figure 5. Benthic microalgae distribution (mg Chl *a* m^{-2}) across Moreton Bay based on contour interpolation of Chl *a* data collected August 1998 from a 55-site sampling grid (redrawn from Udy (58)).

Community composition

The Moreton Bay BMA community is dominated by pennate diatoms (3, 47, 62), a pattern typical of many other temperate and tropical coastal systems (52, 53). BMA species typically found in the Bay include those of genera: *Pleurosigma, Navicula, Achanthes, Cocconies, Cyclotella, Paralia, Grammatophora, Amphora,* and *Dimmeregramma* (3, 47, 62). Like water column phytoplankton, there is spatial variation across the Bay in terms of species composition.

Benthic diatoms, and other BMA, live on top of (epipelic) or attached to (epipsammic) the sediment particles. Moreton Bay benthic diatom assemblages are predominantly epipsammic, due to the presence of tidal sand banks made up of terrestrial and marine sands (54). However, there is increasing silt content in the southern areas of the Bay, and this shifts the diatom community structure, increasing the epipelic fraction. It also increases the overall species diversity and favours larger species (47, 51) in these areas. This silt effect has been found in other studies (63– 65).

Pressures

Vulnerability to chronic terrestrial sediment and nutrient inputs

Catchment development in South East Queensland has elevated sediment and nutrient loads delivered to Moreton Bay. Consequently, in the western and southern regions of the Bay nutrient concentrations, silt content and light attenuation are all higher (66). This has affected the productivity, and community composition of Moreton Bay BMA communities, which negatively affects benthic nutrient assimilation capacity reducing benthic productivity more than 50% compared to pre-European settlement (67).

Elevated nutrient concentrations have the potential to increase benthic productivity under high light conditions (47). However, nutrients also stimulate phytoplankton biomass, which can limit benthic light availability. Grinham *et al.* (47) found that productivity was not significantly higher in western and southern Moreton Bay even though nutrient concentrations were relatively higher (68). It was concluded this was the result of light limitation, caused by elevated phytoplankton and suspended sediment levels. Overall, reduced water clarity narrows the depth in which BMA grow and reduces the productivity of those areas.

Experimental studies in other systems demonstrate that BMA species composition may shift in response to nutrient enrichment (64, 69, 70). Sediment cores suggest that in central Moreton Bay, the diatom community as a whole (benthic and planktonic species) has undergone significant changes following the onset of increased nutrient and sediment yields of the coastal rivers draining into the Bay (71). Most notably, there has been a decrease in the abundance of typically benthic diatoms (*Pleurosigma fenestrata, Cylotella litoralis, Grammataphora, Dimmeregramma*) coupled with an increase in the occurrence of planktonic marine diatoms (*Thalassiosira, Thalassiothri*x) and chain forming species (i.e. *Chaetoceros*, *Ceratulina bicornis*). This was also apparent during the 2011 flood event where planktonic diatoms were stimulated over benthic forms (Fig. 6).

Grinham *et al.* (54) found increased diatom diversity associated with silt content across Moreton Bay. Fine sediments are accumulating in the western Bay (73). However, the impact of muddy sediments on BMA community composition has not been studied. Coates-Marnane *et al.* (73) predicted that the fine sediment accumulation in Moreton Bay may be approaching a threshold beyond which sediment resuspension will accelerate and cause chronic light limitation. Generally, in coastal systems, under extreme light attenuation the structure of BMA communities can undergo large shifts, with biodiversity declining until they are completely lost from the system (10). This may have significant implications for nutrient cycling and water quality, and on populations that depend on BMA communities as a source of nutrition, including some benthic invertebrates and herbivorous fishes.

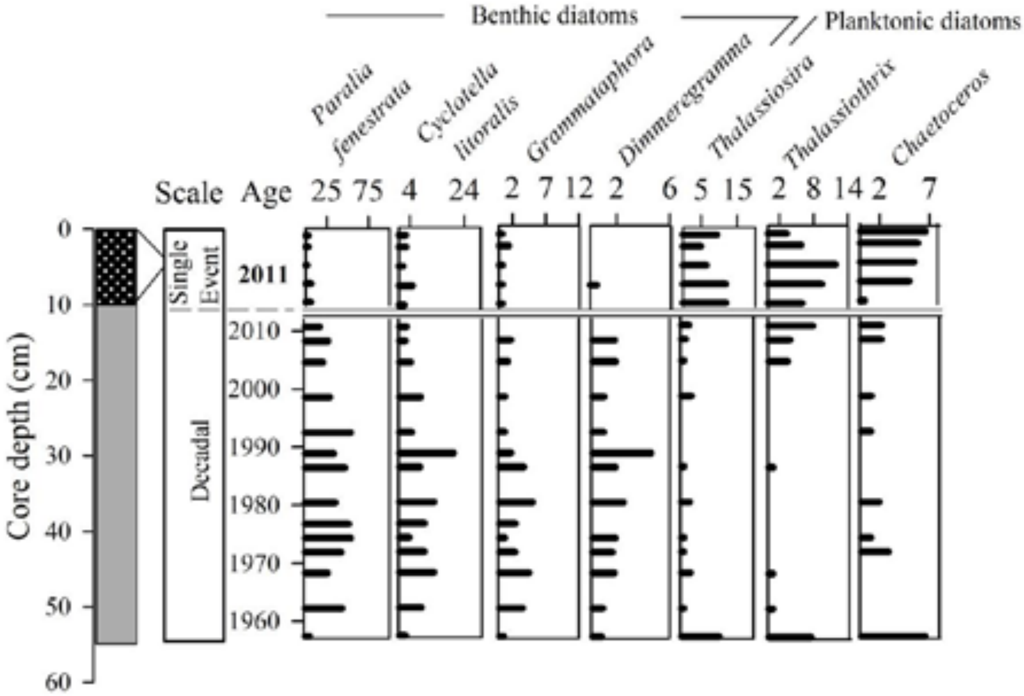

Figure 6. Relative abundance (%) of benthic *(Paralia fenestrata, Cyclotella litoralis, Grammataphora, Dimmeregramma)* and planktonic (*Thalassiosira, Thalassiothrix, Chaetoceros*) diatoms in a sediment core taken from central Moreton Bay representing deposition over the period from 1959 to 2011 (72).

Vulnerability to Lyngbya majuscula *blooms*

Intertidal and subtidal areas of Moreton Bay are vulnerable to blooms of the toxicfilamentous cyanobacterium *Lyngbya majuscula*. This N-fixing and toxin-producing cyanobacteria occurs naturally in the Bay, growing on sediment or attached to macroflora, such as seagrass. Outbreaks of very high biomass can occur when trace nutrients (e.g. Fe) from surface and ground water are available and light and temperature conditions are favourable (59, 74–76). These harmful algal blooms have been occurring in Moreton Bay since 1997, although reports suggest episodic blooms occurred periodically prior to this date, but not at the same scale or frequency (Fig. 7) (77). The increasing occurrences of blooms can be linked to increased nutrient loading. However, the relationship between nutrients and blooms is highly complex and environmental conditions, such as light, temperature, current velocities and redox state of the sediments, must also be favourable (78).

The impact of *Lyngbya* on BMA productivity, distribution and community composition has not been investigated. *Lyngbya* blooms affect light, nutrient and oxygen availability at the benthos (79), which is likely to have a significant impact to the BMA. Studies have found *Lyngbya* blooms can cause shifts in the meiofaunal species assemblages and their depth distribution in the sediments (79, 80). Similarly shifts in the BMA community composition would be expected.

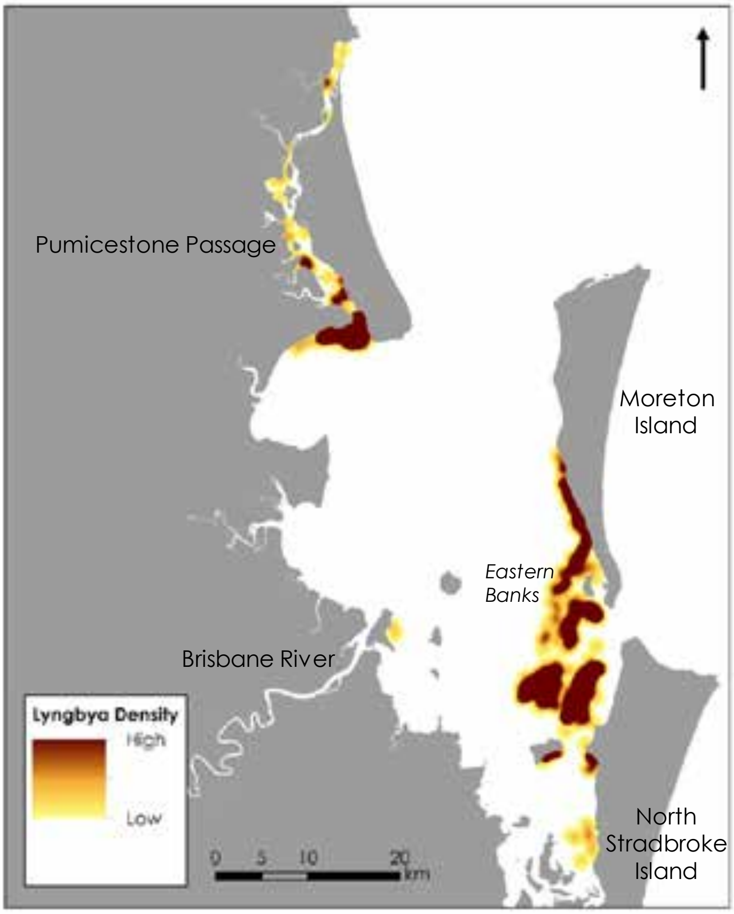

Figure 7. *Lyngbya majuscule* extent based on monitoring data (DEHP, 2003-2012). A kernel density function was applied in GIS using a 1 km density radius to generate the extent and distribution of *Lyngbya* blooms for the time period 2003-2012. This map represents the actual algal bloom risk. An additional kernel density using a 5 km density radius was also generated showing actual and surrounding at-risk areas. The density took into consideration the *Lyngbya* intensity score (4).

Conclusion

Phytoplankton and BMA are critical to the productivity of Moreton Bay and are key indicators of water quality, habitat condition and biodiversity. The Bay remains predominantly oligotrophic with peaks in growth and productivity stimulated by acute nutrient pulses delivered by high rainfall events. Compared to coastal systems around the world, the rates of productivity and abundance of these primary producers are relatively low. This suggests that, despite pressure from human development, the Bay remains relatively healthy and resilient to current levels of nutrient and sediment input from activities within the catchment. Extensive monitoring and management, specifically the investment in upgrades of sewage treatment plants in the early 2000s, have contributed to significant improvements and protection of this resilience.

The Bay's phytoplankton community appears to be resilient to both long-term and short-term changes in nutrient inputs, with no evidence of permanent state shifts to date in response to such changes. Historical trends show that persistently elevated phytoplankton abundance was associated with elevated N concentrations related to sewage nutrient inputs (pre-2003). This appears to have been a temporary change in the community rather than a permanent state shift. The trend was reversed when N in sewage discharges was lowered. This suggests that there was resilience over the long-term to chronic nutrient loads and that management was appropriate. Similarly, on the short-term seasonal scale, phytoplankton abundance and community composition shifts in response to acute nutrient inputs associated with large episodic rainfall events that are typical of sub-tropical and tropical systems. These shifts are also temporary, and the communities return to baseline conditions within approximately two weeks of an event.

The resilience of the Bay's BMA community is less well understood. However, the communities appear to be relatively healthy. Exposure to short-term spikes in sediment loads associated with large episodic rainfall events may cause light limitation at depth and temporarily restrict BMA gross productivity. However, this is a natural and temporary response. More significant is the pressure from chronic sediment loads, with community shifts observed in places exposed to higher levels of siltation. There is a trend of lower BMA biomass in central Moreton Bay, an area of high 'mud content' associated with the Brisbane River plume, and in southern Moreton Bay. Over time high levels of siltation can result in loss of BMA from the system, a state change that would significantly limit Moreton Bay's productivity and nutrient assimilation capacity.

Research on groundwater influences to Moreton Bay indicate that it is a major contributor to the hydrological and biogeochemical cycles, relative to riverine inputs (38). As such, the role of groundwater in driving productivity relative to other nutrient inputs may be significant, however, there is a gap in research in this area. There are also gaps in our understanding of light limitation impacts on phytoplankton and BMA communities, despite research suggesting sediment, which impacts light conditions, is considered a dominant pressure on Moreton Bay (81, 82).

Diffuse nutrient source management is a priority to protect the Bay from the current and growing pressure of siltation and eutrophication. Grinham *et al.* (83) demonstrated that nutrient concentrations and sediment discharge associated with major flood events are even higher than previously thought. As the Bay's catchments remain degraded nutrient loads will continue to increase, as will infilling by sediment (73, 81, 82). These factors will increasingly impact biogeochemical processes and hence primary producers of the Bay. Catchment rehabilitation programs will have the twin benefits of reducing diffuse nutrient loading as well fine sediment particle deposition to the Bay. The reduction in fine sediments would also improve benthic light flux regime within the Bay and allow further reductions in nutrient availability by reducing the sediment nutrient flux contribution.

Maintaining long-term water quality monitoring is also a priority for tracking and responding to shifts in eutrophication pressure on the Bay. Over the years, monitoring of nutrient indicators in the Bay has been instrumental in the identifying and communicating the need for investment in nutrient management (84). However, nutrient pools are dynamic, with regeneration and update occurring at times scales not picked up with monthly monitoring. Nutrient concentrations and loads alone are not useful for predicting ecosystem effects (37). Monitoring programs that couple water quality indicators with ecosystem indicators, such as phytoplankton and BMA community composition and nutrient response, are critical for identifying pressures on the Bay ecosystems.

The conceptual diagrams in Figures 8 and 9 synthesise the existing understanding of phytoplankton and BMA communities of the Bay, and highlight how acute and chronic pressures from nutrient and sediment pollution may affect growth and species composition of these primary producers. While current trends and patterns suggest ecosystem resilience to such pressures, there is evidence that without action, ongoing chronic pressures could threaten and tip this resilience in Moreton Bay.

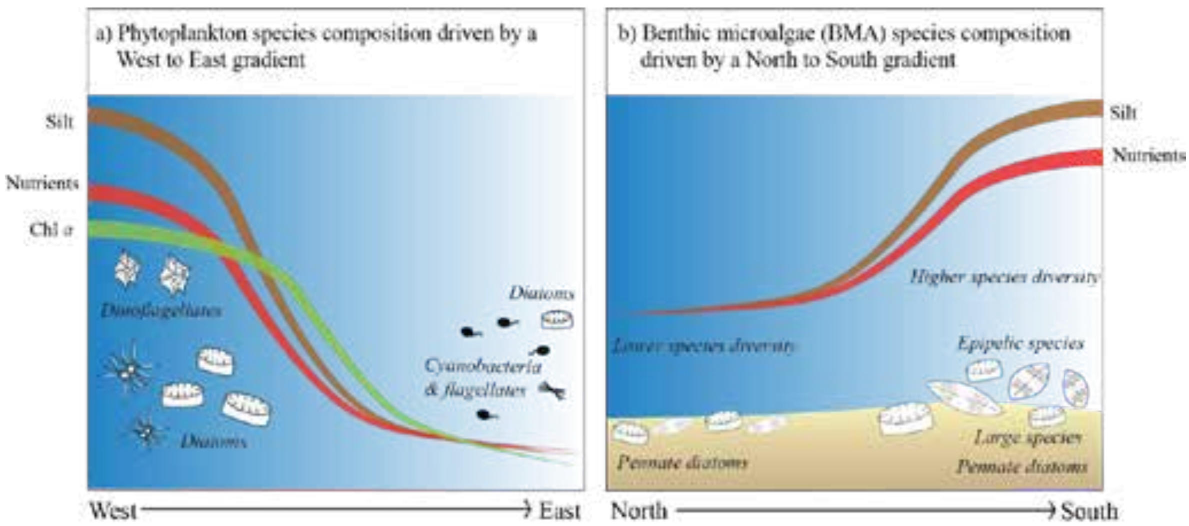

Figure 8. Conceptual diagram summarising how a) west to east gradients in nutrient and sediment affects phytoplankton species composition, and b) north to south gradients affect BMA community composition**.**

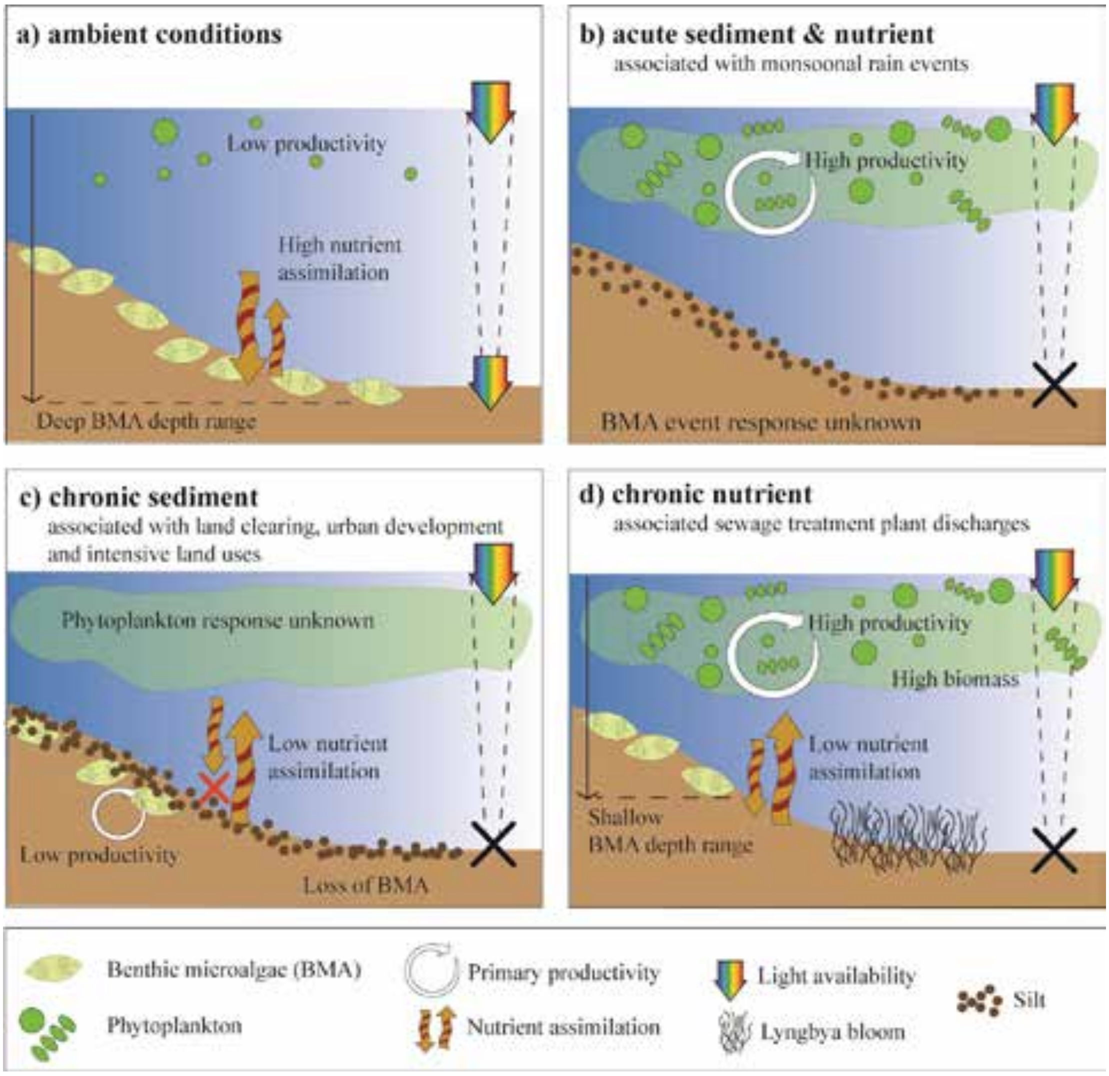

Figure 9. Conceptual diagrams of Phytoplankton and BMA response under different management and climate scenarios 1) ambient conditions, 2) acute sediment and nutrient inputs associated with monsoonal rain events, 3) chronic elevations in sediment loads associated with land clearing, urban development and intensive land uses, and 4) chronic nutrient inputs associate with sewage treatment plant discharges.

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Seagrasses of Moreton Bay *Quandamooka*: Diversity, ecology and resilience

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Abstract

Seagrasses are a dominant feature in the seascape of Moreton Bay. They host numerous animals and provide the region with a wide range of ecosystem services that we are only beginning to better understand. In the past 20 years, the focus of seagrass research in Moreton Bay has shifted towards predictive modelling based on comprehensive ecological understanding. There are seven species of seagrasses in Moreton Bay that persist across a wide range of environmental conditions from muddy sediments in the western Bay to the cleaner, sandier waters of the eastern Bay adjacent to Moreton (Moorgumpin) and Stradbroke (Minjerribah) Islands. There has been an encouraging recovery of meadows in some of the more degraded parts parts of the Bay, yet with an ever-increasing human population in South East Queensland, the threats to seagrasses still require continued research effort and careful management. This paper reviews the current understanding of Moreton Bay's seagrass meadows and provides recommendations for future research.

Keywords: climate change, estuary, eutrophic, sediment, nutrient, flood

Introduction – Seagrasses in the global context

Seagrasses are the dominant habitat-forming component of many shallow coastal zones globally. They provide critical services such as habitat (1), nutrient recycling (2), coastal stabilisation (3) and carbon sequestration (4). These services are estimated to be worth approximately \$27,000 $ha^{-1}yr^{-1}$ (5), yet despite this value, humans have contributed to steady declines of seagrass extent globally. Loss of seagrass has accelerated from 0.7% pre-1945 to 9% annually post-1945 (6). A range of global threats have been documented: declining water quality from increased sedimentation causing light stress, physical removal through land reclamation, eutrophication causing algal overgrowth, increasing sea surface temperature, and increased frequency of storms (7).

The seagrasses of Moreton Bay are not immune to these threats, which have been increasing steadily since the 1990s (8). Sediment accretion in the central basin in Moreton Bay has increased by three to nine times over the past 100 years (9), suggesting large-scale changes to sediment erosion from catchments flowing into the Bay. Major floods have resulted in seagrass loss in the Bay with nearly 20 km^2 lost from southern Deception Bay during the 1996 flood (10). The predicted rise in the population of South East Queensland from approximately 3.5 million in 2016 to 5.35 million by 2040 (8) means that pressures on seagrass ecosystems are likely to increase for the foreseeable future. Despite the forecast, and in the period since the publication of the first Moreton Bay and Catchments book (10), nutrient concentrations in the western part of Moreton Bay have declined significantly (see Saeck *et al.* (11), this volume) due to the nearly \$1 billion spent on improvements to sewage treatment.

This paper outlines advances in our knowledge of seagrass responses to threats that have been collected since the previous Moreton Bay & Catchment book released in 1998. We discuss the current distribution and diversity of seagrass ecosystems in Moreton Bay and how patterns have changed over time, the role of ecological feedbacks in driving resilience of the Bay's seagrasses to floods, the projected effects of climate change and land-use change, and the diversity of fauna that rely on the Bay's seagrass meadows.

The diversity and distribution of seagrasses in Moreton Bay

There are seven species of seagrasses in Moreton Bay. Seagrass is distributed across Moreton Bay (Fig. 1), predominantly in intertidal and subtidal regions to 5 m depth (below lowest astronomical tides, LAT), but some meadows of *Halophila* spp. in the northern Bay grow below 10 m depth. Seagrasses range from colonising species (*Halophila ovalis*), to opportunistic species (*Zostera muelleri*) and persistent species (*Cymodocea serrulata*). Colonising and opportunistic species are faster growing and short-lived, and recover rapidly following disturbance (12) (Fig. 2). Moreton Bay is, however, devoid of the larger, highly persistent species that grow in northern Australia (e.g. *Enhalus* spp.) and southern and western Australia (e.g. *Posidonia* spp.).

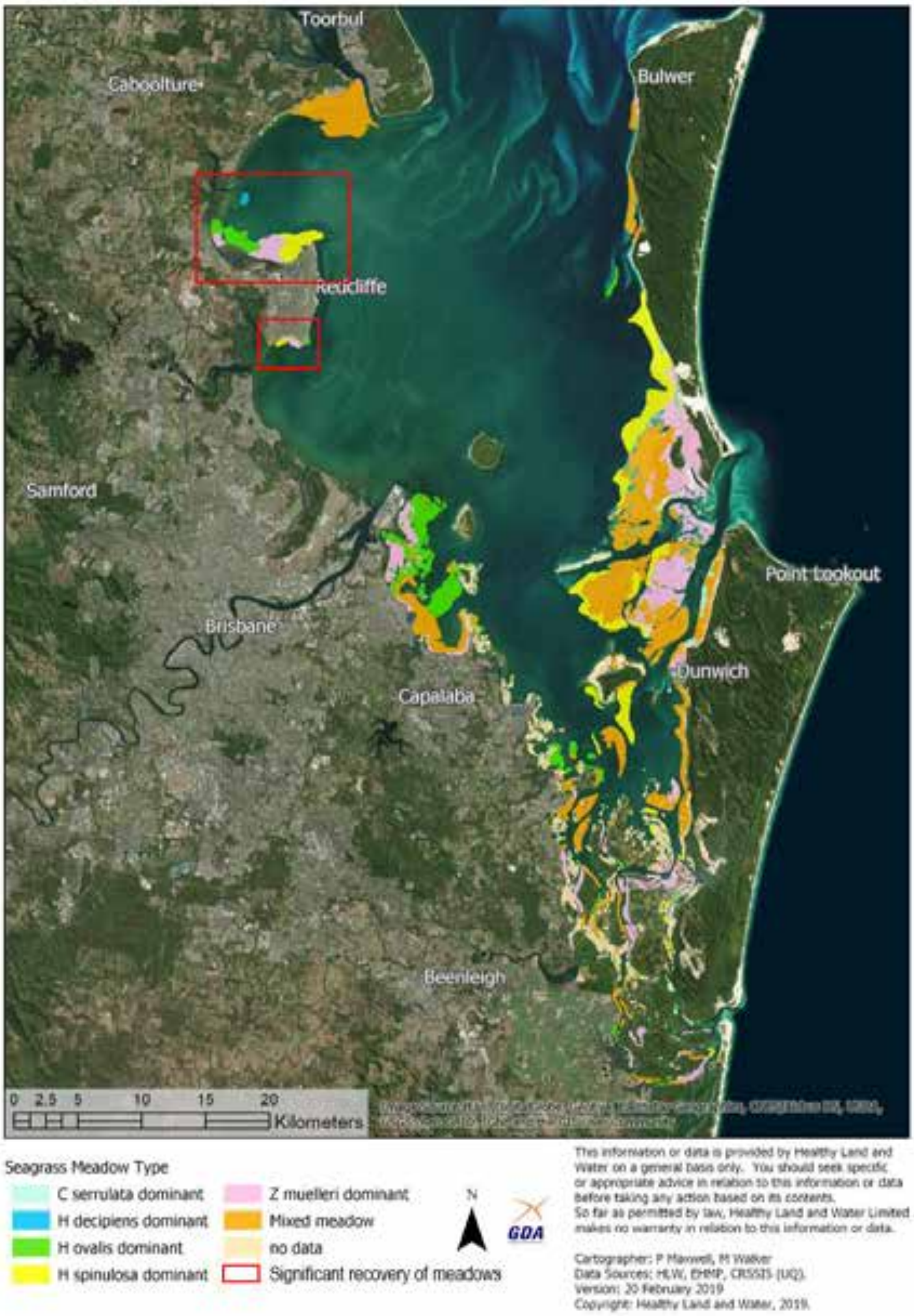

Figure 1. The distribution of seagrass species in Moreton Bay. Mapping conducted as part of the Ecosystem Health Monitoring Program (EHMP) in conjunction with research by the CRSSIS, University of Queensland (funded by Coastal Co-operative Research Centre). First published 2004, last updated 20 Feb 2019 by Healthy Land and Water.

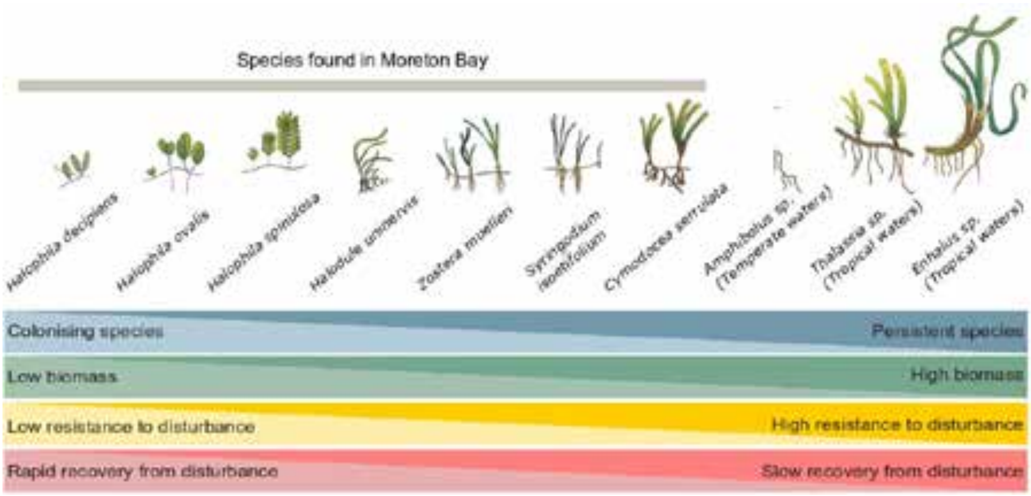

Figure 2. Characteristics of seagrass species found in Moreton Bay. Moreton Bay is dominated by colonising and opportunistic species that tend to be fast-growing and short-lived with a rapid recovery rate following disturbance, providing the conditions growth are suitable. (Adapted from (12)).

The largest expanse of seagrass in Moreton Bay is on the eastern side with mixed species meadows occupying the extensive intertidal and shallow subtidal Eastern Banks between Moreton and North Stradbroke islands. At least six of the seven species are found on and around these banks, with *Z. muelleri, H. univervis* and *H. ovalis* occupying the intertidal areas and *Syringodium isoetifolium* and *Cymodocea serrulata* dominating the shallow subtidal areas between –1 m and –2 m LAT. *Halophila spinulosa* dominates the deeper areas of the eastern Bay between –2 m LAT and –5 m LAT. In this area of the Bay, the species diversity and cover (%) vary through space and time (13), particularly on the Maroom and Amity banks, suggesting that changes in environmental conditions on the Eastern Banks (e.g. sediment movement, current) are a strong influence.

The diversity of species within meadows drops in the poorer water quality regions of the southern and western embayments of Moreton Bay (Fig. 1). These areas contain four species, the dominant being *Z. muelleri* which occupies both the intertidal flats and the subtidal zone down to depths of approximately –3 m LAT. *H. ovalis* typically occupies bare patches within *Z. muelleri* meadows in the intertidal zones and in sparse (~1% cover) ephemeral meadows in the deeper areas (~-5 m LAT) between Peel and Macleay islands and in Waterloo Bay between Manly and St. Helena Island. *H. spinulosa* typically occupies depths below the deep edge of *Z. muelleri* meadows.

The highest cover of seagrass in western Moreton Bay occurs in Waterloo Bay to the south of the Brisbane River. Waterloo Bay is dominated by *Z. muelleri* in the intertidal and shallow subtidal areas and by *H. spinulosa* and sparse *H. ovalis* in the deeper subtidal regions of the Bay (14). In the southern Bay channels, seagrass distribution, predominantly *Z. muelleri,* is limited to the thin strips of intertidal and shallow subtidal (0.5–1.0m below LAT) substrate on the edge of deeper channels (15).

A recent study into the relationship between genetic diversity and disturbance in *Z. muelleri*, one of the most widespread and abundant species in Moreton Bay, showed that seagrass meadows subject to long-term poor water quality have lower genotypic diversity (16). This suggests that in highly disturbed sites in the western and southern regions of the Bay, previous disturbances might have selected for a narrow range of genotypes to enable *Z. muelleri* to cope with poor conditions.

Since 1998 three maps of seagrass extent have been produced, however, each of these has used a slightly different technique to collect the information which has meant that finer scale comparisons (e.g. <5 km^2) of seagrass distribution cannot be made with confidence (17). At the larger 'bay scale', however, there has been significant variation in seagrass distribution particularly in Deception Bay and in the southern Bay. In southern Deception Bay, 20 km^2 was lost in 1996 following a significant flood in the Caboolture River catchment (10) (Fig. 1). Seagrass was absent from the area, replaced in part by substantial meadows of the algae *Caulerpa taxifolia*, until approximately 2009 when small patches of *Z. muelleri* appeared in the intertidal zone. Patches consolidated into sparse meadows in the intertidal and shallow subtidal areas surrounding Scarborough boat harbour. Since 2009, the seagrass extent in southern Deception Bay has steadily moved towards the west (Fig. 1) increasing in depth and therefore increasing in extent to nearly 4 km^2 by the first half of 2013 and to 6 km^2 in August 2016 (18).

The distribution of seagrass in other parts of the Bay has remained similar to that of 1996 (17). As pointed out by Roelfsema *et al.* (17), however, the different methods used to map seagrass distribution and the paucity of field-based data collected in 2011 have made it difficult to fully elucidate differences in distribution. There is still little seagrass cover in Bramble Bay; however, temporary populations of the opportunistic species *H. ovalis* have been recorded on some intertidal flats in this region of the Bay (19) since 2013 and more recently meadows of subtidal *Z. muelleri*, *H. ovalis* and *H. spinulosa* have been observed on the southern end of the Redcliffe Peninsula (15). Despite this encouraging news, modelling using water quality monitoring data, sediment erosion estimates, and seagrass distribution data has indicated that a non-linear decrease in habitat suitable for seagrass is expected with the increase in sediment loads predicted under future climate and management scenarios (20).

Impacts of disturbance on the seagrasses of Moreton Bay

The influence of riverine discharge and ongoing resuspension of fine sediments in the western and southern zones of Moreton Bay results in poor water quality. In contrast, the proximity to ocean water via the northern and two eastern passages into the Bay means water quality is typically good in the eastern zones of the Bay, resulting in an east–west decline in water quality across the Bay (11).

Seagrasses worldwide are used as an indicator of water quality impacts. In Moreton Bay, correlations between water quality and the maximum depth limit of seagrass growth have been used as a biological indicator of light availability in the Ecosystem Health

Monitoring Program since 1996 (21). The program was based on the observation that *Z. muelleri* grew to shallower depths as a result of poor light availability due to higher concentrations of phytoplankton and suspended sediments (22). Correspondingly, *Z. muelleri* meadows on the eastern side of the Bay grew deeper correlating well with the water quality gradient across the Bay.

After nearly 20 years of monitoring, this pattern broadly remains with the two deepest *Z. muelleri* sites in the well-flushed locations of northern Deception Bay (2.81 m below LAT) and at Crab Island (3.1 m below LAT) adjacent to Moreton Island (13) (Fig. 3). The sites with the poorest depth range are in the poorly flushed southern Deception Bay where seagrasses were lost following the 1996 Caboolture River flood, or in southern Moreton Bay close to the Logan River mouth (0.26 m deep at Behms Creek near Jacobs Well).

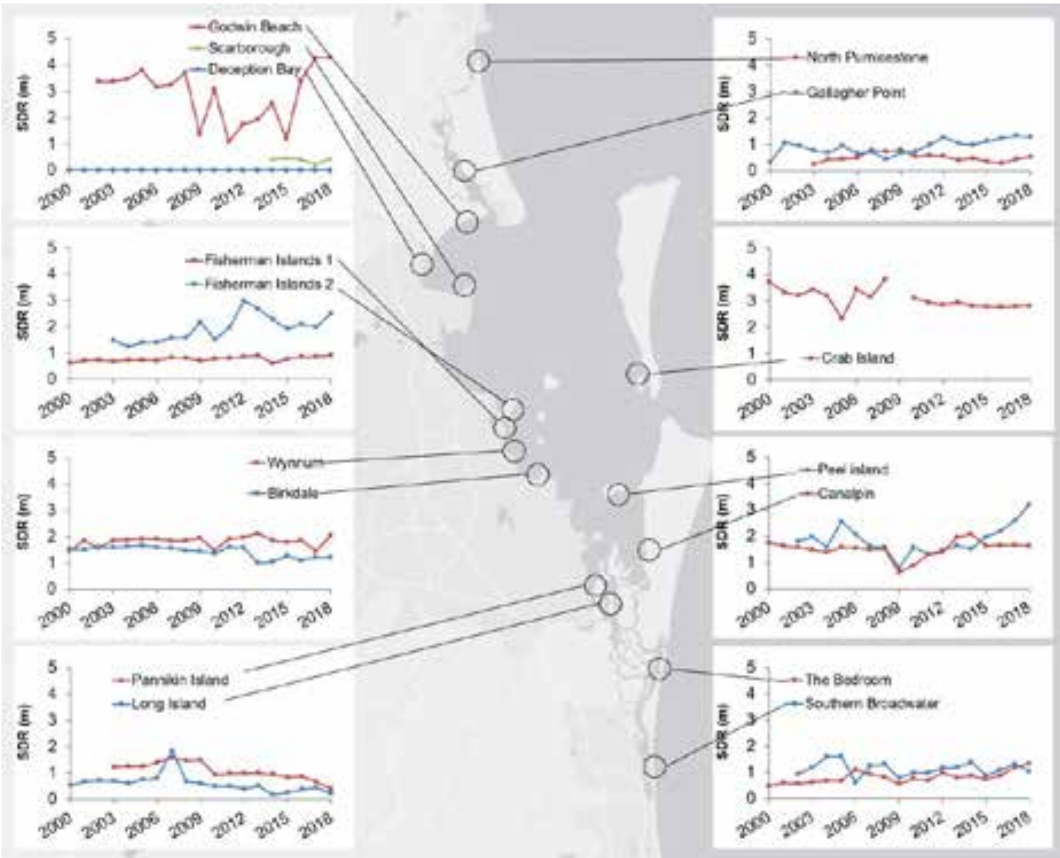

Figure 3. The depth range of *Zostera muelleri* meadows from across Moreton Bay. Typically the meadows in the poorer water quality areas of the western and southern Bays have smaller depth ranges; however, the relationship between water clarity and seagrass depth range is not linear.

At the remainder of the seagrass depth range sites (Fig. 3), the relationship between water quality and *Z. muelleri* depth range is much less distinct. After nearly 20 years of monitoring, the correlation between water quality and depth range is poor (r^2=0.4), with a large variation in mean water quality at the 18 depth range sites outside the extremes.

This suggests that additional factors, rather than just water clarity, are controlling the depth limit at those sites (see section on ‘flood resilience’ for possible alternatives).

The water quality gradient in Moreton Bay does not just influence seagrass distribution. Discharge from rivers on the western side of the Bay delivers organic matter and detritus that accumulates in seagrass meadows throughout the Bay (23). Carbon accumulation in Moreton Bay varies in both space and time (24). Vertical accretion rates and organic carbon burial rates have increased significantly since European colonisation in the catchment. Vertical accretion rates have increased to 0.66 $cm^{-1}yr^{-1}$, highlighting the impact of rapid catchment land-use changes. There is a similar pattern with carbon burial rates, with low rates of both organic carbon (OC) and inorganic carbon (IC) burial prior to colonisation (7 ± 5 g $OC^{-2}yr^{-1}$ and 10 ± 14 g IC $m^{-2}yr^{-1}$ respectively) being much lower than post colonisation (50 ± 82 g $OC^{-2}yr^{-1}$ and 73 ± 115 g IC $m^{-2}yr^{-1}$, respectively) (24).

Despite the stark contrast between pre- and post-European carbon accretion and burial rates, the values from Moreton Bay are generally much lower than worldwide estimates. Pre-European vertical accretion rates in the Bay were recently estimated at 0.06 $cm^{-1}yr^{-1}$, less than half of the world average (25). Various factors may account for this. The rapid pace of land-use change (over approximately 150 years) in South East Queensland compared to the many hundreds of years of land-use change and therefore organic matter accumulation in other areas of the world is a likely factor, particularly in seagrass research hotpots in the Northern Hemisphere where many estimates have originated (26). The relatively low carbon content of South East Queensland soils (27) may play a part as well as the different morphologies and life histories of the smaller, less persistent seagrasses of *Zostera* sp. and *Halophila* sp. compared to the larger, matte-forming temperate seagrass, *Posidonia* (28).

In addition to chronic impacts of water quality, seagrass in Moreton Bay is under threat by large-scale blooms of *Lyngbya majuscula. Lyngbya* is a toxic, filamentous cyanobacteria that attaches to seagrasses and under the right conditions, blooms and smothers the underlying seagrass plants (21). The first well- documented bloom of *Lyngbya* occurred in 1996–97 and covered approximately 7 km^2 of the seagrass meadows off Godwins Beach in northern Deception Bay. Subsequent blooms and reports of the impacts to human health (29) and the crab and finfish harvests in Deception Bay (Greg Savige 2017 pers. comm. 02/04) led to a large-scale, multifaceted program in the mid 2000s to identify the factors that lead to bloom initiation (30–32).

Lyngbya attaches to seagrass and can rise to the water surface after gas bubbles accumulate (33), thereby removing seagrass leaves and causing substantial seagrass impact similar to that seen following light limitation (34). Blooms have been mapped throughout the Bay, varying from 8 to 80 km^2 (35), but have been recorded most regularly in northern Deception Bay and the shallow subtidal seagrass meadows on the Eastern Banks. Multiple interacting factors lead to *Lyngbya* bloom initiation, including the available nutrient pool, water temperature, current velocity and the light environment (32, 36).

Cyanobacteria and algal blooms have a marked effect on the organisms that use seagrass meadows in the Bay. Blooms of *Lyngbya* have a clear negative effect on the nematode, copepod and polychaete assemblages but particularly nematodes which, in meadows affected by blooms, are approximately half as abundant as those of non-bloom meadows (37). The mean density, live mass and number of species of small fish and prawns in seagrass meadows tend to decline during *Lyngbya* blooms, with fish that use both seagrasses and mangroves showing greater decline (38). Epibenthic species show greater decline than demersal species. The effect of blooms also extends to commercial fisheries with data from fishing logs showing how mean monthly fish catch is significantly reduced in bloom years. Despite this, seagrass meadows are not entirely devoid of life during *Lyngbya* blooms, with meadows continuing to function as nursery habitat for a diverse assemblage of fish and prawns (38).

The macroalga *C. taxifolia* has also increased in areal coverage over the past two decades (39–41). *C. taxifolia* is native to Moreton Bay, with museum records dating back to 1946 (42). However, there has been widespread concern over the increasing distribution of *C. taxifolia* given its long history of increasing colonisation in the Mediterranean Sea. Studies in New South Wales and Moreton Bay indicate that *C. taxifolia* is opportunistically colonising unvegetated areas that have already been denuded due to declining water quality, rather than being in direct competition with seagrasses (41, 43, 44). *C. taxifolia* provides some habitat value for fish and invertebrates (45), but selected taxa (most notably Syngnathids (e.g. seahorses and pipefish)) are absent from *C. taxifolia* (45, 46). Additionally, habitat preference studies indicate that fish spent significantly more time in seagrass than *C. taxifolia*, and this is likely due to a combination of structural, visual and chemosensory cues (45).

The rhizome system of seagrasses is easily damaged by bait digging and boat propellers, and even moreso by larger scale removal activities, and if the meadows do recover from such disruption it can take a year or more (47). Unfortunately even low-level trampling (by tourists and educational parties) can have a long-lasting detrimental effect (48).

Resilience to extreme events: the response to the floods of 2011

Extreme events such as floods and cyclones can have sudden, large and potentially destructive effects on the structure and function and ultimately the ecosystem services of marine ecosystems (49). Coastal habitats such as seagrass are especially vulnerable to extreme events, particularly with increases in the likelihood of higher frequency and more intense storms in coastal areas of Queensland.

In January 2011, a flood in the Brisbane River catchment, the largest in 37 years (50) discharged a significant tonnage of sediment into the Bay, reducing the Secchi disc depth (a measure of water clarity) to below 1 m in the western Bay from an average of 2 m (51). The flood caused significant decreases in water quality in the Bay with approximately one million tonnes of sediment estimated to have been deposited following the flood (52).

The most heavily affected meadows in the Bay were in Deception Bay to the north of the river mouth and Waterloo Bay, which is connected to the river via the narrow channel of Boat Passage (Fig. 1). The areas covered by *S. isoetifolium* meadows in northern Deception Bay reduced by approximately 50% following the flood (53). Other seagrass species in the region, predominantly *Z. muelleri* and *H. ovalis,* were largely unaffected by the flood which is likely a result of the salinity range that both species can tolerate (54) compared with *S. isoetifolium*, which in northern Deception Bay is likely at the lower end of its water quality tolerance. This is borne out by the loss of the macroalgae *C. taxifolia* and *Udotea* spp. (53) and the complete absence of epiphytic algae (55), all of which were likely impacted by the predominance of lower salinities following the flood. Loss of species diversity within near-shore meadows in Moreton Bay is highly likely to continue given the predicted increase in extreme storm events. This means that in areas of moderate water quality, diverse meadows could be replaced by mono-specific meadows dominated by *Z. muelleri*, the Bay's most phenotypically plastic species with a wide tolerance for changes in water quality (55).

This plasticity was demonstrated by responses of *Z. muelleri* to the 2011 flood. The meadows closest to the estuarine discharges in the Bay are subjected to chronically poor water quality with light quality that often fluctuates below the minimum light requirements of the species. As a result, *Z. muelleri* in these meadows has physiological and morphological adaptations that maximise photo-efficiency (e.g. increased chlorophyll content, wider and longer leaves, and a greater chl a:b ratio) and enhanced investment in below-ground carbohydrate storage (e.g. increase rhizome starch concentrations) (55).

Z. muelleri in the meadows in the comparatively well-flushed eastern Moreton Bay is characterised by physiological and morphological adaptations typical of plants inhabiting areas of stable water quality and abundant light. Leaves are smaller and thinner with lower chlorophyll content (56, 57), there is a greater energy investment in below-ground biomass and rhizomes are smaller with lower concentrations of carbohydrates. Following the flood, the plants in these meadows exhibited the same physiological response as *Z. muelleri* plants in the western Bay indicating similar levels of stress despite the flood impact being approximately 10% of that felt in the west (55).

The importance of feedback loops for maintaining seagrass meadows

Seagrasses globally are quintessential ecosystem engineers, exerting considerable influence on the environmental conditions that in many cases are essential to their persistence. As seagrass meadows support a diverse range of organisms disproportionate to their area (1), the loss of meadows results in an impact greater than the loss of meadows alone and can significantly reduce their ability to recover. The interactions between seagrass and local environmental conditions can result in non-linear responses to impacts which are controlled to a large degree by the presence of feedback loops (58–60). Feedbacks can result in seagrass persisting in areas that might otherwise be characterised by undesirable environmental conditions, so once lost its absence can reduce the chances of recovery (61).

At least three of the common feedbacks found in seagrasses worldwide have been shown to be present in Moreton Bay. Firstly, high density seagrass reduces near-bed water currents, reducing the physical stress on seagrass plants (3, 62). The above-ground structure of seagrass plants slows water movement across seagrass meadows, allowing suspended sediment and organic matter to fall out of the water column, becoming bound and assimilated by below-ground structures. Roots and rhizomes bind sediments thereby limiting resuspension and both processes improve water clarity. This feedback improves conditions for seagrass growth and ultimately seagrass depth range, which may account for some of the lack of linear relationship between water clarity and seagrass depth range at the sites across the Bay, as noted above (63). Following the 2011 flood, light quantity was significantly higher at sites with seagrass present than at adjacent unvegetated sites (55).

Secondly, slowing water movement across the meadow also enables seagrass and its associated algal and microbial communities to sequester and incorporate dissolved inorganic nutrients (2, 64). In Moreton Bay, uptake rates of dissolved inorganic nitrogen in seagrass meadows following the 2011 flood were highest in meadows closer to the source of the flood (55). Nutrient uptake in unvegetated sites was lower than at all sites where seagrass was present (55). This suggests that the capacity for seagrasses in the Bay to assimilate nutrients from the water column, as elsewhere, is likely dependent on the above-ground meadow traits, (e.g. the length and density of shoots) and the extent of nutrient loading (2, 65).

The vulnerability of seagrasses in the Bay to competition from micro- and macroalgae is also reduced by herbivore grazing rates (66). The seagrass canopy provides significant predation protection for meso-grazers (e.g. gastropods, amphipods, isopods and herbivorous fish) that graze on algae (67). Grazing rates were tested in Moreton Bay following the 2011 flood. Rates were significantly higher at seagrass meadows impacted by the flood (25% wet weight algae lost over three days compared to 10% at sites with lower flood impact). Rates were also much higher in seagrass-dominated sites generally than in unvegetated sites (5% loss of algal wet weight after three days) (55).

When considered together, the strength of these three interacting feedbacks can be used to predict the likelihood of bistability (where ecosystems can theoretically exist in one of more states, such as bare or vegetated) in the Bay. A critical first step in integrating an understanding of non-linear dynamics into management plans for conserving and restoring the Bay's seagrass ecosystems (61). While large-scale restoration is not yet considered practical, recent research suggests that seagrass restoration may actually be cost-effective for increasing seagrass extent in Moreton Bay (20). Emerging techniques for seagrass restoration have been used successfully over relatively large scales in other regions (68). Using a Bayesian Network, regions of the Bay have been assigned a likelihood of bistability due to the strength of the interacting feedback loops controlling seagrass presence, as described above. Large sections of the intertidal and shallow subtidal areas of the western Bay, including southern Deception Bay, northern Bramble Bay and the southern Bay, were predicted to be bistable. Some of these areas have experienced seagrass loss since 1987 (69) most notably in southern Deception Bay and the southern Bay channels. These are therefore areas in the Bay where any natural recovery after the loss of seagrass is likely to be delayed due to the breakdown of the feedbacks controlling the presence of seagrass.

Fish and invertebrate communities of seagrass meadows

Seagrasses provide a significant habitat for a wide range of fauna, and are recognised globally as critical nursery habitats for commercially important fish and invertebrate species (1, 70). They are also recognised as hotspots for biodiversity (71), the effect of which increases with the size and proximity of seagrass meadows to other habitats (72, 73). The fauna of seagrass meadows in Moreton Bay is dominated by invertebrates (74), fishes, turtles and dugongs, and these groups have been the focus of a substantial body of research, much of it published since the first synthesis on Moreton Bay. Although knowledge of where fauna assemblages in the Bay stand in relation to global seagrass assemblages is incomplete, and despite significant inroads into establishing an inventory of benthic invertebrates, changes to the faunal composition of the Bay's seagrass meadows over time and across the multiple stressor gradients remain unknown.

There are many factors that impact fauna assemblages in the seagrass meadows of Moreton Bay. For example, current speed, light penetration to the seabed, and even the potential success rates of various predators could all influence the relative importance of species present in the Bay's meadows. Surprisingly, the proportion of the total assemblage numbers in each functional group is effectively constant across at least small-scale space, e.g. over 0.4 ha of the Deanbilla Bay region of North Stradbroke Island (Fig. 4) (75).

The larger animals in the seagrass meadows (e.g. the highly visible sea pens, sea cucumbers, strawberry cockles, sentinel and hermit crabs, and mud whelks) are well known. However, more than 250 smaller species (defined as <4 mm in at least one dimension) have also been recorded from the seagrass meadows of North Stradbroke Island and they dominate the fauna both numerically and ecologically (74). This 'small animal' category includes the two overwhelmingly abundant and most widespread elements of the seagrass fauna, the < 2 mm long gastropod *Calopia imitata* and the < 5 mm crab *Enigmaplax littoralis*. Indeed, *C. imitata* is one of the most widely distributed and abundant snails in southern Moreton Bay, yet the biology and ecology of both species is still largely unknown (74, 76).

The denser seagrasses of the Bay support two to three times as many individual animals and species per unit area as adjacent bare sandflats (77). The contrast is still apparent even in relatively sparse *Halophila ovalis* meadows. This general disparity in richness between the two habitats leads to concerns that any ongoing loss of seagrass meadows in the Bay will result in decreases of animal abundance and biodiversity. Species composition and overall abundance of fauna is incredibly patchy in space, varying markedly even over distances of centimetres (78) with 42% of species represented by only one or two individuals. Despite this, the total number of individuals and species per unit area is remarkably consistent even over kilometres in the absence of environmental gradients.

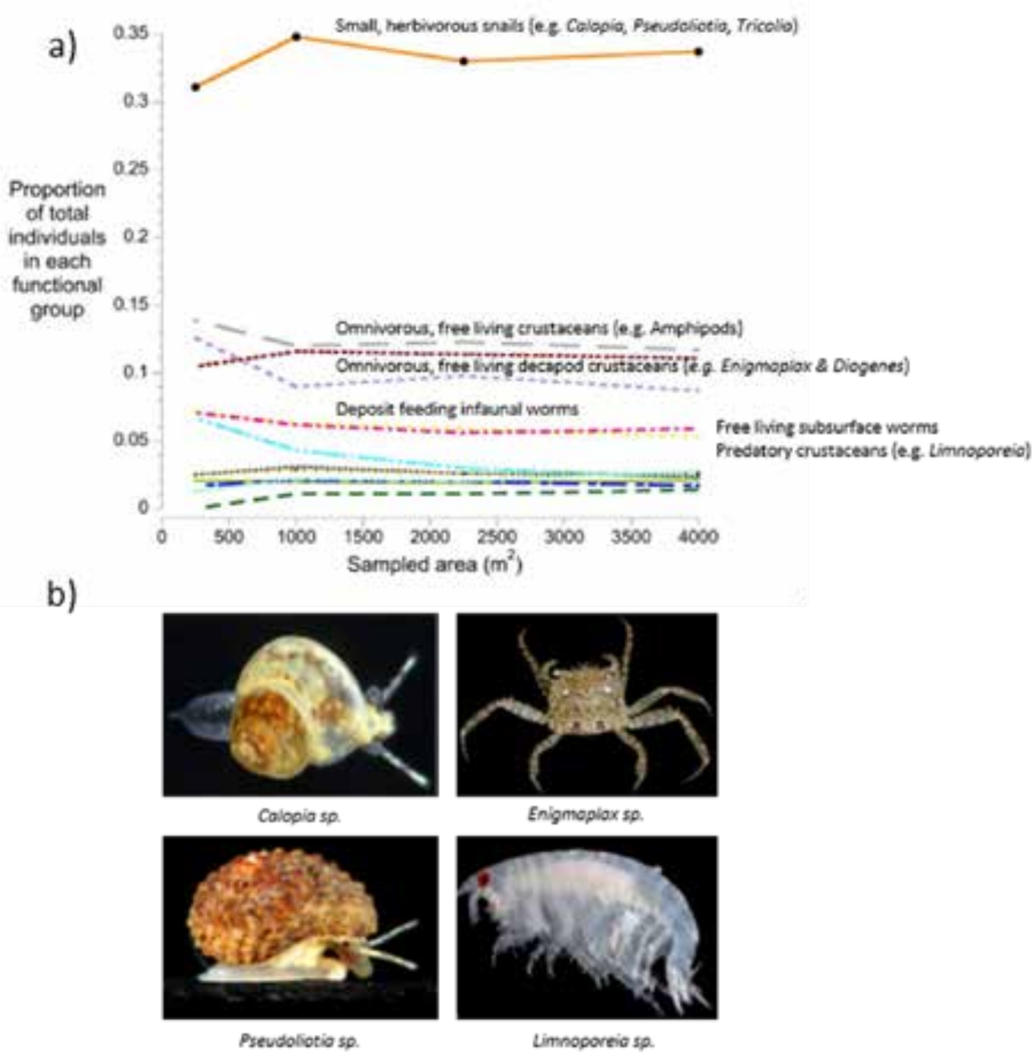

Figure 4. (a) Cumulative plots showing the effect of spatial extent on the proportion of the total individuals contained in each functional group across scales of 250 m^2 (4 stations), 1,000 m^2 (16 stations), 2,250 m^2 (36 stations) and 4,000 m^2 (64 stations) (Adapted from (75)). Note that the proportion of the total individuals contained within each group is effectively constant. (b) The four most abundant and widespread animals in the intertidal North Stradbroke Island seagrass meadows (Figure reproduced from (74)). [Images: *Calopia* from australianmuseum.net.au/blogpost/amri-news/amri-seagrass-grazers-coming-out-of-their-shells, © The Australian Museum; *Enigmaplax* and *Pseudoliotia* courtesy of and © Denis Riek (www.roboastra.com); *Limnoporeia*, reproduced here courtesy of Jim Lowry and Alan Myers through R Barnes)

Despite the contrast in animal diversity and abundance between seagrass beds and bare substrates, densities in Moreton Bay's seagrasses are relatively low, < 4,000 individuals m^{-2} (79) compared with estimates in other regions (e.g. in the NW Atlantic) which can exceed 80,000 individuals m^{-2} (80). This is likely due to 'top-down control' exerted by all juvenile prawns and small fish that use them as nursery grounds (66).

In Moreton Bay, the positioning of seagrass meadows throughout the seascape is a critical influence on the abundance and types of species that use them. Many of the commercially important fish species harvested in the Bay use seagrass meadows at some point throughout their life cycle, with key species like whiting initially settling in habitats adjacent to seagrasses before eventually moving into them (80). Larger numbers of fish and prawns use seagrass meadows that are nearer to mangroves than those further away (72, 82). This is likely due to the dietary benefit of organic matter derived from exported mangrove detritus for seagrass users. The effect is consistent despite variation in the density of the seagrass meadow suggesting that connectivity between habitat types is a greater influence than structural complexity of the meadow (83). This contrasts with findings in other regions that the density of seagrass residents is influenced by seagrass morphology, cover and size of the seagrass patch (84). In the Eastern Bay, fish species richness and assemblage composition are most influenced by the proximity of the meadow to the ocean exchange at the South Passage and to mangroves, with beta diversity (a measure of the number of distinct groups or communities) being most affected by the structure of the meadow (seagrass leaf length and shoot density) as well as the proximity to mangroves (83).

The positive effect that proximity to receiving waters has on seagrass fish assemblages is also replicated in the river estuaries that drain into Moreton Bay. The distance of habitats within estuaries to both mangroves and the mouth of the estuary is a significant driver of fish community composition; however, the proximity of those habitats to seagrass is a more dominant influence (85) with sites in estuaries closer to seagrass patches always supporting more species and containing more individuals than those further away from seagrass. This highlights the importance of retaining the linkages between seagrass meadows and adjacent fish habitats in and around the mouths of estuaries in order to support commercial and recreational fisheries and biodiversity of the Bay as a whole (86, 87).

Many seagrass inhabitants are either directly or indirectly consuming seagrass leaves or the epiphytic algae that grow on them. Grazing has been shown globally to be an important mediator of the structure and function of seagrass ecosystems (88). The feeding habits of the megaherbivores (e.g. green turtles and dugongs) in the Bay are relatively well known. Dugongs feed selectively to maximise their intake of the high nutrient, low fibre seagrass species such as *H. ovalis* (89) avoiding more extensive but more fibrous *Z. muelleri.* Dugongs have been shown to prevent the spread of *Z. muelleri* by intensively grazing areas such as the Eastern Banks and effectively cultivating areas for the preferred *H. ovalis* (89). Dugongs are found throughout the Bay (90, 91);

however, it is likely that the magnitude of their influence in shaping the structure and function of meadows in the western and southern Bay is reduced considering their numbers are generally low in those areas (2–5% of total population) (91). Consumption of seagrass by green turtle is likely to have a similar influence with simulated repeated grazing trials resulting in increased leaf regrowth of the preferred *H. ovalis* relative to ungrazed controls (92).

The influence of fish and invertebrate herbivores on the structure and function of Moreton Bay seagrasses is less well known but efforts to understand that influence have increased in recent years. Seagrass is consumed by herbivorous fish in the Bay, particularly rabbit fishes (Family Siganidae), the juveniles of which have a preference for the dominant *Z. muelleri* (93). Similarly, small gastropods like the abundant nerite *Smaragia souverbiana*, also have a preference for *Z. muelleri,* directly targeting seagrass leaves and avoiding those with an excess epiphytic algal load (94). The ecological function of these seagrass-consuming gastropods is not well known in Moreton Bay but there is some evidence that they target the more fibrous and less digestible *Z. muelleri* due to lower phenol content, a metabolite know to deter grazers (95). Lower phenol content could also account for small fish grazers preferring *Z. muelleri* (96). This could represent something of a trade-off between phenol content and digestibility, a local-scale process that could create more complicated seagrass–grazer interactions at a Bay-wide scale.

In contrast to direct seagrass consumption, other small fish and invertebrates inhabiting the Bay's seagrass meadows target the epiphytic growth (both algal and otherwise) on seagrass leaves, thereby improving the light environment available for photosynthesis (97). The contribution of fish and invertebrates to seagrass and algal epiphyte dynamics is extensive with the exclusion of small meso-grazers such as amphipods and juvenile shrimp shown to increase epiphytic algae by 2.5 times at one site in Waterloo Bay (66). Small fish like leatherjackets (Family Monacanthidae) and sabre-toothed blennies (Family Blennidae) that are ubiquitous in the Bay's meadows exert a similar, albeit lesser influence, on epiphytic algal biomass (35% and 15% reduction respectively in one 18-hour experiment) (97). The influence of these algal grazers in enhancing seagrass persistence is therefore likely to be substantial, particularly in the regions of Moreton Bay that have elevated nutrient loads (61).

Conclusions and recommendations

The understanding of the biology and ecology of seagrass meadows in Moreton Bay has come a long way since the previous Moreton Bay and Catchment book (10). In 1996, the focus of seagrass research in the Bay was on drawing attention to the declining extent and condition of the Bay's meadows and a focus on the threats and stressors that need to be addressed to protect and enhance this valuable habitat. Since those studies, the region has been galvanised into action, with significant work being done to reduce the point-source nutrient loads entering the Bay. In the past 20 years we have seen significant recovery of seagrass meadows in the heavily impacted western embayments of southern Deception Bay and more recently parts of Bramble Bay. While this is a positive step, the Bay's seagrasses are still under considerable threat from urbanisation and land-use change in the catchment and the likely impacts of climate change. Our understanding of the organisms that inhabit the Bay's seagrasses has improved significantly since 1998. However, we are unable to say without qualification what the existing extents of seagrasses are, how much they vary over temporal scales, and therefore we cannot quantify the economic, social and ecological value of seagrasses for the human community in the region. We need to further investigate the importance of the linkages between estuarine seagrass habitats and the meadows in the Bay and the causes of change in seagrass extent and condition, including the complex relationships between the effects of multiple stressors, so that management activities can target pressures.

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Mangroves and saltmarshes of Moreton Bay

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Abstract
The mangroves and saltmarshes of Moreton Bay comprising 18,400 ha are important habitats for biodiversity and providing ecosystem services. Government policy and legislation largely reflects their importance with protection provided through a range of federal and state laws, including the listing of saltmarsh communities in 2013 under the *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act). Local communities also conserve and manage mangroves and saltmarshes. Recent scientific research on these ecosystems in Moreton Bay has described food webs, habitat use by fauna, carbon sequestration and effects of climate change. The area of saltmarsh has declined by 64% since 1955 due to mangrove encroachment into saltmarsh habitats and past conversion to rural and urban land uses. Mangrove encroachment into saltmarsh habitats, which has been reported in other locations in Australia and across the world, has increased the area of mangrove habitat by 6.4% over the same period. This is consistent with predictions of habitat changes under climate change, and demonstrates the need for management strategies that ensure these ecosystems are maintained.

Keywords: coastal wetlands, intertidal, wetland management, EPBC Act, wetland change, drivers of wetland change, South East Queensland, soil carbon stocks

Introduction
Mangroves and saltmarshes, which are components of the estuarine wetlands of Moreton Bay, are dominated by salt-tolerant vegetation that occurs from approximately mean sea level to the highest astronomical tidal plane. They occur within the river systems and tidal creeks of Moreton Bay as well as on the comparatively open coasts of the Bay where they fringe both islands and the mainland. Mangroves are distributed over the intertidal zone and can occur from approximately mean sea level to the elevation of the highest neap tides, with saltmarshes usually occurring at higher elevations up to the elevation of the highest astronomical tides (1). In 2012 mangroves covered 15,231ha and saltmarshes 3,171ha of the Moreton Bay area (Fig.1,

(2)). These forests, shrublands, grasslands and sedgelands with their associated algal and microbial communities support a wide range of fauna, including many species of importance to commercial and recreational fisheries (3). Additionally, they provide a range of ecosystem services that arise from the structure and productivity of the vegetation, fauna and soils. These services include supporting biodiversity and fisheries, protecting coasts, mitigating floods, enhancing water quality and sequestering carbon. They are also important for cultural identity, recreational use, tourism and education (4). However, mangroves and saltmarshes are also habitats for mosquitoes, sandflies, weeds and feral animals, posing challenges to the highly urbanised environment of the catchments of Moreton Bay (5).

Since European colonisation of the region, mangroves and saltmarshes have been highly modified, having been affected by land use changes in the catchment and converted to alternative land uses (6) as has been observed elsewhere in Australia (7). Even though the remaining habitat is protected by legislation and international agreements (8), developments within mangrove and saltmarsh habitats still occur. This paper provides an overview of the state of mangroves and saltmarshes of Moreton Bay; it also discusses the current and future threats to these ecosystems. We review key aspects of recent research on these ecosystems which examine how to minimise the impacts of threats and maintain sustainable mangroves and saltmarshes for the Bay into the future.

Diversity of mangrove plant species

The mangrove plant community of Moreton Bay is typical of the low-energy coastlines of subtropical regions in Australia that support moderate tree species diversity. Moreton Bay has 7 tree species (Table 1) compared to 28 for the Daintree River in tropical north Queensland and 1 in the mangroves of southern Australia. Standing biomass and productivity of mangroves are also lower than observed in the wet tropics but higher than in southern Australia (9,10). The community includes additional primary producers such as algae and microphytobenthos that attach to pneumatophores and the sediment surface (11), and a diverse community of lichens growing on tree trunks (12). *Avicennia marina* subsp. *australasica* is both the most widely distributed and most abundant mangrove tree species in Moreton Bay. This species forms forests up to 15 m tall on the seaward edges of the mangrove zone and extensive scrub forests (trees <2 m tall) in the high intertidal zone where they mix with saltmarsh species and extend onto the high intertidal saltmarsh and salt flats often present as low, open-scrubland (Fig. 2). The net primary productivity of *A. marina* forests was observed to be 6.42 t dry biomass ha^{-1} yr^{-1} in seaward fringing forests declining to 3.4 t dry biomass ha^{-1} yr^{-1} for the closed-scrub and 1.94 t ha^{-1} yr^{-1} for the low, open-shrubland (9). These values are similar to those reported previously (8–9 t ha^{-1} yr^{-1} (13)) and typical for subtropical mangrove forests globally (14).

While *A. marina* dominates the mangroves of Moreton Bay, *Rhizophora stylosa* is abundant on soft unconsolidated marine clays or on sandy soils of the eastern and southern shores of the Bay, with other mangrove species having high fidelity to its other environments (15). For example, *Bruguiera gymnorhiza* is common in high intertidal sites with freshwater seepage (e.g. on North Stradbroke Island); *Ceriops australis* favours marine clay sites in the high intertidal zone; *Aegiceras corniculatum* occurs in brackish/riverine conditions, often as an understory of *A. marina*; *Excoecaria agallocha* is limited to the highest intertidal zone (usually at the marine–terrestrial interface) in brackish/riverine settings where *Crinum pedunculatum*, the swamp lily, may also occur.

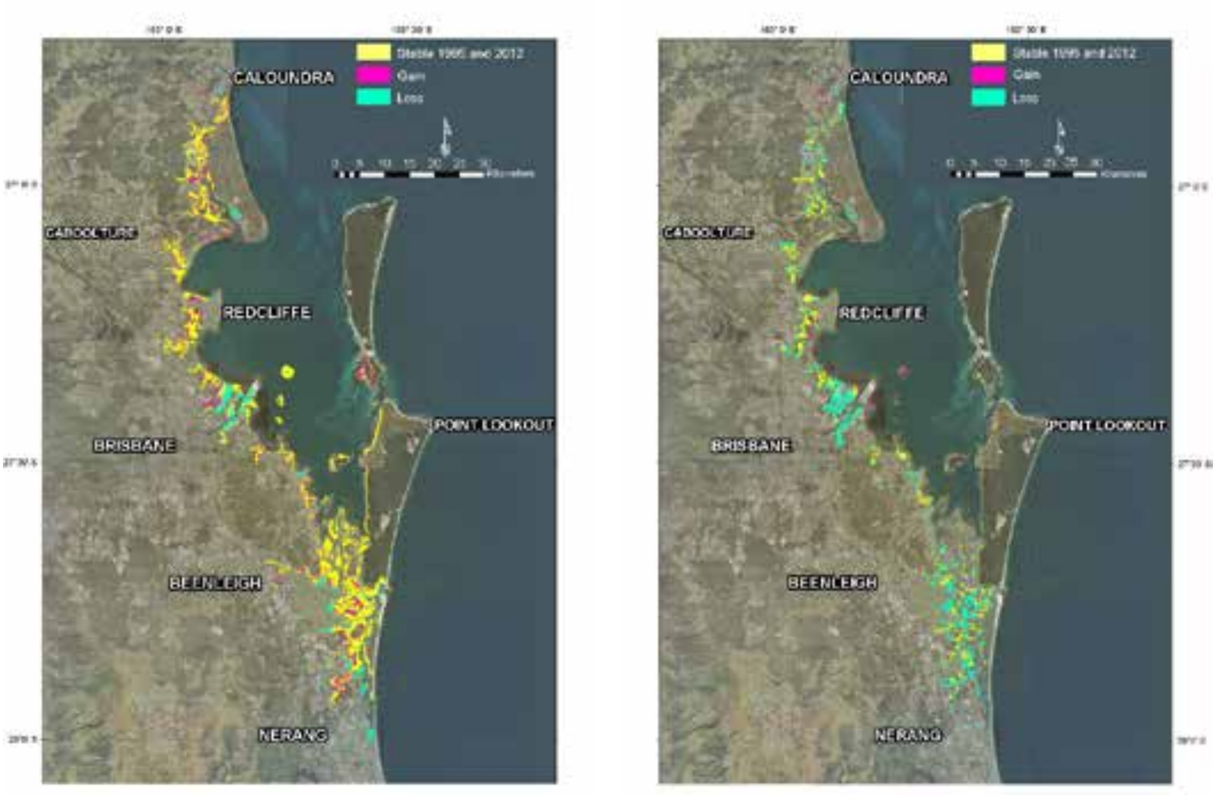

Figure 1. The distribution of mangrove forests (left) and saltmarsh (right) communities hroughout Moreton Bay and losses and gains in their cover from 1955–2012 (2).

Diversity of saltmarsh plants

The saltmarsh plant community has higher species richness than the mangroves (16). Its approximately 20 species represent 20% of the total saltmarsh species of Australia (17). Saltmarsh plant diversity within Australia increases with latitude (18) in contrast with the mangrove pattern of increasing species diversity towards the equator. Saltmarshes generally form at the high intertidal zone, at the landward edge of the mangroves in Moreton Bay (and regionally), and are submerged during high spring tides (1). The limited tidal inundation combined with moderate rainfall and high evaporation produces hypersaline conditions (i.e. salinity is higher than seawater) in some saltmarsh soils. These conditions are unfavourable for growth of species that do not have high physiological tolerance of highly saline soils. This leads to vegetation communities dominated by highly salt-tolerant herbs, for example *Sarcocornia quinqueflora*, *Suaeda* spp. and *Sporobolus virginicus* (Table 1).

Table 1. List of plant species typical of mangrove and saltmarsh ecosystems of Moreton Bay

Mangrove species	Common name
Acanthaceae	
Avicennia marina subsp. *australasica*	Grey mangrove
Combretaceae	
Lumnitzera racemosa	Black mangrove
Euphorbiacaeae	
Excoecaria agallocha	Blind-your-eye mangrove
Myrsinaceae	
Aegiceras corniculatum	River mangrove
Pteridaceae	
Acrostichum speciosum	Mangrove fern
Rhizophoraceae	
Rhizophora stylosa	Red mangrove (stilted mangrove)
Bruguiera gymnorhiza	Orange mangrove
Ceriops australis	Yellow mangrove
Saltmarsh species	
Aizoaceae	
Carpobrotus glaucescens	Pigface
Sesuvium portulacastrum	Sea purslane
Chenopodiaceae	
Tecticornia indica	Glasswort
Tecticornia pergranulata subsp. *queenslandica*	Glasswort
Tecticornia halocnemoides subsp. *tenuis*	Glasswort
Tecticornia indica	Glasswort
Cyperaceae	
Fimbristylis ferruginea	Rusty sedge
Fimbristylis polytrichoides	Rusty sedge
Isolepis cernua	Nodding club rush
Chenopodiaceae	
Sarcocornia quinqueflora	Bead weed
Suaeda australis	Seablite
Suaeda arbusculoides	Seablite
Juncaceae	
Juncus kraussii	Sea rush
Juncaginaceae	
Triglochin striata	Streaked arrow grass
Poaceae	
Phragmites australis	Common reed
Sporobolus virginicus	Saltwater couch
Portulacaceae	
Portulaca oleracea	Pigweed
Samolaceae	
Samolus repens	Creeping bushweed

Figure 2. Mangrove scrub of *Avicennia marina* encroaching into *Sarcocornia quinqueflora*-dominated saltmarsh at Tinchi Tamba Wetland Reserve.

Hypersaline salt flats occupied by *S. quinqueflora*, *Suaeda* spp. and *S. virginicus,* and often encrusted by cyanobacterial mats, are extensive in Moreton Bay, with particularly well-developed areas within the Tinchi Tamba Wetlands, Geoff Skinner Reserve and Point Halloran Reserve (Fig. 3). These hypersaline habitats tend to increase in area at the expense of mangrove forests during periods of prolonged drought (19) associated with El Niño phases of climate. However other factors, for example variation in sea level, may also be important. Mangrove encroachment into hypersaline marsh and high intertidal salt flats is occurring in Moreton Bay (2). This encroachment is consistent with the expected effects of increasing sea level. Higher sea level leads to increased frequency of inundation of the high intertidal zone. This aids the movement of mangrove propagules into the high intertidal zone and provides more favourable conditions for their growth.

Where soil salinity is ameliorated by the surface expression of groundwater (e.g. on the sand islands in the east of Moreton Bay) or by river flows (e.g. Boondall Wetlands and Point O'Halloran on the western side of the Bay), a broad range of reeds (e.g. *Juncus kraussii*), rushes and herbs can establish within the brackish soil. These brackish communities can have high diversity, but have been under intense pressure from urban development (2).

Figure 3. High intertidal, hypersaline saltmarsh and claypan at Point Halloran Reserve.

Fauna and food webs

Gastropods and crustaceans dominate the epibenthic macrofauna of estuarine wetlands in Moreton Bay. The relatively stable substratum, especially at the high intertidal saltmarsh, supports a high density (>350 individuals m^{-2}) of air-breathing pulmonate gastropod species grazing on the microphytobenthos and vascular plant detritus (20). Grapsoid (e.g. *Parasesarma, Neosarmatium, Metopograpsus*) and ocypodid (*Uca*) crabs dominate vegetated and open areas within mangroves and saltmarshes, respectively, reflecting segregation in their food sources (21). Some ocypodid crabs (e.g. *Australoplax*, *Heloecius*) occur in both vegetated and unvegetated habitats of the intertidal zone and may have a specialised mixed diet of microphytobenthos and fine vascular plant detritus.

The firm, high intertidal soils of mangroves and saltmarshes generally support a low abundance of infaunal species. Whereas diversity and abundance of burrowing and burying macrofauna, dominated again by brachyuran crabs, increase from the high to low intertidal zone. Polychaete and sipunculid worms may also be locally abundant within mangroves and saltmarsh. The meiofauna of mangroves and saltmarsh in Moreton Bay are dominated by nematodes and harpacticoid copepods (22). The macrofauna and meiofauna provide a trophic base for transient nektonic predators (fish and prawns) visiting these habitats during the high tide (20, 22).

Despite the limited research, other components of faunal diversity are being revealed. There are studies of insect diversity (23, 24) and discoveries such as finding the endangered Illidge's ant blue butterfly (25). Knowledge of the distribution of vertebrates, including the water mouse (*Xeromys myoides*) which is listed on the IUCN Red List (26, 27), is also increasing. Some insects (e.g. mosquitoes and biting midges) are, however, of considerable public health concern, prompting active management in local saltmarsh and mangrove habitats (28).

Research into estuarine food webs in Moreton Bay has found that saltmarshes are important habitats and provide food sources for fish, such as commercially important species such as whiting and mullet (29–31), and the giant mud crab (32). Abundant crab larvae are important resources from the saltmarsh (31, 33, 34). Mangroves encroaching into these habitats can reduce feeding and roosting sites for migratory shorebirds. This is of particular concern with several species being listed in 2013 as critically endangered under the *Environment Protection and Biodiversity Conservation Act 1999*. For mangrove forests, commercial fish catches are correlated with the area and perimeter of mangrove forests (3, 35, 36) as well as proximity to adjacent habitat (37). This highlights their importance as nurseries, refugia, and for food resources both within the habitat and organic matter, that is exported to adjacent habitats (38).

Habitats directly seaward of mangroves are generally comprised of intertidal sand and mud flats which are important for shore birds, including migratory species which are covered by international agreements with Japan (Japan–Australia Migratory Bird Agreement), China (China–Australia Migratory Bird Agreement) and Korea (Republic of Korea–Australia Migratory Bird Agreement) (39). The macroinvertebrate biomass and diversity of these low intertidal sand and mud flats is critical for maintaining shorebird populations (38). The connectivity of mangrove and saltmarsh habitats to subtidal habitats, such as reefs and seagrass meadows, also supports fish communities (40, 41).

Crabs are important ecosystem engineers that modify sediments and meiofauna through bioturbation and predation (22); this in turn provides food for mobile fauna (31). Many mangrove crab species bury and process decomposing mangrove leaves (21, 42), including fresh litter (43). Litter processing by crabs is an important process linking mangrove productivity to fisheries production prawns and fish. However, evidence for direct links between mangrove biomass and fisheries using tracers of naturally stable isotopes of carbon and nitrogen has been equivocal (44). But more recent evidence suggests that mangrove leaf material has a more important role in coastal food webs than previously thought. These new studies have found that there is isotopic fractionation of organic matter by crab bacterial gut symbionts or the crab's physiological pathway (45). Incorporating this new information into food-web studies indicates a strong role for mangrove biomass production and its consumption by crabs and possibly other invertebrate detritivores in coastal food webs (45, 46).

Threats and change over time

Globally, intertidal estuarine areas where mangroves and saltmarshes occur are under intense pressure because the coastal zone has high human population densities, which has led to urban, industrial and agricultural development that directly and indirectly affect mangroves and saltmarshes (47). Similar to other coastal and estuarine areas throughout the world, mangrove and saltmarsh habitats in Moreton Bay have been converted to alternative uses and degraded by a range of pressures that have varied over time (Tables 2 and 3). They are also influenced by extreme climatic events, natural variations in climate and climate change (Table 2). Losses of tidal wetlands since 1955 have been particularly evident for saltmarshes, which have been reduced in area by 64% (Table 3) due to encroachment by mangroves (47%) and conversion to urban and industrial uses (46%, Table 3 (2)). For mangroves there has been a net increase in area by 6.4% since 1955. However, losses have been largely matched by gains, indicating that approximately 28% of the current mangrove is relatively young (recruited since 1955). It may therefore have different characteristics and offer different ecosystem services than older forests that were present before 1955.

In addition to conversion to alternative land uses (Type 1, Table 2, e.g. the airport accounts for 12% of total losses), many mangrove and saltmarsh areas were used for dumping rubbish or specifically designated as landfill sites (Type 2, Table 2). In creating many of Moreton Bay's wetland parks and during the few restoration projects in the Bay, hundreds of wrecked cars have been removed (e.g. (48)). Currently saltmarshes, despite their protected status, are still vulnerable to direct disturbance by off-road vehicles and grazing by stock (49). Off-road vehicles directly disturb habitat. They also create depressions and ponds in the high intertidal zone harbouring mosquitoes that require control through enhanced management (see below).

While conversions and direct disturbance are relatively easy to observe, indirect effects that may also degrade the habitat are less easy to document, but are still apparent in the Bay (Table 3). The increased sediment supply to the coast after European settlement of Moreton Bay has increased rates of sediment accretion in intertidal habitats (50) and has therefore likely increased the area of mangrove habitat (6). However, high sediment loads may have also altered species composition and ecosystem functioning (51), as primarily sandy habitats have transitioned into more mud-dominated habitats, particularly in the western Bay.

Table 2. List of impacts for 11 key types of change affecting mangroves of the Moreton Bay region during three historical periods of the last two centuries. Types of change are grouped into four categories (A–D) based on human and natural influences on coastal and estuarine habitats. Updated from (6). Light green indicates no impact; yellow – minor impacts; dark green – moderate impact; red – severe impacts.

Type of change	Pre 1860	1860–1946	1946–2016
A. Direct – Intended and obviously human related			
1. Conversion to alternative land uses (Reclamation loss)	**Impact:** None/unknown	**Impact:** Moderate **Driver:** Chiefly industrial, upstream port development and river channel.	**Impact:** Severe **Driver:** Chiefly urban, industrial, airport and downstream port development – effects accumulative and irreversible.
2. Direct damage	**Impact:** Minor **Driver:** Occasional tree cutting, access paths and tracks.	**Impact:** Moderate **Driver:** Numerous access paths, tree cutting, access paths, tracks, trampled roots and soils, dumping.	**Impact:** Moderate **Driver:** Numerous access paths, trampled roots, although areas generally better protected than prior periods, dumping.
B. Direct – Unintended and obviously human related			
3. Altered tidal exchange	**Impact:** None/unknown	**Impact:** Minor **Driver:** Impoundment, built-up roads, drainage for agriculture.	**Impact:** Moderate **Driver:** Impoundment, drainage for mosquito control, built-up roads – proportional to urban growth.
4. Spill damage	**Impact:** None/unknown	**Impact:** Minor **Driver:** Occasional oil spills proportional to shipping volume.	**Impact:** Minor **Driver:** Oil spill incidents proportional to shipping volume – accumulation may exceed toxicant degradation rates.
C. Indirect – Unintended and less obviously human related			
5. Depositional gains and losses	**Impact:** Minor **Driver:** Increased frequency of fires in catchment reduced ground vegetation and increased sediment in run-off.	**Impact:** Minor **Driver:** Clearing of catchment vegetation and increased crop agriculture increased sediment run-off, resulting in shallower waters around the mouth of the Brisbane River. Dredging maintained channel	**Impact:** Moderate **Driver:** Hard surfaces of city-urban roads and built-up areas and reduction in catchment croplands, altered and increased sediment run-off. Dredging spoil from channel maintenance.

6. Mutations and genetic decline	**Impact:** None/unknown	**Impact:** None/unknown	**Impact:** Minor **Driver:** Loss of reproductive fitness and re-establishment of mangroves. Presence notable, but no apparent loss of natural regeneration or seed production.
7. Subsidence of soils associated with dieback	**Impact:** None/unknown	**Impact:** None/unknown	**Impact:** Locally severe **Driver:** Unknown but may be linked to high levels of nutrients and pesticides and extreme climatic events.
D. Not obviously human related			
8. Wrack accumulation	**Impact:** Minor **Driver:** Debris from blooms, storm waves – occasional.	**Impact:** Minor **Driver:** Litter debris, debris from increased number of blooms, storm waves.	**Impact:** Minor **Driver:** Litter debris, debris from increased number of blooms, storm waves. Recent *Lyngbya* blooms.
9.Herbivore /insect attack	**Impact:** Minor **Driver:** Insect plagues – occasional.	**Impact:** Minor **Driver:** Insect plagues – occasional.	**Impact:** Minor **Driver:** Insect plagues – occasional.
10. Storm damage	**Impact:** Minor **Driver:** Severe storm, hail, lightning, storm waves – occasional.	**Impact:** Minor **Driver:** Severe storms, hail, lightning, storm waves – occasional.	**Impact:** Minor **Driver:** Severe storms, lightning, storm waves – occasional. Notable hail damage in particular areas in Moreton Bay region.
11. Ecotone shift and zonal shifts in plant species	**Impact:** Minor **Driver:** Climate variability, including variation in sea level and rainfall.	**Impact:** Minor **Driver:** Climate variability, including variation in sea level and rainfall.	**Impact:** Moderate **Driver:** Climate variability and climate change, particularly sea-level rise and extreme drought. Sea-level rise linked to changes in bay hydrology – longer term responses.

The onset of industrialisation also led to increases in heavy metals in intertidal soils (Table 2), which may have negative impacts on all components of saltmarshes and mangroves (52). Increases in land cleared for agriculture and human populations in the catchments of the Bay over time have led to a rise in nutrients and sediments reaching the marine habitats of the Bay (53). This rise may increase mangrove growth, but high nutrient levels reduce the allocation of biomass to root systems (54). This may increase susceptibility of mangrove trees to drought and other stressors (55).

Table 3. Area in hectares, losses and gains in mangrove forests and saltmarshes from 1955–2012 (2). While high levels of loss have occurred in both ecosystems, there has been a large net loss of saltmarshes.

Ecosystem		1955 (ha)	Change between 1955 and 2012 (ha)	2012 (ha)	% net change
Mangrove		14,273		15,231	+6.4
	Mangrove losses		3282		
	Mangrove gains		4209		
Saltmarshes (including clay pan)		8901		3171	–64.0
	Saltmarsh losses		6410		
	Saltmarsh gains		710		
Total area		23,174		18,402	–20.6

Mangrove dieback events in Moreton Bay were responsible for 12% of mangrove losses from 1955–2012 (2). Although the causes are debatable, reduced groundwater and other freshwater flows due to drought and infrastructure interrupting groundwater flows may be important drivers. Groundwater is abundant in Moreton Bay (6.7×10^7 m^3/day, i.e.18 times greater than the average annual discharge of the major river inputs into the Bay (56)) and mangroves use groundwater to support their metabolism (57). Mangroves use combinations of fresh water and saline water, but fresh water has been shown to enhance growth rates in some species (58), suggesting that continued access to fresh water sources is important for maintaining mangrove productivity.

Other threats to mangroves and saltmarshes include local physical disturbances, which affect crab and mollusc communities (59). Introductions of non-native species are also likely to be important in mangrove and saltmarsh ecosystems. Foxes and cats exist in the tidal wetlands of Moreton Bay and have negative effects on native fauna, including IUCN-listed vulnerable species such as the water mouse *X. myoides* (60). Weeds also occur within saltmarshes and control measures, including herbicides and mechanical removal, are frequently used in Moreton Bay wetlands.

The Queensland Herbarium has monitored cover and change in cover of mangroves and saltmarshes reported this through State of the Environment reports and the annual Healthy Waterways Report Card (http://hlw.org.au/report-card). Since 2011, the Queensland Herbarium has established permanent monitoring sites across the Bay where floristics and biomass are measured every three years. Citizen science, including programs such as Mangrove Watch, has begun to emerge in the region (61). Individual researchers and community organisations have also conducted long-term monitoring (e.g. Queensland Wader Study Group).

Climate change

Increases in atmospheric carbon dioxide (CO_2) and associated increases in temperature and sea level, and expected reductions in rainfall (http://www.climatechangeinaustralia.gov.au/en/climate-projections/climate-futures-tool/projections/) will have a strong influence on mangroves and saltmarshes of the region (62, 63). Elevated levels of CO_2 (63) and elevated winter temperatures at subtropical and temperate locations can enhance plant growth rates (64). Increasing temperature may make the Bay more suitable for the growth of species that have more tropical distribution, for example *R. stylosa* (65). Plant growth and the extent of mangrove habitat (and the encroachment of mangroves into saltmarsh) are correlated with rainfall (19, 58). However, future rainfall projections have a high level of uncertainty and thus future changes in productivity and distribution in response to variation in rainfall are uncertain.

Climate change is an important driver of environmental change that will influence the distribution of mangroves and saltmarsh. The extent of mangrove and saltmarsh habitat is determined by the interactions between sea level and local topography because plants have specific tolerances to levels of inundation. Increasing sea levels could have negative effects on the distribution of mangroves if seaward fringing forests are submerged, but positive effects on mangrove area if higher sea levels promote invasion of mangroves into saltmarshes and landward expansion into other low-lying lands (60, 66, 67). Rising sea levels will have a negative influence on the area of saltmarshes in circumstances where mangroves encroach on land at a suitable elevation in the intertidal zone (Fig. 2), or if this land is unavailable due to human development on the landward edge. This reduction of available habitat between high intertidal barriers and encroaching mangroves is referred to as ‘coastal squeeze’ (68). It may already be evident as mangrove encroachment is responsible for approximately 50% of recent changes to saltmarshes cover (2).

To maintain mangroves and saltmarshes in their current position in the landscape with rising sea level, they must accrete vertically (raise the elevation of their soil surface) at the same rate as the level rises. Otherwise inundation tolerance will be exceeded and recruitment will be impeded. Monitoring accretion in mangroves and saltmarshes indicates it to be occurring at a rate similar to or exceeding that of sea-level rise in some sites, particularly on the sand islands (5.8 mm per year), while others are accreting at rates slightly lower than that of sea-level rise (1.7 mm per year (69)). In contrast, saltmarsh soil surface elevation gains are lower than local rates of sea-level rise (rates of accretion of 0.8–1.5 mm per year), suggesting that these habitats are likely becoming suitable for colonisation by mangroves as sea-level rise accelerates (69).

Ecosystem services – climate change mitigation, sediments and nutrients

Carbon stored in mangroves, saltmarshes and seagrass meadows has been called ‘blue carbon’. These ecosystems can be important in climate change mitigation strategies. This is due to the large carbon stocks that can be released as CO_2 emissions if the ecosystems are disturbed coupled with the high carbon sequestration rates when they are intact (70). They are also important in adaptation to climate change as they protect the coast against waves and storm surges and raise the seafloor through sediment accretion (71). An extensive survey of soil carbon stocks in Moreton Bay estimated between 4,100,000 and 5,200,000 Mg of sediment organic carbon (72) with mean carbon sequestration rates of 76 g C m^{-2} $year^{-1}$ for mangroves; 9 g C m^{-2} $year^{-1}$ for marshes dominated by *S. quinquefolia*, and 207 g C m^{-2} $year^{-1}$ for *J. krausii* marshes (62). Carbon sequestration rates for mangroves of the Bay are low to moderate compared to tropical mangrove forests (70), while *Juncus* marshes have similar rates to some of the highest carbon sequestration rates observed globally in saltmarshes (73, 74). The stocks of soil carbon over the landscape, being higher in landward compared to seaward mangroves (72, 75), reflect the sea level history of Moreton Bay (72) and the substantial risks from CO_2 emissions if these ecosystems are degraded and converted to alternative land uses (76).

In addition to their role in regulating CO_2, mangroves and saltmarshes regulate the greenhouse gases methane (CH_4) and nitrous oxide (N_2O), which are formed by microbial activity in their low oxygen soils. These greenhouse gases have warming potentials of 28–36 and 265–298 times that of CO_2 respectively (77). Methane emissions are very low when soil salinity is high; for example, on North Stradbroke Island methane and N_2O emissions were higher in brackish *Juncus* marshes (mean of 30 mg C-CH_4 m^{-2} h^{-1} and 50 µg N-N_2O m^{-2} h^{-1}, respectively) compared to the adjoining more saline mangrove, where emissions were very low, except in areas where groundwater emerged at the soil surface (78). For both methane and N_2O, the rates of emissions increased with added nutrients (79). Thus restoring mangroves and saltmarshes may reduce greenhouse gas emissions where these ecosystems have become brackish through altered hydrology (e.g. as a result of impoundment).

Mangroves and saltmarshes are also important for trapping sediments, particularly in fringing mangroves of riverine ecosystems (80) and for nutrient retention and cycling. Coastal wetlands are important sites of nitrogen retention in soils and plant biomass and for denitrification (81), where nitrogen in water and soil is converted to nitrogen gas (N_2) through microbial activity. Measurements in Moreton Bay waterways found that during a tidal cycle, mangroves retained up to 28% of nitrates (NO_x), 51% of soluble phosphorus, and 83% of the ammonium (NH_4) in tidal water (82). Thus losses of mangroves and saltmarshes over time (Table 3) are likely to have contributed to reduced water quality in the Bay, as has been observed in other estuaries globally (83).

Management

The Queensland Government shares responsibility for managing wetlands with the Australian Government, local governments, landholders and the wider community. These responsibilities are formalised in laws passed by the Queensland and Australian governments and through international obligations and management agreements such as Ramsar (Table 4).

Laws, policies and programs administered by government agencies manage our wetlands. These can be accessed through the portal on the Queensland Government's Wetland*Info* website (https://wetlandinfo.ehp.qld.gov.au/wetlands/management/policy-legislation/) which is updated regularly. The Wetland*Info* portal also provides a range of products that support wetland management, including mapping, fact sheets and guidelines (https://wetlandinfo.ehp.qld.gov.au/wetlands/).

Table 4. International, federal and state laws and policies relevant to the conservation and management of mangroves and saltmarshes in Moreton Bay. Modified from (8).

International	Reference or link
Ramsar Convention	http://www.environment.gov.au/water/wetlands/ramsar
A range of bilateral agreements on migratory birds with China, Korea and Japan (accommodated within the *Environment Protection and Biodiversity Conservation Act 1999* – see below)	http://www.environment.gov.au/biodiversity/migratory-species/migratory-birds
Convention on Biological Diversity (Bonn Convention)	http://www.environment.gov.au/biodiversity/international/un-convention-biological-diversity
Australian Government	
Environment Protection and Biodiversity Conservation Act 1999 (listed subtropical and temperate coastal saltmarsh communities as a nationally threatened ecological community in 2013)	http://www.environment.gov.au/epbc
State Government	
Fisheries Act 1994	https://www.daf.qld.gov.au/fisheries/consultations-and-legislation/legislation
Vegetation Management Act 1999	https://www.legislation.qld.gov.au/LEGISLTN/CURRENT/V/VegetManA99.pdf
Marine Parks Act 2004	https://www.legislation.qld.gov.au/Acts_SLs/Superseded/SUPERS_M/MarinePA04.htm
Planning Act 2016	https://www.legislation.qld.gov.au/LEGISLTN/CURRENT/P/PlanningA16.pdf
Environmental Protection (Water) Policy 2009	https://www.ehp.qld.gov.au/water/policy/seq-moretonbay.html

Mosquito control is one of the most intensive management activities in mangroves and saltmarshes in the Bay. These habitats harbour *Aedes vigilax* (Skuse) mosquitoes that are vectors for viruses causing the serious diseases of Ross River and Barmah Forest virus (84, 85). While other subtropical locations (e.g. Florida) achieved mosquito control by impounding and/or draining wetlands, in Moreton Bay an approach called 'runnelling' was developed. In this method, standing water in the saltmarsh is drained using small channels to dewater larval habitats and combined with aerial spraying of mosquito-specific insecticides (86). Successful models of mosquito habitat suitability are strongly linked to hydrological characteristics that can predict the need for larvicide applications based on rainfall and tidal inundation (87). 'Runnelling' is more compatible with maintaining wetlands in a state consistent with conservation goals compared to other methods of mosquito control (28), although there is some possibility that runnels have increased mangrove penetration into the saltmarshes of the region (88). Mosquito control is vital in urban settings where disease risks are high and thus developing management compatible with conservation goals is a high priority.

Restoration has been attempted to reduce the overall loss of saltmarsh and mangrove in Moreton Bay. The significant loss of mangroves during construction of the Brisbane Airport was followed by a large-scale restoration project (89), although the long-term success of this project is yet to be assessed. The Bulimba Creek Catchment Coordinating Committee restored mangroves and saltmarsh in the Bulimba Creek Oxbow that had previously been impounded for industry (48, 90). More recently, a small mangrove wetland was created in southern Moreton Bay as an offset measure for the construction of the Southport Park by the City of Gold Coast.

Given the losses experienced in saltmarsh habitats in Moreton Bay, future management actions could include increasing the size of the reserve network to accommodate landward migration of this ecosystem (91). However, the opportunities for this are rare as areas landward of saltmarsh have largely been developed or are habitat for rare freshwater wetlands and other species. Other interventions, for example adding sediment to build elevation of the saltmarsh, have been used in the USA (92) and could be appropriate in some locations. Recent research has shown that fisheries values and carbon sequestration (see above) could offset the costs of purchasing land to extend the reserve network for coastal wetlands (67). Additionally, explicitly considering the coastal protection functions and other ecosystem services in land-use planning can be highly cost-effective (66). A survey of how people in Moreton Bay value mangroves has indicated that the role of mangroves in coastal protection resonates with all stakeholder groups assessed, but these areas are highly contested for coastal development (5, 93, 94). Conserving and restoring coastal wetlands therefore depends on sound science and clear communication of the value of ecosystem services to the communities in specific locations and the various levels of government operating within Moreton Bay (94).

Conclusions

Mangrove forests and saltmarshes of Moreton Bay are clearly valuable environmental assets, and while they are dynamic systems, they have been subject to human-induced change over time with the loss of 64% of the area of saltmarshes observed since 1955. Even though a suite of laws, policies and international agreements protect mangroves and saltmarshes they continue to be lost. Little is being done to reverse these losses through restoration, and none has been initiated on a large scale. The ecosystem services provided by mangroves and saltmarshes, particularly those that are relatively well understood in the region (fisheries, carbon sequestration, nutrient cycling, cultural identity and education), provide the rationale for increasing the area allocated for mangroves and saltmarshes (e.g. increasing the reserve network, planning for landward migration). Given that sea-level rise will place pressure on saltmarshes due to coastal squeeze, this is a particularly important strategy to pursue. Benefits of maintaining or increasing the area of these habitats are consistent with society's aspirations for biodiversity, fish production and clean water, although they must be balanced with consideration of the vulnerability of adjacent freshwater wetlands and their dependent fauna.

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Freshwater wetlands of Moreton Bay, Quandamooka and catchments: biodiversity, ecology, threats and management

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Abstract
Freshwater wetlands of the Moreton Bay Region and Bay islands are prominent landscape features of high biodiversity performing essential ecological functions and providing ecosystem services. This paper reviews the types, extent, biodiversity and ecology of freshwater wetlands in the region, and documents the main threats to wetland ecosystems. These wetlands are protected and managed under Queensland and federal legislation, international obligations and a range of laws, policies and programs administered by government agencies. Important initiatives include the Queensland Wetlands Program, the Healthy Waterways and Catchments and Resilient Rivers alliance, and Queensland's water management plans. The ongoing challenge for those managing the Moreton Bay Region and Bay islands is to appreciate the importance of freshwater wetlands as essential landscape components and sources of valuable ecosystem services, and to recognise how human activities threaten their biodiversity, integrity and future in spite of rigorous monitoring, dedicated management programs and conservation initiatives. Recommendations to ensure the future of freshwater wetlands in the Moreton Bay region and Bay islands include: (i) sustaining and enhancing wetland biodiversity, functions and ecosystem services in the context of expanding human populations, growing demands for water and infrastructure, and likely threats associated with climate change; (ii) increasing support for research, monitoring, communication and management of freshwater wetlands on the mainland and Bay islands; and (iii) maintaining a well-coordinated holistic approach to integrated land, water and wetland management based on sound multidisciplinary science, societal values and expectations, and partnership arrangements (such as the Healthy Waterways and Catchments and Resilient Rivers Alliance).

Keywords: habitat types, wetland extent, vegetation, fish, invertebrates, monitoring, conservation, climate change

Introduction

Freshwater wetlands in catchments of the Moreton Bay region (from Deception Bay to the Jumpinpin Bar) and offshore (Bay) islands of South East Queensland (SEQ) are prominent landscape features of high biodiversity (Fig. 1). Wetlands deliver essential ecological goods and services such as supplying food and water, trapping and transforming pollutants, regulating climate and flooding, sequestering carbon, providing habitat for biodiversity, and presenting opportunities for recreation and tourism (1–3). The Moreton Bay region is a semi-enclosed basin bounded on its eastern side by two large vegetated sand islands (Moreton and North Stradbroke) and a deltaic coast on the western side, where six large rivers (Nerang-Coomera, Logan-Albert, Brisbane, North-South Pine) and multiple smaller rivers and creeks discharge to the Bay from a combined catchment of approximately 22,000 km² (Fig. 1). Part of the region forms the Moreton Bay Ramsar site which was listed in 1993 as a wetland of international importance (4) due to its large size (approx. 1,206 km²); diverse freshwater, estuarine and intertidal wetlands; significant waterbird and shorebird populations; as well as diverse, rare and endemic flora and fauna (5). Moreton Bay and the Bay islands have important cultural, social, economic and recreational values. The site of Wallum Wallum Creek, on the west coast of North Stradbroke Island, has evidence of continuous Aboriginal occupation extending back some 20,000 years, with present-day hunting, fishing and the gathering of local food plants continuing the cultural and provisional traditions of the Quandamooka people. The Moreton Bay region offers major opportunities for nature-based tourism and recreation, with more than 12 million visits annually (6).

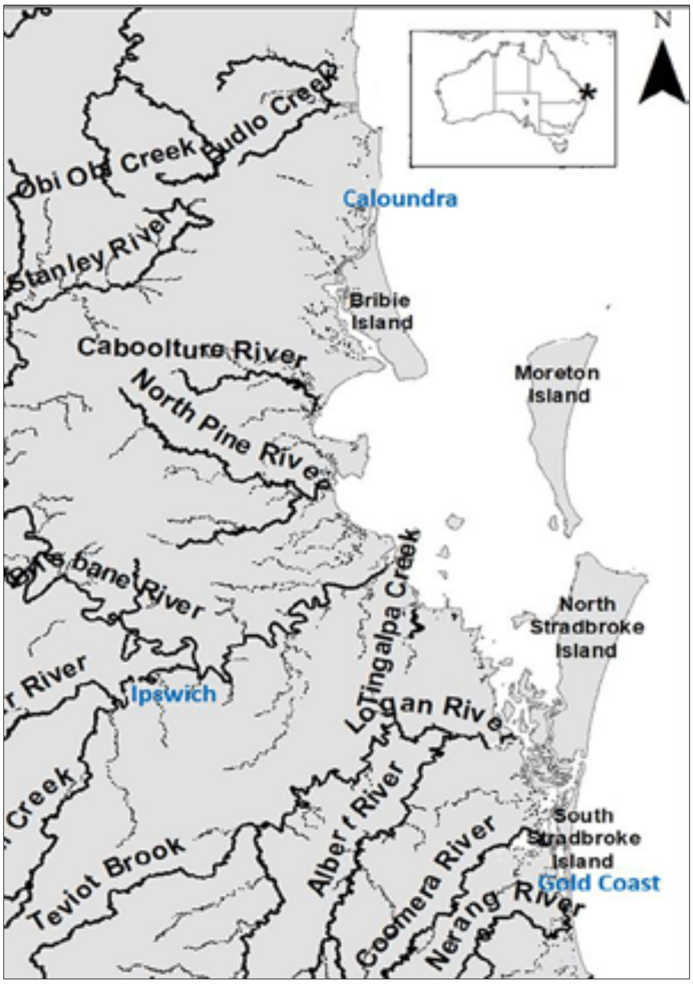

Figure 1. Moreton Bay and its catchment area. Our study boundaries were Caloundra in the north, Ipswich in the west and the Gold Coast to the south.

This paper begins with a summary of the freshwater wetland systems and their pattern of extent within the Moreton Bay catchment and Bay islands, followed by an overview of the ecological functions and biodiversity of selected wetland flora and fauna. Freshwater wetlands on the mainland and Bay islands are threatened by increasing land-use change, water infrastructure and use, pollution, habitat loss/fragmentation, and alien animals and plants. A brief account of threats to wetlands, including the implications of climate change, is followed by an outline of management activities underway to assess wetland condition, mitigate threats, and maintain the ecological integrity and ecosystem services of freshwater wetlands. The paper ends with recommendations for future wetland research, monitoring, management and conservation**.**

Wetland systems and extent

The Queensland Government's *Strategy for Conservation and Management of Queensland Wetlands* (7) defines wetlands as 'Areas of permanent or periodic/intermittent inundation, whether natural or artificial, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed 6 metres'. This definition has been modified to make it more practical to apply in mapping and legislation (8). At the broadest level Queensland wetlands have been grouped into lacustrine (lake), palustrine (swamp, marsh), riverine, estuarine, marine and subterranean systems; these systems have been classified at a finer habitat level and the Queensland Government has mapped them state wide (9).

The types and extent of freshwater wetlands in river basins draining into Moreton Bay vary with catchment area, natural environmental characteristics (e.g. climate, geology, topography, soils, surface and groundwater hydrology) and human influences. Table 1 presents summary data on the extent of wetland systems (assessed in 2013) for the large river basins draining into Moreton Bay, and the Bay islands. In the populous Brisbane catchment (area 13,541.7 km²), the dominant wetlands by areal extent in 2013 were riverine and artificial or highly modified wetlands (e.g. dams, ring tanks, irrigation channels), together forming 90% of total wetland area (495.9 km²); palustrine and lacustrine wetlands were numerous (approx. 1,048 in this catchment); however, they made up only 7.3% and 1% of the total wetland area respectively (10). In contrast, freshwater wetlands on the two barrier islands and several small islands in Moreton Bay (total area 547.2 km²) in 2013 were mainly palustrine (e.g. sedge and *Melaleuca* swamps) forming 48.9% of total wetland area; lakes (1.3%) and artificial or highly modified wetlands (1.6%) made up the rest of freshwater wetland area on Bay islands (10). Small streams flowing to the coast add further habitat diversity (e.g. Eagers Creek, Spitfire Creek on Moreton Island; Myora Creek on North Stradbroke Island).

Table 1. Wetland systems and extent (km^2) in the large river catchments draining to Moreton Bay and on Moreton Bay islands (10)

Catchment	Total area	Artificial	Estuarine	Lacustrine	Palustrine	Riverine	Total wetland area
Coomera–Nerang	1,303.9	36.3	34.9	0.2	20.5	18.0	109.8
Logan–Albert	4,149.8	26.9	21.8	5.2	34.0	45.9	133.9
Brisbane	13,541.7	206.6	8.0	4.7	36.2	240.1	495.9
North-South Pine	1,484.4	36.4	45.7	0.2	39.7	26.7	148.7
Moreton Bay islands	547.2	2.1	63.6	1.7	64.6	0	132.0

Biodiversity and ecology of mainland freshwater wetlands

Describing the biodiversity and ecology of mainland freshwater wetlands of the Moreton Bay Region is a challenge given the richness of their flora and fauna and the diversity of wetland types. Ecological features of the Brisbane catchment and species lists for freshwater flora, invertebrates and fish were published in *The Brisbane River: a source-book for the future* (11–13). Although dated, these papers offer comprehensive species lists and a benchmark for analysis of changes in diversity over time. Since then numerous studies (14–20), two books (21, 22) and a Special Issue (23) have documented aspects of the biodiversity and ecology of streams, rivers, lakes and impoundments in Moreton Bay catchments and the Bay islands.

By comparison, there has been far less research on the biodiversity and ecology of palustrine wetlands. This began to change with establishment of the Queensland Government's *Strategy for Conservation and Management of Queensland Wetlands* (7) and the Queensland Wetlands Program (QWP) in 2003. Wetland*info,* developed through the QWP, is the major portal for information on Queensland's wetlands, which are home to 130 species of freshwater fish, around 210 species of waterbird and 3,000 plant species (24). The Aquatic Conservation Assessment (25) of riverine and non-riverine wetlands in 16 catchments of the SEQ mainland and Moreton Bay islands is another useful resource. Descriptions of Broad Vegetation Groups (BVGs – high level groups of plant communities throughout Queensland's bioregions) provide further information on wetland typologies and floristics (26). The following brief account of the functional roles and diversity of wetland flora and fauna focuses on three important components of most riverine and palustrine wetlands — riparian vegetation, hydrophytes (aquatic plants) and fish.

Riparian vegetation

A healthy biodiverse riparian (fringing) vegetation corridor is universally recognised as essential to wetland functioning and ecological health (27, 28). Riparian vegetation can promote nitrogen transformation and the processing of nutrient and sediment fluxes from upland catchments to streams (29, 30). Shading by riparian trees and shrubs influences the light environment and water temperatures that in turn govern many biological processes, including primary production, invertebrate and fish recruitment and aquatic biodiversity (31, 32). Riparian and littoral vegetation stands, and root systems contribute physical structure to stream banks and beds, constrain bank erosion and shape channels and wetland aquatic habitat (32, 34). Large woody debris and other vegetation fragments derived from riparian trees and shrubs influence water flows, channel formation and aquatic habitat (35). Submerged logs and leaf packs create structure where invertebrates and fish find refuge from thermal extremes, protection from predators and safe spawning sites (36, 37). In forested headwater catchments, riparian inputs (leaves, flowers, fruits) contribute energy to aquatic food webs through biological processing by microbes and invertebrates, while further downstream the aquatic food web is usually more dependent on production by algae and plants (38, 39). Riparian plants and connected corridors of vegetation along riverbanks provide habitat and movement pathways for birds, mammals, reptiles, frogs and invertebrates (40).

The riparian vegetation associated with wetlands of the Moreton Bay region is diverse and may include small, medium and large trees (over 30 m), woody shrubs, vines, grasses, rushes, sedges, herbs, forbs, ferns, mosses and palms. Community diversity and composition reflect interactions between climate (especially rainfall), topography and soils, moisture availability and duration of inundation (20). Riparian communities in the Moreton Bay region have been assigned to BVG 16a 'Open forest and woodlands dominated by species of *Eucalyptus* fringing drainage lines' (26). Surveys of the riparian vegetation of SEQ streams and rivers from the Mary River in the north to the Nerang River south of Brisbane recorded over 191 species of woody trees and shrubs (20). In this study area, the most abundant native species were sandpaper fig (*Ficus coronata*), black bean (*Castanospermum australe*), three-veined laurel (*Cryptocarya triplinervis*), and weeping lilly pilly (*Syzygium floribundum*), with bottlebrush (*Melaleuca viminalis*) and black tea-tree (*M. bracteata*) in areas of lower rainfall. Alien taxa comprised 26.5% of all individuals recorded, with the most abundant alien species being Chinese elm (*Celtis sinensis*), lantana (*Lantana camara*), leucaena (*Leucaena leucocephala*), camphor laurel (*Cinnamomum camphora*), and broad-leaved privet (*Ligustrum lucidum*).

Hydrophytes (non-riparian)

Hydrophytes are plants that are adapted to and dependent on living in wet conditions for at least part of their life cycle (24). Non-riparian hydrophytes (often called aquatic macrophytes, which include macroalgae) colonise many different types of wetland including ponds, lakes, impoundments, palustrine wetlands, streams and rivers, rapids and waterfalls. They are important features of shallow aquatic ecosystems, where they influence ecological processes (e.g. nutrient cycling and physicochemical properties of the water column such as dissolved oxygen and pH), channel morphology, habitat structure, and the diversity and species composition of invertebrate and fish communities (17, 41). The physical forms (emergent, floating, submerged) and structures of aquatic plants create habitat complexity and provide shelter for invertebrates, fish and waterbirds, as well as spawning substrate for some aquatic species, crimson-spotted rainbow fish (*Melanotaenia duboulay*) for example (22). High rates of primary production support aquatic food webs based on living plants (grazing food webs) and dead organic matter (detrital food webs) (28, 39).

Vegetation complexes in Queensland's wetlands belong to BVG 34 'Wetlands associated with permanent lakes and swamps, as well as ephemeral lakes, claypans and swamps; includes fringing woodlands and shrublands', within which seven sub-groups capture the floristic characteristics of riverine, lacustrine and palustrine wetlands (26). For example, BVG 34c 'Palustrine wetlands … on coastal floodplains dominated by sedges and grasses such as spikerush (*Oryza* spp., *Eleocharis* spp.) or cord rush (*Baloskion* spp. /*Leptocarpus tenax*/*Gahnia sieberiana*)/ sword grass (*Lepironia* spp.) is a common vegetation formation in coastal areas of SEQ (26).

Surveys of aquatic plants at 44 sites in SEQ streams and rivers from the Mary River to the Nerang River have recorded 74 taxa (42). The most common taxa were the submerged species *Potamogeton crispus*, *Myriophyllum* spp., mosses, and the emergent species *Lomandra* spp., *Carex* spp., *Hydrocotyle* spp. and *Persicaria decipiens*. Alien species comprised 27% of the flora recorded, the most common species being watercress (*Rorippa nasturtium-aquaticum*), mist flower (*Ageratina riparia)* and the sedge *Cyperus eragrostis*. Prominent alien species in lacustrine and palustrine wetlands include floating forms (*Pistia*, *Salvinia, Eichhornia*) and robust emergent species, typically grasses and sedges (e.g. species of *Cyperus*). Invasive alien plants such as ponded pasture grasses (*Urochloa mutica* and *Hymenachne*) and water hyacinth (*Eichhornia crassipes*) disrupt the hydrology, habitat structure, native fish communities and ecological processes of streams and wetlands (43).

Fish

Fish are important components of most freshwater ecosystems (44, 45). They contribute to biodiversity and ecological functions by their uptake, storage and transport of nutrients, consumption of organisms at lower trophic levels, and regulatory effects on a variety of ecosystem-level properties, such as food-web structure (45, 46). Fish assemblage structure and distribution patterns reflect large-scale predictors such as climate and geology, catchment characteristics, channel structure, riparian processes, habitat complexity and water quality (18, 19, 41). These dependencies and the sensitivity of fish to the common pressures on freshwater ecosystems (water pollution, barriers to movement, altered flow regime, habitat loss/fragmentation and alien species) make them very useful biological indicators of ecological condition (1, 18). Fishing for food or pleasure is an important human activity globally, with many societal benefits, including food security, providing important micronutrients and essential fatty acids, generating wealth, and supporting livelihoods, health and wellbeing (44). However, poorly managed fisheries and recreational activities can affect fish population levels, assemblage composition and ecological functions associated with healthy and resilient aquatic ecosystems (44, 45).

A recent compilation identified 42 native freshwater species (i.e. species that either breed or spend most of their life cycle in freshwater) indigenous to the SEQ wetlands. These fish records come from the large catchments draining to Moreton Bay, small coastal creeks and the Bay islands (Table 2). The region supports Oxleyan pygmy perch (*Nannoperca oxleyana*) listed as 'Endangered' under the *Environment Protection and Biodiversity Conservation Act 1999 (Cwlth)*. It also supports species of recreational and commercial importance such as Australian bass (*Percalates novemaculeata*) and sea mullet (*Mugil cephalus*).

Table 2. Number of native, translocated and alien fish species in wetlands of the large catchments draining to Moreton Bay, small coastal creeks and Moreton Bay islands*

Catchment	Total Area	Native species	Translocated species	Alien species
Coomera–Nerang	1,303.9	**29**	**4**	**8**
Logan–Albert	4,149.8	**33**	**3**	**7**
Brisbane	13,541.7	**37**	**6**	**10**
North-South Pine	1,484.4	**29**	**5**	**5**
Moreton Bay islands	547.2	**25**	**0**	**1**

*Compiled by MJ Kennard, Griffith University (June 2018) from references 18, 22, 24, 25

Six Australian native species have been introduced (i.e. translocated) to the region from other Australian catchments, saratoga (*Scleropages leichardti*), golden perch (*Macquaria ambigua*), barred grunter (*Amniataba percoides*), silver perch (*Bidyanus bidyanus*), Lake's carp gudgeon (*Hypseleotris* sp.) and Australian lungfish (*Neoceratodus forsteri*). A further 14 species in four families (Poeciliidae, Cyprinidae, Cichlidae and Cobitidae) introduced to Australia from other countries have been recorded in SEQ. Most of these alien species have been introduced via the aquarium trade and spread deliberately (e.g. for mosquito control) or accidentally (e.g. escapes from ornamental ponds, dispersal in flood waters) into many water bodies (47). The mosquitofish (*Gambusia holbrooki* – Poeciliidae) is widely distributed in the Moreton Bay region and also occurs on the two large Bay islands (22, 48, 49). Streams and rivers, impoundments and farm dams across the large catchments draining into Moreton Bay support many of these native and alien species, but their occurrence patterns in palustrine wetlands are less well known and warrant more investigation.

Biodiversity and ecology of mainland coastal wallum and Bay island wetlands

The freshwater wetlands of the Bay islands have long attracted scientific interest (23, 50–52). Wetland hydrology on the sand islands is influenced by rainfall recharge, evaporation, sub-surface infiltration, groundwater flows and, for some creeks and lakes, the surface expression of groundwater (51). Many wetlands can be classed as groundwater-dependent ecosystems and require permanent or intermittent access to groundwater to meet all or some of the water requirements of plant and animal communities. This access maintains ecological processes and services (53). Groundwater-dependent ecosystems have been mapped throughout the Moreton Bay region (54, 55).

Variations in hydrology, physical form and water quality distinguish several prominent wetland types of the Bay islands. Perennial streams are typically shallow (<1 m deep) coastal streams that experience enduring flow (e.g. the creek flowing from Blue Lake to Eighteen Mile Swamp, North Stradbroke Island). Chain-of-pond streams form a series of pools of varying depth and with intermittent connectivity, depending on the level of flow. Palustrine wetlands (including peat swamps) form large swathes along the coastal lowlands of dune islands. Eighteen Mile Swamp (Fig. 2a) on North Stradbroke Island is considered to be one of the largest coastal peat swamps in Australia (52). Dune lakes are of two common types. Perched lakes (e.g. Brown Lake, North Stradbroke Island) are separated from the regional groundwater table by semi-permeable indurated layers. Water table window lakes (e.g. Blue Lake, North Stradbroke Island) form between dunes in depressions that extend below the upper surface of the regional groundwater-table (Fig. 2b). Blue Lake's depth and shoreline have remained essentially unchanged over the past century despite climatic variability such as extended droughts (50, 54, 55). This lake forms an important freshwater refuge sustained by groundwater inflow from the island's large unconfined sand aquifers.

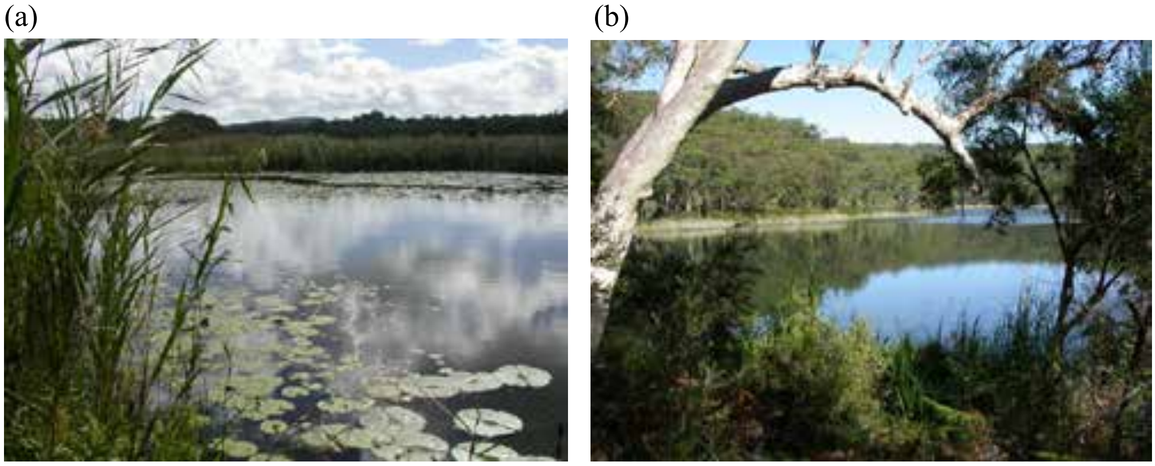

Figure 2. (a) A palustrine wetland, Eighteen Mile Swamp, North Stradbroke Island; (b) A watertable window, Blue Lake, North Stradbroke Island. (Photographs courtesy of Jonathan Marshall, Queensland Government)

Wetlands of the sand islands and similar coastal landforms on the mainland are typically located in heathlands referred to as 'wallum', a term derived from the Indigenous word for *Banksia aemula*, a small tree characteristic of these areas. Fringing vegetation associated with wallum wetlands is typically BVG 22a 'Open forests and woodlands dominated by swamp paperbark (*Melaleuca quinquenervia*) in seasonally inundated lowland coastal areas and swamps' (26). Lakes and palustrine wetlands often have dense fringes of sedges and rushes such as *Lepironia articulata* and species of *Eleocharis, Baumea, Schoenus, Juncus* and *Gahnia* (Fig. 2). The deeper areas of lakes are generally vegetation free, although the clear waters of Blue Lake on North Stradbroke Island allow sedges to grow at depths over 10 m (50).

The marginal (littoral) vegetation of dune lakes provides habitat for a variety of aquatic invertebrates as well as food, shelter and spawning sites for higher order organisms — fish, frogs and turtles. Two new species of Odonata (dragonflies and damselflies) *Orthetrum boumiera* and *Austrolestes minjeribba* (56) were first discovered at Brown Lake, and a primitive aquatic worm (*Rhizodrilus arthingtonae*) lives in the sandy shallows. Brown Lake lacked fish in the 1970s (50) allowing planktonic midges (*Chaoborus* spp.) and an aquatic bug (*Anisops*, Hemiptera) to assume the role of apex predators in the lake's food web. The recent introduction (date and mechanism unknown) of *G. holbrooki* (the predatory alien mosquitofish) may alter phytoplankton and zooplankton communities and the structure of the food web in this iconic perched dune lake.

The endangered Oxleyan pygmy perch (*Nannoperca oxleyana*) and ornate rainbowfish (*Rhadinocentrus ornatus*) are coastal wallum wetland habitat specialists restricted to wetlands of the sand islands and mainland coastal wallum (57). Their populations are often geographically isolated from one another leading to high levels of genetic divergence (58–59). Frogs associated with wallum wetlands include the wallum froglet (*Crinia tinnula*), Cooloola sedgefrog (*Litoria cooloolensis*), wallum rocketfrog (*Litoria freycineti*) and wallum sedgefrog (*Litoria olongburensis*). These 'acid frogs' are adapted to the unusual water quality of dune lakes and wetlands, particularly the acidity (low pH) of their waters (60).

Threats to mainland freshwater wetlands

Wetlands are one of the world's most threatened ecosystems, as humans have historically exploited them for freshwater, sewage and solid waste disposal, aquaculture production, fertile arable land and recreation/tourism (61, 62), or claimed them for urban and heavy industry infrastructure (63). Over half the world's freshwater wetlands have been lost (62) and only 11% of the remaining wetlands have some level of conservation protection (3). Wetlands of the major catchments draining to Moreton Bay are embedded in a matrix of: protected areas; patterns of land-use; urban, civic and industrial developments; transport corridors; and open spaces (1, 21) that also have different levels of protection under legislation. The human footprint is increasing with Brisbane's population (>2.4 million in 2018) expected to rise by 820,000 residents over the next two decades (64). Rivers and palustrine wetlands have been degraded (and reduced in extent) through widespread catchment disturbance, deforestation including riparian loss and fragmentation, catchment and bank erosion, water pollution, river corridor engineering, dams and water diversions, wetland drainage, groundwater depletion, aquatic habitat loss and fragmentation, establishment of alien species, and fishing (20, 34, 49, 65–67). Climate change is likely to exacerbate these threats and intensify impacts on wetland ecosystems (68).

Threats to mainland coastal wallum and Bay island wetlands

Wetlands of the mainland coastal wallum and Bay islands are highly susceptible to many threats — tourism and recreation, urban developments, sand and mineral mining, forestry and land clearing, groundwater extraction, water pollution, fire, weeds, grazing, and alien animals and plants (23, 69). Developments along the coastal mainland have resulted in extensive loss of paperbark (*Melaleuca*) swamp forests. Local changes to hydrology and water quality impacts associated with groundwater extraction may threaten wetland vegetation, rare invertebrates, endangered freshwater fishes, and acid frogs (51, 52, 57). Tourism and water-based recreation can add nutrients to freshwater wetlands of low nutrient status and cause algal blooms and disrupt aquatic food chains (69). The alien mosquitofish preys on fish eggs and may compete with two habitat specialists, the endangered Oxleyan pygmy perch (*N. oxleyana*) and ornate rainbowfish (*R. ornatus*), for food and habitat (48). Sand mining can adversely affect wetlands but is expected to cease on North Stradbroke Island in 2019.

Freshwater wetland management in the Moreton Bay Region

Wetlands are protected and managed under Queensland and federal legislation, international obligations and a range of laws, policies and programs administered by government agencies. Ramsar-listed wetlands are among the matters of national environmental significance protected under the *Environment Protection and Biodiversity Conservation Act 1999 (Cwlth)*. The quality of Queensland waters is protected under the Environmental Protection (Water) Policy 2009. Environmental values and water quality objectives have been determined for all areas of the Moreton Bay region.

The conservation values of Queensland's freshwater wetlands have been formalised through Aquatic Conservation Assessments applying the Aquatic Biodiversity Assessment Mapping Method 'AquaBAMM' (70) to palustrine, lacustrine and riverine wetlands of 16 SEQ catchments (25). Overall, approximately 53% of river reaches scored 'Very high' or 'High' for the overall AquaScore. These reaches tended to be in the higher elevation areas of catchments and on Bay islands where wetlands are relatively less disturbed than in many lowland areas of the region.

The Environmental Health Monitoring Program regularly monitors the ecological health of streams and rivers in SEQ based on 15 indicators of water quality, biodiversity (invertebrates, fish) and ecological functions (1, 71). However, the ecological health of palustrine wetlands is not assessed under this program. The formation of Healthy Waterways and Catchments in 2016 combined two not-for-profit organisations — Healthy Waterways and SEQ Catchments. These entities and the Resilient Rivers Initiative herald a new era of coordination and partnership in land and waterway management in the region.

Water management is a high priority in the Moreton Bay Region with its history of prolonged drought, devastating floods and a population demanding high quality water. Queensland's catchment Water Plans are legislated under the *Water Act 2000* with the aim of ensuring that the health, biodiversity and productivity of the environment is maintained or enhanced for the benefit of future generations. Water Plans have been developed for the Moreton Basin, Logan and Gold Coast areas using novel frameworks for assessing catchment-scale risk (72). The Water Plan (Moreton) 2007 established important ecological outcomes relevant to wetlands, for example, to provide freshwater flows necessary to maintain the long-term pattern of inflows to, and ecological functions of, wetlands and minimise changes to brackish water habitats (73).

Emerging issues — a synthesis for moving forward

The Queensland Government shares responsibility for managing wetlands with the Commonwealth and local governments, landholders and the wider community. Protecting and restoring the ecological health of SEQ wetlands is the focus of several initiatives, including the Queensland Wetlands Program, the Healthy Waterways and Catchments and Resilient Rivers Alliance, and Queensland's water management plans. Nevertheless, freshwater wetlands have been lost and the extent of artificial and highly modified wetlands has increased between 2001 and 2013. For example, the Logan–Albert catchment (Fig. 1) lost 1.4 km^2 of riverine wetland and gained 14.5k m^2 of artificial and highly modified wetland during this period (10). On the Bay islands, palustrine wetlands decreased in extent by 0.2 km^2, while artificial and highly modified wetlands increased by 1.8 km^2. The biodiversity and ecosystem service losses and risks associated with increasing artificial and highly modified wetland extent are well known in impounded and regulated waterways (20, 66, 67, 72). However, until recently, freshwater palustrine and floodplain wetlands have received far less attention. Assessing progress with wetland management in Queensland, Choy (74) called for greater investment in fundamental science to inform management and conservation.

Climate change projections for the Moreton Bay Region predict warming in all seasons, greater intensity of extreme rainfall events, harsher bush fires and storms and rising sea levels (75). Freshwater ecosystems are vulnerable to changes in water temperature and altered hydrology and are likely to be impacted by altered environmental regimes associated with shifting climates (31, 68). Regime changes are likely to affect wetland character, values and ecosystem services, and may lead to further wetland loss or reduced resilience to many other stressors. Rising sea levels could change the extent and character of low-lying wetlands with implications for the species they contain and the cultural values they provide (75).

Conclusion

The ongoing challenge for the Moreton Bay Region and Bay islands is to sustain and enhance wetland extent, diversity and ecosystem services in the context of expanding human populations; growing demands for water, infrastructure and food; and the likely threats imposed by climate change in a region that already suffers from variable weather patterns, drought and flooding. Climatic shifts interacting with common stressors are likely to profoundly influence the future of the region's freshwater wetlands. Ecological surprises, losses and gains, and societal adjustments can be expected in the uncharted landscapes and wetlands of changing climate futures. Important recommendations for the future of freshwater wetlands in the Moreton Bay region and Bay islands include:

(i) Sustain and enhance wetland biodiversity, functions and ecosystem services in the context of expanding human populations, growing demands for water and infrastructure, and likely threats associated with climate change;

(ii) Increase support for research, monitoring, communication and management of freshwater wetlands on the mainland and Bay islands;

(iii) Maintain a well-coordinated holistic approach to integrated land, water and wetland management based on sound multidisciplinary science, societal values and expectations, and partnership arrangements (such as the Healthy Waterways and Catchments and Resilient Rivers Alliance).

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Zooplankton of Moreton Bay

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Abstract

Moreton Bay is a subtropical bay in south east Queensland that supports important populations of seabirds, marine mammals, reptiles and fish. Zooplankton, being small, are often overlooked, but are important nutrient cyclers and a critical link between primary producers and higher trophic levels. Here we synthesise available information on the zooplankton of Moreton Bay, from copepods to jellyfish, and describe their important roles in marine food webs. Zooplankton research in the Bay has a long history, focusing primarily on taxonomy, key taxa, seasonality, demersal zooplankton and jellyfish. Copepods dominate the fauna in the Bay, accounting for 74% of the permanent members. The temporary members of the zooplankton comprise early life stages of littoral species of molluscs, decapods, barnacles, annelids and fish. The dominant large zooplankton species is the jellyfish *Catostylus mosaicus* that swarms periodically, and its large biomass at times contributes significantly to nutrient cycling. Compared with immediately offshore, zooplankton in the Bay are more abundant but generally smaller in size and contain more meroplankton. In addition, the copepod community is more similar to communities of other tropical shallow coastal regions than zooplankton immediately offshore. Water quality models for the Bay have provided new insights into the variation of zooplankton in time and space that are difficult to investigate using standard sampling approaches. We conclude by highlighting key research gaps that need to be filled, namely the impact of flood events on zooplankton; the use of zooplankton as indicators of water quality to complement solely physico-chemical variables; harnessing historical data to

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assess the degree to which zooplankton communities have changed over recent decades; and the validation of the zooplankton components in water quality models.

Keywords: coastal ecology, subtropical, meroplankton, holoplankton, demersal, copepods, jellyfish, chaetognaths, larvaceans, IMOS

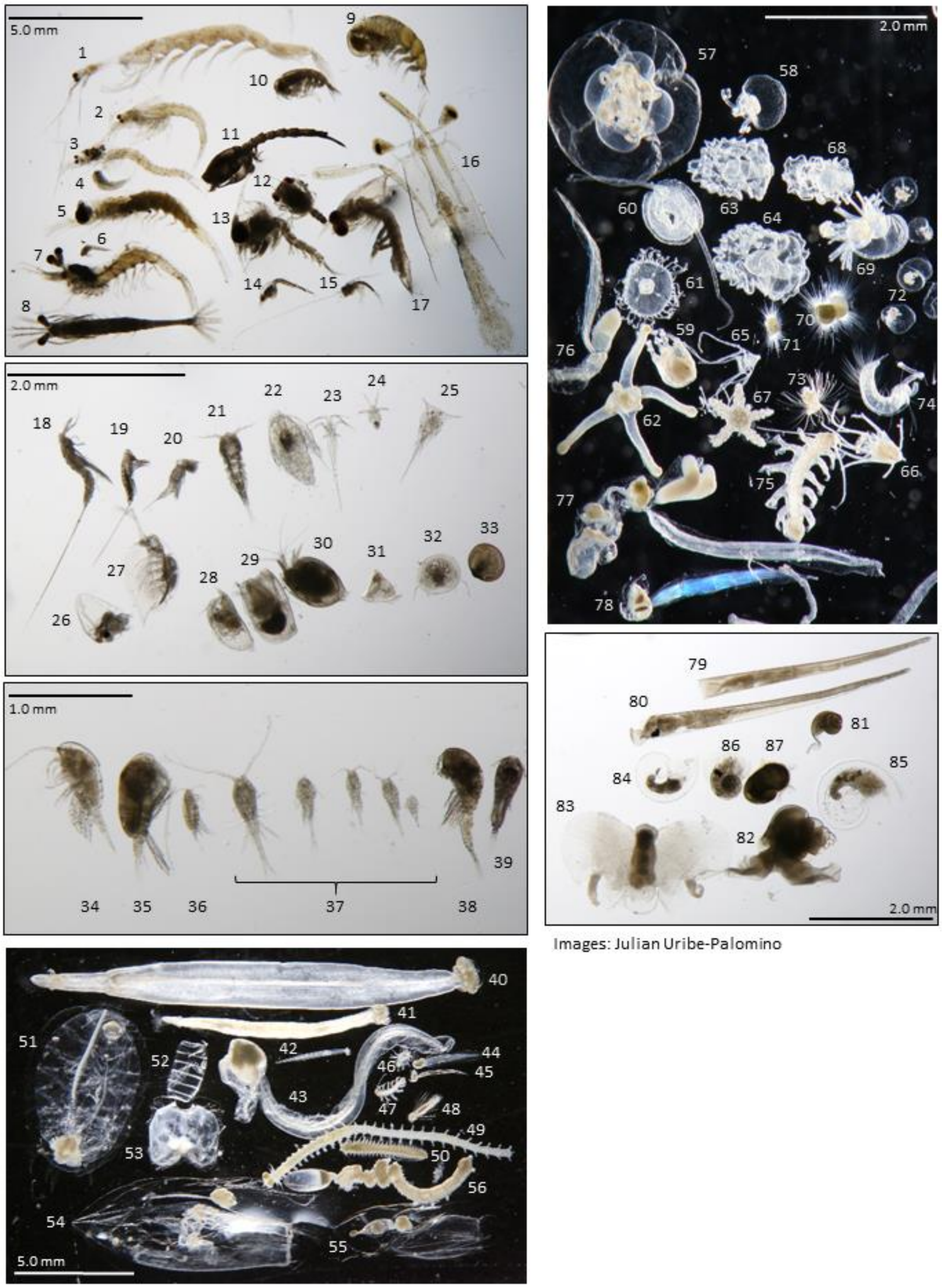
What is zooplankton?

The word 'plankton' is derived from the Greek planktos meaning 'to drift', and although most zooplankton are motile, none can progress against currents. Most plankton are microscopic, but some such as jellyfish may be up to 2m in bell diameter and can weigh up to 200 kg. Plankton communities are highly diverse, containing organisms from almost all kingdoms and phyla (Fig. 1). Plankton can be separated into the photosynthetic component (phytoplankton) and the animals (zooplankton). The permanent members of the zooplankton are known as holoplankton, and these include copepods (Subclass Copepoda), chaetognaths (Phylum Chaetognatha) and cladocerans (Superorder Cladocera). However, as almost all marine species shed their sperm and/or eggs directly into seawater to enhance dispersal, most marine animals are planktonic at some stage in their lifecycle. These temporary members of the zooplankton are called meroplankton. Like a caterpillar metamorphosing into a butterfly, many meroplankton look nothing like the adult form. Meroplankton, including mussel, barnacle and fish larvae, are more common in coastal areas where their progenitors live, and are generally more abundant at night than during the day because many species spawn then and others move up in the water column during the night.

Why is zooplankton important?

Zooplankton are critical to the functioning of estuarine and coastal food webs because of their sheer abundance and vital ecosystem roles. The most prominent zooplankton, the copepods, could be the most abundant multicellular animals on Earth, perhaps 1,000 times more abundant than insects (1). The high phylogenetic diversity of zooplankton contributes to their diverse ecosystem functions. Arguably, the most important role of zooplankton is as the major grazer in food webs, providing the principal pathway for energy from primary producers (the phytoplankton) to larger consumers such as fish, marine mammals, jellyfish and sea turtles. Interestingly, some of the largest animals in the ocean, such as baleen whales, feed solely on zooplankton. This is in stark contrast with terrestrial ecosystems, where the largest animals are generally herbivores.

Zooplankton not only support the large, highly visible, and charismatic components of ocean food webs, but also the microbial community. Their feeding mechanisms, secretions and excretions play an important role in nutrient cycling (2, 3) and support microbial (4, 5) and phytoplankton production. Microbes colonise zooplankton faecal pellets and carcasses (3), making them rich sources of organic carbon for detrital feeders in the water column and benthos. In shallow coastal regions, demersal zooplankton play an important role in transferring energy and nutrients between the sea bottom and water column (6), and are also food for fish whilst in the water column (7, 8). Zooplankton grazing has the potential to exert selective pressure on phytoplankton community dynamics (9–13) that may determine the fate of algal blooms. Understanding the relationship between environmental drivers and zooplankton dynamics is an important step in safeguarding the ecological and economic resources of coastal regions and their resilience to anthropogenic nutrient enrichment and climate change.



Images: Julian Uribe-Palomino

Figure 1. Images of mixed zooplankton from Moreton Bay. 1. Lucifer shrimp 2-3. Mysids 4. Juvenile mysid 5. Euphausiid, 6. Juvenile euphausiid 7-8. Juvenile decapods 9-10. Hyperiid amphipods 11.

Cumacean 12. Brachyuran megalopa 13. Brachyuran zoea 14. Anomuran zoea 15. Porcellanid (Anomuran) zoea 16-17. Juvenile stomatopods 18-21. Harpacticoid copepods (18. *Macrosetella gracilis* 19. *Microsetella* 20. *Euterpina acutifrons* 21. *Clytemnestra*) 22-24. Calanoid copepod nauplii 25. Barnacle nauplius 26-27. Cladocerans (*Pseudevadne tergestina, Penilia avirostris*) 28-30. Ostracods 31. Bryozoan larva 32. Brachiopoda larva 33. Bivalve veliger 34-39. Adult copepods (34. *Temora turbinata* 35. *Acrocalanus gracilis* 36. *Parvocalanus crassirostris* 37. *Oithona* 38. *Oncaea venusta female* 39. *Oncaea venusta* male) 40-42. Chaetognaths 43-45. Oikopleurid appendicularians 46-50. Polychaetes 51. Salp; *Thalia democratica* 52. Doliolid; *Doliolum nationalis* 53-55. Siphonophores 56. Siphonophore pneumatophore 57-59. Anthoathecata medusae 60. Narcomedusa; *Solmundella bitentaculata* 61. Leptothecata medusa; *Obelia*, 62. Anthozoa larva (Cnidaria) 63-64. Tornaria larvae (Hemichordata) 65-66. Echinoderm pluteus larvae 67. Echinoderm ophiuroid juvenile 68. Echinoderm bipinnaria larva 69. Phoronid larva 70-71. Globigerinid foraminiferans 72. *Noctiluca scintillans* (dinoflagellate) 73-74. Polychaete larvae 75. *Tomopteris* (holoplanktonic polychaete) 76-77. Appendicularians 78. Oikopleurid appendicularian 79-83. Gastropod molluscs (79-80. *Creseis* 81-82. *Limacina* 83. *Desmopterus*) 84-85. Echinospira mollusc larvae 86. *Atlanta* (pterotracheoid mollusc) 87. Prosobranch mollusc

History of zooplankton research in Moreton Bay

Although there has been relatively little zooplankton research in Australia over the past century compared with temperate regions in the northern hemisphere (for an example see (14)), Moreton Bay has had a surprising number of studies. The first studies were limited in area and descriptive. The earliest account of zooplankton research in Moreton Bay is from a January 1938 expedition by Laing (15), who undertook six net hauls east of Peel Island. She briefly described the plankton composition in broad taxonomic groups and noted a day/night difference. This was followed by Munro (16), who studied the general composition of zooplankton in Waterloo Bay and the night-time emergence.

Zooplankton studies published between the 1960s and the late 1990s have been reviewed by Greenwood (17). Succeeding zooplankton work by Greenwood in 1999 (18) formed a component of the broader Moreton Bay Study initiated by stakeholders to inform improvement of water quality for the Bay and its estuaries. While the taxonomic resolution was low, it extended the knowledge base for zooplankton abundance, size fractions and night/day population differences upstream to the Bremer River, northward to Deception Bay and southward to Pelican Banks.

There has been relatively little work in Moreton Bay in the 21st century. Greenwood (19) investigated the demersal zooplankton of the Brisbane River estuary and found that dredging led to a significant decline in zooplankton abundance, but had little impact on composition or distribution. In a study of the bacterioplankton using molecular techniques, Hewson and Fuhrman (20) found that some bacterioplankton taxa were restricted to distinct environments, whereas others had a ubiquitous distribution from the Brisbane River to the outer Bay. Recently, Uribe-Palomino *et al.* (21) described a new, tiny (2 mm) jellyfish species of the genus *Merlicertissa* whose holotype was collected in the Bay.

Dominant taxa

Copepods

As in most subtropical water bodies (22), copepods numerically dominate the fauna in the Bay, accounting for 74% of the holoplankton and 50% of the total zooplankton (23). The copepod community is always dominated by calanoids (average 76% of total copepods). Approximately half of the 68 calanoid species recorded by Greenwood (24) were found in fewer than 5% of the samples, with just 11 species present in 50% or more of the samples. These 11 species were also numerically important components of the zooplankton. Greenwood (24) found that the most frequently captured calanoid copepods in Moreton Bay, listed in descending order were, *Pseudodiaptomus mertoni, Tortanus barbatus, Temora turbinata, Acartia pacifica, Bestiolina similis, Acartia tranteri, Parvocalanus crassirostris, Acrocalanus gibber, Centropages furcatus, Pseudodiaptomus colefaxi,* and *Calanopia australica.*

Interestingly, two species in each of two genera were in the top 11 species, raising the question of how they coexist despite competing for shared resources. For example, the dominant calanoid copepod species, *A. tranteri*, an estuarine species endemic to Australia, and the more cosmopolitan, estuarine-coastal *A. pacifica*, are from the same genus. It is thought they are able to coexist because of seasonal and spatial niche separation (25). *A. tranteri* was typically dominant in colder temperature waters (14–21°C) and lower salinities between 30–36.5‰, whereas *A. pacifica* was dominant above 22°C and from 34–36.5‰. The same study similarly concluded *P. colefaxi* was more of a generalist, with broader temperature and salinity preferences, than its specialist congenitor *P. mertoni* (25).

Greenwood (23) found cyclopoid copepods typically constituted one-fifth of the total copepod fauna when collected using a 195µm mesh net. However, these characteristically smaller copepod species were sometimes dominant during the Task Plankton Trophodynamics Study (18), which used finer mesh nets. Thwin's (26) time series work recorded 34 species of cyclopoids, with 10 of these in <2% of the samples. The three small species *Oithona brevicornis, Oithona nana* and *Coryceaus andrewsi* were the most frequent constituents of the cyclopoid fauna.

Globally, a mere 0.5% of described harpacticoid species permanently inhabit the pelagic realm (27). Unsurprisingly, harpacticoids constitute the smallest fraction of the copepod fauna in Moreton Bay, averaging just 2.7% and 1.4% of the copepod and total zooplankton abundances, respectively (23). Neritic and oceanic species such as *Euterpina acutifrons, Microsetella* spp., *Macrosetella gracilis, Goniopsyllus rostrata* (originally identified as *Clytemnestra rostrata* in (28)) and *Metis holothuriae* (probably benthic and associated with seagrass) have been collected in the Bay. Interestingly, *M. gracilis* uses the colonial cyanobacterium *Trichodesmium* both as a food source (29) and buoyant substrate for juvenile development (30). *Trichodesmium* is a major contributor to primary productivity in oligotrophic tropical and subtropical oceans (31), and periodically forms dense surface slicks in the Bay (32). *M. gracilis* may thus be an important trophic link between *Trichodesmium* and higher trophic levels in the more oligotrophic areas of the Bay, such as towards the eastern barrier islands.

Other zooplankton

Greenwood (23) found that the most numerous holoplanktonic groups, in order of numerical importance, were the appendicularians, cladocerans, chaetognaths and cnidarians.

Appendicularians (larvaceans, (tunicates)) occasionally represented 60% of the non-copepod zooplankton. The Moreton Bay population was dominated by *Oikopluera longicauda*, with *Oikopluera doica* also common and *Fritillaria pellucida* rare (23). While often outnumbered by copepods, growth rates for larvaceans typically surpass those of copepods at the same temperature (33, 34). Larvaceans are one of the few metazoans to efficiently feed on the picoplankton (0.2–2 µm-sized particles), which are filtered from the water column using a mucous feeding structure known as a 'house' (35). Their filtration rates are high, and once they are clogged with phytoplankton, bacteria, ciliates, detritus and faecal pellets, houses are shed and replaced. New houses are secreted regularly; Sato *et al.* (36) observed house renewal rates from 2–40 per day for ten species from Tokyo Bay, Japan. *O. longicauda* produces and discards up to 24 per day and the carbon content of particle-loaded, discarded houses corresponds to 18% of somatic carbon (36). Given their abundances and ubiquity, larvaceans are thus an important source of secondary production in the coastal and oceanic systems they inhabit. In addition, larvacean houses are colonised by bacteria and flocculate with other organic detritus, forming marine snow (37). The subsequent breakdown of discarded houses not only makes organic matter available for remineralisation by the microbial community (37), but these macroscopic aggregates provide food for copepods (38) otherwise unable to consume picoplankton-sized particles due to the limitations of their feeding structures (39). Discarded houses thus represent an important link between the microbial and classical food webs.

To date, four of the world's eight known marine cladocera species have been recorded in Moreton Bay (23, 28). Cladocerans are important links in the microbial loop because they are capable of feeding on organisms ranging from <2 µm (flagellates) up to 100 µm (diatoms, dinoflagellates and ciliates) (40–42) and in turn are preyed on by higher trophic consumers such as chaetognaths (43) and planktivorous fish (44) in classical food webs. Owing to their short developmental times and unique ability among the planktonic crustaceans to reproduce asexually (by parthenogenesis), cladoceran populations can respond rapidly to favourable environmental conditions and reach high densities (42). Moreton Bay's cladoceran population is typical of other neritic subtropical waters, with the dominance and almost constant presence of *Penilia avirostrus,* one of the more abundant and geographically widespread species (45). Highest observed densities were 635 m^{-3} but annual average was one-tenth of that maximum at 64 m^{-3} (23). As a group, the cladocerans averaged 3.8% of the total zooplankton (23). Other species captured in the Bay were *Pseudevadne tergestina, Evadne nordmanni* and *Pleopis polyphemoides*.

Chaetognaths are known as arrow worms and are raptorial carnivores. They are found across most marine habitats including estuaries, bays, and open oceans from polar to equatorial waters (46). They are ambush predators, and prey include copepods and cladocerans (47). Globally they are often reported in abundances second only to copepods in the mesozooplankton (48, 49), and indeed they are among the dominant taxa in Moreton Bay. This group formed 3.4% and 5% of the total zooplankton and holoplankton, respectively, in a study in years 1963–1966, with notable species being the cosmopolitan *Flaccisagitta enflata* and Indo-Pacific-distributed *Aidanosagitta neglecta* (23).

The meroplankton in Moreton Bay are largely composed of early life stages of littoral species. In Greenwood's (23) collections, the most numerous meroplankton were the larvae of molluscs, decapods, barnacles and annelids. Only the copepods outnumbered molluscan veliger larvae, whose abundances averaged 23% of the total zooplankton. Gastropod veligers, found throughout the year, were more numerous than bivalve veligers. The decapod component was diverse and dominated by brachyuran zoeae, but included penaeid larvae and *Lucifer* and porcellanid crab zoeae. Barnacle (cirripede) nauplii and cyprids averaged 38 individuals m^{-3} and were present year-round. However, nauplii were much more common than cyprids, which are a more mature, briefer and non-feeding developmental stage. Many of the planktonic annelids, which were present in all months were spionid and polynoid polychaete larvae. Other, less common, polychaetes included the Terebellidae and the holoplanktonic *Tomopteris* sp.

Cnidarians are a diverse and widespread group of largely colonial invertebrates that includes many captivating forms such as corals, sea fans, sea anemones and the floating Portuguese man o'war, (aka blue bottle). All cnidarians possess nematocysts, the specialised stinging organelles feared by bathers. Some cnidarians have only a sessile polyp stage (e.g. corals), others have only a pelagic medusa stage (e.g. some true jellyfish species), but many cnidarians have alternation of generations, switching between the asexual polyp and the sexual pelagic medusa stage. Gelatinous, planktonic cnidarians include the siphonophores (Class: Hydrozoa), box jellyfish (Class: Cubozoa) and true jellyfish (Class: Scyphozoa).

The cnidarian community from Moreton Bay has been characterised in seven studies, a number of which are unpublished theses or reports, and most are taxonomic accounts (16, 23, 50-54). Gelatinous animals are notoriously difficult to sample effectively; they are often too large for most sampling gear, or so small and delicate that they disintegrate upon capture, and their mucus has a tendency to clog net mesh and compromise entire samples.

About 58 species of cnidarians have been recorded in Moreton Bay, 52 of which are reported and reviewed by Gershwin *et al.* (54) from collections and literature, including descriptions for seven new species and new distribution records. It is remarkable that such an extensive appraisal of Cnidaria exists for the Bay, although this taxon list does not include the species *Diphyes subtiloides* and genera *Corymorpha* sp. (as *Steenstrupia* sp.), *Sarsia* sp., *Melicertissa* sp. (as *Melicertiasa* sp.), *Mitrocomidae* sp. (as *Cosmetira* sp.), *Lensia* sp. found by Munro (16). Gorman (52) sampled cnidarians and ctenophores from seven stations in the Bay and, using a wider net than Greenwood (23), described a more abundant and more diverse community dominated by hydrozoans, with many fewer scyphozoans. The hydrozoans *Octophialucium medium* and *Aequorea australis* were most abundant by one to two orders of magnitude (52). Interestingly, neither of these species was recorded in Payne's (50) five common species for the Bay, highlighting the patchiness in space and time of the planktonic cnidarians.

Siphonophores and other hydrozoans have been found year-round within the Bay and average combined densities have reached $43m^{-3}$ (23). By contrast, the larger *Catostylus* and *Cyanea* scyphozoans are observed sporadically, with *Catostylus* occasionally forming dense swarms (23, 52). Thus, while they represent only a minority of the planktonic fauna by number, cnidarians can attain significant biomass in the Bay. Other notable taxa include the hydrozoans *Physalia physalis* (bluebottle) and *Velella velella* (by-the-wind-sailor), both cosmopolitan, buoyant, bright blue, and conspicuous when blown onto beaches. There is currently little known about the micro-medusae (mature form < ~5 mm bell diameter) from this region.

Seasonality

Moreton Bay is a subtropical embayment and thus is likely to have a dampened seasonal cycle compared with higher latitudes. Thwin (26), for example, observed that cyclopoid copepods formed three main assemblages: (i) estuarine species, (ii) inshore species present at all times, and (iii) seasonal offshore intruders. In other words, the primary division of these groups was based on estuarine and non-estuarine species, with temperature only secondarily driving a division into cold and warm water groups.

Greenwood (23) found that total zooplankton, total copepods, holoplankton, and meroplankton did not show typical seasonal patterns, with all having multiple peaks throughout the year (Fig. 2). Many taxa, however, exhibit strong seasonal patterns. Meroplankton such as bivalve, gastropod, decapod, polychaete and echinoderm larvae contributed most to total zooplankton abundances in summer (23), and Tafe (55) found cumacean species richness was lowest in winter and highest in summer. There is strong evidence for seasonality in copepod species richness, with more oceanic copepods during late summer to winter, which leads to a peak of copepod species richness in winter (24). This is probably due to the annual intrusion of oceanic water that delivers oceanic species and increases species richness in Moreton Bay (24) (Fig. 3). Other oceanic species of chaetognaths, larvaceans, and salps have been recorded in the Bay during this period; for example, the chaetognath *Flaccisagitta enflata* exhibits a positive correlation with salinity, suggesting oceanic water intrusion (23).

Peak abundances of the cladoceran *Penilia avirostrus* were found in cooler months (23), in contrast to other subtropical bays where the species typically peaks in warmer months (55–57). We have no indication of what drives this difference, although *Penilia* populations in tropical Kingston Harbour, Jamaica, are not generally food limited (45). Rose *et al.* (45) could find no seasonal patterns and no correlation of abundances with chlorophyll concentrations, nor indeed with any measured physical variables within the Harbour. They surmised this neritic population may instead be regulated by predation, which may likewise be the case in Moreton Bay.

The most robust dataset on jellyfish abundance in Moreton Bay has been collected by the Queensland Government's Ecosystem Health Monitoring Program, which has recorded the presence or absence of *C. mosaicus* each month since 2002 at >100 sites in Moreton Bay. Within years, *C. mosaicus* exhibits strong seasonality, with juvenile medusae recruiting during spring and summer and populations declining in autumn, although medusae may occasionally be encountered during winter (Fig. 4) (56). Limited data exist for other species of jellyfish in Moreton Bay.

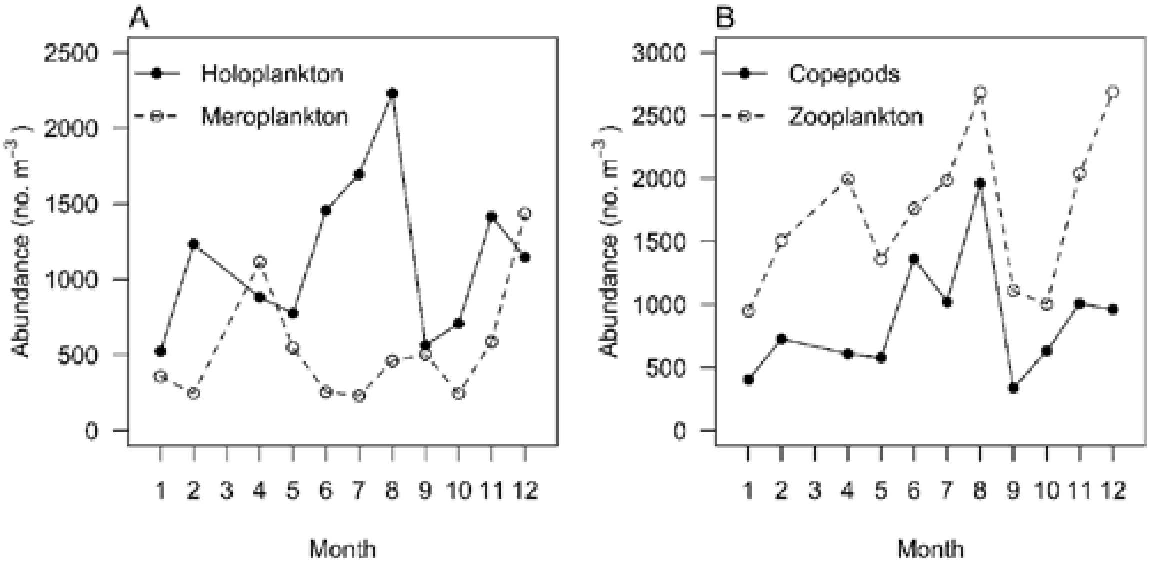


Figure 2. Seasonality of (A) Holoplankton and meroplankton, and (B) Zooplankton and copepods (from (23)).

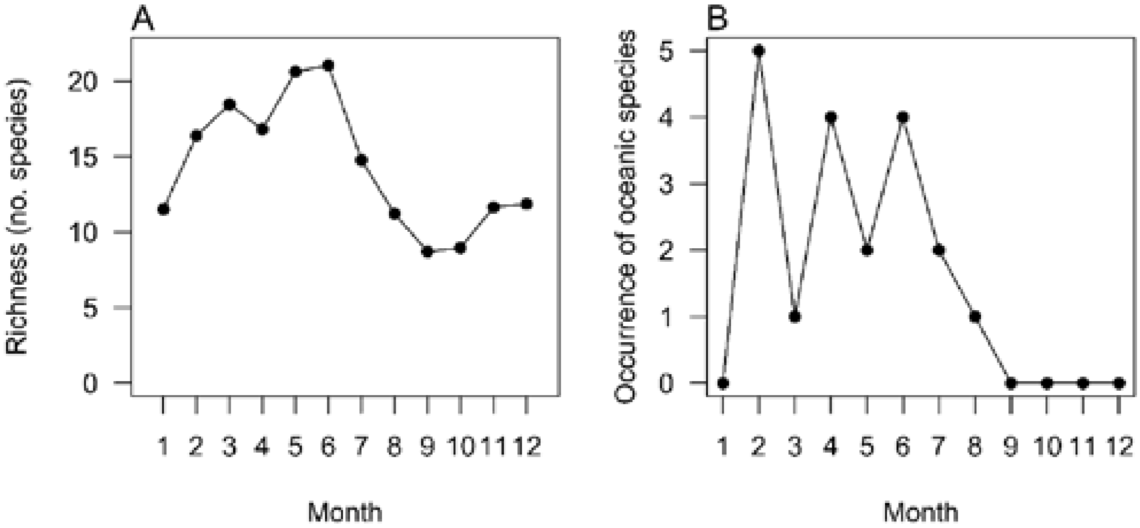


Figure 3. Seasonality in (A) Copepod species richness, and (B) Occurrence of oceanic indicator species (based on data from (24))

Despite limited evidence of strong repeated seasonal cycles, most studies have only been conducted over a single year. Further studies are needed to confirm the degree of seasonality, and whether multiple peaks are indeed consistent each year or simply indicative of a subtropical environment with periodic and ephemeral productivity pulses. Subtropical estuaries often have more pronounced spatial variation in community structure of subtropical zooplankton across salinity and water quality gradients than seasonal differences (57). Many studies have grouped taxa together, which can hide seasonality if there are different peaks and troughs in various taxa, so species-level analyses might prove more informative. No work has investigated the association between the summer rainy season and the elevated freshwater inputs and nutrient loads at that time.

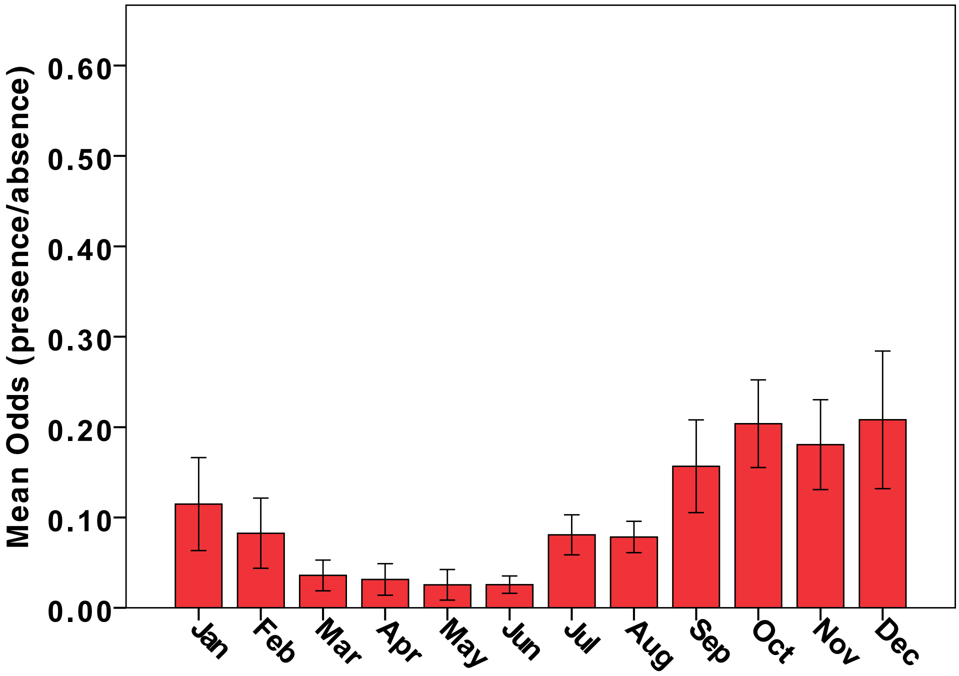


Figure 4. Intra-annual variation in mean odds (±SE) of encountering *Catostylus mosaicus* in Moreton Bay (Data provided by Ecosystem Health Monitoring Program; from Joensen (56))

Demersal zooplankton

Estuaries, bays and coastal waters the world over contain resident zooplankton that dwell in, on or just above the seafloor during the day and emerge into the water column at night. This demersal fauna has received considerable attention in Moreton Bay, and numerous studies have shown pronounced diel changes in the composition of its zooplankton. Jacoby and Greenwood (58) used emergence traps, re-entry traps and surface tows to study vertical migration patterns in the zooplankton. While they found differences in taxa and abundances captured using different nets and across seasons, they observed a general pattern of emergence at night using surface tows (Fig. 5). A total of 17 of the 23 taxa investigated showed night-time emergence, with the larger zooplankton taxa, especially crustaceans, exhibiting nocturnal emergence (58). Mysids, a shrimp-like crustacean, showed the strongest emergent signal at night. Laing (15) and Munro (16) similarly collected mysids more frequently in night-time hauls and in higher abundances than those taken in daylight. Copepods of the genus *Pseudodiaptomus* are well known to be demersal (59, 60), with varying degrees of affinity to the substratum (58). *Pseudodiaptomus colefaxi* is a species of calanoid copepod dominant in the Bay whose abundances are higher in surface waters at night. Its congener, *P. mertoni,* was found throughout the water column during the day but in greater numbers at night. More mature developmental stages of *Pseudodiaptomus* spp. had demersal habits similar to those of adults. Emergence was observed in other copepods including harpacticoids, *Oithona* and *Acartia* spp., as well as mollusc larvae (e.g. bivalve and gastropod veligers).

Jacoby and Greenwood (58) found substratum type to be an important factor governing emergence patterns of demersal plankton. Moreton Bay has diverse subtidal habitats including coral, seagrass beds, and sandy, muddy and rocky bottoms. Substratum type determined how many and which taxa emerged, with 41 of the 43 demersal taxa studied emerging in greater numbers from more structurally complex coral and seagrass than from the more uniform coral rubble and mud habitats. Further, for most taxa, they recorded emergence in densities about 10 times greater than for taxa from their Heron Island lagoon study (61). This has important ramifications for zooplankton productivity and links to higher trophic levels, particularly given recent studies documenting increases in terrestrially derived mud content and mud distribution across Moreton Bay (62, 63).

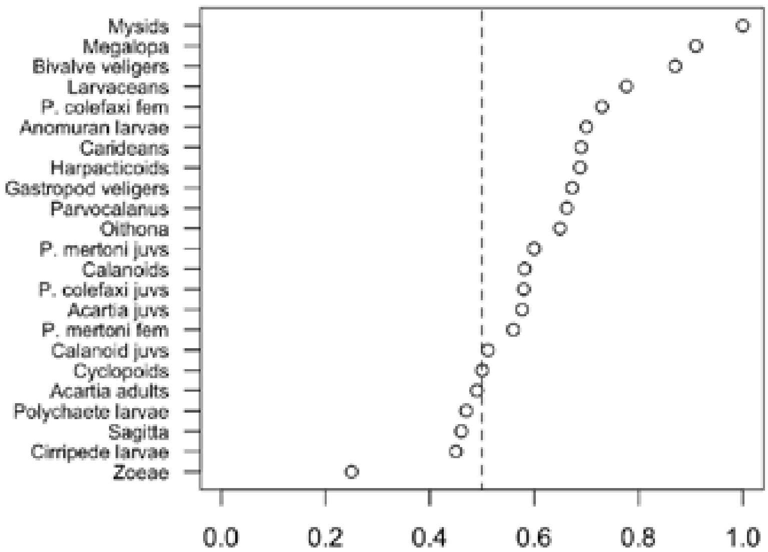


Figure 5. Night-time emergence of zooplankton captured in surface tows. (Adapted from (58)).

Emergence of demersal zooplankton is also common in the lower reaches of rivers entering Moreton Bay. Larger zooplankton such as the sergestid shrimp *Acetes sibogae,* present throughout the Bay but primarily concentrated in the lower reaches of its tributaries, spends daylight hours at or near the sediment–water interface and migrates into the water column at night on flood tides (64). Greenwood *et al.* (19) sampled the near-bottom zooplankton populations in the Brisbane River during a study on the impacts of gravel extraction, and 33 of 90 taxa captured during daytime tows were generally considered to be demersal. Common demersal zooplankton included the copepods *Gladioferens pectinatus*, *Pseudodiaptomus* spp., *Stephos morii* and *Brianola*, and isopods, amphipods, mysids, tanaids, numerous decapods, and planktonic stages of fish.

There are numerous drivers of emergence in demersal zooplankton. Many demersal zooplankton emerge in the water column at night to feed on phytoplankton, holoplankton or other emergent zooplankton. During the day, demersal zooplankton tend to return to the substrate to hide from visual predators. Nocturnal migrators tend to be relatively large, with highly discernible swimming movements, rendering them vulnerable to predation by visual predators such as planktivorous fish (7, 65). Emergence from the seafloor can also have the benefit of population maintenance in a region. For example, the sergestid shrimp *Acetes* *sibogae* times its emergence at night to the flood tide to maintain its position in the estuary (64). Some benthic crustaceans emerge at the same time to increase the likelihood of finding a mate (66). Smaller zooplankton or transparent larval forms are less subject to visual predation and often show weaker emergence or vertical migration. Emergence into the water column also has the benefit of facilitating passive transport to exploit new feeding regions.

Regardless of its cues and adaptive significance, this cyclic movement of living organisms is an important process in bentho-pelagic coupling as it transfers energy from surface waters to the substrate and vice versa. Larger crustaceans such as mysids and sergestids, for example, are important dietary components of resident juvenile fishes (65). Understanding diel patterns in the contribution of such taxa to the planktonic population is necessary for establishing their role in trophic pathways.

Jellyfish ecology

Jellyfish are common and conspicuous members of Moreton Bay zooplankton assemblages. Scyphozoan jellyfish are the most visible and some species form spectacular blooms that comprise a substantial proportion of the pelagic biomass. Jellyfish are voracious predators of other zooplankton, including other jellyfish species (67) and act as hosts for numerous species of fish and invertebrates (67, 68) and so have an important role in the ecology of Moreton Bay. They are also likely to influence nutrient dynamics within the Bay, particularly when large blooms of jellyfish collapse suddenly and decompose on the sea floor. Moreover, due to their sheer numbers, they can sometimes impart substantial socio-economic effects. For example, in 2005, the aircraft carrier *USS Ronald Reagan* departed the Port of Brisbane earlier than scheduled when the blue blubber (*Catostylus mosaicus*), Moreton Bay's most abundant large jellyfish, interfered with the cooling intakes of the ship.

Inter-annual variation

Populations of jellyfish typically exhibit strong inter- and intra-annual variability in abundance. Data from the Queensland Government's Ecosystem Health Monitoring Program hints that populations of *C. mosaicus*, like many other species of jellyfish (69), exhibit distinct cycles of abundance, with jellyfish being very abundant for several years, followed by years when jellyfish are scarce or absent (Fig. 6) (56). Until data tracking multiple complete cycles are available, cyclic behaviour of *C. mosaicus* populations in Moreton Bay cannot be confirmed.

Trophic interactions

Jellyfish are voracious predators of zooplankton and, when abundant, can influence the dynamics of zooplankton and phytoplankton communities (70, 71). As jellyfish swim continuously, they capture prey throughout the day and night and thus also consume nocturnal emergent taxa (67). In Moreton Bay, *C. mosaicus* captures about 50% of the zooplankton taxa that are present in the water column (67). Gastropod and bivalve veligers, copepods, brachyuran crab zoeae and amphipods are the most common species captured by *C. mosaicus* in the Bay, whilst ostracods and barnacle nauplii either evade capture or are rejected by the jellyfish (67).

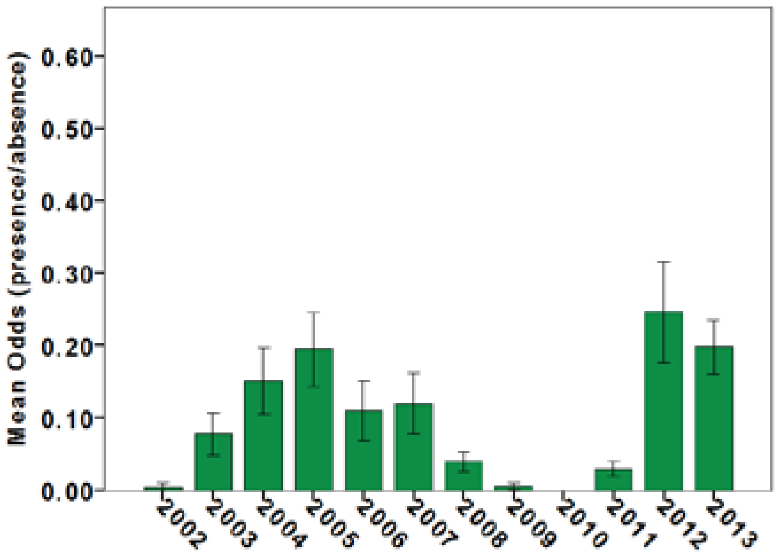


Figure 6. Inter-annual variation in mean odds (±SE) of encountering *Catostylus mosaicus* in Moreton Bay. (Data provided by Ecosystem Health Monitoring Program; from Joensen (56)).

Until recently, jellyfish were considered to be trophic 'dead ends' as they were thought to be consumed by just a few species that specialise on feeding on them (such as leatherback turtles and sunfish). The diversity of animals that prey on jellyfish, however, is likely to have been grossly underestimated since jellyfish tissue decomposes rapidly in the guts of predators and is difficult to identify using traditional gut content techniques. Emerging technologies, such as using cnidarian-specific mtDNA assays (72) is revealing that a much greater diversity of animals prey upon jellyfish than once thought and this is also likely to be the case in Moreton Bay. Having healthy populations of jellyfish may thus be important in sustaining populations of a diverse range of species, including the numerous species of sea turtle that inhabit Moreton Bay.

Commensal relationships

A diversity of organisms associate with jellyfish in Moreton Bay, including dinoflagellates (zooxanthellae; 73), fish (68), copepods (74), and anemones and isopods (75). The relationship between jellyfish and the animals they host varies and includes parasitism, whereby the associates may feed on or deposit their eggs and larvae within the tissues of the host jellyfish, thus harming it (e.g. Brown *et al.* (75)); commensalism, whereby one partner may benefit from the association but the other partner is unharmed (such as the fish *Trachurus novaezelandiae* that appears to shelter under the umbrella of *C. mosaicus* but not harm it (76)); and symbiosis *sensu stricto*, in which both partners benefit (such as the dinoflagellates that associate with *Cassiopea* sp.). Jellyfish, therefore, are likely to have a major role in supporting pelagic biodiversity within Moreton Bay. Indeed, the diversity of organisms that associate with jellyfish in the Bay is likely to be much greater than stated here, since in other regions of Australia, *C. mosaicus* associates with anemones and isopods (75), and intermediate stages of digenean (Class: Trematoda) parasites (77).

Influence in nutrient cycling

Due to their 'boom and bust' population dynamics, and their sheer abundances, jellyfish have a major role in biogeochemical cycling (78). As populations of jellyfish grow, they assimilate carbon and nutrients from their prey, and excrete nitrogenous wastes and dissolved organic carbon into the water column. Blooms of jellyfish thus represent significant repositories of

Figure 7. Large numbers of *Catostylus mosaicus* stranded on the beach at Deception Bay in February 2017. (Image courtesy of Charlotte Lawson)

carbon and nutrients that are subsequently released when the populations collapse during autumn. Senescent jellyfish rapidly sink to the sea floor and may be consumed by benthic scavengers such as fish, or be remineralised by bacteria (79). In Moreton Bay, jellyfish carcasses are more likely to be scavenged than remineralised, since potential scavengers are abundant. Winds and tidal currents often strand large numbers of jellyfish on the beaches of Moreton Bay (Fig. 7). These stranding events are likely to provide important, although episodic, trophic and nutrient subsidies to the sandy shore environments, where *in situ* levels of productivity are typically low.

Zooxanthellate jellyfish influence nutrient cycling differently than non-zooxanthellate species since the nitrogenous wastes and carbon dioxide excreted by the host jellyfish are almost entirely used by their symbionts and thus recycled internally within the holobiont (80). Moreover, zooxanthellate jellyfish can assimilate dissolved inorganic nitrogen and phosphorus from the water column (81).

How do zooplankton differ inside and outside Moreton Bay?

Zooplankton in coastal bays are often substantially different from neighbouring oceanic regions. The zooplankton community in Moreton Bay exhibit lower biomass, higher abundances and lower species richness than at an oceanic site outside the Bay according to data from the Integrated Marine Observing System (IMOS) National Reference Station off North Stradbroke Island (Fig. 8A–C). This is typical of zooplankton communities in coastal waters at lower latitudes, which generally exhibit higher abundances and lower species richness in more eutrophic, inshore waters than in more oligotrophic offshore waters (57, 82, 83). Copepods in Moreton Bay are smaller than in oceanic waters (Fig. 8D), which explains the lower biomass yet higher abundance in Moreton Bay relative to the oceanic site; eutrophic bays commonly have smaller zooplankton (84, 85). Both the total abundance of meroplankton and the ratio of meroplankton to holoplankton are higher in the Bay than outside, as expected given more larvae of littoral forms (e.g. molluscs, barnacles, prawns) (Fig. 8E, F).

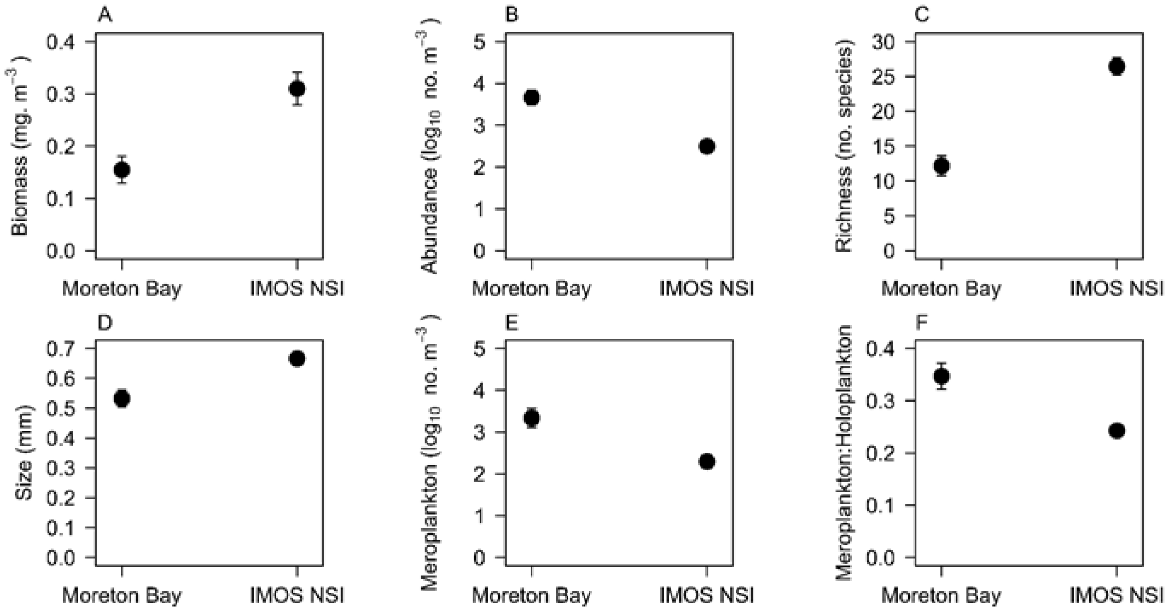


Figure 8. Comparison of zooplankton from inside Moreton Bay (Peel Island) and outside at the IMOS NSI (North Stradbroke Island) National Reference Station: (A) Zooplankton biomass, (B) Copepod abundance, (C) Copepod richness (number of species), (D) Mean copepod size, (E) Meroplankton abundance, and (F) The ratio of no. of species of meroplankton:total no. of species in a sample.

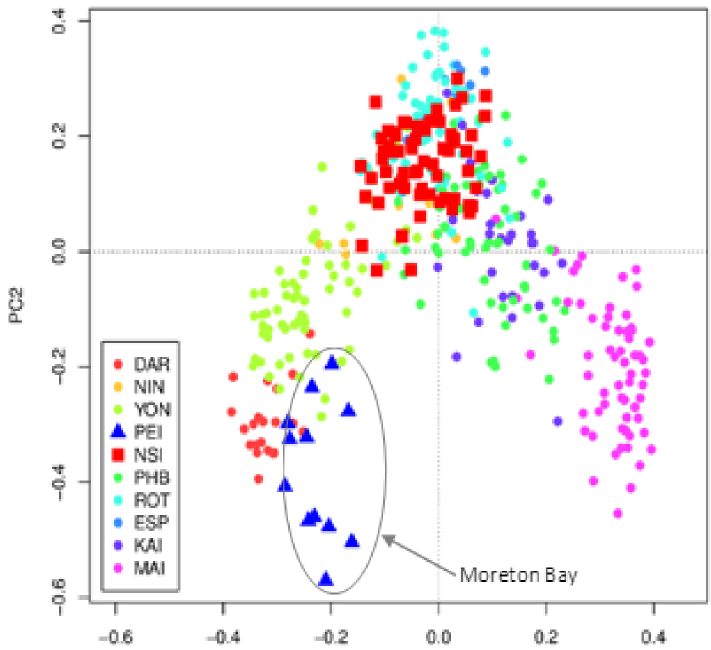


Figure 9. Principal components analysis of Moreton Bay zooplankton (from Peel Island and labelled PEI) with other data from the IMOS National Reference Stations: DAR = Darwin Harbour, NIN = Ningaloo, YON = Yongala, NSI = North Stradbroke Island, PHB = Port Hacking Station B, ROT = Rottnest Island, ESP = Esperance, KAI = Kangaroo Island, MAI = Maria Island.

How does Moreton Bay compare with other areas in Australia?

The IMOS network of National Reference Stations (NRSs) provides an ideal dataset for comparing Moreton Bay zooplankton with the fauna of other areas around Australia. We analysed copepod abundance and species composition from samples from Peel Island in Moreton Bay, collected with a 100 µm mesh net that was used throughout the IMOS NRS network, with data from various IMOS stations around Australia (12 samples from Peel Island in 2009 and 388 samples from the NRS sites 2010–16). The first two Principal Components Analysis (PCA) axes accounted for 14% and 7% of the variance in species composition, respectively (Fig. 9). There was strong differentiation in the copepod assemblages among stations. Copepod communities on the right-hand side of the PCA are from temperate regions and those on the middle and left side are from subtropical and tropical regions. Interestingly, Moreton Bay (Peel Island) communities are distinct from those of neighbouring North Stradbroke Island, and are most similar to Darwin Harbour communities, followed by *SS Yongala* off Townsville. Based on an index of species indicator value (86) calculated for sites and combined pairs of sites, species characteristic of Peel Island and Darwin Harbour (as a pair) included the copepods *Parvocalanus crassirostris*, *Oithona attenuata*, *Oithona simplex* and *Euterpina acutifrons*. Species characteristic of Peel Island, Darwin Harbour and *Yongala* (as a group) were *P. crassirostris* and *O. simplex.* These three sites are situated close to land prone to extreme and rapid fluctuations in freshwater run-off, and hence tend to be inhabited by species adapted to variability in temperature and/or salinity. *P. crassirostris,* for example, is a well-known euryhaline and eurythermal marine copepod (57, 87–90). Species that set the two south east Queensland sites apart included *P. crassirostris, Oithona brevicornis* and *Oithona australis* at Peel Island versus *Oncaea venusta*, *Clausocalanus furcatus* and *Oithona plumifera* at North Stradbroke Island. The North Stradbroke Island IMOS station, being situated outside the Bay, is more likely to experience variability associated with coastal upwelling and oceanic intrusions than freshwater flows and thus the copepods tend to be from mixed coastal and oceanic communities. *C. furcatus,* for example, is typically associated with warm, nutrient-poor oceanic waters (91).

Copepod species diversity in Moreton Bay is very high compared with Australian tropical and temperate bays such as Darwin Harbour and Port Phillip Bay respectively, while mean abundances in Darwin Harbour substantially outnumber those in more southern sites (57, 88, 89, 92).

Modelling zooplankton

The South East Queensland Regional Water Quality Management Strategy was prepared by the Healthy Waterways Partnership in 2001 to address concerns about declining water quality. The Strategy identified a need for a model to determine management and remediation strategies for water quality in the Bay system. A Receiving Water Quality Model (RWQM) (93) related the transport and fate, including uptake in plankton, of nutrient sources (nitrogen and phosphorus) in the water and sediment. This model is used as a predictive tool to assess environmental and economic impacts of different management scenarios. The RWQM has two size-based groups of zooplankton. The first is ‘small zooplankton’, which represents microzooplankton <200 μm in size such as heterotrophic flagellates, tintinnids, ciliates, rotifers, small copepod nauplii and polychaete larvae. They are mobile, feed on small phytoplankton and have rapid turnover rates. The other group is ‘large zooplankton’, which represents mesozooplankton such as copepods and small fish larvae. They are mobile, and feed on large phytoplankton, microphytobenthos and dinoflagellates. ‘Large zooplankton’ have a slower growth rate than small zooplankton, which results in a lag between enhanced primary and secondary production. For both zooplankton groups, grazing success depends on the food encounter rate, which in turn is related to zooplankton swimming speed, food size and density. Excretion and inefficient feeding return dissolved and particulate material to the water column. Zooplankton mortality and predation by higher consumers, such as fish, are not simulated within a nutrient-phytoplankton-zooplankton-detritus model structure and so are represented using a closure term.

Although the RWQM has had little zooplankton validation to date, it provides insight into the temporal and spatial variation of zooplankton that has not previously been available. There were several notable features (Figs. 10, 11). There is higher biomass of 'large zooplankton' than 'small zooplankton'. There is also higher biomass of both 'large zooplankton' and 'small zooplankton' in the western compared with the eastern Bay, a consequence of the east–west gradient in chlorophyll levels from eutrophic conditions in the west to oligotrophic conditions in the east. Generally, there is higher zooplankton biomass in spring and summer than in autumn and winter, as wet season flows during spring/summer are important sources of nutrients that stimulate algal blooms. Finally, the seasonal and spatial changes are more marked in the 'large zooplankton' than in the 'small zooplankton'. Many of the model's findings remain to be validated through fieldwork, but it has provided insight into spatial and temporal variation of the zooplankton community overall.

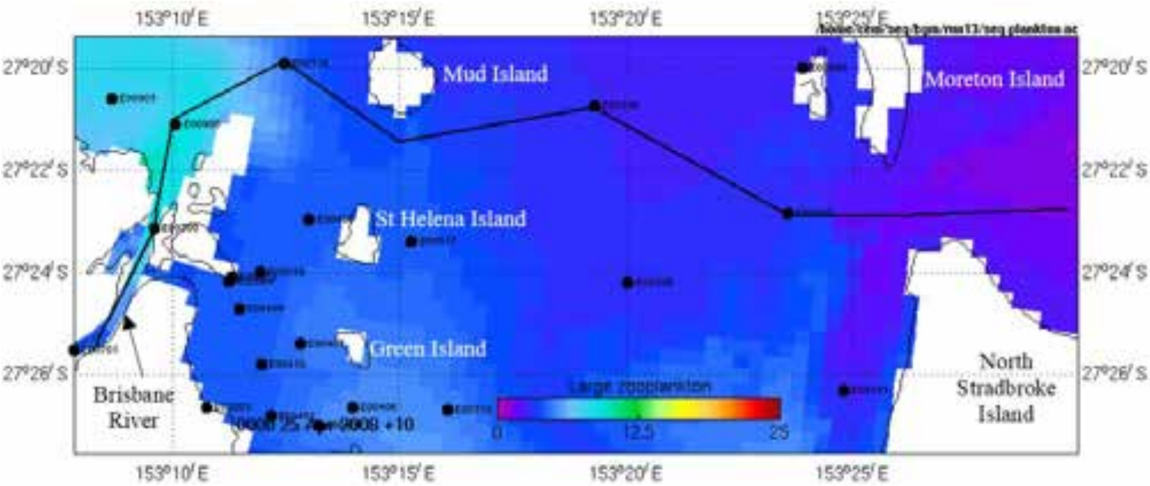


Figure 10. A transect (black line) of sites across central Moreton Bay where zooplankton biomass was predicted using the Receiving Water Quality Model (see Fig. 11). Black circles represent Ecosystem Health Monitoring Program sites.

Key recommendations for research priorities

While the primary focus of zooplankton research in Moreton Bay has been documenting the fauna (e.g. 26, 94-98), and in some cases recording species new to science (e.g. 99), earlier studies have examined the compositional change in zooplankton across the estuarine axis of Moreton Bay (23, 24, 100), and the contribution of emergent demersal forms to the plankton (58). However, there remain several key knowledge gaps that need to be filled. First, there has been no work investigating the seasonality of zooplankton associated with the wet season in south east Queensland (November to April) that elevates freshwater inputs and nutrient loads. The RWQM suggests that there should be higher zooplankton biomass in spring/summer associated with increased rainfall, but this has not been tested in the field as almost all studies have been shorter than a year and none have traced the evolution of zooplankton biomass and community following a flood event.

A. Small zooplankton (<200 µm) B. Large zooplankton (>200 µm)

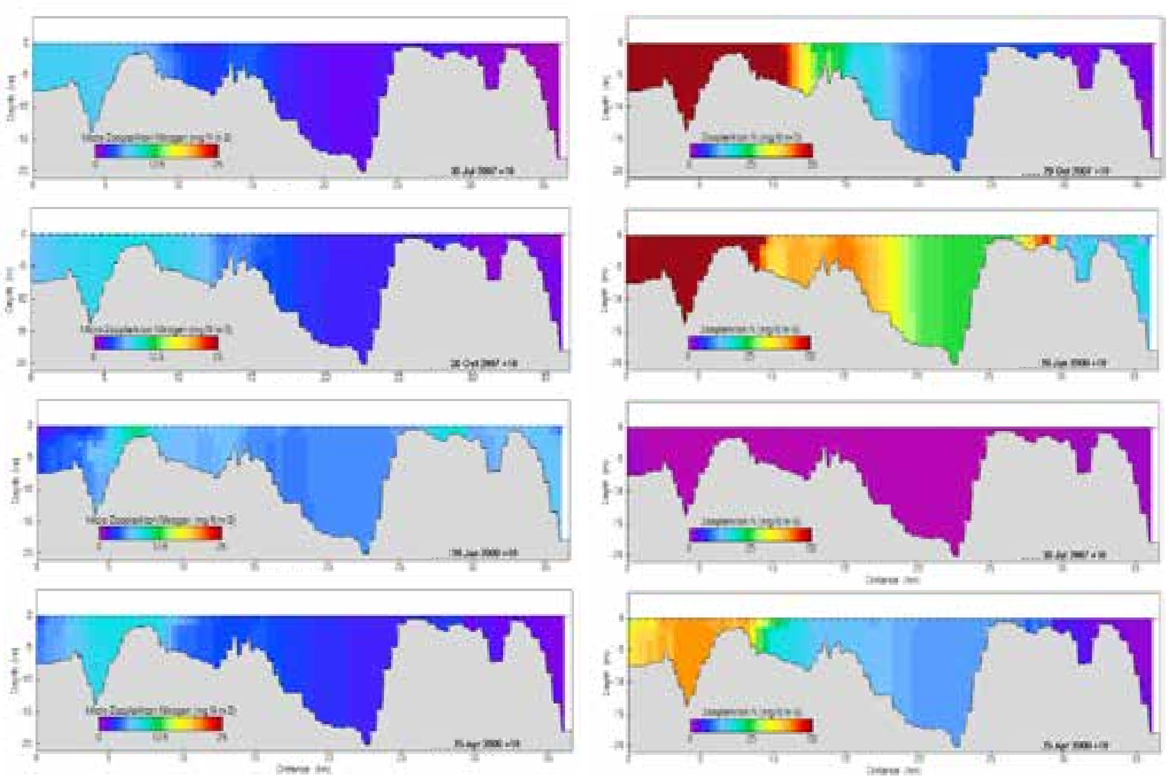


Figure 11. Seasonal biomass estimates of the A. ‘small’ (<200 µm) and B. ‘large’ (>200 µm) zooplankton size fractions along the transect (see Fig. 10) from Brisbane River mouth in western Moreton Bay extending to Rous Channel in the eastern reaches of the Bay, as predicted by the uncalibrated RWQM3 for the period July 2007 to April 2008. Zooplankton biomass is expressed in mg N m^{-3}.

Second, small zooplankton needs to be sampled more thoroughly. The RWQM suggested that small zooplankton are abundant and cosmopolitan in the Bay, yet historical zooplankton studies have used a relatively large mesh size of 195 µm and have thus under-sampled smaller taxa. Smaller copepods are likely to dominate when finer mesh samples are collected, and these species are likely to exert high grazing pressure on the abundance and biomass of phytoplankton assemblages than previously thought. In addition, copepods feed not only on the classical food chain (i.e. phytoplankton) but also on heterotrophic protists. Estimates of zooplankton biomass and abundance will be much higher once the smaller zooplankton component is adequately sampled.

Third, physico-chemical status and phytoplankton biomass are used as ecosystem indicators in the current Ecosystem Health Monitoring Program, particularly in response to nutrients, but zooplankton have not been considered. Zooplankton could be ideal ecosystem indicators because they are ubiquitous and are responsive to environmental change, eutrophication, pollution and climate change. For example, changes in zooplankton community size structure have been linked with eutrophication (84, 101).

Increasing nutrient concentrations can also cause changes in zooplankton biomass (101), abundance (85), size spectra (84) and feeding behaviour (88). In response to nutrients, there have been pronounced shifts in copepod community structure from dominance of larger to smaller species: in mesocosms in Norway (102); in Kingston Harbour, Jamaica (87); in Chesapeake Bay, United States (85); and in Tokyo and Osaka bays in Japan (84). Indeed, Tokyo and Osaka bays experienced an increase in nutrient loading in the 40 years following World War II that resulted in the replacement of large copepods by small ones (84). The lowest median body weight of the zooplankton community occurred closest to shore within each bay and steadily increased with distance from inshore stations. Median weight for the zooplankton community in the comparatively less eutrophic Osaka Bay was one to two orders of magnitude higher than for Tokyo Bay. All these patterns are potential candidates for ecosystem indicators of nutrient loading focused on zooplankton. Mouillot *et al.* (103) argue that alternative descriptors such as body size, proportions and diversity of various functional groups, and productivity of key species, have greater local relevance than taxonomic-based approaches such as indicator species, taxon richness and diversity indices. These characteristics could be analysed to assess their potential to supplement more traditional abiotic indicators of ecological status.

Fourth, there is opportunity to assess how changes in environmental conditions, particularly nutrients over >50 years, could influence the zooplankton community. Most of the historic work of Jack Greenwood on zooplankton was based on samples collected in the 1960s and there are several publications with data tables. If the challenges associated with accounting for different sampling methods can be overcome, such comparative studies can provide unique insights into long-term ecosystem change in response to environmental change.

Last, the RWQM can provide valuable insights into zooplankton dynamics in the Bay, but it has had minimal validation of the zooplankton component. In particular, zooplankton biomass data— along a nutrient gradient—are critical for model assessment. Currently there are no reliable zooplankton biomass estimates, as the few estimates thus far have been taken with large mesh sizes that miss much of the zooplankton. Once the RWQM data have been validated, they could then provide the spatial and temporal extrapolation needed to understand Bay-wide zooplankton dynamics; something not possible to extract from site-specific field sampling data.

Note
We follow World Register of Marine Species, and the classifications contained here are correct at the time of publication.

Acknowledgements

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Coral and micro-benthic assemblages from reef habitats in Moreton Bay

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Abstract

The subtropical coral reefs of Moreton Bay support a rich diversity of corals and micro-benthic organisms. These high-latitude reef communities exist in marginal environments that include relatively cooler, more light-limited, and more variable environmental conditions than those in the tropics. Holocene reef coral communities formed episodically over the Bay's 7000-year history, with a high degree of persistence in community structure and reef accretion rate until European colonisation of the Queensland coastline. However, during the most recent phase of the Bay's reef development, reductions in water quality have transformed the Bay's coral assemblages from predominantly large, fast-growing and branching acroporid corals to predominantly slower growing and smaller massive corals. The modern composition and diversity of benthic foraminiferal and micro-molluscan communities is driven mainly by substrate and water-quality parameters and shows a striking gradient from the variable and stressed water conditions of the western Bay to the more open-marine higher water quality habitats of the eastern Bay, including Myora Reef. Episodic changes also occurred in the Holocene benthic microfaunal composition, confirming the fluctuating nature of the Bay's marine environments. Recent increases in foraminifera diversity and symbiont-bearing taxa signals a subtle improvement in water quality from the 1970s to 2008; however, for micro-gastropods, comparisons between fossil and modern death assemblages illustrate a decline in the condition of modern Bay habitats. The Holocene variation in the taxonomic composition and diversity of coral and micro-benthic assemblages of Moreton Bay reveals a history of recovery and rapid reef growth. Rapid recovery may still be possible if the causes of anthropogenic degradation are reversed and for this the highest priority is to reduce sediment and nutrient delivery into the Bay's marine habitats.

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Introduction

As tropical coral reefs worldwide are threatened by over-exploitation and climate change (1–5), the ecological importance of high-latitude reefs and reefal communities has become more recognized, both as potential refuge areas for tropical species (6–8) and for their inherent ecological values. While tropical coral reefs tend to occur in warm, clear, shallow, oligotrophic, fully saline and aragonite supersaturated seas, high-latitude coral reef assemblages exist at the margins of species distributions and environmental tolerances, particularly for temperature, light availability and aragonite saturation (9–11). High-latitude coral communities are primarily non-reef building (though exceptions occur), and are distinguished from framework building coral reefs in a geological sense by their inability to accrete calcium carbonate reefs (12). Instead, they commonly grow as low-relief veneers of living coral on non-reefal substrates that follow the existing seafloor morphology (13). High-latitude reef communities are also characterized by a unique biogeographic overlap with other benthic organisms, many with temperate distributions (Sommer unpubl.) (14–16). High-latitude reefs therefore fit the definition of marginal reefs in several ways, as they occur where biodiversity patterns, environmental conditions and ecosystem function differ substantially from those associated with 'classical' tropical coral reefs (9, 17, 18). High-latitude reefs generally occur above 23.5° latitude (9) in a range of locations around the globe (see Fig. 1 in 14). In the southern hemisphere the highest latitude true coral reefs (i.e. framework building, accreting) are located at 31°33'S at Lord Howe Island, Australia (19, 20) and at 33°48'N at Iki Island, Japan, (21) in the northern hemisphere (22).

Located ~400 km south of the southernmost cay (Lady Elliot Island) on the Great Barrier Reef and adjacent to a major city, the reefs of Moreton Bay provide a rare instance of subtropical, marginal coral reefs in an urbanised environment (23). Abundant coral communities and reefs have characterised the history of Moreton Bay, South East Queensland. These shallow-water coral assemblages have experienced episodic reef growth throughout the Holocene related to periods of sea-level and natural climate change. Living corals now grow as a veneer on these Holocene carbonate deposits (23). Indeed, the Moreton Bay Region has the highest coral diversity along the eastern Australian subtropical-to-temperate transition zone, with a marked reduction in species richness further south (15, 16, 24, 25). Some high-latitude reefs, such as Flinders Reef at 26°58'S in Outer Moreton Bay, harbour rich coral faunas (e.g. 125 scleractinian species from 35 genera (23), and are important stepping stones for tropical coral species in this biogeographic transition zone.

In this paper, we focus on three components of subtropical reefal biodiversity — corals, large benthic foraminifera and benthic micro-gastropods — because they are easily fossilisable and thus provide important clues as to the history of Moreton Bay. Though we provide some information about the Bay in general, we focus on ecological patterns that have been compared between modern and ancient settings from western, central and eastern sites within the Bay: Wellington Point, Peel Island and Myora Reef. We follow the Wallace et al (23) geographic separation of Moreton Bay into an inner region composed of the body of water partly enclosed by North and South Stradbroke, Moreton, and Bribie islands, and an outer region composed of the rocky reefs immediately outside these large islands, including Flinders Reef near Moreton Island and Flat Rock, Shark Gutter and Shag Rock off the north-east corner of North Stradbroke Island. Further information on the geological history of reef habitats in Moreton Bay is found in Lybolt & Pandolfi 2019, this volume (26).

Contemporary diversity of corals and benthic microfauna

Corals

Coral species richness and community composition in the Bay is variable in space and time. The spatial pattern of richness generally follows the dominant water-quality gradient from poor water-quality reefs with lower species richness near the mainland to better water-quality reefs with greater richness towards the oceanic inlets in the east (27–29). The modern reefs in the inner Bay exhibit reduced cementation, coral cover (2–30%) and richness (S=64 species from 26 genera), compared to Flinders Reef from the outer Bay, which contains 28–40% cover and higher richness (S=125 species from 35 genera) (Fig. 1) (23). In inner Moreton Bay, based on current taxonomy, Merulinidae is the dominant coral family, followed by Lobophylliidae, Acroporidae and Dendrophylliidae, while in outer Moreton Bay Acroporidae are dominant based on the number of species and genera present (23).

The modern reefs of outer Moreton Bay (Fig. 1) host about half as many species as Lord Howe Island, a pattern generally following water-quality gradients from exceptional at Lord Howe to poor in Moreton Bay (29), though other factors such as substrate quality and water circulation also play a part in this distribution (15). Although the inner/outer Bay distribution of species suggests a nested pattern of richness, 18 inner Moreton Bay species are not found in the outer Moreton Bay reefs. Therefore, winnowing out the less hardy species is not the only major process driving differences in coral assemblage composition — some degree of local adaptation coupled with variance in competition or other aspects of biotic interactions or niche constraints are also likely to be involved.

Recent studies show that, although the coral species on high-latitude reefs of eastern Australia generally also occur on the Great Barrier Reef, high-latitude coral assemblages tend to have narrower taxonomic, functional and phylogenetic breadth than coral assemblages on the Great Barrier Reef (10, 24, 30). High-latitude reefs are characterised by widely distributed, generalist, stress-tolerant and opportunistic coral species with massive and horizontally spreading morphologies and by diminishing influence of tropical taxa at higher latitudes (24). Flinders Reef in outer Moreton Bay is the exception, with broad areas showing high abundance of the tall, branching species *Acropora intermedia* (24, 30), which tends to be common on tropical coral reefs (31, 32) and absent or rare at other reefs in the eastern Australian subtropical-to-temperate transition (24, 30). Using a biogeographic classification of corals into ‘tropical’, ‘subtropical’ and 'cosmopolitan' species, Sommer et al (24) showed that Flinders Reef and Flat Rock in outer Moreton Bay have the greatest abundance of tropical corals on rocky reefs south of the Great Barrier Reef, with cosmopolitan and subtropical species dominant on rocky reefs in New South Wales (24).

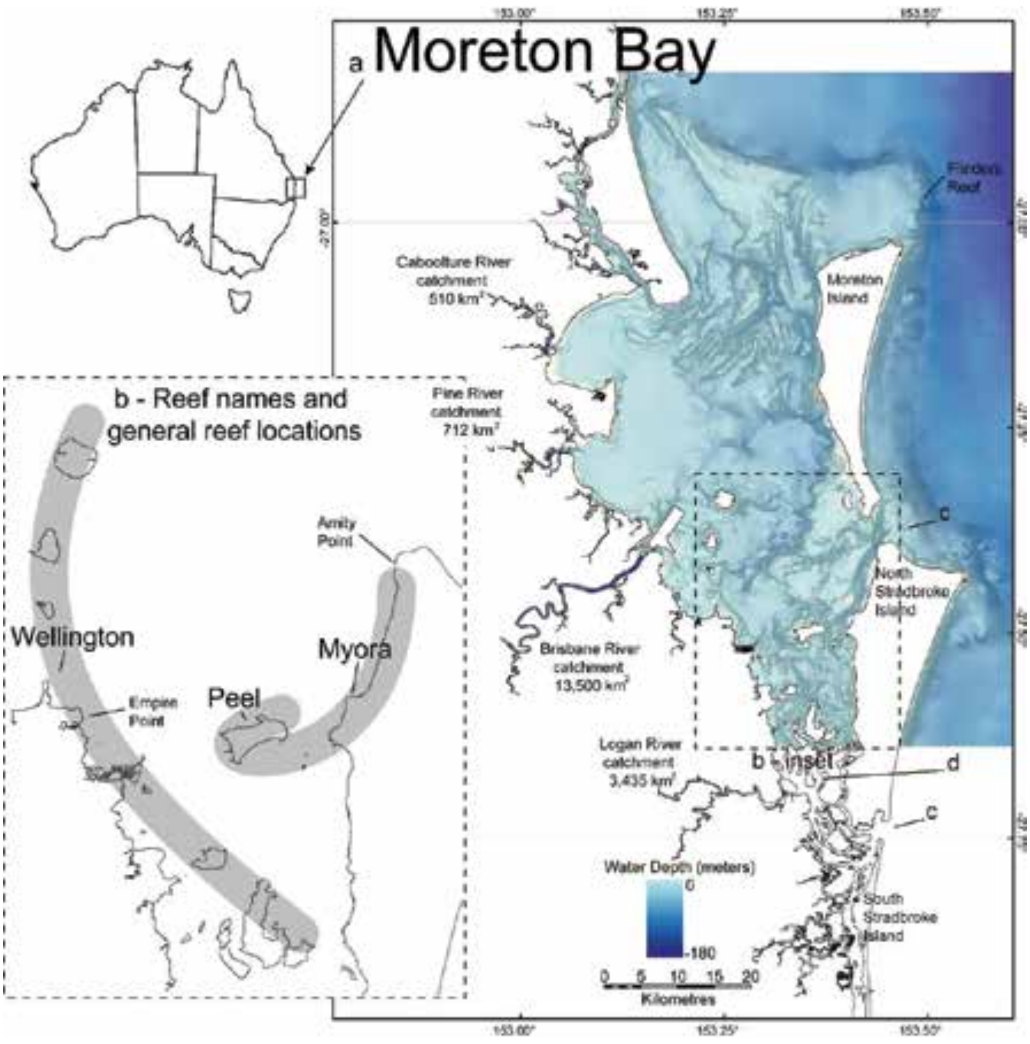

Figure 1. (a) Overview of Moreton Bay with bathymetry depicting a network of tidal and river channels amidst generally shallow waters, (b) Gray bands show the general areas of major Holocene reef growth, (c) Historically ephemeral inlets, (d) Modern tidal node.

Environmental tolerance is important for corals in these marginal environments, and species with unsuitable traits cannot persist in the relatively cooler, more light-limited and more variable environmental conditions of the subtropics (10, 24, 30). Coral species unable to tolerate these marginal conditions are excluded from high-latitude reefs. The important role of abiotic processes in structuring high-latitude coral communities is further supported by strong relationships between coral biodiversity patterns and environmental gradients in the region (10). Climate envelope modelling shows that the relative importance of environmental drivers varies among species (10).

Light availability best explains gradients in species richness and the distribution of tropical corals, whereas cold stress and temperature variability best explained gradients in Shannon diversity, functional diversity and the distribution of subtropical coral species (10). Nevertheless, the dominant influence of abiotic filtering at high-latitudes does not diminish the importance of biotic interactions (e.g. competition) on high-latitude reefs. Indeed, patterns in phylogenetic diversity suggest that species interactions (e.g. competition for space or light) are also important drivers of biodiversity patterns at local scales, such as at Flinders Reef (30), where corals with a 'competitive' life-history strategy (i.e. large, branching and plating species that grow quickly, occur at shallow depths and reproduce by broadcast spawning; 33) were particularly abundant (24, 30).

Benthic microfauna

Benthic foraminifera

Benthic foraminifera are abundant and widely distributed in marine sediments across a broad range of marine environments (intertidal sand and mud flats, seagrass meadows and coral reefs) in Moreton Bay (34–36). The foraminiferal species abundance, diversity and community composition vary spatially along a (west-to-east) gradient in water and substrate quality, from nearshore, riverine-influenced to near-oceanic and well-flushed conditions (34). This environmental gradient drives differences in foraminiferal species composition with a total of 69 benthic foraminiferal species representing relatively low Shannon–Wiener species diversity (H'=1.4 to 2.2) and Margalef's richness index (d=0.9 to 5.9) (34). Overall, the foraminiferal species composition, low diversity assemblages and the resulting FORAM Index values, a metric for determining water quality (based on the relative proportion of three functional groups of foraminifers: opportunistic, heterotrophic and symbiont-bearing large benthic foraminifers) (37), are consistent with the prevalence of contemporary, turbid, eutrophic–mesotrophic, marginal marine conditions in Moreton Bay (34, 38).

Narayan & Pandolfi (34) found a significant positive relationship between community composition and sediment types from the Bay-wide environments. Foraminiferal communities that occurred in the muddy, (coarse-grained) quartz sand sediments of the westernmost, nearshore, riverine-influenced environments were compositionally different from the communities found in the calcareous sands-muds and coral-algal (reef flat) rubble of the western-central Bay and also from the clean, quartz and calcareous sand sediments from the (reef- and seagrass-dominated) tidal delta flats of the eastern Bay (34). The species diversity was found to be higher in western Waterloo Bay (e.g. Wellington Point, Green and St Helena islands), central Bay (Peel Island) and the eastern Bay (north of Peel Island and south-western Moreton Island) than in the Brisbane River delta or Deception Bay environments (34). The latter environments are highly influenced by estuarine conditions and impacted by sediment run-off (34, 39, 40). However, in contrast to species composition, sediment types did not significantly influence species diversity, even though species richness was greatly reduced in the nearshore-riverine sediments compared with the other sediment types (muddy sands, sandy muds, clean tidal sands, biogenic sands) encountered in the Bay (34).

Cosmopolitan, opportunistic foraminiferal taxa (i.e. *Ammonia* spp. and *Elphidium* spp.), which can tolerate a wide range of water quality, salinities and (low) oxygen conditions (37, 41, 42), overwhelmingly dominated (with a frequency of occurrence of 92% and 80%, respectively) in the marine sediment samples of Moreton Bay (34). The relatively stress tolerant *Ammonia* sp. cf. *A. aoteana* (formerly *A. beccarrii* in (34)) and other agglutinated taxa dominated the biocenosis (assemblage) of the westernmost nearshore, riverine-influenced environments (34). Generally, this assemblage corresponds with low mean species diversity (d=1.4±0.2) and extremely low mean FORAM Index values (≈1) reflecting poor water and sediment quality (34). Moving westward, the large, shallow-water, opportunistic-mixotrophic species *Elphidium craticulatum* (and *E. discoidales multiloculum*) dominates the biocenosis of the calcareous muds and sand sediments of the seagrass meadows and marginal reefs, which occur from the western Waterloo Bay (Wellington Point, Green and St. Helena islands) to the central Bay (Peel Island) region (34). The abundance of mixed opportunistic-heterotrophic (miliolinids) assemblage corresponds with a slightly higher mean species diversity (d=2.2±0.3) and low mean FORAM Index values (≈2), which again indicate variable and stressed water quality conditions generally not conducive to reef growth, despite the presence of patchy coral colonies (23, 28, 38, 40, 43). The cosmopolitan symbiont-bearing large benthic foraminifera (LBFs, i.e. *Peneroplis* spp., *Alveolinella quoyi*), which are indirect indicators of clear water-quality conditions, increased in average percent relative abundance (3.5±3.7 to 62.2±12.4) and dominated the biocenosis of the tidal sand flats of the eastern Bay, where abundant seagrass meadows supported LBF epiphytes (34). In the eastern Bay, the increased abundance of LBFs corresponds with a mean species diversity of d = 2.1±0.2 and a significantly improved FORAM Index value (7.6). This improved water quality corresponds with the occurrence of low diversity, water-quality sensitive, fast-growing *Acropora* coral communities found to occur in the eastern Bay locality of Myora Reef (Fig. 1).

Benthic micro-gastropods

Information on the nature and distribution of marine micro-molluscs and the linkages between different habitats are rare (44, 45), and this is particularly true for micro-gastropods in subtropical estuaries in Australia (46). In Moreton Bay, recent analysis of micro-gastropod relative abundance data showed that gastropod assemblage distribution is driven mainly by substrate and water-quality parameters (turbidity, total nitrogen, temperature and dissolved oxygen) (47). Rachello-Dolmen (47) identified 219 species belonging to 115 genera and 46 families from modern death assemblages (grab samples) from Moreton Bay. The variation in the distribution of taxonomic composition of micro-gastropod assemblages in the Bay is in part explained by substrate, total nitrogen, temperature, turbidity and depth. Environmental conditions were associated with species traits: (i) species with discoidal shape and nodulose sculpture exhibited the most pronounced preference for western sites, near the Brisbane River, linked with turbidity and high nitrogen concentrations; (ii) ectoparasite species on echinoderms or actinarians, anemones and corals were associated with western central Bay sites associated with high phosphorous and chlorophyll *a*; (iii) tropical, subtropical and temperate species of small to medium size, fusiform shape, carnivorous, and found in the lower intertidal zone were associated with eastern central Bay sites linked with good light penetration, high oxygen concentrations and normal marine salinity; and (iv) globose species of medium size, herbivore- grazers found in the upper intertidal zone exhibited a preference for eastern sites, away from the Brisbane River mouth, with relatively constant temperature and pH. Water temperature plays a significant role in driving changes in rare species. The rare species were found mostly at Peel Island (17 species) and Myora Reef (7 species) where recruitment is apparently sustained by the influx of the East Australian Current through the South Passage between Moreton and North Stradbroke island (48, 49).

Holocene marine benthic faunas

Holocene coral communities

Coral richness, for both genera and species, is at its highest today (S=64 (23)), and was lower in the early 1970s (S=24 (50)) and in the early 1950s (S=24 from 12 genera (51)). Earlier surveys listed a number of species and described coral communities that seem similar to today including Myora's unique *Acropora*-dominated community (52–54). Changes in the coral assemblage over longer temporal scales are already known for some genera, although the timing of the changes is poorly understood. The fossil reefs of the Bay were first shown to host 36 species from 20 genera (51), and the single Pleistocene reef discovered in the Bay included 39 species from 25 genera (55). In the rough time frame of modern, Holocene and Pleistocene only 10 genera are common to all three. For example, *Montipora* is known from the Pleistocene and Holocene fossil deposits but is absent from the living coral assemblage in Moreton Bay, although it is present on artificial structures near oceanic inlets (23, 51, 55). Nonetheless, the modern assemblage of 26 genera is greater than both Holocene (20 genera) and the single Pleistocene (25 genera) fossil reef assemblages.

Coral reef development in the Bay was episodic during the past 7000 years of the Holocene, when both the taxonomic composition of the coral assemblages and reef accretion rates of Moreton Bay were striking for their consistency over time (26, 56). Within each reef site of the Bay, there is no change in the taxonomic composition of coral assemblages over time and no change in reef accretion rate over time (Fig. 2, (56)).

Holocene benthic microfauna

Benthic foraminifera

Spatio-temporal distribution patterns and species composition of the benthic foraminifer microfauna derived from Holocene sediment deposits were assessed from three sites (Wellington Point, Peel Island and Myora Island) along a west to east gradient of water quality in Moreton Bay (34, 57). The results showed that low-diversity and low-density assemblages of benthic foraminifers dominated throughout the Holocene, between 0.4 to 7.4 cal ka yBP (57). However, episodic changes in the microfaunal and sediment composition confirm the highly fluctuating nature of the Bay's marine environments, since the onset of reef initiation (as represented by pre-Holocene terrestrial basal sedimentary layers) (38, 57). The episodic disruptions in reef sediment deposition (38) are supported by shifts in the foraminiferal assemblages, which are associated with sedimentological (biofacies) changes over time (57), despite Holocene sea level being ~ 1.5 to 2m higher than today. For example, reef sediment cores from Wellington Point clearly document a transition from older (3.9–4.9 cal ka yBP) reefal carbonate mud and sands, rich in foraminifer shells, to younger (3.6–3.7 cal ka yBP) clean medium-course shell hash/sands, with minor occurrences of foraminifer shells, indicating a shoaling event from a deep, subtidal (depositional) reef slope setting to a (non-depositional) intertidal environment over time (57).

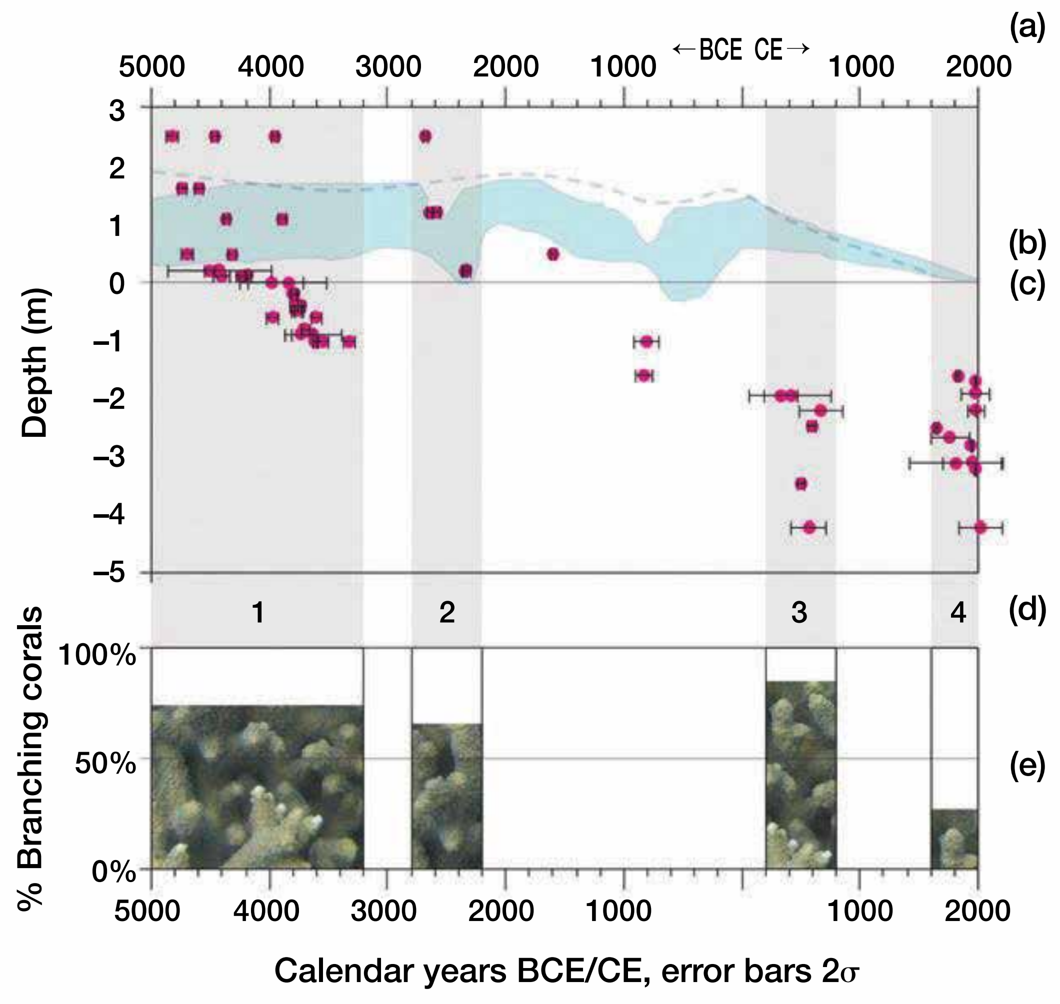

Figure 2. Age, depth, and community composition of coral death assemblages from Moreton Bay, Queensland, Australia. (a) Scatter plot of coral death assemblage age versus depth relative to lowest astronomical tide, uncorrected for paleo sea level, (b–c) Sea-level fluctuations after Lewis et al. (87, 88) (shaded blue area) and Sloss et al. (88, 89) (dashed blue line), (d) Statistically significant episodes of coral growth, (e) Coral community composition depicted as percent branching corals versus other corals (from Lybolt et al. (37, 38)).

Holocene foraminiferal species composition consistently displayed a relatively high abundance (~60%) of foraminiferal assemblages dominated by miliolid, small-heterotrophic taxa (e.g. *Quinqueloculina* spp., *Spiroloculina* spp. and *Triloculina* spp.) (57). This is indicative of normal marine conditions, likely as a result of higher sea levels than today (57). The stress-tolerant rotalid, opportunistic taxa (e.g. *Ammonia* sp. cf. *A. aoteana*, *Elphidium craticulatum* and *E. hispidulum*) followed in abundance (~20–30%) (57). For example, the large, mixotrophic-opportunistic *E. craticulatum* was found to dominate in the shallow-water (2 m) intertidal reef flats during the Holocene and today (34, 57). In contrast, low percentages (~ <10%) of symbiont-bearing large benthic foraminifers (LBFs, predominantly epiphytic *Peneroplis* spp.) were recorded, with their highest frequency in the eastern south-west Peel Island and Myora Island reef sites (57). The symbiont-bearing LBF assemblage, indicative of good water- quality conditions optimal for coral reef growth, and their predominance in the eastern Bay reefs and tidal flats is comparable to their distribution today (57). Over time, the FORAM Index value remained below 4 in the western Wellington Point Reef, indicating the prevalence of variable but mostly marginal marine conditions throughout the Holocene (57). However, the FORAM Index at times exceeded 4 in the south-west Peel Island and Myora Island reefs, suggesting episodic improvements in water quality (57).

Benthic changes since European colonisation

Coral community changes

The coral reefs of Moreton Bay exhibited robust growth in the mid-Holocene that gradually declined in the absence of major anthropogenic disturbance, but recently exhibited significant modern degradation (4, 28, 38). Previous studies of the marginal reefs of Moreton Bay have proposed that changes in temperature, sea level, El Niño–Southern Oscillation intensity, and sedimentation led to natural reef declines sometime between 3000 and 8000 years ago (28), prior to major anthropogenic disturbance. Further decline, due to over-exploitation and water-quality degradation, has been indicated since European settlement began in 1824 (4, 40).

Anthropogenic stressors in the Bay and its catchment occurred in three periods closely tied to land-use practices. The early and mid-Holocene probably had negligible cumulative anthropogenic impacts aside from small weirs built as fish traps (58). During the second period, the late Holocene, the primary anthropogenic impact was selective burning to promote grasslands for hunting (40, 59–61). This practice, termed ‘firestick farming’, was only possible after ~5000 ybp because the enhanced mid-Holocene precipitation regime prevented most fires (60, 62). Increased erosion and sedimentation associated with natural fires and burning by Aboriginal people would have impacted the Bay, but the magnitude of this impact probably did not increase through the late Holocene because fire frequency did not increase during this time (62). During the third period, rapidly accumulating anthropogenic impacts followed European settlement from the early 19th century, ~ 1850 CE to present, particularly land-use changes that enhanced erosion by 2–10 times (63, 64), direct impacts of coastal construction, overharvesting, and increased nutrient loading from husbandry, agriculture and sewage (4, 28, 45, 65). The naturalist and photographer Saville-Kent noted the coral mining in Moreton Bay and wrote that ‘By these means, beyond doubt, the original abundant growth of coral in this special area has been materially diminished’ (52 p96). Direct harvest of Moreton Bay corals for use as building materials persisted until 1997 (66).

The modern coral assemblages of Moreton Bay are strikingly different from the fossil assemblages (23, 28, 38). The modern assemblage is dominated by massive, encrusting and foliose genera such as *Favia*, *Goniastrea*, *Goniopora* and *Turbinaria*, whereas branching *Acropora* is uncommon. Dominance in the fossil assemblage is reversed, and branching *Acropora is a* dominant component of the Holocene assemblage (23, 38). This distinction was noted very early in the study of the Bay (52, 53) and first quantified by Wells (51). Subsequent research in Moreton Bay confirmed these observations and included constraints on the potential timing of the change from branching to massive-coral-dominated assemblages. Flood (67) attributed the shift to a ≈1 m sea-level fall estimated at 4000–3000 years ago. Johnson and Neil (28) attributed the shift to synergistic impacts starting 5500 years ago and progressively worsening to modern times. However, Lybolt et al. (38) and Lybolt (56) demonstrated that the shift occurred in modern times. There was no evidence of the assemblage shift while reefs were growing from 7400–165 years ago, but sometime between 165 and 52 years ago (1852 and 1956 CE) most reefs in the Bay ceased to be *Acropora*-dominated.

The timing of this unprecedented change between fossil and modern assemblages strongly suggests a modern anthropogenic cause. European settlement of the area began in 1824, and within decades radical landscape changes and habitat destruction caused more than a threefold increase in sedimentation to nearshore waters (39, 63, 68). Furthermore, the modern *Acropora*-dominated assemblage at Myora, a living remnant of the Bay's formerly typical coral assemblage, demonstrates that water quality near the oceanic inlets remains suitable for this assemblage. This shift in community dominance is unlikely to indicate senescence (69) because it is recorded across the depth range of corals in the Bay (29), rather than confined to those shallowest portions of the reef most affected by reduced accommodation space. The trajectory of decline in Moreton Bay, however, is not monotonic. Wells (51) found three genera living but absent in the fossil reefs, and nine genera in the fossil reefs but absent from the living assemblage. In 1955, the fossil coral assemblages were richer than the living coral assemblages. The situation today is reversed. Wallace et al. (23) found seven (colonial) coral genera in the living assemblages but absent from the fossil assemblage within Moreton Bay, while there are only four (colonial) coral genera found in the fossil reefs but absent from the living assemblage. While this apparent increase in Moreton Bay coral diversity since 1955 is not significant (56), a potential reversal of a trajectory of anthropogenic degradation would be encouraging, and seldom seen in studies of historical range of variation (4) (though see Hawaii example in (70)). Alternatively, more recent higher diversity might also stem from temperature increases allowing successful recruitment of larvae arriving from the north.

Benthic microfauna changes

Benthic foraminifera
The calcium carbonate tests of benthic foraminifers are well preserved and abundant in shallow to deep-water marine sedimentary deposits worldwide (71, 72). They have been used as important ecosystem bio-indicators for reconstructing present and past environmental changes and in

understanding the baseline conditions prior to significant human-induced impacts in the coastal marine environments of eastern Australia (57, 73). A comparison of foraminiferal species composition data between samples collected by the Geological Survey of Queensland in the 1970s (36) and samples collected in 2008 revealed significant differences in species composition (74). The finding of an increase in diversity in the Brisbane River delta and the Waterloo Bay areas and the presence of epiphytic, symbiont-bearing LBF taxa (*Peneroplis* spp.) in the Waterloo Bay area signals a subtle improvement in water quality in the latter period, a surprising result considering that the catchment now hosts more than two million people (74).

Benthic micro-gastropods

Comparison of micro-gastropod community data derived from Holocene cores with data collected from modern reefs at the same location has great potential to inform assessments of long-term reef ecological trajectories (75). In Moreton Bay, the taxonomic composition of fossil and modern micro-gastropod assemblages varies significantly (47). At Wellington Point, fossil assemblages are composed predominantly of Rissooidea (biofilm grazer) and modern assemblages by Columbellidae (herbivore or carnivore); both families can live on algae, coral rubble, under stones, soft substrate or seagrass (76). At Peel Island, fossil assemblages are composed predominantly of Rissooidea and modern death assemblages of Scaliolidae (biofilm grazer) and Cerithiidae (detritivore), both families living in soft substrate. Certihiidae also can be found on hard substrates. At Myora Reef, fossil assemblages are composed predominantly of Cerithiidae, Calopiidae (biofilm grazer), Triphoridae and Cerithiopsidae (both ectoparasites of sponges). All these families live on soft or hard substrata and seagrass. Modern death assemblages in Myora are composed predominantly of Trochidae (carnivore or grazer or herbivore) and Columbellidae (carnivore or herbivore), both families can live on algae or hard or soft substrate and seagrass. Data on substrate and feeding type are abundant for gastropod families (76), but environmental and biotic parameters associated with micro-gastropods are unknown.

Differences between fossil and modern death assemblages in the Bay are probably due to the anthropogenic stressors that occurred in the three periods closely tied to land-use practices noted above. During European colonization, fisheries and dredging activities were developed, coinciding with marked ecosystem changes. Relative changes in rare vs intermediate abundance of families can be an indication of human-disturbed environments (77), and in Moreton Bay, micro-gastropods show a decreasing number of rare families coupled with an increasing number of families with intermediate abundance in modern samples compared with Holocene occurrences. The larger number of rare species encountered in the fossil assemblages resulted in slightly higher diversity in fossil assemblages than in modern death assemblages. Patterns of changing diversity and family abundance distribution have the potential to serve as environmental indicators (78), and in Moreton Bay illustrate a decline in the condition of modern reefs (47).

Threats and management considerations

The condition of reefs is directly related to the duration and intensity of human impact on reef systems and, as a consequence, reefs worldwide are threatened by the cumulative effects of overfishing and pollution (4). Moreton Bay is no exception to the effect of these threats. Studies of processes structuring species assemblages and temporal and spatial variation in the fauna are necessary in Moreton Bay as they will have implications for attempts to manage diversity and to monitor trends in the health of Moreton Bay reefs (44, 79). Management strategies that help maintain large populations are likely to best facilitate the continuity of high-latitude reefs and their refuge potential (14). For example, the larger populations of tropical species in South East Queensland than in New South Wales means that tropical corals in South East Queensland are likely to be less dependent on Great Barrier Reef source populations for their replenishment than their New South Wales counterparts. These South East Queensland populations may also provide important stepping stones for higher-latitude reefs located further south (22).

Moreover, larger populations tend to have greater standing genetic variation and to be less susceptible to genetic drift, likely also bestowing higher evolutionary potential (80, 81). A phylogenetic signal found in seven tested coral species traits indicates that environmental tolerances of corals are likely to be stable over time, and that corals will only expand their ranges to regions where environmental conditions are similar to conditions experienced in their core ranges (30). The high abundance of tropical coral species in the Moreton Bay Region (24) therefore suggests that this region has high refuge potential for tropical coral species (22) as Great Barrier Reef populations become threatened by increasing temperature (5). Environmental conditions at outer Moreton Bay sites are less light limited and warmer than sites in New South Wales (10) and probably more favourable for establishment of tropical coral species than higher latitude regions (22).

The key benefit of applied palaeoecology is improved natural resource management planning and setting goals that consider the region's history. Reefs in Moreton Bay grew episodically over 7000 years with no significant change in community composition or accretion rate. However, in the past 200 years the coral species composition of Bay reefs changed substantially, and for the first time in 7000 years the corals of Moreton Bay persist in a degraded state caused by increased sediment and nutrient run-off from anthropogenic land-use changes (38). This means that natural resource managers hoping to reverse this degraded state should target any prescription that reduces sediment and nutrient loads onto the reefs. The historically relevant indicator of success, over the short-term, is any increase in the abundance of *Acropora* (i.e. increases in the abundance of *Acropora* indicate the success of natural resource management actions to improve water quality in the catchment). Even a marginal reef habitat such as Moreton Bay has a history of recovery and rapid reef growth, and rapid recovery may yet be possible if the causes of anthropogenic degradation are reversed.

A review of active and passive management initiatives suggests that stringent protection of reefs in no-take marine protected areas is critical to foster ecosystem resilience and refuge potential of high-latitude reefs (14). Moreton Bay reefs are currently protected in marine parks, however a concerning trend in recent years has been a reduction in the level of protection and size of protected areas along the subtropical-to-temperate transition zone; a trend that needs to be urgently reversed to maximise marine park effectiveness (82).

Effective coastal marine management practices that aim to preserve ecosystem services can benefit from the incorporation of relevant marine bio-indicators, which can provide an indirect link between environmental conditions such as water quality and ecosystem (coral reef) health (83, 84). Micro- and meio-benthic organisms, especially benthic foraminifers, have been successfully applied in short- and long-term water quality and coral reef health assessments by several studies including those from Moreton Bay and the Great Barrier Reef (34, 73, 85–87). Foraminifers are considered high-priority bio-indicators for long- and short-term monitoring programs (37, 42, 83). While the necessity for taxonomic expertise has been considered the main limiting factor in the application of foraminifers to ecological monitoring practice, developing and successfully establishing foraminiferal metrics such as the FORAM Index (37) has made it possible for researchers and/or marine managers with limited taxonomic expertise to quantify species composition. In addition, foraminifer bio-indicators provide a means for quick, low-cost collection with a low ecological footprint where there are limited technological resources available for monitoring (37, 42). Their continued application for assessing short- and long-term environmental changes in Moreton Bay, along with studies of benthic micro-gastropods, is highly recommended.

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Fishes of Moreton Bay: Ecology, human impacts and conservation

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Abstract
Moreton Bay is a heterogeneous seascape containing a mosaic of habitats that support a diversity of fish. The fish fauna includes many species that are harvested by recreational and commercial fishers as well as numerous taxa that are of conservation concern. The fish fauna of mangroves, seagrasses, inshore reefs and intertidal flats is well sampled. By contrast, fish surveys in saltmarshes, soft sediments, offshore reefs and surf zones are sparse and incomplete. Fish diversity and abundance are typically highest on reefs and seagrass meadows, but most species move among habitats to feed and spawn. These movements connect habitats and link both fish assemblages and food webs across seascapes. The combined effects of water quality, coastal urbanisation and fishing also shape fish assemblages in Moreton Bay. Fish diversity and abundance increases from the urbanised western to the less developed eastern Bay. This spatial pattern mirrors gradients in water quality and habitat condition across the Bay. The shorelines of many estuaries and ocean beaches have been developed, and this coastal urbanisation has altered fish diversity, abundance and diet. Numerous species have, however, adapted to capitalise on the abundance of food and shelter in urban estuaries. No-take marine reserves prohibit fishing, and this promotes fish abundance and diversity in some ecosystems (e.g. coral reefs, seagrass meadows), but not in others (e.g. estuaries, ocean beaches). Important challenges for future research in Moreton Bay include: (i) testing how multiple human pressures combine to modify fish assemblages and fish habitats; (ii) identifying how the ecological attributes of ecosystems and seascapes shape conservation outcomes; and (iii) examining how fish assemblages, habitats and fisheries change in response to range shifts of tropical species that move south with rising sea temperatures.

Keywords: coastal waters, estuary, fish, fisheries, habitats, marine reserves, reef, seascape ecology, seagrass

Introduction

Moreton Bay contains a diverse fish fauna that is of immense cultural, social and economic value to a broad range of people (1, 2). Historically, the region was an important fishing area for Indigenous Australians (3, 4); it now attracts large numbers of recreational anglers each year (5, 6) and supports significant commercial fisheries (7, 8) (Thurstan *et al.* 2019, this volume). Many fish species are prized by recreational anglers (9, 10) or are harvested in commercial fisheries (7, 11). The region also provides essential habitat for numerous fish species that are of international conservation significance (12–14).

Descriptive accounts of fish catches date back to the early 1900s (15), but research on the biology and ecology of fish in Moreton Bay did not commence until the 1970s (1). Early studies described patterns in fish abundance, size and diet, and discussed how assemblages vary among habitats or between different parts of the Bay (16, 17). The range of fish research in the Bay is now considerably broader and encompasses a large body of publications on habitat use, health, trophic ecology and population biology (1, 18). The fish assemblages of Moreton Bay are diverse and of considerable value to the economy; but have also been heavily modified by the combined effects of water quality degradation, coastal urbanisation and fishing (2, 19, 20).

Synthesis of research on fish in Moreton Bay

To describe the thematic focus and distribution of research on fish in Moreton Bay, we reviewed published literature on fish in the region by searching the Elsevier Scopus and Thompson Reuters Web of Science databases using the keywords: ‘Moreton Bay’, ‘fish’, ‘shark’, ‘ray’, ‘elasmobranch’ and ‘teleost’. This search yielded 166 studies (Table 1) with most focused on describing how fish use different ecosystems as habitat (n=69). A sizable proportion of research also addressed questions about fish health (n=58), trophic ecology (n=38) and population biology (n=25). Fewer studies have examined the impacts of human activities on fish populations (n=21), the benefits of conservation for fish (n=15) or the effects of fish on ecological functions (n=12). Therefore, examining the combined effects of human pressures on fish assemblages, identifying the ecological features of seascapes that affect conservation performance, and testing whether, and how, fish modify ecosystem functioning will be promising avenues for future research.

Research on how fish use habitats in Moreton Bay is dominated by studies in seagrass meadows (n=20), coral and rocky reefs (n=19), and sand/mud flats (n=17) (Table 1). Less research has been done on fish in mangrove forests (n=11), estuaries (n=10), urban waterways (i.e. canals, artificial lakes, modified estuaries) (n=7), saltmarshes (n=5) and the surf zones of ocean beaches (n=2). The body of research on fish health primarily comprises descriptive studies of fish parasites (n=55) and the accumulation of toxins in fish tissues (n=3). Research on fish trophic ecology encompasses studies of fish diets (n=29) and food webs (n=9). Studies of fish population biology include research on reproduction (n=12), movement (n=7), growth (n=7), morphology (n=3) and behaviour (n=3). Research on human impacts has examined the ecological effects of heavy fishing pressure (n=8), urbanisation (n=8) and water quality degradation (n=5) on fish populations. Conservation research has focused on the effectiveness of marine reserves (n=12) for fish and the ecology of threatened fish species (n=4). Functional ecology research has examined the role of fish in performing herbivory (n=8), predation (n=3) and scavenging (n=2).

Table 1: Summary of research on fish in Moreton Bay illustrating focal research themes, and the number of studies and citations for each topic (n=166).

Research themes	Studies	References
Habitat	**69**	
Seagrass	20	(10, 13, 21-38)
Reef	19	(19, 20, 39-55)
Sand/mud flat	17	(11, 17, 21-23, 26, 29, 38, 56-65)
Mangroves	11	(21, 22, 25, 29, 37, 41-43, 65-68)
Estuaries	10	(11, 21, 22, 29, 62, 63, 69-72)
Urban shores	7	(63, 71-75)
Saltmarsh	5	(76-80)
Surf zones	2	(9, 81)
Health	**58**	
Parasites	55	(82-136)
Toxins	3	(137-139)
Trophic ecology	**38**	
Diet	29	(21, 23, 30, 32-34, 38, 45, 46, 49, 52, 63, 64, 66, 70, 75, 76, 79, 80, 140-
Food webs	9	(40, 41, 59, 69, 71, 72, 150-152)
Population biology	**25**	
Reproduction	12	(3, 14, 140, 153-161)
Movement	7	(13, 14, 16, 162-165)
Growth	7	(38, 140, 156, 159, 160, 166, 167)
Morphology	3	(168, 169)
Behaviour	3	(35, 170)
Human impacts	**21**	
Fishing	8	(36, 52, 143, 171-175)
Urbanisation	8	(9, 63, 71-74, 176, 177)
Water quality	5	(10, 20, 45, 47, 62)
Conservation	**15**	
Marine reserves	12	(10, 11, 13, 19, 20, 31, 42, 43, 45, 47-49, 54)
Threatened species	4	(13, 14, 62, 167)
Functional ecology	**12**	
Herbivory	8	(20, 32, 33, 45, 46, 49, 141, 145)
Predation	3	(64, 66, 145)
Scavenging	2	(63, 70)

Fish diversity in Moreton Bay

The fish assemblages of Moreton Bay are diverse and comprise at least 1,190 species (12, 17). This diversity reflects the subtropical location of the Bay and the range of tropical and subtropical taxa it supports; one-third of all fish species in the region are at the latitudinal limit of their known distribution (1, 12). More tropical species are expected to arrive as sea temperatures rise (20, 49). The high diversity also indicates that Moreton Bay is a heterogeneous seascape that contains a rich mosaic of fish habitats (18, 44, 179).

Recent studies have sampled fish from surf zones (9), estuaries (11), soft Bay sediments (65), mangroves (65), seagrass meadows (10), inshore reefs (19) and offshore reefs (53) with baited remote underwater video stations (BRUVS). Fish species richness was greatest on offshore reefs, followed by structurally complex habitats within Moreton Bay, including reefs and seagrasses (Fig. 1). By contrast, few species appear to inhabit the shallow waters of mangroves, the soft sediments of estuaries, the central Bay or adjacent surf zones. These differences in fish species richness may result from variation in structural complexity, habitat heterogeneity and water depth across ecosystems (28, 42, 47, 53). This hypothesis has not been tested using empirical data. Survey effort has, however, been concentrated in estuaries, seagrasses and inshore reefs (Fig. 1), and we suggest that there might be numerous species that are yet to be recorded from mangroves, surf zones and offshore reefs (9, 53).

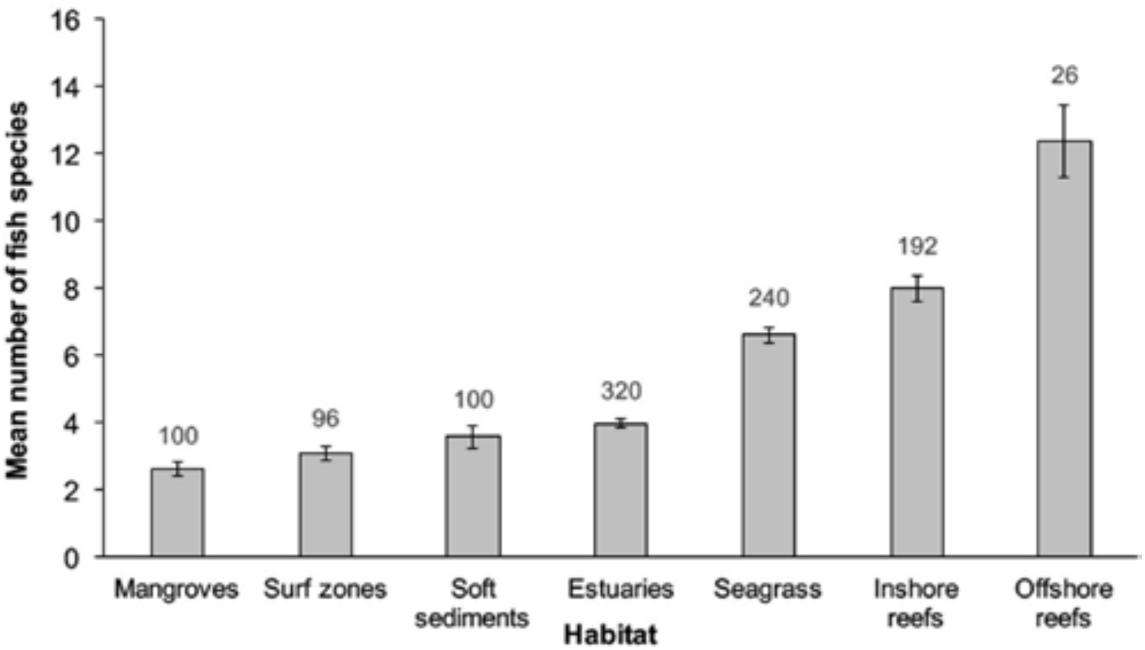

Figure 1. Mean number of fish species observed (± SE) in one hour from baited remote underwater video stations (BRUVS) deployed in seven habitats in Moreton Bay. Survey effort (i.e. total one-hour BRUVS deployments) is displayed for each habitat type above bars. Data based on surveys in mangroves, surf zones, soft Bay sediments, estuaries, seagrass meadows, inshore reefs and offshore reefs (9, 10, 19, 63, 65).

Ecological roles of fish habitats

Fish use different habitats as feeding areas, refuges from predation, spawning sites and juvenile nurseries, and as stepping stones during migrations from inshore to offshore waters (1, 18). Whilst these purported habitat functions are frequently cited as important factors thought to structure the spatial distribution of fishes, they are rarely explicitly tested (44).

There is clear empirical evidence that fish forage in the saltmarshes (76), mangroves (66), intertidal flats (64), seagrasses (32), surf zones (9), coral reefs (46) and rocky reefs (53) of Moreton Bay. There is little data, however, to link primary production from these habitats to changes in fish nutrition and growth. The strongest trophic links are for seagrasses and mangroves, which support fish nutrition both within these habitats and across adjacent seascapes (41, 59, 150). The role of habitats in providing a refuge from predators has been tested in predation experiments (using tethered whiting, *Sillago* spp.) in mangrove forests, intertidal mudflats and seagrass meadows, and is supported for both mangroves and seagrasses (66).

The location of spawning sites has not been formally reported for most fish species. Data on spawning and breeding aggregations are available for: trumpeter whiting (*Sillago maculata*) (159) and double-ended pipefish (*Syngnathoides biaculeatus*) (160) from seagrass meadows; sea mullet (*Mugil cephalus*) (16) and tailor (*Pomatomus saltatrix*) (180) from coastal-shelf waters; pink snapper (*Chrysophrys auratus*) (54) and grey nurse sharks (*Carcharias taurus*) (14) from offshore reefs; and yellowfin bream (*Acanthopagrus australis*) (165) and sand whiting (*Sillago ciliata*) (154) from surf bars where Moreton Bay joins the open sea.

Saltmarshes, mangroves and seagrasses in Moreton Bay are widely reported to provide nursery habitats for many fish because they support abundant juveniles (21, 67, 79). To function as an effective nursery for juvenile fish, habitats must also promote fish growth and survival, and allow individuals to migrate to adult habitats and reproduce (181). These criteria are, however, difficult to test and have not been sufficiently examined for most habitats in Moreton Bay (1, 18). Seagrasses provide the best evidence for the nursery function as they can be hotspots for larval recruitment and support abundant juveniles that grow rapidly in the seagrass meadows before migrating to other habitats as adults (29, 182, 183).

Many fish species migrate from habitats within Moreton Bay to spawn over surf bars (165) or move from shallow juvenile habitats to deeper adult habitats in offshore waters (40). Others move into Moreton Bay from offshore habitats to feed, or spawn, in estuarine habitats (54). On these inshore-to-offshore migrations, the shallow reefs of central Moreton Bay play an important role as stepping stones for some species, including sea bream (Sparidae), tropical snapper (Lutjanidae) and grouper (Serranidae) (44, 50).

Fish modify ecosystem functioning

Fish perform many significant ecological functions in ecosystems (e.g. herbivory, predation, scavenging) that help to sustain biodiversity, maintain the structure of food webs and modify the composition of benthic communities, including coral reefs, seagrass meadows and kelp forests (184–186). In Moreton Bay, fish are functionally important herbivores and predators that modify food webs in mangrove forests (41, 66), seagrass meadows (32, 145) and coral reefs (19, 46). Furthermore, herbivorous fish consume algae that might otherwise overgrow seagrass and corals in Moreton Bay (45, 187); a function that improved the capacity of both ecosystems to recover from flood impacts in 2011 (20, 188).

Fish are also prominent scavengers that consume animal carcasses and recycle nutrients in coastal food webs (189). In Moreton Bay, the consumption of carrion by estuarine fish is sensitive to changes in water quality, fishing pressure and urbanisation, and might prove useful as an indicator of ecosystem health (63, 70).

Connectivity shapes fish assemblages and food webs

Fish move among habitats in coastal waters to feed, spawn and disperse, and this functionally links populations, food webs and habitats across seascapes (183, 190, 191). In Moreton Bay, seascape connectivity (i.e. spatial linkages among habitats) alters the composition of fish assemblages in mangrove forests (43), seagrass meadows (28), coral reefs (44) and surf zones (9). These effects of connectivity shape the spatial distributions of many fish populations (10, 42), alter food-web structure (41, 150), modify ecological functions (45, 145), and can change the composition of benthic communities (20, 46). For example, herbivorous dusky rabbitfish (*Siganus fuscescens*) are most abundant on coral reefs near mangroves (43) (Fig. 2a). They migrate on the rising tide into mangroves to feed, and the contribution of mangrove carbon to their diet decreases with reef isolation (41) (Fig. 2b). Dusky rabbitfish also consume algae on coral reefs, and their feeding activities help to both reduce the cover of turf algae and increase the number of coral recruits on reefs near mangroves (45) (Fig. 2c).

Human pressure on fish assemblages

The fish assemblages and fish habitats of Moreton Bay have been substantially altered by human actions, including eutrophication (20, 47), sedimentation (10, 188), urbanisation (9, 74) and fishing (10, 55). Changes in water quality have detrimentally impacted the condition of numerous fish habitats (20, 188), altering the composition and abundance of fish assemblages in estuaries (62), seagrass meadows (10) and coral reefs (19). Fish diversity in mangroves, seagrasses and over coral reefs is also strongly correlated with water quality and declines from east to west across Moreton Bay with increasing distance from the open ocean (Udy *et al.* 2018, this volume) (Fig. 3a).

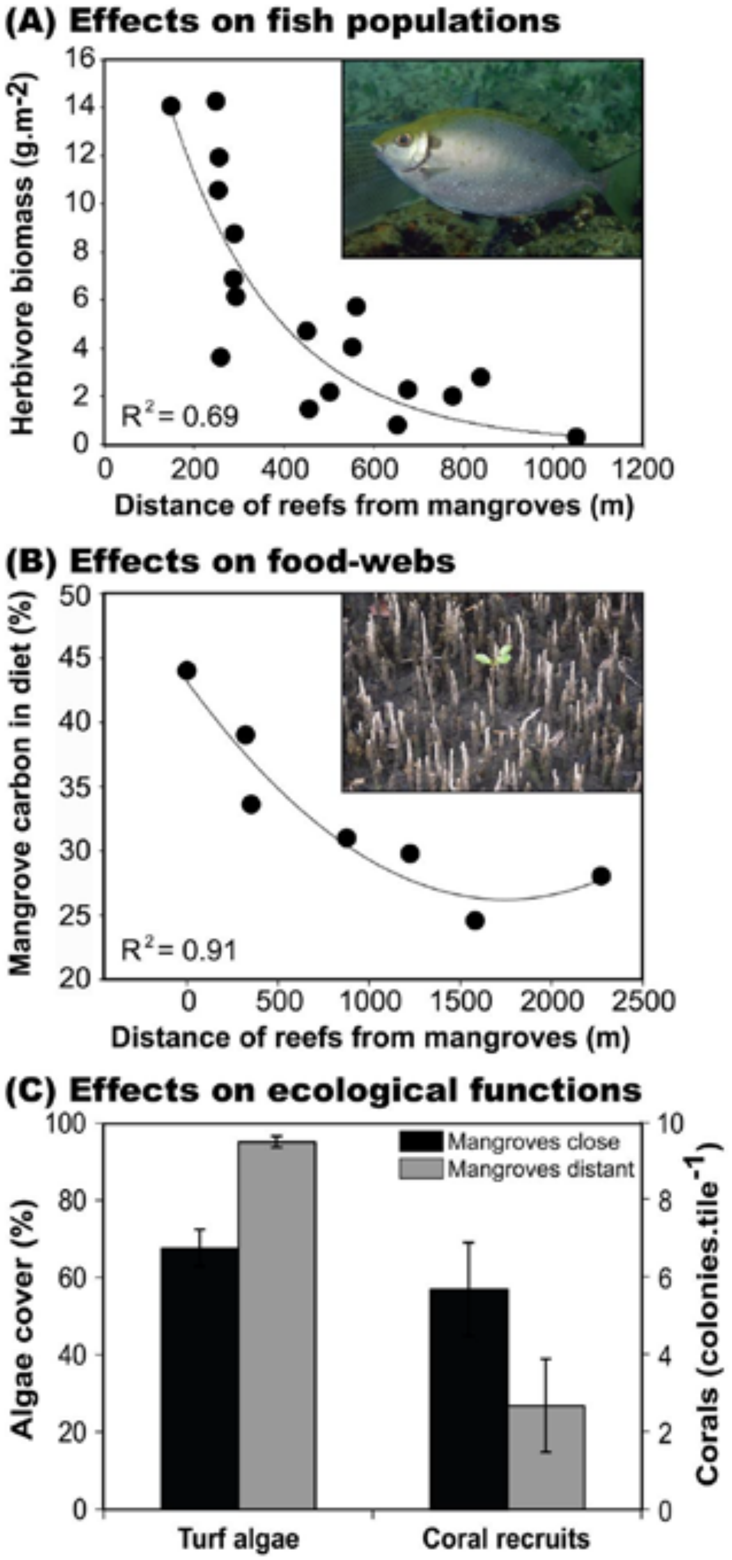

Figure 2. Seascape connectivity shapes fish assemblages, food webs and ecological functions in Moreton Bay: (a) herbivorous rabbitfish (*Siganus fuscescens*) are most abundant on coral reefs near mangroves (34); (b) they migrate tidally into mangroves to feed and the contribution of mangrove carbon to their diet decreases with reef isolation (28); and (c) they consume algae on coral reefs and this reduces the cover of turf algae and increases the number of coral recruits on reefs near mangroves (67).

Coastal cities abut many ocean beaches in the region, and extensive networks of canals and artificial lakes have been constructed in the estuaries of Moreton Bay (18). These urban shorelines provide habitat for fish, but typically support different fish assemblages than natural habitats (9, 74). In estuaries, fish diversity is negatively correlated with the cover of urban land in adjoining catchments, whereas in the surf zones of ocean beaches fish diversity is greatest adjacent to beaches that have been moderately urbanised (Fig. 3b). Furthermore, some fish species (e.g. yellowfin bream; snub-nosed garfish, *Arrhamphus sclerolepis*) have capitalised on the regular supply of food and abundance of shelter in urban estuaries. Yellowfin bream are important scavengers that aggregate under artificial structures where they consume carrion and recycle nutrients (63). Snub-nosed garfish are also common in artificial waterways and have adjusted their diet in response to urbanisation; they consume seagrass and crustaceans in natural estuaries, but feed on algae and insects in canals (72).

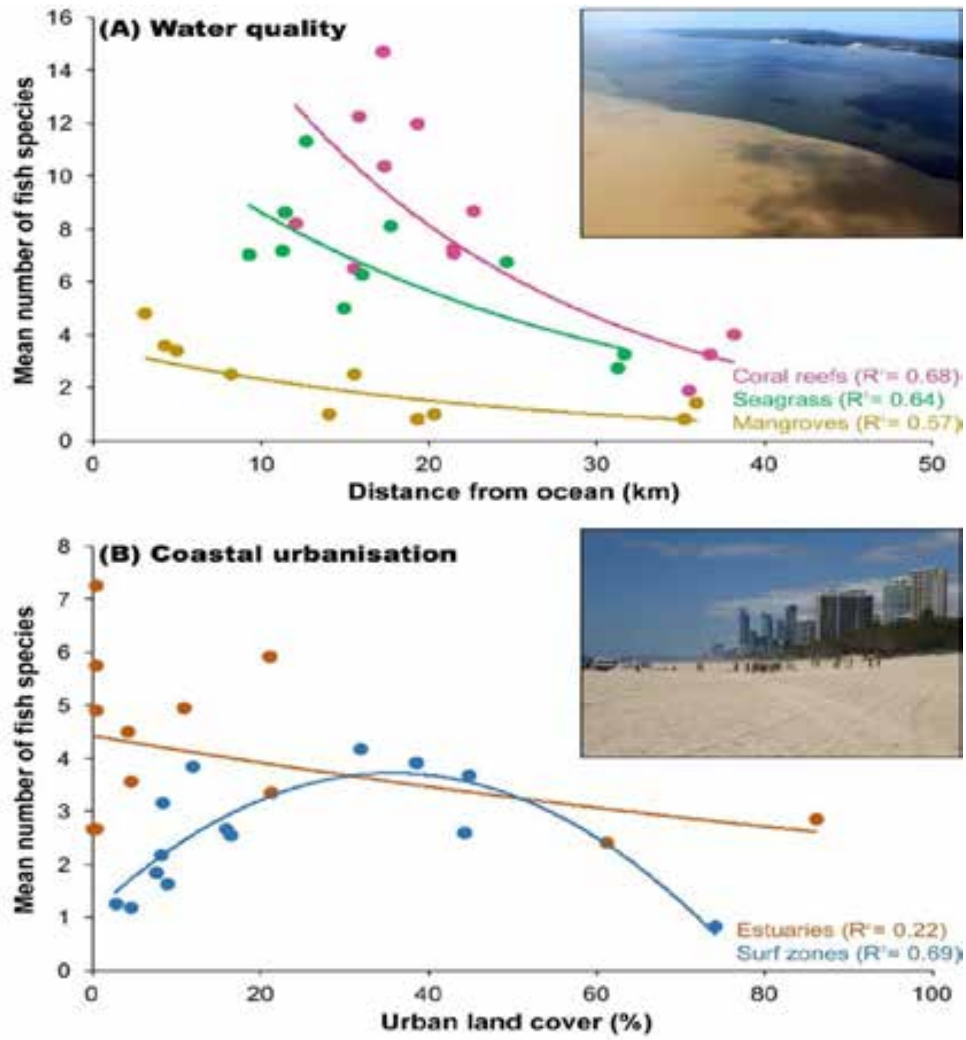

Figure 3. Effects of water quality (a) and coastal urbanisation (b) on the mean number of fish species observed on BRUVS deployments in coral reef, seagrass, mangroves, estuaries and surf-zone habitats in Moreton Bay (9, 10, 19, 63, 65). Water quality effects were indexed as the position of sites along Moreton Bay's strong west-east gradient in physico-chemical water quality (18, 19). Coastal urbanisation was measured as the percentage cover of urban land bordering each study site (9, 11).

Moreton Bay supports both recreational and commercial fisheries that extract sizeable numbers of fish each year from the Bay, ocean beaches of barrier islands, and offshore reefs (5–7). These fisheries are tightly managed to ensure the sustainability of individual fish stocks (Thurstan *et al*. 2018, this volume). However, the impacts of fishing and other anthropogenic activities, including pollution and degradation of water quality, have contributed to changes in the composition of fish assemblages and declines in the ecological condition of some seagrass meadows (10, 192), coral reefs (45, 55) and soft-sediment epibenthic communities (193). Well-designed and managed marine reserves can be effective at promoting the abundance of harvested fish and reversing the impacts of fisheries on fish habitats (190, 194). In Moreton Bay, fish assemblages differ between reserves and fished locations in estuaries (11), seagrass meadows (10) and coral reefs (43) (Fig. 4), but not in the surf zones of ocean beaches (195, 196). Existing reserves that conserve seagrass and reefs in the Bay support greater numbers of numerous harvested species, whereas reserves in estuaries support fewer harvested fish (Gilby et al 2018, this volume). These differences in the effectiveness of reserves among habitats are not linked to variation in reserve size, but might reflect differences in the ecological value of the seascapes that are targeted for conservation (10, 11, 43). Furthermore, reserves work better for many reef fish when they conserve reefs and mangroves that are close together (42).

Many tropical fish species are moving towards the poles with rising sea temperatures, and their arrival in higher latitudes is altering the composition of fish assemblages and the structure of subtropical and temperate fish habitats (197–199). The coastal waters of Moreton Bay are experiencing species range shifts and are recognised as a potential refuge for tropical species that are migrating south with climate change (200, 201). Consequently, we require empirical data to test how the fish assemblages, habitats, and fisheries of Moreton Bay are changing in response to the arrival of tropical species (49).

Conclusions

Moreton Bay supports a high abundance and diversity of fish, many of which are caught by recreational anglers and commercial fishers (1, 2). Most research on the fish of Moreton Bay has focused on describing how fish use different ecosystems as habitat (24, 67, 79), or addressed topics relating to fish health (101, 128, 137), trophic ecology (41, 142, 150) or population biology (13, 38, 157). Fish assemblages have been sampled with reasonable intensity in mangroves (43), seagrass beds (27) and inshore reefs (19), but few published data exist for subtidal sediments (23), surf zones (9) and offshore reefs (53). Whilst some functions of fish habitats are widely cited or posited, few studies have explicitly tested either the ecological roles of fish habitats (67, 76, 165), or the ecological functions fish perform in different habitats (46, 63, 66) in Moreton Bay. Fish diversity is typically high over coral reefs and seagrass meadows, and comparatively low in shallow mangroves and over unconsolidated soft sediments (e.g. sandy and muddy substrates in estuaries, Bay waters and surf zones) (9, 10, 19). However, many species and individuals move among habitats, and this exchange of

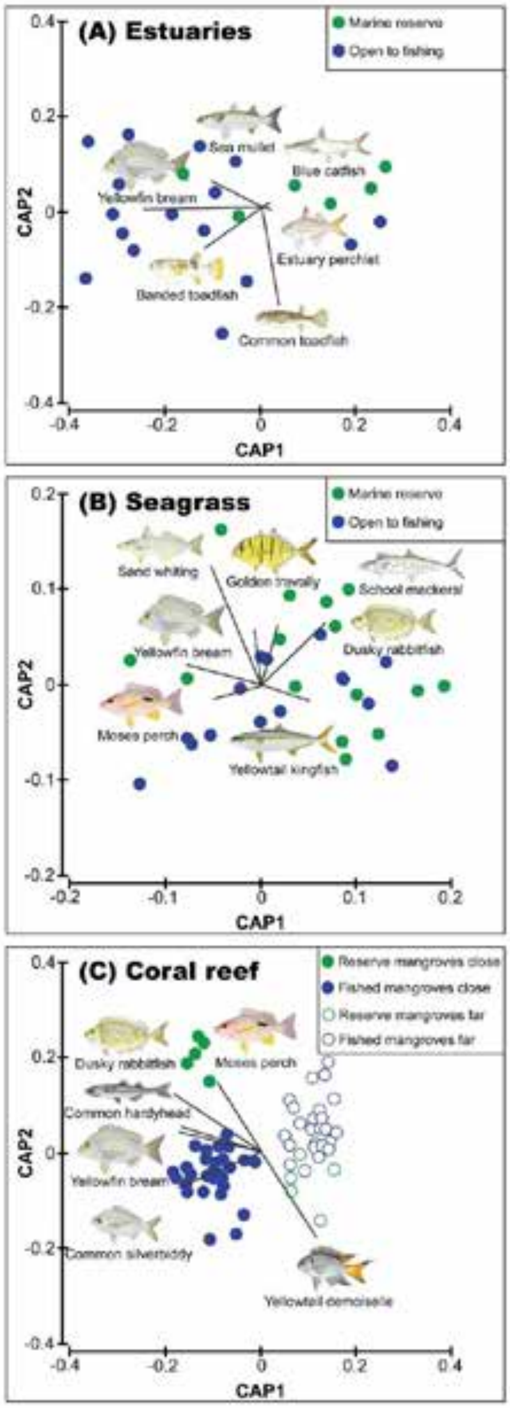

Figure 4. Canonical analysis of principal coordinates (CAP) ordinations illustrating differences in the composition of fish assemblages between marine reserves and fished locations. Individual dots represent the fish assemblages at each site surveyed. In estuaries (A), most species are more abundant in fished locations than in reserves (note the overlap of green and blue dots) (11). In seagrass meadows (B), several species are more abundant in reserves (note the separation of green and blue dots) (10). On coral reefs (C), most species were more abundant in reserves, but only when protected reefs were also close to adjacent mangroves (note the separation of solid green and blue dots, but not outlined dots) (43). Fish illustration and vectors display species correlations with canonical axes. For example, yellowfin bream were most abundant in: (A) estuaries that were open to fishing; (B) seagrass meadows that were protected in reserves; and (C) reefs that were both protected in reserves and close to mangroves. Fish illustrations sourced from www.efishalbum.com.

individuals functionally links assemblages, food webs and ecosystems across the seascape of Moreton Bay (41, 50, 191).

The fish assemblages of Moreton Bay have been altered by the effects of water quality degradation, coastal urbanisation and fishing, which have combined to reduce fish abundance and diversity in estuaries (63), seagrass meadows (27), coral reefs (19) and the surf zones of ocean beaches (9). Marine reserves that prohibit fishing are effective at promoting the abundance of harvested fish over seagrass meadows (10) and coral reefs (43) in Moreton Bay, and have also improved the capacity of these ecosystems to withstand disturbance (e.g. the recovery of coral reefs from flood impacts in 2011 (20)). We propose three broad and interconnected research fields that are likely to improve fish conservation and fisheries management in Moreton Bay in the coming decades: (i) evaluate effects of multiple human pressures on fish assemblages and fish habitats (e.g. 48, 63); (ii) identify the ecological features of habitats and seascapes that promote marine reserve performance (e.g. 11, 190); and (iii) determine how the arrival of tropical species that move south with rising sea temperatures will functionally change fish assemblages, habitats and fisheries in Moreton Bay (e.g. 46, 49).

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Marine turtles in Moreton Bay

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Abstract

Six species of marine turtle from two families have been recorded foraging within the waters of Moreton Bay. Of those species, two (green turtle, *Chelonia mydas* and loggerhead turtle, *Caretta caretta*) are resident in substantial foraging populations that contribute annually to nesting populations of their southern Great Barrier Reef and South Pacific Ocean genetic stocks, respectively. Capture-mark-recapture studies of resident foraging populations in Moreton Bay commenced in 1990, serving as a platform supporting a wide range of additional studies of turtles in Moreton Bay that have garnered valuable insights into the diet, habitat use, physiology, toxicology, genetics and population dynamics of the resident turtle populations. This paper provides a summary of the research completed over the past few decades on turtle biology within Moreton Bay and highlights areas of future research.

Keywords: capture-mark-recapture, diet, health, physiology, toxicology, population dynamics

Introduction

The shallow coastal waters of Moreton Bay have supported marine turtle populations since sea levels rose following the last ice age. They were hunted for food by the local Indigenous people and, following the arrival of European settlers, hunted commercially from 1824 to 1950 (Fig. 1) (1, 2).

In recent times, six species of marine turtle from two families have been recorded foraging in the waters of Moreton Bay. Five species of the family Cheloniidae are year-round foraging residents: loggerhead turtle, *Caretta caretta,* (3); green turtle, *Chelonia mydas* (4); hawksbill turtle, *Eretmochelys imbricata* (5); olive ridley turtle, *Lepidochelys olivacea* (6); flatback turtle, *Natator depressus* (6). Leatherback turtles (*Dermochelys coriacea*), from the family Dermochelyidae, are migratory visitors (6, 7). Marine turtles within Australian waters are afforded protected under the Australian Government's Environment Protection and Biodiversity Conservation Act 1999 (EPBC Act) and by state and territory legislations. Two species (green and loggerhead) migrate into the Moreton Bay waters and nest annually at low density on the ocean beaches of the Bay islands (6). Small post-hatchling loggerhead and green turtles travelling south with the East Australian Current from the nesting beaches of the southern Great Barrier Reef (GBR) region pass through the waters offshore Moreton Bay on their way south and east into the South Pacific Ocean (8). This review does not address biological data associated with debilitated or dead marine turtles that have washed in from the pelagic waters of the Coral or Tasman seas.

Figure 1. Green turtle (*Chelonia mydas*) harvest in Moreton Bay circa 1934 (49).

Immature marine turtles recruit from a pelagic foraging life-history phase in the open ocean to benthic foraging in coastal waters at different sizes: loggerhead turtles recruit to benthic feeding in Moreton Bay at a mean curved carapace length (CCL) of 78.2 cm (SD=3.75, n=52) at approximately 16 years of age (9); green turtles similarly recruit to benthic feeding in Moreton Bay at CCL = 44.2 cm (SD=3.97, n=98) and CCL = 45.1 cm (SD=3.24, n=54.0) for females and males respectively. Hawksbill turtles are believed to recruit to Moreton Bay benthic foraging areas at approximately CCL = 36.0 cm (10).

Large immature and adult leatherback turtles are not permanent residents of Moreton Bay; they are transient visitors to Moreton Bay during the autumn and winter months. The frequency of encounters with leatherback turtles in the Moreton Bay region has substantially declined in recent decades (11).

Most green turtles foraging in Moreton Bay are from the southern GBR genetic stock as defined by FitzSimmons and Limpus (12): > 90% of adult females based on flipper tag recoveries (13), 95% of adults and 85% of immature green turtles based on population genetics analysis (14). A small proportion of the foraging green turtles in Moreton Bay originate from the northern GBR, New Caledonia, Vanuatu, French Polynesia and the eastern Pacific (14). Only loggerhead turtles from the south-west Pacific genetic stock that breed in eastern Australia and New Caledonia have been recorded in eastern Australia, including Moreton Bay (12). There is no clear definition of the genetic stock of origin for hawksbills that forage in Moreton Bay.

Systematic Department of Environment and Science (DES) capture-mark-recapture (CMR) studies of foraging marine turtles in Moreton Bay commenced in 1990 and identified that the most abundant species in the Bay were green, loggerhead and hawksbill turtles (3–6). These studies contributed to the development and implementation of the Moreton Bay Marine Park, with the identified high use areas for foraging turtles designated within Marine National Park green zones and mandatory go slow areas for recreational and commercial vessels. Turtles are most commonly encountered on the shallow seagrass-dominated Eastern Banks adjacent to Dunwich on North Stradbroke Island northwards along the western face of Moreton Island. Turtles are also encountered along the fringing mangroves and shallow muddy flats at the southern extent of the Bay and throughout Deception Bay in the north-west.

The green turtle population in the Moreton Banks has approximately tripled during the 25 years of the CMR study from 1990–2014 (15). Satellite telemetry studies have demonstrated that green turtles maintain long-term fidelity to their respective foraging sites in Moreton Bay (16). Based on satellite telemetry, the home range of green turtles foraging in eastern Moreton Bay was 128.8 km^2, 23.7 km^2 in southern Moreton Bay and 121.8 km^2 in north-western Moreton Bay (17). Adult female green turtles resident in Moreton Bay commenced breeding during 1990–2007 at a mean CCL = 108.7 cm (SD=4.56, n=32) (13). The green turtles in Moreton Bay are on average amongst the largest and fastest growing in eastern Australia (18).

Once recruited to benthic foraging residency, the loggerhead turtles show high fidelity to their respective foraging areas across decades (19, 20). These recruited turtles retain fidelity to their foraging areas following displacement (21). Based on satellite telemetry, the home range of loggerhead turtles foraging in eastern Moreton Bay was 155.8 km^2, 32.7 km^2 in southern Moreton Bay and 15.6 km^2 in western Moreton Bay (17). Adult female loggerhead turtles of the south-west Pacific breeding stock nesting at Mon Repos commence breeding at a mean CCL = 93.65 cm (SD=4.25, n=69) (9).

Marine turtles that forage in Moreton Bay migrate to breed at widely dispersed and usually distant nesting beaches, with most green turtles that forage in Moreton Bay migrating to breed on the islands of the Capricorn-Bunker Group in the southern GBR between North West Island and Lady Elliot Island. Small numbers of the Moreton Bay green turtles have been recorded nesting at Raine Island in the northern GBR, on islands within the Recifs d'Entrecasteaux in north-western New Caledonia and Vanuatu (Fig. 2a). Most loggerhead turtles that forage in Moreton Bay migrate to breeding grounds on the mainland beaches between Bundaberg and Agnes Water (Woongarra coast being the major breeding site). Smaller numbers of Moreton Bay loggerhead turtles have been recorded on the islands of the southern GBR between the Swain reefs and Lady Elliot Island; isolated nesting records have occurred in northern New South Wales and eastern New Caledonia (Fig. 2b).

The CMR studies have been a platform to support a wide range of additional studies of turtles in Moreton Bay, including but not limited to diet, habitat use, physiology, toxicology, genetics and population dynamics. DES CMR studies from the early 1990s to the present demonstrated a robustly increasing green turtle foraging population on the eastern banks of Moreton Bay but a declining population of loggerhead turtles for the same area. The successes for green turtles are attributable to a consistently increasing green turtle nesting population in the southern GBR since strong protection of the species and their habitats commenced in 1950. Recruitment of new immature green turtles taking up residency is a regularly observed feature.

The problem for the declining loggerhead population originates from excessive mortality of small post-hatchlings ingesting plastic debris as they travel in the East Australian Current and

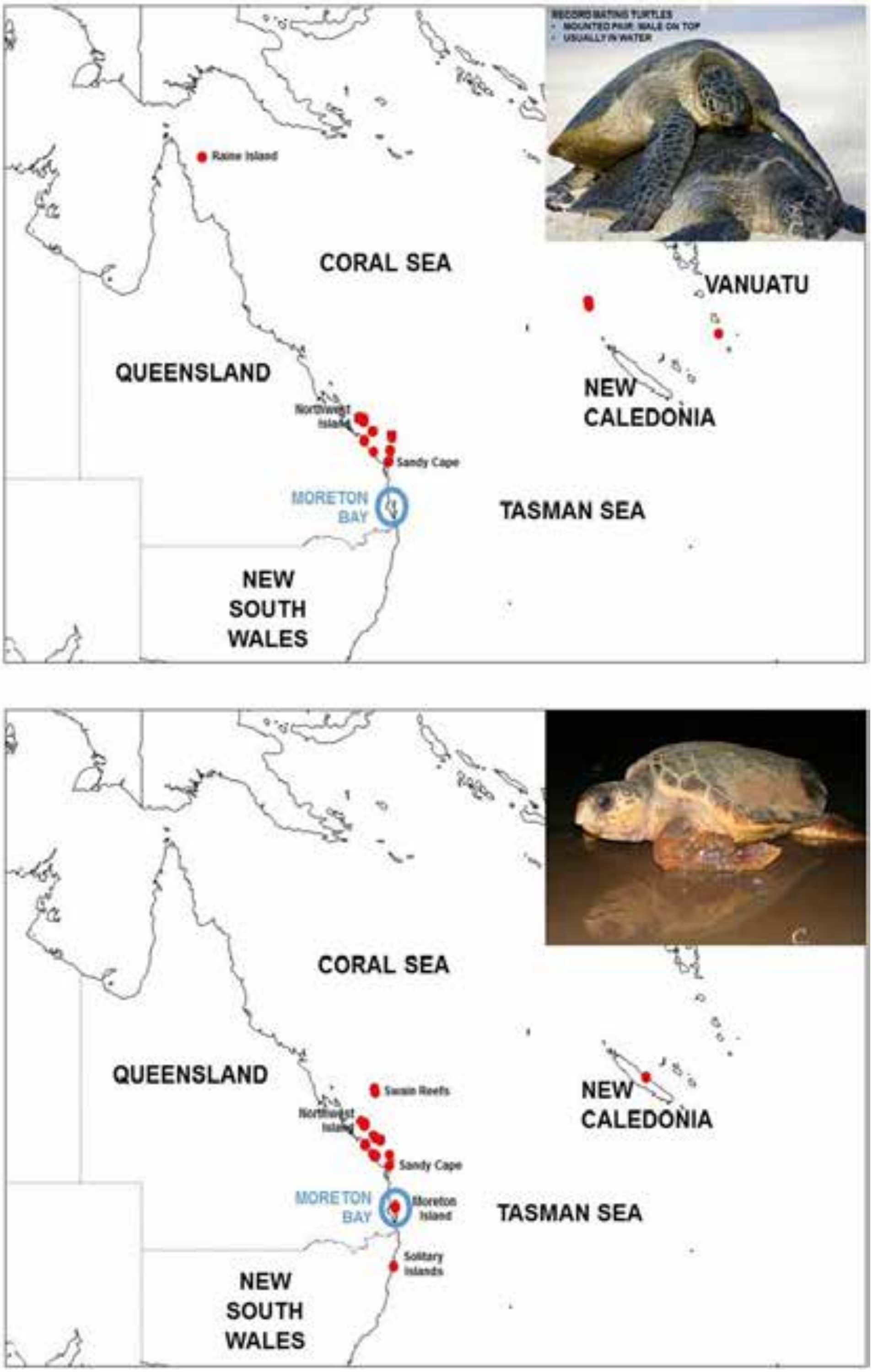

Figure 2 Recorded nesting rookeries of the South Pacific (a) green (*Chelonia mydas*) and (b) loggerhead (*Caretta caretta*) turtles that forage in Moreton Bay. Photos by Col Limpus.

additional mortality from fisheries bycatch in the eastern Pacific. These post-hatchling mortalities have resulted in a severely depleted recruitment of young loggerheads into residency in Moreton Bay since the early 1990s.

Diet and habitat use

Marine turtles undergo a number of distinct life stages accentuated by changes in foraging habitat and diet (22). For most marine turtle species this begins with a protracted open-ocean foraging period post hatching. Marine turtles exhibiting this oceanic-neritic development pattern subsist on a predominantly carnivorous diet borne of pelagic macro-zooplankton; they then shift foraging strategy and diet composition upon recruitment to neritic foraging habitats (23). Boyle and Limpus (8) have documented the diet, including ingested plastic, of the small post-hatchling green and loggerhead turtles passing Moreton Bay on the East Australian Current.

Loggerhead turtle (*Caretta caretta*)

Following recruitment to benthic foraging in Moreton Bay, loggerhead individuals occupy a range of habitats including intertidal and subtidal seagrass meadows, coral and rocky reefs, and the soft-bottom, deeper, subtidal habitats. While foraging loggerheads in South East Queensland have been reported feeding on over 100 taxa, in Moreton Bay they are most commonly found to forage on species of portunid crabs and a range of benthic gastropod and bivalve molluscs (Table 1). While loggerheads feed extensively on epifaunal species they will also mine the substrate to obtain infauna prey items (24, 25) and take prey items from the mid-water column and at the surface (26).

Table 1. Summary of findings from dietary studies on the loggerhead turtle (*Caretta caretta*) in the Moreton Bay region.

Loggerhead turtle (*Caretta caretta*)		
Preen (24)	1996	– 'Infaunal mining' foraging method observed (n=13) – Polychaeta, thin-walled Mollusca and Bivalvia
Limpus *et al.* (26)	2001	– Gut and faecal content (n=53) – 94 benthic and near-benthic taxa – Predominantly Mollusca or Crustacea, Echinodermata, Porifera, Cnidaria and Osteichthyes – Diet a function of feeding area not sex or size
West (25)	2005	– Faecal contents (n=24) – Predominantly Crustacea and Mollusca
Boyle and Limpus (8)	2008	– Gut content (n=7) of oceanic post-hatchlings – Pelagic Cnidaria, Crustacea and Mollusca – > 50% of sampled individuals observed to have ingested synthetic materials
Limpus and Limpus (51)	2008	– Mortalities from predation on porcupine fish (n=12)
Coffee (52)	Unpubl. data	– Faecal contents (n=12) – Predominantly Crustacea and Mollusca

Green turtle (*Chelonia mydas*)

Within the Moreton Bay area, foraging populations of green turtle have been observed to feed within tidal and subtidal habitats, grazing primarily on algae (*Gracilaria* sp. and *Hypnea* sp.) and seagrass (*Zostera capricorni* and *Halophila ovalis*) and opportunistically on mangrove (*Avicennia marina*) leaves and propagules (Table 1). At higher trophic levels, observations of opportunistic foraging on gelatinous animal material in Moreton Bay (27–29) are consistent with findings from other foraging populations (Fig. 3) (30–33).

Figure 3. Neritic-foraging immature green turtle prey on jellyfish, northern NSW. Image by Owen Coffee (50)

Table 2. Summary of findings from dietary studies on the green turtle (*Chelonia mydas*) in the Moreton Bay region

Authors	Year	Dietary observations
Brand, Lanyon and Limpus (53)	1999	– Digestive retention and dietary compositions (n=3) – Predominantly seagrass *Halophila ovalis* and algae *Gracilaria* sp. – Digestive retentions of 6.5–13.5 days
Brand-Gardner, Limpus and Lanyon (54)	1999	– Oesophageal lavage (n=20) – Observed preference for *Gracilaria* sp. – Inverse relationship with fibre levels and preferred species
Read and Limpus (55)	2002	– Oesophageal lavage (n=240) – Predominantly seagrass *Halophila ovalis* and red algae *Gracilaria cylindrica* and *Hypnea spinella* – Animal material and cotyledons of mangrove *Avicennia marina* observed
Arthur et al. (27)	2007	– Animal-borne imaging (n=6) – Individuals foraged upon gelatinous animal material in the water column – One sampled individual recorded foraging on seagrasses
Arthur, Boyle and Limpus (28)	2008	– Stable isotope analysis (SIA) (n=64) at distinct life stages (hatchlings, pelagic juveniles, small immature, large immature and adult) – Elevated $\delta^{15}N$ in recent recruit neritic juveniles consistent with individuals foraging at higher trophic levels
Boyle and Limpus (8)	2008	– Gut contents (n=31) of oceanic post-hatchlings – Observed pelagic Cnidaria, Crustacea (predominantly Malacostraca) and Mollusca – Over 65% of sampled individuals observed to have ingested synthetic materials
Brine (29)	2008	– Oesophageal and SIA (n=24) – Lavage identified seagrasses *Halophila* sp. and *Halodule* sp. as largest contributors to diet – SIA identified elevated $\delta^{15}N$ in recent recruits and larger size classes, indicative of higher trophic feeding
Townsend et al. (56)	2012	– Necropsy (n=2) – Multi-stage mass spectrometry identified envenomation from accidental ingestion of blue-ringed octopus (*Hapalochlaena fasciata*) as cause of death

Hawksbill turtle (*Eretmochelys imbricata*)

While there are no studies on the foraging ecology of the resident hawksbill turtles of Moreton Bay, individuals foraging off the coast in the Northern Territory and the northern GBR have been recorded foraging on algae (Rhodophytes, Chlorophytes and Phaeophytes), with a significant contribution of sponges and soft corals to their diet (34, 35). These observations are consistent with those from foraging individuals sampled in the Caribbean and the Indian Ocean (36, 37). There have been observations of individual adult size hawksbills selectively feeding on large sea anemones on the subtidal rocky reef on the seaward side of North Stradbroke Island (6).

Leatherback turtle (*Dermochelys coriacea*)
Unlike cheloniid marine turtles, the leatherback turtle does not recruit to a benthic, life-history phase. Instead they retain a surface-water foraging habitat whether they are in oceanic or neritic waters throughout their life. In the north-west Pacific and the Atlantic their diet is primarily large, gelatinous, macro-zooplankton (cnidarians, ctenophores and colonial tunicates such as *Pyrosoma* sp.) (38–41). While limited data exist on their foraging ecology in the south-west Pacific, they have been regularly reported to feed on the blue blubber jellyfish (*Catostylus mosaicus)* in Moreton Bay (11).

Olive ridley turtle (*Lepidochelys olivacea*)
Following an oceanic developmental period, olive ridley turtles in Australia have been reported recruiting to neritic foraging environments (42). While there is a paucity of data on the foraging ecology of recruited immature and adult olive ridleys, they are thought to subsist on a carnivorous diet composed primarily of gastropods, cnidarians and benthic crustaceans (42, 43), consistent with observations on the diet of adult olive ridley sampled off the coast of Mexico (44).

Flatback turtle (*Natator depressus)*
Forgoing a pelagic developmental period, flatback turtles spend their post-hatchling through to their adult life stages in neritic foraging environments (22). While limited observations exist on the foraging ecology of flatback turtles, it is posited that foraging individuals in the Moreton Bay region have diets consistent with those reported in individuals throughout the east and west coasts of Australia. They subsist on carnivorous diets, composed primarily of soft-bodied invertebrates such as sea pens, soft corals, holothurians and jellyfish (43–46).

Health, physiology and toxicology

A substantial marine turtle population lives within the semi-enclosed waters of Moreton Bay, which receives the outflow of five rivers (Albert, Logan, Brisbane, Pine and Caboolture). These rivers receive the chemical discharge associated with more than two million human inhabitants and their urban development, agricultural and pastoral activities, and industry. As such, the turtles of Moreton Bay are more likely to be impacted by river outflow than any other population of marine turtles in Queensland. Elevated levels of heavy metals and organo-halide compounds have been detected in marine turtles resident in Moreton Bay; to date no studies have demonstrated a detrimental impact of these substances on turtle biology (Table 3). The

associated health, toxicology and physiology related studies on marine turtles within Moreton Bay are summarised in Table 3.

Boat strike, entanglement in crab pots and fishing gear and to a lesser extent, the ingestion of synthetic debris, were the primary sources of anthropogenic mortality for turtles within Moreton Bay (9, 13, 47, 48). Indigenous harvest of marine turtles in Moreton Bay is not quantified.

Summary

Since the start of capture-mark-recapture studies in 1990, research, in tandem with the state's tertiary institutes, has determined which species inhabit the Bay, their genetic stocks and population dynamics, and has worked toward the conservation and management of the resident populations. This paper has outlined some of the research achievements of the past few decades, however, as identified, many questions remain. The large numbers of resident foraging turtles within Moreton Bay are ideally situated for ongoing studies by research institutes in the vicinity of the Bay, allowing new research techniques to be developed and the anthropogenic impacts on these species to be quantified into the future.

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Table 3. Summary of findings from health, physiology and toxicology studies on marine turtles in the Moreton Bay region. See footnote for abbreviations.

Authors	Year	Observations
(57) Gordon, Kelly and Lester	1993	– 1991, of a cohort of 70 green turtles which died in Moreton Bay, n = 24 stranded green turtles were euthanised and examined by necropsy – Severe enteritis or encephalitis was prevalent in the examined turtles, associated with *Caryospora cheloniae*, a coccidial pathogen – At the time of study such infections had only been observed in captive- reared hatchling green turtles – Concluded that *C. cheloniae* was pathogenic for all life stages of green turtle
(58) Gordon Kelly and Cribb	1998	– n = 96 stranded green turtles were examined by necropsy – Spirorchid fluke infection (spirochetosis) was identified as the cause of mortality in ~ 10% of necropsied turtles – Spirochetosis was diagnosed in 98% of examined turtles with flukes observed in 45% of stranded turtles – Spirorchids were likely to contribute to the strandings of green turtles with concurrent disease
(59) Gordon, Pople and Ng	1998	– 1990–91, n = 50 (38 green turtles, 8 loggerheads, 3 hawksbills and 1 olive ridley) stranded turtles were sampled for trace metal concentrations – Arsenic (As), cadmium (Cd), mercury (Hg), selenium (Se) and zinc (Zn) concentrations were sampled from the kidneys and livers of the sampled individuals – Cd concentrations in all turtle species (1.7–75.9 $\mu g\ g^{-1}$ wet weight) were amongst the highest recorded for marine vertebrates globally at the time of publication – Decreasing concentrations of Cd, Se and Zn were associated with increasing curved carapace length (CCL) in kidney tissue, whilst Zn concentrations increased with CCL in liver tissue
(60) Hermanussen *et al.*	2004	– No information existed at the time of the study on the sensitivity of reptiles to dioxins and dioxin-like compounds – The carapace fat tissue was sampled from stranded immature to adult green turtles (n=4) – Concentrations of PCDD/F and TEQs were on average 10 times higher in green turtles when compared to dugongs – PCDD/F and TEQ concentration in sediments in Moreton Bay could be considered negligible compared to polluted areas in the Northern Hemisphere, concentrations in green turtles are comparable to those found in reptiles of the Great Lakes and St Lawrence basins – Sediment retention of these pollutants is up to 15 times higher in seagrass beds compared to bare sediment – A trend of increasing concentration with decreasing degree of chlorination was observed in the turtles when compared to the sediments
(61) Hamann *et al.*	2005	– 1996–99, blood samples from (n=25) non-vitellogenic female green turtles – The highest plasma triglyceride concentration and lowest plasma cholesterol concentration were found in the non-vitellogenic female green turtles in Moreton Bay during the El Niño year of 1997 – These same Moreton Bay females in 1997 had higher plasma triglyceride and lower cholesterol concentration than those recorded in non-vitellogenic females foraging on Heron Reef and in Shoalwater Bay in 1997 – Turtles feeding during El Niño years could obtain higher levels of body condition
(48) Gordon	2005	– 1990–96, n=108 green turtles were examined for cause of morbidity and mortality – Direct anthropogenic causes (including trauma, ingestion of marine debris and drowning) accounted for 34% of mortalities in sampled turtles – Fibropapillomatosis accounted for 7% of mortalities – Naturally occurring diseases accounted for the remaining 59% of stranding

(62) Hermanussen *et al.*	2006	– Total dioxin/furans (POPs) concentrations ranged from 14–213 pg/g lipid for greens, 93–137 pg/g lipid for hawksbills and 151–319 pg/g lipid in loggerhead turtles from Moreton Bay – Trophic level influenced the bioaccumulation of certain POPs and the highest TEQ levels are present in carnivorous loggerheads and lowest in herbivorous green turtles – A trend of increasing tissue concentrations and TEQs was observed with increasing habitat contamination zones
(63, 64) Muusse; Muusse *et al.*	2006	– 2004–05, blood and eggs were sampled for total PCDD/F and PCB concentrations from n = 6 (5 loggerheads and 1 flatback) Moreton Bay foragers nesting at Mon Repos, Qld – Blood data were consistent with other turtle studies from Moreton Bay – Total PCB concentrations were higher in blood than in egg samples – PCB TEQs were higher and transferred in higher percentages in experienced breeders
(65) Hermanussen *et al.*	2006	– Sediment samples (n=100) and blood samples (n=29) from green turtles were collected to analyse for PCDD/F exposure – Average PCDD/F concentrations were higher for turtles in sub- populations proximal to river inputs – PCDD/F congener profiles in green turtles reflected that observed in sampled sediments – It is uncertain whether the levels found have the potential to result in adverse effects for green sea turtles
(66) Flint *et al.*	2010	– 2007, n = 125 green turtles were assessed from Moreton Bay to determine health status using blood samples – 18 blood chemistry and 8 haematology variables were investigated – 7% of turtles were classified as clinically unhealthy – Clinically unhealthy turtles were biased towards small immature males – Small immature turtles with > 20 *Chelonibia* barnacles on the plastron were 3 times more likely to be unhealthy than those with no barnacles
(67) Flint *et al.*	2010	– 2007–08, n = 101 loggerhead turtles were assessed to determine health status using blood samples – 13 blood chemistry variables and 3 haematology variables were investigated – 66% of turtles were classified as clinically healthy and 23% as unhealthy – Neither sex nor maturity influenced the risk of being clinically unhealthy – Loggerhead turtles in Moreton Bay required separate reference intervals for immature and mature turtles for thrombocyte counts and for male and female turtle for lymphocyte, heterophil and total white cell counts – A single reference interval for other parameters can be used regardless of age or sex
(68) Flint *et al.*	2010	– 2008, a subset of n = 155 green turtles from Moreton Bay and a further n = 569 from Shoalwater Bay were examined during annual monitoring – Corneal fibropapillomatosis was observed in four (0.5%) of examined individuals – The corneal lesions were deemed to have detrimental effect on the vision of the affected turtles – Documented the occurrence of corneal fibropapillomas in the South Pacific green turtle population, a condition previously restricted to observations in Hawaii, mainland USA and Florida
(69) Flint *et al.*	2010	– 2006–09, n = 100 stranded green turtles were examined from southern Queensland to assess causes of disease and mortality – Parasitism from spirorchid flukes was most commonly attributed to cause of mortality (41.8%) – Spirochetosis was observed most frequently in summer when compared with other seasons (P=0.029) and in immature turtles (n=70) more severely than in mature (n=19) turtles (P=0.032)

		– Disease (spirochetosis, gastrointestinal impaction etc.) were considered to contribute to cause of death in 92.8% (n=142) of examined green turtles, with 7.2% (n=11) of mortalities assigned to anthropogenic misadventure
(70) Schuyler *et al.*	2012	– 2006–11, n =115 marine turtles were examined by necropsy – 54.5% (n=12) of post-hatchling pelagic foraging immature turtles had ingested marine debris, in contrast to 29.0% (n=27) of benthic foraging turtles with marine debris ingestion – Approximately 90% of ingested debris was plastic in origin – Pelagic foraging turtles ingested significantly more rubber and hard plastic than benthic foraging turtles, which exhibited selectivity for white and clear soft plastics
(47) Meager and Limpus	2012	– 2011, n = 1793 marine turtle stranding and mortalities were reported – The regions between the Gold Coast and Hervey Bay (28°S to 25°S) accounted for 41% of records (n=728) – Within Moreton Bay n = 51 marine turtles were recorded as killed or injured by vessels – Marine strandings were close to twice those reported the previous year for the Queensland coastline – Elevated strandings were likely influenced by extreme weather events in late 2010 to early 2011 which affected seagrass availability
(15) Limpus, Jones and Chaloupka	2016	– Fibropapillomatosis was observed in the foraging population of green turtles in Moreton Bay at the commencement of capture-mark-recapture studies – The highest frequency of green and loggerhead turtles with fibropapillomatosis is from the eastern banks of Moreton Bay – Hawksbill turtles have only been recorded with fibropapillomatosis at low frequency on the eastern banks of Moreton Bay
(71) Flint *et al.*	2017	– Investigated the relationship between extreme weather events and marine turtle strandings – Rated most influential, freshwater discharge was associated with increased marine turtle strandings 10–12 months later for events with a cumulative effect (multiple months) and 7–9 months later for non-cumulative events (single month only) – Increased strandings post extreme freshwater discharge were attributed to reduced seagrass coverage in foraging areas

Note: PCDD/F – polychlorinated dibenzo(p)dioxins and furans (‘dioxins’), TEQ – toxic equivalent, PCB – polychlorinated biphenyl, POP – persistent organic pollutant, pg/g – pictogram/gram, PCDD – polychlorinated dibenzodioxins

Ecology of the marine mammals of Moreton Bay

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Abstract

The subtropical waters of Moreton Bay support a diverse and abundant marine mammal fauna. Year-round residents include populations of dolphins and dugongs, and winter visitors include humpback and southern right whales. Due to its proximity to a major capital city and relatively sheltered waters, Moreton Bay has been the site of the some of the most intensive marine mammal research in Australia over the past twenty years. This chapter gives an up-to-date overview of the biology and ecology of the populations of marine mammals encountered within the Bay, their current status and threats.

Keywords: dugong, dolphin, whale, humpback whale, megafauna, population, conservation, threats

Introduction

Moreton Bay has one of the most diverse and abundant marine mammal faunas of any part of the Australian coast (1, 2). Resident populations of subtropical and tropical species of dugongs and dolphins are joined by seasonal visitors when humpback and southern right whales travel along their coastal migration paths. Whilst Moreton Bay's sheltered waters provide refuge for migrating whales, there are also habitats for those mammals that choose to make it their principal residence.

The distribution and abundance of marine mammals within the Moreton Bay region have changed in the twentieth century as a result of rapid coastal development, an increase in boating traffic, a decline in water quality, the operation of commercial fisheries and burgeoning ecotourism. These impacts saw a depletion of visiting whales, a pronounced shift of dugongs away from the western Bay, and apparent impacts on dolphin feeding regimes. This paper summarises the current status of dugongs and cetaceans (whales and dolphins) in Moreton Bay early in the twenty-first century, with information gathered from research programs conducted on their population biology, ecology and health over the past 20 years. Current and emerging threats to marine mammals are also considered.

Dugongs of Moreton Bay

The most abundant marine mammal in tropical to sub-tropical Australian coastal waters is the dugong *Dugong dugon* (3) and Moreton Bay is no exception. The extensive shallow seagrass beds of Moreton Bay support the largest, southern-most resident population of dugongs on the east coast (4, 5). The vast majority (>95%) of dugongs in the Bay occur in the Eastern Banks area, primarily on the Maroom, Boolong and Coonungai Banks, where the water is relatively clear, seagrass communities comprise the genera favoured by dugongs, boating traffic is light, and deep-water refugia are close (4, 5). In each tidal cycle, grazing herds of dugongs move up over the shallow seagrass beds with the tide. Groups of 10 to 100 animals are common, but herds of 300 have been recorded (5). As the tide ebbs, dugongs drift off the banks but may continue to feed on sparse seagrasses (mostly the low-light tolerant genus *Halophila*) in water as deep as 18–25 m (6). In the winter months, dugongs disperse across the Eastern Banks, foraging widely in response to a decline in abundance and nutritional quality of their seagrass food (4, 5). They also move back and forth between the warmer oceanic waters of South Passage and the cooler Bay waters through Rous Channel. These erratic small-scale movements may be a strategy to reduce exposure to cold water at this extreme of their latitudinal range (4, 7). Small numbers of dugongs are also found elsewhere in Moreton Bay. These animals are associated with shallow seagrasses in the western and southern parts of Moreton Bay (5, 8) and in Pumicestone Passage (9).

The most recent available population estimates of dugongs for Moreton Bay are from aerial surveys: 759 ± 181 in 2013 (8) and 601 ± 80 for 2016 (10). Aerial surveys have been conducted since the 1970s (11–13), initially as a means of examining distribution and movements in defined areas of the Bay (4) and then for population estimation of the entire Bay at a minimum of five-yearly intervals (5, 8, 10, 14–16). Quantitative aerial surveys over the past 20 years have yielded population estimates ranging from as low as 344 ± 88 (17) up to 1019 ± 116 (5), with most estimates between 500 and 1,000 (18). Comparably, population estimates of 700–800 over the years 2002–07 (JM Lanyon, unpubl. data) have been obtained based on a capture-mark-recapture (CMR) program running since 2001 (19). As of 2018, more than 780 individual dugongs had been gene-tagged in Moreton Bay as part of this program, suggesting this as a baseline minimum count.

The apparently fluctuating population size of dugongs in the Bay has been variously interpreted as indicating emigration and/or immigration, implying connectivity between Moreton Bay and other populations to the north (16,18) and/or episodes of dugong mortality (20, 21), but with no significant carcass recovery. More realistically, variation in these population estimates is probably an artefact and related to differences in survey design (including transect intensity and layout, altitude), sighting conditions (poor, good weather), tidal phase (high, low) and/or season (5). Fewer dugongs are sighted when the weather is poor, survey altitude is low (because of their clumped distribution), the tide is low (5) and dugongs are in deeper waters (22). Broad agreement between population estimates obtained from aerial surveys in the 1990s and again within the past five years, and also with population estimates from a CMR program, suggests a stable population with no discernible population decline. Furthermore, there is evidence that the dugong population in Moreton Bay is a resident one with little gene flow in or out (23).

Genetic evidence suggests against regular mass migration of dugongs along the southern Queensland coast. The dugongs of Moreton Bay constitute part of the broader southern Queensland stock (A McGowan, unpubl. data) but are probably a unique breeding population, genetically distinct from the closest, more northern dugong populations of Hervey Bay and the Great Sandy Straits (24). Although studies utilising satellite tags have recorded a few dugongs ranging between Moreton and Hervey Bays (25) only one dugong 'Jeff' that was physically tagged in Moreton Bay has been recovered in Hervey Bay (JM Lanyon, unpubl. data). Pedigree reconstruction (family trees) of the southern Queensland dugongs (26) using genetic markers to identify individuals (27, 28) and their offspring, and locations of each, suggests that only small numbers of adults of breeding age undergo true dispersal, i.e., movements coupled with breeding events (23). Other movements into and out of Moreton Bay might more properly be described as ranging movements but with no associated breeding. The level of outbreeding is not sufficient to disrupt these separate breeding units in southern Queensland (23, 24).

Moreton Bay has become the most intensively studied dugong population in the world over the past 20 years, with projects examining movements and distribution (e.g., 6, 25) and a longitudinal CMR program running annually since the summer of 2000–01 (19). As part of this program, more than 120 dugongs are captured (29) and/or skin sampled (30) each summer, their identities established and biological data collected. In addition to studies examining distribution and population structure, aspects of diet (31–33), behaviour (34–36), reproduction (37–40), metabolism and energetics (41–44) and health (45-48) have been examined through this direct hands-on approach. Some of the more interesting results regarding the biology of Moreton Bay dugongs are related to their subtropical environment and proximity to a major city of more than two million people.

The dugongs of Moreton Bay live at the southern end of the species' range and are consequently prone to marked seasonal shifts in water temperature, seagrass abundance and nutritional quality. Their dependence on seagrass and the dynamic nature of the seagrass environment is reflected in almost all aspects of the life history of dugongs (3) with a pronounced seasonality in their reproductive pattern (49). The dugongs of Moreton Bay are slow to grow to maturity and undergo a protracted pubertal period but appear to achieve larger final adult body sizes than dugongs elsewhere (37, 38). Breeding is also slow and the long periods between successive calves and prolonged lactation (several years) may have its basis in seagrass availability. The onset of the mating season for dugongs coincides with the end of winter and thus at the end of a period of lowest nutrient availability. At this time, adult males spend less time in herds and more time roaming, presumably in search of mating opportunities (39). They participate in numerous conflicts with other males at this time as they compete for females (36, 39). This competitive mating strategy takes its toll. In these conflicts, male dugongs suffer significant injury from tusks of other dugongs, elevated chronic stress, loss of body condition (36, 39, 40), and their relatively low thyroid hormone (T4) levels indicate some physiological (probably nutritional) stress (50). It is possible that they are prone to immune-compromise at this time and may be more susceptible to diseases.

In response to unusual pathologies observed on some free-ranging dugongs during the CMR program, an annual health assessment program of the dugongs in Moreton Bay was established in 2008 (41), following the basic protocols for manatee health assessment (51). The major aim of this program is to screen for emerging health-related problems in this most urbanised of dugong populations, with a view to detecting and mitigating against health-related threats. To this end, each year a random sample of up to 20 dugongs of both sexes and all ages (except dependent calves and nursing cows) are captured and removed from the water so that clinically valuable samples such as blood, urine and faeces can be collected. Dugongs can also be examined for pregnancy using sonography, and weighed (Fig. 1). At the time of writing, just over 200 dugongs have been medically examined in Moreton Bay. Baseline clinical reference intervals for blood haematology (46), serum biochemistry (45) and stress hormones (39) have been determined for apparently healthy dugongs, and samples have been collected for endocrine, microbial and contaminant analysis, and disease screening.

Figure 1. Wild dugong on the deck of a research vessel for annual health assessment in Moreton Bay. From top left of photograph and clockwise: researchers are measuring nasal temperature with a temperature gun; preparing to douse the animal with a bucket of water; marking the dorsum with a waterproof crayon to prevent short-term recapture; providing shade; palpating the pectoral fin prior to blood collection; filming via a Go-Pro camera; and two attendants wait to receive blood tubes from dugong phlebotomy.

To date, few infectious disease agents have been detected in the live dugongs of Moreton Bay. Immunological evidence of exposure to the disease pathogens *Toxoplasma gondii* and *Neospora caninum* has been demonstrated in these dugongs, but signs of clinical disease or active infection have not yet been recorded (47). The fact that pathogens of terrestrial origin may have been detected in dugongs several kilometres offshore in eastern Moreton Bay and that the associated antibody levels were highest in 2011, the year after a severe flood event in the region, suggests offshore influence of coastal habitation and development. Furthermore, levels of several heavy metals (including mercury, aluminium and cobalt) were elevated in circulating blood from live wild dugongs sampled in the Bay post-flood (JM Lanyon, unpubl. data). Since levels of chemicals in dugong tissue have been found to reflect local land use and pollutants released into coastal waterways elsewhere (e.g., 52, 53), it is reasonable to assume that the same may be happening in Moreton Bay. The long-term effects of contaminants on dugong health and reproduction are unknown, but are potentially concerning (45, 55).

Threats to dugongs are regionally specific and change through time, but throughout the dugong's range, the main threat is degradation or loss of seagrass habitat on which they depend (3). In the past, major threats to dugongs in Moreton Bay also included hunting (both commercial and Indigenous) and net entanglement. In the mid-1990s, boat strike appeared to be an emerging threat. This led to reduced vessel speed in areas of critical dugong habitat that were first introduced by the Moreton Parks (Moreton Bay) Zoning Plan 1997 and later extended by the Marine Parks (Moreton Bay) Zoning Plan 2008. However, with increasing frequency and severity of storms and coastal flooding, expected to be exacerbated by global climate change, the focus must now be redirected to the threats caused by physical and chemical degradation of coastal seagrass habitats. An additional potential emerging threat is terrestrial disease-causing pathogen exposure as a result of coastal pollution. It is recommended that monitoring of the health of dugong populations and individuals continue in the Bay, but also on a global scale as coastal and ocean habitats deteriorate and global climate change proceeds.

For Moreton Bay dugongs specifically, their viability and chances of survival in the long term is entirely in our hands. We now know that whilst 25 years ago, the Moreton Bay dugongs' offshore habitats and relative anonymity were thought to be one of their greatest forms of protection (2), their habitats are well within reach of coastal destruction and pollution. Conservation of this unique and genetically discrete population is dependent on timely identification and management of local threats to the health and survival of dugong habitat.

Cetaceans of Moreton Bay

Humpback whales

Humpback whales (*Megaptera novaeangliae*) are found in a number of discrete populations around the world. In the Southern Hemisphere, humpback whales feed primarily on Antarctic krill (*Euphausia superba*) during summer in the Antarctic, and then migrate long distances during autumn to winter breeding grounds in the tropics where they fast. One population of humpback whales migrates along the eastern coast of Australia to breeding areas inside the Great Barrier Reef (56). During their migrations, these whales pass very close to Point Lookout (North Stradbroke Island) and Cape Moreton (Moreton Island) (56, 57), and during the southward spring migration in particular, many whales enter the northern part of Moreton Bay, and some have even been found south of Peel Island.

Eastern Australian humpback whales were subjected to whaling in the 1950s and early 1960s. After World War II, whaling stations were set up at Tangalooma, Byron Bay and Norfolk Island to exploit this large population. Tangalooma on Moreton Island was the largest station and had an annual quota of up to 660 whales (57). Catch per unit effort was steady for most of the 1950s but fell sharply in 1961 with a collapse in the whale population, and all of the east coast whaling stations, suffering the same fate, closed in 1962 (57). It was not until the 1990s that data published by Russian whaling biologists showed that Soviet whaling fleets had operated in the Antarctic region in the summers from 1959–68, impacting this population by illegally taking 22,000 humpback whales in just two seasons (1959–60 and 1960–61) from the waters south of eastern Australia and New Zealand (58). While the original eastern coast humpback whale population is currently thought to have been approximately 26,000 whales (59), it is likely that the population was reduced to no more than a few hundred whales by the mid-1960s (57, 59, 60).

After the whaling stations closed, few whales were sighted until the late 1970s when Robert and Patricia Paterson, keen naturalists at Point Lookout (North Stradbroke Island), began noticing occasional passing whales from their holiday house (56). The Patersons started keeping a log of occasional passing whales, and this turned into an annual survey in the early 1980s. Michael Bryden from The University of Queensland also started a series of surveys around the same time, and these two series of surveys continued until the early 2000s (56, 60–65). Despite using different vantage points at Point Lookout, different watch structures and different data analyses, the two series of surveys showed similar results: a rapid increase in the size of the humpback population over time, which has continued, as demonstrated by more contemporary surveys. The most recent population survey, conducted in 2015, estimated a long-term population growth rate of 11% per annum (95 % CI) (Fig. 2), with an abundance estimate of 25,454 whales (95 % CI) (66). This means that the eastern Australian humpback whale population is likely fully recovered; however, the continued rapid increase in the population is of some concern. It may indicate that either the whales are heading for a higher carrying capacity than previously thought, or that their recovery may follow an irruptive pattern, with an overshooting of carrying capacity followed by a sudden increase in mortality and fall in the population as it fluctuates around the carrying capacity for some time (67).

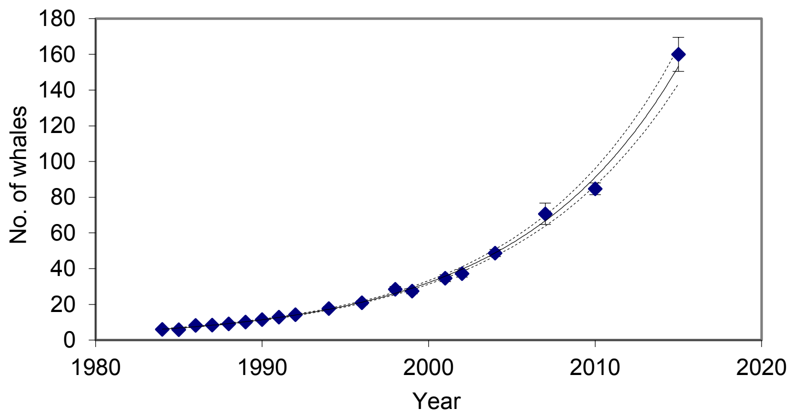

Figure 2. The average number of northbound humpback whales (mean with SE) passing Point Lookout per 10-hour day over the peak four weeks of the migration. Most surveys ran from 0700 to 1700 every good-weather day. The trend line represents an 11.0% per annum increase (95% CI dotted lines). Data prior to 2004 are from Paterson surveys (56, 60–63). SE: standard error, CI: confidence interval.

Southern right whales

Southern right whales (*Eubalaena australis*) were one of the first casualties of European settlement in Australia. Whaling was one of white Australia's first industries. Many small whaling stations sprang up around the southern coastline of the mainland and Tasmania to take advantage of the large numbers of right whales in particular. By 1850, barely 60 years after European settlement, southern right whales had been hunted into commercial extinction (68, 69).

The first likely sighting of a southern right whale in Queensland waters by Europeans was by whalers working from Tangalooma in the 1950s. They radioed their finding back to the whaling station and asked permission to kill it, but permission was denied. The first confirmed and documented sighting of a southern right whale was in 1998 (70). The whale was spotted in waters off the surf club at Point Lookout (outside the Bay) and then moved around the headland and out to sea. A southern right whale, presumably the same one, was sighted later in the season, off Point Lookout. The following year a southern right whale was sighted within

Moreton Bay and since then they have become relatively frequent visitors to the Bay environs and south-eastern Queensland (71, 72). They have also been sighted as far north as offshore from Gladstone (Department of Environment and Science, unpubl. data). This suggests that while the South East Queensland coast was probably part of the normal distribution of these whales, this had not been realised until recently as numbers had been severely depleted prior to European settlement of Queensland (73).

Although the re-colonisation of south-eastern Queensland waters is a welcome sign of the recovery of the southern right whale, it has not been without setbacks. Two southern right whales, a presumed mother and yearling calf, were hit by a passenger ferry just north of Goat Island in 2014 resulting in the death of the younger whale (72). Southern right whales are well known for their vulnerability to ship strike due to their slow swimming speeds and extended periods spent at or near the surface. The previous year, 2013, another southern right whale was found floating dead off the southern Sunshine Coast close to the northern end of the Bay. The whale was towed out to sea but later washed up on Bribie Island. A post-mortem examination of the whale found wounds consistent with a ship strike to the skull, but was not able to determine whether the strike was ante- or post-mortem (72). Ship strike and entanglement are likely to be the most serious threats to southern right whale recovery in Australia (74).

Indo-Pacific bottlenose dolphins

There are two species of bottlenose dolphins inhabiting the Moreton Bay region: the darker larger offshore species found outside the Bay on the seaward side of the barrier islands (75), and the coastal inshore form (lighter grey with speckled belly) found within the Bay (1,76). The larger offshore species is the common bottlenose dolphin, *Tursiops truncatus* and they have not been well studied in the Moreton Bay region. Two common bottlenose dolphins were satellite tracked off Point Lookout in the late 1990s, and appeared to be resident in relatively small home ranges over the continental shelf (77).

Inshore bottlenose dolphins (*Tursiops aduncus*) are found commonly within the Bay and have been studied on and off since the 1970s (78). The most recent population estimate in 2010 has shown that there are approximately 550 animals in two distinct sub-populations: one that lives in the wider, deeper northern part of the Bay, and the other that inhabits waters closer to the central and eastern areas of the southern Bay (79). These sub-populations are genetically distinct with limited mixing, and are adapted to different ecological niches (80, 81). The smaller southern sub-population, estimated at ~200 dolphins, may be under greater ecological and anthropogenic stress due to its more inshore distribution (more exposed to human activities) and foraging preferences. These dolphins prefer to feed in shallow waters along the developed coast and polluted river mouths of the western Bay (79, 81). Whether or not this sub-population is steady or in decline is not known and will require further surveys into the future (79).

In the late 1990s, it was demonstrated that inshore bottlenose dolphins in eastern Moreton Bay formed two distinct but sympatric communities. One group of dolphins followed prawn trawlers and appeared to forage from trawler discards, whilst the other group did not (82). Trawling effort in the Bay underwent a considerable decline from 1999 until 2008. The trawler and non-trawler dolphin community structure disappeared with the changes in fishing practice, reverting to a more conventional fission–fusion association pattern for dolphins (83). The high rates of shark injuries on bottlenose dolphins in the Bay reported in a study in the 1980s (evidence of injuries in 36.6% of dolphins identified) may have been in part related to a concentration of sharks and dolphins around trawlers (84). Indo-Pacific bottlenose dolphins in Moreton Bay are found in groups that average six members but may number up to 35 (83), and in mixed groups with Australian humpback dolphins (see below).

There is a long history of associations between bottlenose dolphins and people in Moreton Bay, from the early cooperative hunting that occurred between Indigenous fishers and dolphins (85), to tourists handfeeding dolphins over the past 25 years (86). The impact of this feeding regime on the movements, foraging patterns and reproductive success of these dolphins is not fully understood (87), but it is hoped that the positive up-close experience with wild dolphins encourages conservationist attitudes (86).

Australian humpback dolphins

The most southerly resident population of the Australian humpback dolphin (*Sousa sahulensis*) occurs in Moreton Bay. Owing to small, discrete populations, this tropical to subtropical inshore species is listed as 'Vulnerable' in Queensland under the Nature Conservation Act 1992 (Qld). In spite of the southerly location, the population size and density of Australian humpback dolphins in Moreton Bay is within the range of other east-coast populations (88–90). The earliest study using photo identification reported two population estimates for the Bay for overlapping time periods, with estimates of 163 (95% CI: 108–251, 1984–86) and 119 humpback dolphins (95% CI: 81–166, 1985–87) (91, 92). A subsequent study reported as few as 100 dolphins in the mid-1990s, but did not provide information on how this estimate was derived (93). From surveys conducted in 2014 to 2016, the population was estimated at between 128 and 139 adult-sized dolphins (95% CI: 67–274) (J Meager & E Hawkins, unpubl. data).

A recent genetic study along the east coast of Queensland indicated that the Moreton Bay group of humpback dolphins is a putative local population with limited gene flow to the nearest population in the Great Sandy Strait, 150 km north (94). However, occasional sightings and strandings along the intervening ocean-exposed coast suggest that some demographic exchange may be occurring (95). Movements of up to 130 km have been recorded further north along the Capricorn Curtis Coast in central Queensland (96).

Australian humpback dolphins have a more restricted inshore distribution than bottlenose dolphins. In Moreton Bay, the core habitat for humpback dolphins extends from the lower reaches of the Brisbane River to Mud Island and north to the Western Banks off Scarborough. Peripheral core habitats for the species include the waters close to the southern shores of Bribie Island and the Amity Channel near North Stradbroke Island (97). A shift in habitat use away from the landward margins of Deception and Bramble Bays since the 1990s has been attributed to a decline in habitat quality that has been exacerbated by periodic floods (97).

Social structure may also play a role in shaping habitat use by Australian humpback dolphins in the Bay. A recent study suggests five distinct social communities of humpback dolphins in the Bay (E Hawkins, unpubl. data). Two of these communities have comparatively little spatial overlap with the others - one occurring mainly in northern Moreton Bay near Bribie Island and the other near Amity at North Stradbroke Island. As explained above, humpback dolphins in the Bay are often found in mixed groups with Indo-Pacific bottlenose dolphins (91, 95). Little is known of interactions between the species, but bottlenose dolphins appear to be dominant in terms of competition for food (98), and are more numerous (99, 100).

Australian humpback dolphins tend to occur in smaller groups than bottlenose dolphins, with typical group sizes around 3 - 4, although groups of up to 31 have been reported (101). Group sizes tend to be the largest when these dolphins are socialising and smallest when they are travelling. They are mostly generalist piscivores, taking various demersal and pelagic prey, but they also feed opportunistically on trawler bycatch in the Bay (91).

Tiger, bull and white sharks are likely predators of humpback dolphins in Moreton Bay, with evidence of shark attacks in 36% (18 of 50) dolphins examined in a study in the 1980s (91). Anthropogenic threats to humpback dolphins in the Bay are similar to those described elsewhere (102, 103) and include vessel traffic, entanglement in fishing gear/debris, noise, unpermitted provisioning, prey depletion, incidental catch in the shark control program, introduced pathogens, and pollution (95, 104). A comparison of tissue contaminant concentrations in humpback dolphins, stranded/by-caught in the Moreton Bay region, with toxicological thresholds for other marine mammals found that some contaminant groups (polychlorinated biphenyls (PCBs) and the dichlorodiphenyls DDXs) were above or close to the levels where a range of physiological adverse effects can occur (105). There are no known contemporary sources of these chemicals in the Bay, suggesting that the dolphins had been exposed to pollutants that have remained in the environment from past use in industry and agriculture. However, the levels of contaminants reported underscore the need to monitor the health of this important population of humpback dolphins.

Other marine mammals

Although not as commonly seen as humpback whales, dwarf minke whales (*Balaenoptera acutorostrata*) are often seen off North Stradbroke and Moreton Islands and are occasionally seen in the Bay (1), probably during their (as yet poorly defined) migrations. Other occasional visitors to the region include killer whales (*Orca orcinus*), Eden's whales (*Balaenoptera edeni*), sperm whales (*Physeter macrocephalus*), pygmy sperm whales (*Kogia breviceps*), blue whales (*B. musculus*) and Blainville's beaked whales (*Mesoplodon densirostris*) (1). These animals have been sighted primarily offshore and rarely in the Bay. Short-beaked common dolphins (*Delphinus delphis*) are abundant offshore from Moreton Bay and occasionally strand on the eastern oceanic shores of Moreton and Stradbroke Islands, but have not been recorded inside the Bay. Other cetacean species that have stranded on the ocean-exposed coastline of the border islands include the short-finned pilot whale (*Globicephala macrorhynchus*), Risso's dolphin (*Grampus griseus*), Fraser's dolphin (*Lagenodelphis hosei*), false-killer whale (*Pseudorca crassidens*) and Pantropical spinner dolphin (*Stenella longirostris*). In contrast, a mass stranding of 53 melon-headed whales (*Peponocephala electra*) occurred on the sheltered south-west shores of Moreton Island in 1976 (106).

Small numbers of long-nosed fur seals (*Arctocephalus forsteri*) are sighted annually in the Bay from June to September; Subantarctic fur seals (*Arctocephalus tropicalis*) are also occasionally recorded (Department of Environment and Science, unpubl. data). For about a month in winter 2018, a long-nosed fur seal became a regular sight around the southern shores of Bribie Island, earning the moniker of 'Neil the Seal' before disappearing, presumably to travel south again.

Threats to Moreton Bay marine mammals

Unquestionably, the greatest anthropogenic threat to marine mammals in Moreton Bay is habitat loss, which includes loss of food sources (prey or seagrass depletion) and degradation of habitat from reduced water quality that may result from chemical pollution and pathogenic contamination, including from terrestrial sources. Entanglements of dolphins in fishing lines and hooks have also increased in recent years (107), which could be reduced by simple measures such as using corrodible hooks, avoiding fishing near dolphins and not discarding gear into the Bay waters. Although most of the core habitat for dugongs now occurs within designated Go-slow areas within Moreton Bay Marine Park, other marine mammals and dugongs whose home ranges extend far beyond the restricted speed areas are still vulnerable to vessel strikes.

If we want to conserve our Moreton Bay megafauna in a healthy state for the next 20 years, it is time to act now. Limiting boating speed and stepping up patrols of the marine park are small but important steps. We must also consider the quality of water that runs into Moreton Bay, the extent and impact of this outflow and its effects on marine mammal habitat. Significant improvements have been made to water quality through upgrades to wastewater treatment plants, and water quality is monitored collaboratively by the Department of the Environment and Science, and Healthy Land and Water (108). Yet there is still work to do, especially towards revegetating coastal waterways and improving stormwater run-off to reduce sediment discharge into the Bay, and to effectively contain our chemicals and terrestrial debris.

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Migratory shorebirds of Moreton Bay

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[†]David tragically passed away during the preparation of this manuscript, and we dedicate it to his memory.

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Abstract
Tens of thousands of migratory shorebirds return to Moreton Bay each year from their breeding grounds in the Arctic. The Bay's extensive tidal flats provide a rich feeding resource for the birds while they recuperate from their long migration flight and prepare for their next one. The abundance of many migratory shorebird species has declined dramatically in Moreton Bay, and while some of the causes are located elsewhere along the birds' migration routes, there are significant threats to the birds and their habitats within the Bay, ranging from habitat loss to disturbance. New partnerships between conservation management agencies and NGOs have led to exciting examples of conservation action to reduce some of these threats, including collecting high quality monitoring data, careful zoning of recreational and commercial uses to avoid important areas for shorebirds, and extensive awareness-raising activities. Migratory shorebird conservation will become more and more critical as the human population using the Bay continues to increase over the coming decades.

Keywords: birds, population declines, monitoring, zoning, marine park

Introduction
Migratory shorebirds undertake some of the longest regular migrations of any animal group, with many species breeding in the high Arctic tundra and migrating all the way to the Southern Hemisphere to spend the non-breeding season, often stopping along the way to refuel in the vast tidal flats of East Asia (Fig. 1). Small tags fitted to the birds have revealed the magnitude

of the journeys they undertake, and the bar-tailed godwit, *Limosa lapponica*, is one of the best studied species (1–3). The subspecies *baueri* flies from eastern Australia north to the eastern coast of the Yellow Sea to refuel (2, 3), then on to Alaska to breed. Following breeding, it flies non-stop across the Pacific Ocean in a flight of almost 12,000 km to its non-breeding grounds in eastern Australia and New Zealand (4).

Figure 1. The East Asian–Australasian Flyway. An asterisk shows the position of Moreton Bay in this flyway, a critical non-breeding destination for many migratory shorebird species.

What does all this mean for Moreton Bay? Moreton Bay is the crucial end point of the journey of the bar-tailed godwit and a number of other species. Moreton Bay has supported up to 33,900 migratory shorebirds annually in the period since 2011 (Table 1). It is one of the most numerically important non-breeding sites for shorebirds in Australia, and supports internationally significant numbers (>1% of the total flyway population) of at least nine migratory shorebird species (Table 1) (5, 6). In 1993, the Bay was declared both an internationally important wetland under the Ramsar Convention on Wetlands and a marine park, partly on the basis of the bird populations. A zoning plan providing for the ecologically sustainable use of the park was produced in 1997 (7).

Ecologically sustainable use is of course critical for the long-term health of migratory shorebird populations in Moreton Bay, where birds are continually affected by habitat loss and disturbance (8, 9). Coastal ecosystems in Moreton Bay are critical for providing food and shelter for the shorebirds to recover from their long migration, conduct a feather moult, and gain condition again before the next long migration back to the breeding grounds. Such migrations may seem extreme, but the birds are uniquely adapted to undertake these journeys (10), which allow them to exploit a summer flush of resources in the Arctic, and spend the non-breeding season feeding on the rich benthic infauna of sediments in estuaries such as Moreton Bay. Yet many migratory shorebird species are in rapid decline in the East Asian–Australasian Flyway (11–13). In Moreton Bay, at least six species of migratory shorebird were identified as in rapid decline in an analysis of monitoring data collected by the Queensland Wader Study Group (QWSG) between 1992 and 2008 (red knot, bar-tailed godwit, ruddy turnstone, common greenshank, great knot and whimbrel), and a further two were possibly in decline (greater sand plover, far eastern curlew) (14).

The declines are thought to be mostly driven by habitat loss in the East-Asian stopover areas where, for example, more than two-thirds of intertidal habitat has been lost in the Yellow Sea in the past 50 years, primarily as a result of land reclamation for infrastructure development (15). Indeed, recent studies have shown that the Australian species declining most quickly are those that are highly dependent on the Yellow Sea while on migration (13), and that survival rates are declining for migratory shorebirds that depend on the Yellow Sea (16). Yet migratory species depend on a complete chain of intact habitats along their migration routes (17), and habitat degradation anywhere along the chain can impact the birds (18). Thus, the proper management of important sites such as Moreton Bay is crucial in the context of the birds' lengthy migration journeys.

Table 1. Species and highest count of migratory shorebirds estimated in Moreton Bay regularly since 2008 (61). Data are extracted from the Queensland Wader Study Group monitoring database. Note that all migratory shorebirds are listed as migratory/marine under the *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act) — the conservation listings shown here relate to listings as threatened species only.

Species	Count	Internationally significant numbers	Conservation listing (EPBC Act)
Asian dowitcher	< 20		Not listed
Bar-tailed godwit	11,650	Yes	Vulnerable
Black-tailed godwit	694		Not listed
Broad-billed sandpiper	131		Not listed
Common greenshank	187		Not listed
Common sandpiper	< 20		Not listed
Curlew sandpiper	2,126	Yes	Critically Endangered
Double-banded plover	307		Not listed
Far eastern curlew	3,158	Yes	Critically Endangered
Great knot	1,433		Critically Endangered
Greater sand plover	187		Vulnerable
Grey plover	57		Not listed
Grey-tailed tattler	2,430	Yes	Not listed
Latham's snipe	< 20		Not listed
Lesser sand plover	1,949	Yes	Endangered
Marsh sandpiper	125		Not listed
Pacific golden plover	739	Yes	Not listed
Red knot	1,044		Endangered
Red-necked stint	4,919	Yes	Not listed
Ruddy turnstone	160		Not listed
Sanderling	6		Not listed
Sharp-tailed sandpiper	1,550		Not listed
Terek sandpiper	195		Not listed
Wandering tattler	< 20		Not listed
Whimbrel	1,140	Yes	Not listed

Status and ecology of migratory shorebirds in Moreton Bay

About 23 species of migratory shorebird regularly occur in Moreton Bay, with another five migratory species recorded irregularly along with another 13 locally breeding, non-migratory species of shorebird. The most abundant migratory shorebird is the bar-tailed godwit, followed

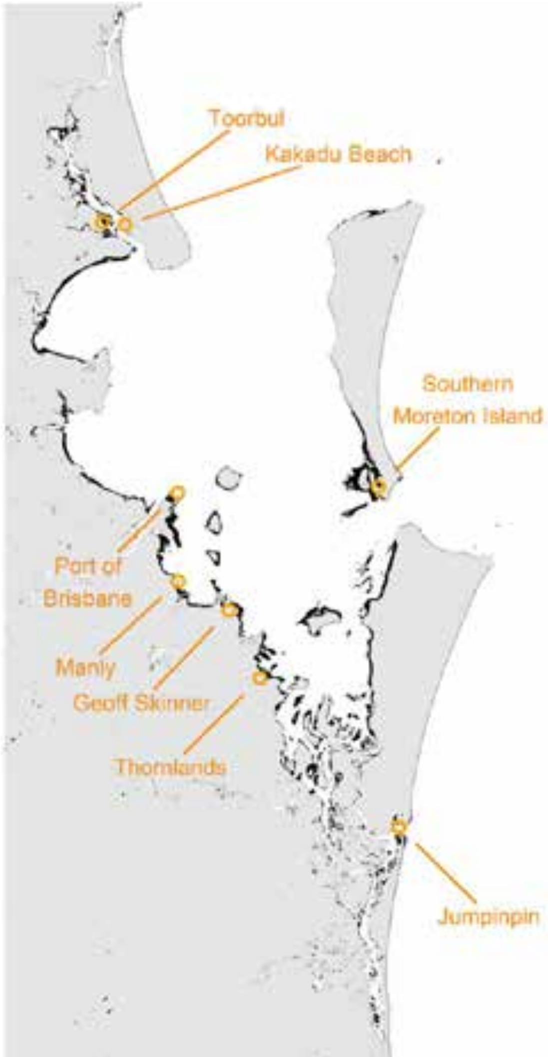

Figure 2. Moreton Bay, showing the major migratory shorebird roosting sites, noting that there are dozens of other roosts throughout the Bay, with important numbers of birds. Tidal flats (from (60) are shown in black.

by the red-necked stint. Moreton Bay also supports all the threatened species of migratory shorebird listed under the federal *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act) (Table 1). It has one of the largest populations of the 'Critically Endangered' far eastern curlew in Australia, and is now one of the last major strongholds in the world for this rapidly declining species. Non-breeding shorebirds typically feed on invertebrates that live in or on intertidal habitats, mostly within soft sand and mud in Moreton Bay (19, 20). As the tide comes in and covers feeding habitats, birds move to high-tide roost areas, where they often gather together in large numbers to rest, preen and sleep, and supplement their feeding if the opportunity arises. High-tide roosts are often in claypans, rocky headlands, mangroves, or a range of artificial sites where they can roost away from disturbance and where they have good visibility of the surrounding area to scan for approaching predators (21, 22). This dependence on two markedly different kinds of habitat every day is a crucial factor for understanding the ecology and conservation management needs of shorebirds. To occupy an area, shorebirds need access to high-quality feeding sites, but also nearby suitable roosting sites (21, 23). Energy reserves can be conserved by minimising the flight distance between roosting and feeding areas. For far eastern curlew in Moreton Bay, the typical distance travelled between roosts and feeding grounds is 5 to 10 km (23). As the mainland coast of Moreton Bay has become increasingly developed, there are now few places where significant numbers of birds can gather to roost free of disturbance, and disturbance of roosting birds is a significant management challenge (Fig. 2) (24).

Migratory shorebird monitoring in Moreton Bay

Migratory shorebirds in Moreton Bay have been systematically counted by volunteers at up to 180 coastal sites from 1992 onward (25, Box 1). Monthly counts are conducted around high tide (80% of visits made within 2 hours of the time of high tide), when birds are concentrated at roost sites (22). The number of sites visited per year increased between 1992 and 1995 and has remained relatively stable thereafter. The spatial extent of survey effort was also greater in summer months (January–March) when non-breeding migrants are most abundant.

Box 1. Queensland Wader Study Group shorebird monitoring

The Queensland Wader Study Group, a special-interest group of Birds Queensland, was established in 1992 to monitor and conserve shorebird populations. Run entirely by volunteers (like most shorebird monitoring in Australia), close interaction between organisers and surveyors has been key to the accuracy, precision, coverage and longevity of shorebird monitoring in Queensland. Unlike any other regional shorebird- monitoring effort around the nation, one notable feature of monitoring in parts of Queensland is monthly counting, which reduces within-year count variability and increases statistical power to detect trends compared with less frequent monitoring elsewhere.

Habitats for migratory shorebirds in Moreton Bay

(i) Intertidal soft sediment and hard substrates

Moreton Bay contains a complex system of intertidal flats totalling some 23,000 ha at low tide (26), providing a range of feeding habitats for shorebirds. Substrate types within the Bay are diverse and have been broadly categorised into sand, coral, sandy-mud and mud (27). Sand is more prevalent in the eastern side of the Bay and tends to be more penetrable than mud or sandy-mud. This is because the latter frequently contains higher proportions of resistant material such as rocks, coral or shells just below the surface (19). Therefore, there is a need to look below the substrate surface to assess the suitability of feeding habitat for deep-probing shorebirds. Substrate penetrability has been shown to be a good predictor of far eastern curlew feeding density at the broad scale within Moreton Bay, with lower densities of far eastern curlew in areas where the substrate has a low penetrability (19). This is hardly surprising when one considers that the bird can rapidly thrust its whole head into the substrate, reaching a depth of over 20 cm, to capture large, deep-burrowing crustaceans. Pressure-sensitive receptors in the bill of some probing shorebirds allow them to detect solid objects embedded in the wet substrate (28), but inanimate objects buried within the substrate could also interfere with prey detection and capture, and even damage the birds' bills. Several shorebird species have been shown to switch between tactile hunting on soft substrates and visual hunting on hard substrates (e.g. 29, 30). In terms of assessing and monitoring the quality of feeding grounds for deep-probing shorebirds, a simple measure of substrate penetrability would be the most efficient method, and it could be used to map their probability of use across landscapes.

(ii) Supra-tidal, mangroves, saltmarshes, artificial habitats as roosting and supplementary feeding sites

A subset of the shorebird species that spend their non-breeding season in Moreton Bay has a strong affinity with mangroves for roosting and sometimes feeding. There are three main species that associate regularly with mangroves for roosting. These are grey-tailed tattler, Terek sandpiper and whimbrel. Whimbrel also feed close to and among mangroves in many parts of Moreton Bay, such as Pumicestone Passage and the southern Bay islands.

The main artificial habitats in Moreton Bay used by shorebirds are in the Port of Brisbane reclamation area at the mouth of the Brisbane River. Bunded ponds in various stages of partial reclamation provide extensive roosting habitat adjacent to the rich intertidal feeding grounds at the mouth of the river. These reclamation ponds also provide non-tidal feeding habitat for the smaller migratory shorebirds such as curlew sandpiper and red-necked stint. During the early stages of reclamation, sediment from dredging of the main shipping channel is pumped into the ponds. These sediments contain small invertebrates, including bivalves and crustaceans, that are prey of small shorebirds. The provision of these additional feeding opportunities has led to an increase in the overall Moreton Bay population of red-necked stint and their concentration within the Port of Brisbane reclamation area. It is unclear how these shorebirds will respond when the reclamation is complete and the additional artificial feeding habitat is lost.

Threats to migratory shorebirds in Moreton Bay

There are numerous threats to migratory shorebird populations in Moreton Bay, and more generally in the flyway, including climate change, which may affect wetland breeding habitat in the Arctic (31); loss of stopover sites in mainland Asia (15, 32, 33), and reduction in the area and quality of non-breeding grounds, primarily in Australia (34).

In Moreton Bay, far eastern curlews require deep, soft sediment to be able to use their extremely long bill to its full potential and achieve their greatest foraging success (20). Any structural modification of soft-sediment feeding flats that reduces substrate penetrability may inhibit successful foraging and be detrimental to deep-probing shorebirds (20). Direct and indirect effects on the structure of soft sediments could come from activities including intertidal oyster farming, bait harvesting, the compaction of sediments by vehicles, beach nourishment, nutrient enrichment and the dumping of rubbish or debris (35).

Additional threats include loss of habitat through development, changes in benthic food availability, changes in mangrove and seagrass distribution, and human disturbance.

Management of migratory shorebirds in Moreton Bay

The commitment of Australian governments to protect shorebirds in Australia is reflected in federal and state legislation such as the EPBC Act 1999, *Nature Conservation Act 1992* and *Marine Parks Act 2004*. Such legislation provides for the listing of shorebird species, declaration of marine and terrestrial protected areas, development of recovery plans, and assessment of actions that may impact shorebirds or their habitat.

Development and land-use planning in the coastal zone managed under the *Coastal Protection and Management Act 1995* and state planning policies provide protection and management of coastal resources and link to matters of state interest such as marine park highly protected areas, ecologically significant wetlands and wildlife habitat. Numerous other pieces of legislation exist to protect marine resources and habitat to the benefit of shorebirds such as the *Environmental Protection Act 1994* and *Fisheries Act 1994* and declared fish habitat areas.

The Moreton Bay Marine Park aims to conserve the unique values of Moreton Bay whilst allowing activities such as commercial and recreational use to occur. This balancing act is achieved through zoning that protects representative habitat types and regulates entry and use via the Marine Park (Moreton Bay) Zoning Plan 2008. Protecting sensitive habitats and species is a key consideration in administering the marine park and the zoning plan contains specific provisions intended to protect shorebirds and their habitat from unreasonable disturbance. Disturbance levels at shorebird roost sites in Moreton Bay are strongly related to marine park zones, with marine national park zones, the most highly protected zone, showing the lowest frequency of disturbance to shorebirds (36).

The Migratory Shorebird Conservation Action Plan and Shorebird Management Strategy of Moreton Bay provide guidance to cooperatively manage shorebirds. The Shorebird Management Strategy of Moreton Bay adopts a multifaceted approach to shorebird management, including protecting critical shorebird habitat, protecting shorebirds from disturbance and conducting research and monitoring. Practical mechanisms for achieving this include assessment and the placement of conditions on activities, compliance enforcement, education and awareness, regulation of access or activities, and cooperative management with local councils.

Active shorebird management in accordance with the above statutory and non-statutory tools depends on the responsibility and jurisdiction of relevant authorities. While there is a solid legislative basis on which to base and guide shorebird management, resources and funding allocation is a matter of competing priority within governments. Therefore, effective management is best achieved in collaboration with natural resource management bodies and non-profit organisations that are eligible to apply for grant funding.

Managing migratory shorebirds is challenging for three interlinked reasons:
(i) complex multi-uses of the landscape
Moreton Bay Marine Park is a multi-use marine reserve with areas designated as general use, habitat protection, conservation park and marine national park. Recreational and commercial access is allowed to most areas under the provision that shorebirds are not disturbed. Despite regulations against disturbance, the reality of allowing recreational activities on beaches means that birds are regularly in contact with kite surfers, horse riders, fishers, four-wheel-drive vehicles and dog walkers.

Human recreational use of natural areas can incur immediate behavioural costs to birds, including increased energy expenditure and loss of foraging time as a result of increased time spent being vigilant. In some cases, temporary or permanent avoidance of suitable habitat can occur, ultimately reflected in lower local abundance, poorer physiological condition or impaired reproductive success (8, 37). An analysis of QWSG data showed dogs, walkers and fishing to be the most frequent anthropogenic causes of disturbance to roosting shorebirds in Moreton Bay (36). Notwithstanding education, signage and enforcement of shorebird disturbance laws in the marine park, a high level of disturbance is still occurring at the majority of shorebird sites in the Moreton Bay Marine Park (Fig. 3).

Dog walking in particular can have a large impact on shorebirds, as many dogs are not kept on leashes on the beach (38). Furthermore, dogs actively and repeatedly chase shorebirds, forcing birds to either repeatedly take flight, to increase their vigilance, or even to leave an area. Disturbance by dogs is also a major issue in the terrestrial environment, and substantial reductions in woodland bird abundance have been documented as a result of dog disturbance, suggesting a need to restrict access by dogs in sensitive conservation areas (39).

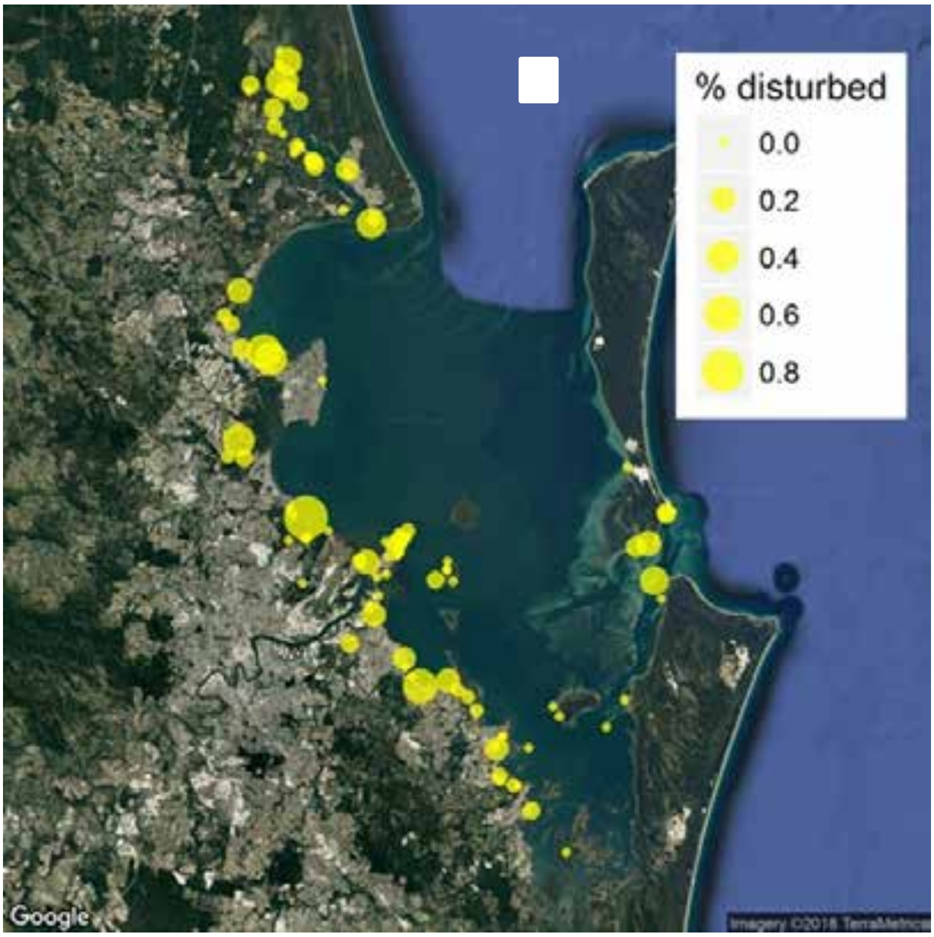

Figure 3. Shorebird disturbance in Moreton Bay, as measured by the proportion of counts in which disturbance to shorebirds was noted. Larger circles indicate more frequently reported disturbance events. (Data: Queensland Wader Study Group).

Dogs must be kept under close control across the intertidal areas of Moreton Bay, yet the reality of living in a city means that beaches are one of the few places where dog owners can let their dogs run freely. Though common, disturbance by dogs is also one of the most easily manageable threats to shorebirds in Moreton Bay. There are two primary methods for managing disturbances to shorebirds: one is to manage public access to important shorebird areas; the other is to allow access to beaches while managing activities. The reality of restricting access to beaches in populated areas, however, means that large nature reserves such as Moreton Bay are difficult to enforce, particularly when management boundaries differ at the council, state and national levels, as is the case for intertidal habitats. Furthermore, restricting access creates conflict in highly populated areas.

In fact research shows that increasing access for people walking their dogs off-leash, and ensuring a smaller more restricted area important for shorebirds is better enforced (8, 24), can produce a win–win situation whereby important shorebird habitat is protected, and dog walkers have the area needed to exercise their dogs.

(ii) energetic consequences of disturbance
Long-distance migrations are energetically demanding, and shorebirds have developed a range of physiological adaptations enabling them to achieve such journeys. Prior to migration, shorebirds are able to increase their energy stores over very short periods through rapid weight gain of 50 to 80% of their body mass (40). To allow for this weight gain and for an increase in the size of flight muscles, birds must compensate through drastic shrinkage of certain organs (41, 42). During flight, energy consumption can remain relatively low and energy is burned straight from organs if needed (42). Refuelling prior, during and after migration is therefore essential in ensuring survival of the species. Repeated disturbance to shorebirds can prevent individuals from gaining the necessary weight to complete migration.

Shorebirds feed in the intertidal zone and roost during high tide, when large numbers concentrate into a small area. Disturbance during feeding can interrupt foraging, and disturbance during roosting can cause birds to take flight, wasting energy reserves. Indeed, shorebirds are highly responsive to anthropogenic stimuli and thus are readily disturbed (38). In the short-term, disturbance can result in increased levels of stress and behavioural changes (43). In the long-term, disturbance can result in chronic avoidance of disturbed habitat and abandonment of otherwise suitable habitat as individuals move to less-disturbed areas (44), increasing density and therefore competition between individuals at undisturbed sites (45).

Shorebirds can better conserve their energy at sites where there is little disturbance (46). The worst case is when birds are forced to stop feeding altogether or have to leave for a lower quality feeding area. Faster human movements (i.e. running as opposed to walking, jetskiing as opposed to canoeing) cause greater disturbance to shorebirds (47, 48). It is possible for shorebirds to adapt to human disturbance, by either extending their feeding period or by becoming habituated to the disturbance (49). It has been suggested that larger shorebirds may be less tolerant of human disturbance than smaller shorebirds (50, 51).

(iii) both local and remote drivers of change could be impacting the health of shorebird populations in Moreton Bay
Because many shorebird species are migratory, the number of birds we see in Moreton Bay can be influenced not only by conditions in Moreton Bay, but also by conditions hundreds, if not thousands, of kilometres away. Moreton Bay like much of Australia suffers from extreme rainfall and drought events, both of which can negatively impact shorebirds. The first by changing sediment structure and therefore food availability (52, 53), the latter by reducing inland habitat availability, thus forcing large numbers of birds to concentrate into a small

number of coastal roosting sites and increasing their susceptibility to disturbance events. Repeated disturbances force birds to repeatedly take flight with nowhere else to go.

Though these impacts can be small in isolation, they can have a cumulative effect on birds by preventing them from gaining the necessary weight to start migration in an optimal body condition. As a result, migratory fitness can be reduced, and likewise migratory endurance and speed, meaning some birds will not be able to fly the required distances to reach their stopover sites spread across East Asia. Stopover sites are few and far between, making each individual site important for replenishing depleted fat reserves.

Within the East Asian–Australasian Flyway, the most strategically situated and nutritious stopover sites are located in the Yellow Sea. Most shorebirds funnel through this region on their way to the breeding grounds, creating a large migratory bottleneck (18). However, the Yellow Sea is one of the most populated regions in the world, and hunting, pollution, habitat loss and disturbance there are potentially impacting on the number of birds able to return to Australia each year (54). Loss of even small habitat patches in this location can result in disproportionately large contributions to shorebird declines (55).

Poor resting and refueling conditions in stopover sites mean birds continue their journey in poor physiological condition, and may not reach the breeding grounds in good enough condition to establish a good quality breeding territory. Shorebirds are primarily income breeders, meaning they gain some resources for breeding while in the breeding grounds (56). Conditions upon arrival are therefore important in determining the number of eggs and clutches produced, as well as chick survival. The Arctic is however one of the habitats most sensitive to climate change. Not only is the amount of available habitat predicted to decrease for shorebirds (57), but so is the timing of arctic green-up and peak abundance of arthropod prey, on which shorebirds depend while breeding. Indeed, warmer summers are predicted to cause an increase in mosquito growth rate, resulting in a shorter period where mosquitoes are available as a food source for shorebirds. A shorter season also means birds grow less and there is already evidence of red knots developing shorter bills (58). Once back in their tropical intertidal habitats, these birds with shorter bills have difficulties accessing their usual prey items buried in the mudflats, and suffer higher rates of mortality as a result.

Emerging issues

With the human population in the Greater Brisbane projected to grow rapidly in the coming decade (59), pressure on the natural environment of Moreton Bay looks set to intensify both in terms of recreational and commercial use, and major development projects. From the perspective of migratory shorebirds, we urge careful thought about the following five issues:

(i) Continued generation of high-quality monitoring data, ideally through monthly shorebird monitoring at the major sites throughout Moreton Bay, with comprehensive bay-wide counts at least quarterly.

(ii) Integration of shorebird monitoring data into all relevant planning and decision-making tools within local and state government, together with continued updating of information.

(iii) Use of decision-support tools to plan and enforce recreational zoning across Moreton Bay, ideally as a partnership between state government and all local government areas adjacent to Moreton Bay.

(iv) Provision of data and availability of expertise to assist interpretation, supporting investigations of the impacts of proposed development projects.

(v) Periodic expert analysis of shorebird monitoring data to assess any impacts of Moreton Bay's changing environment on bird numbers, and to identify success or failure of conservation efforts.

Moreton Bay is a critically important site for migratory shorebirds in the East Asian–Australasian Flyway. Enormous efforts have been made, and are being made, to protect its ecological integrity in the face of strong demand for recreational and commercial use. Continued proper management and protection of key habitats are paramount for its long-term future as a non-breeding destination for migratory shorebirds.

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Chapter 6 - Citizen Science

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Jenn and Chris successfully nominated the Moreton Bay Marine Park as Mission Blue Hope Spot in 2016, with special recognition for the citizen science efforts in the region.
See https://mission-blue.org/2016/12/citizen-science-supports-protection-in-the-moreton-bay-hope-spot/

How does citizen science contribute to sustaining Moreton Bay? A discussion of approaches and applications.

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Abstract
Citizen science in Moreton Bay *Quandamooka* has a long history of engaging the community in collecting, sharing and applying scientific information. A range of coastal and marine citizen science activities takes place within and around the Moreton Bay Marine Park, complementing research from government and academic organisations. Numerous benefits of citizen science are acknowledged, including environmental, educational, social, collaborative, policy and capacity building outcomes. Yet, the sector continues to face shared challenges in dealing with the uptake and application of data, supporting volunteer engagement, and achieving continuity through secure consistent resourcing. As the citizen science sector continues to grow in scope and scale, it prompts discussion regarding how programs can be developed to further enhance their contributions to sustaining the Bay. This chapter presents an overview of coastal and marine citizen science relevant to the Moreton Bay region and presents recommendations for fostering citizen science that contributes to sustaining the Bay.

Keywords: volunteers, monitoring, data, capacity building.

The context of citizen science in Moreton Bay
Across Moreton Bay's catchments, coasts and marine habitats, community members are variously involved in environmental research through citizen science projects. Citizen science has been broadly defined by the Australian Citizen Science Association as 'public participation and collaboration in scientific research with the aim to increase scientific knowledge'. Citizen participation in science has been longstanding in the natural history sector (1) and the methods of engagement and outcomes continue to evolve.

The diversity of citizen science activity is evident from the wide range of habitats from which volunteers collect information across the Moreton Bay region; these encompass catchments, coasts and the marine environment. The papers in this citizen science chapter focus on citizen science projects that are directly relevant to the marine environment in Moreton Bay and are conducted in the marine and coastal zones (Fig. 1). Participants, including scuba divers, snorkellers, subtidal walkers and boaters, can collect data in the marine environment. Numerous coastal projects intend to improve understanding of environmental assets such as waterbird populations, the presence or range of threatened species and trends in marine debris.

Citizen science initiatives in Moreton Bay include a range of program types, most typically *contributory* or *collaborative* models of engagement (2). The *contributory* model involves the public in data collection, and is one of the most common forms of participation (3). Universities, government agencies, schools, not-for-profits and community members develop initiatives that support community participation in various research activities. The type of engagement in data collection varies dramatically across programs. Program participation may be quite short, such as casual photographic sightings (e.g. Project Manta), or self-guided data collection methods for simple assessments (e.g. CoralWatch). A more intermediate engagement type may require short practical training sessions with in-field facilitation (e.g. SeagrassWatch and Mangrove Watch). Other programs encompass extensive training courses with various time frames. For example, volunteers may undertake a multi-day training course to prepare for intensive data collection over short projects (e.g. UniDive Point Lookout Ecological Assessment (PLEA) project) or for ongoing engagement in annual monitoring (e.g. Reef Check Australia).

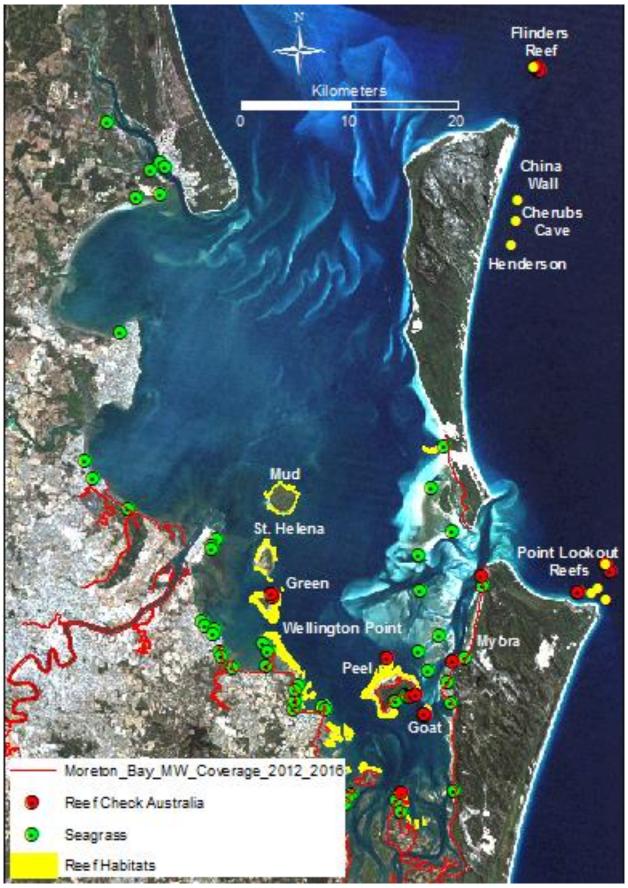

Figure 1. Locations of several long-term marine citizen science monitoring programs in Moreton Bay Marine Park, including Seagrass Watch, CoralWatch and Reef Check Australia.

Citizen science goes beyond data collection. Volunteers can also be involved in *collaborative* project models and perform tasks such as analysing data (e.g. the production of the UniDive PLEA technical report) and sharing project findings with their local communities (e.g. the Reef Check Australia Reef Ambassadors community outreach initiative). Importantly, by integrating a better understanding of the environment with community engagement, citizen science programs can improve local knowledge and stewardship for the ecosystems or species being monitored (3). For example, data contributed by the Queensland Wader Study Group has shown a dramatic population decline in several shorebird species visiting Moreton Bay (4). Community involvement has resulted in several grassroots campaigns that address wader management in Moreton Bay (e.g. Save the Sandgate Waders).

Citizen science can be 'top down' to help augment or fill gaps in data or complement formal research and monitoring programs. It can also be driven by communities, or 'bottom up', to collect data relevant to their concerns (5–7). The number of citizen science projects is on the rise (8, 9), likely driven by factors such as community interest and concern for environmental issues (10, 11), new technology (12) and limited formal research budgets (13). The increasing trend in documented citizen science initiatives (9) offers growing opportunities for the range of stakeholders with an interest in citizen science, ranging from schools to government officials. In Australia, a national survey of 1145 marine users demonstrated that there is a high level of public interest in assisting marine research (11). Engaging marine user groups depends on many factors (such as the organisation behind the research, providing feedback, and aligning with volunteers' interests), but the study showed that some members of the public are willing to contribute many hours to marine citizen science. For example, over half of respondents were willing to volunteer at least seven days a year.

Benefits of citizen science

Marine citizen science can provide a multitude of benefits beyond the scientific data (14). For coastal and marine environments in Australia in particular, citizen science has contributed to environmental knowledge and health, public education, social outcomes, stakeholder collaboration, conservation management, and the careers of scientists and volunteers.

Environmental knowledge

Engaging volunteers in citizen science projects can help to identify and fill gaps in available scientific data and knowledge. Local volunteers may provide additional detail, local and/or historical data, and knowledge for projects. Volunteers in citizen science programs can be highly skilled with some possessing expertise relevant to the species or system they choose to monitor. Participation from a wide range of people can help to cover temporal or geographic scales that would otherwise not be possible.

For example, community-based ambient water quality monitoring has occurred in South East Queensland since 2005. Many volunteers in community-based water quality monitoring get involved due to their previous extensive professional experience in the same field, their subsequent interest in waterway health and resulting capacity to provide input to the program (pers. comm. Apanie Wood). Since its inception, the program has monitored ambient water quality at more than 500 sites across the region. It provides long-term, comprehensive water quality data otherwise unavailable at this scale. It further provides a platform for highly skilled volunteers to enhance the program by collecting high-quality data. This affords technical interpretation for their communities and contributes valuable local-scale understanding and interpretation of data outputs.

Further regional examples of citizen science contributing to data gaps includes annual reef health monitoring data from Reef Check Australia on more than 20 reef sites across South East Queensland. Many of these sites do not have other regular monitoring programs. In another example, Redlands City Council identified the need for data on raptor nests to manage disturbance to the nesting birds. To fill this gap, Redlands City Council partnered with local community groups and residents to build a comprehensive map of the coastal raptor nests within the Redlands mainland and islands using the 'Atlas of Living Australia Citizen Science Portal' (https://www.ala.org.au/citizen-science-central/).

Citizen science data can also increase the temporal and spatial scale of a project (5, 15) as the following examples demonstrate. The Australian Marine Debris Initiative program coordinated through Tangaroa Blue Foundation has helped to document marine debris hotspots and litter sources. The program targets policy action by providing standardised clean-up and data-collection protocols along with a centralised online database. In the case of the Redmap project, the public reports observational data on possible range extensions of marine species at a national level. eBird, the online bird checklist, provides a platform for citizen scientist birders to collate huge volumes of data with the goal of better understanding species distributions and population size. These programs also open-up opportunities for analysing large datasets through online platforms, greatly enhancing the processing speed for projects such as image analysis.

Educational benefits
Citizen science can deliver unique educational benefits for those actively participating, as well as the wider community. Citizen science volunteers have the opportunity to participate in authentic science activities (16). This can build knowledge and skills (3, 17), enhance awareness and ecological literacy (16, 18, 19), boost place-based connections (20) and foster environmental stewardship behaviours such as reducing plastic use (21, 22). However, the educational and behavioural outcomes from citizen science participation remain an understudied area in the field, and there is still much to be learned about how projects can lead to increased knowledge and behaviour change (21, 23, 24).

Participants in citizen science projects can also help inform the community and improve awareness of the topic (25). For example, CoralWatch offers an extensive range of educational programs that explain the biological, ecological and social implications of coral bleaching to support program participants, including a Moreton Bay education pack.

Social benefits
Citizen science programs can strengthen social relationships within participant groups (26), and between participants and scientists (17, 27, 28). Creating and maintaining social relationships between participants and the project team is integral to volunteer recruitment and retention (29). Participation in community-based groups and programs, such as citizen science, has long been known to create social cohesion and capital by bringing people together to share ideas and collaborate to address environmental issues (30, 31). At the individual level, benefits can include outcomes such as learning something new, increasing self-efficacy (or competence), appreciating nature, and being outdoors (24, 32).

Collaborative benefits
In addition to social benefits for individuals and cost-effective solutions for some types of research, citizen science offers a platform to bring together diverse and sometimes disparate stakeholder groups. This has the potential to improve stakeholder communication (33) and

build trust across stakeholder groups (18, 33, 34). Collaboration between citizen science programs and Traditional Owners is particularly strong in the Bay region through collaborations with Quandamooka Yoolooburrabee Aboriginal Corporation and Quandamooka Land & Sea Management Agency. This has the potential to unite traditional knowledge with citizen science data collection and build capacity for land and sea management.

Participating in citizen science projects can help community members communicate about environmental issues in an objective language based on evidence, an outcome which is particularly important when managing environmental conflicts. For example, the Queensland Government uses WildNet to manage wildlife data collected from public and private sector sources. Data collected by the community submitted to WildNet is vetted and then made freely available from the Queensland Government, and the Atlas of Living Australia. With these data available, communities may better communicate their interests in preserving habitat for species of concern, which previously may have been unsupported by evidence.

In addition to benefitting from the time donated by volunteers, citizen science projects often partner with other stakeholders in the community such as businesses, government, and research and tourism bodies to leverage in-kind support for projects (24). This support, such as reduced fees for transport or services, data analysis or software contributions, expert advice, and/or donations of equipment can offer excellent value for investment. For example, citizen scientists partner with the Moreton Bay Environmental Education Centre to access chartered vessels for Moreton Bay MangroveWatch surveys. The education centre provides a large in-kind contribution to the program, and in return students at the centre can participate and learn from MangroveWatch citizen scientists. Citizen science and educational programs have also been highlighted as a potential marketing tool, offering benefits to local business (35).

Conservation management benefits

Informed advocates, data and products from citizen science projects provide tools for communities to drive evidence-based conservation management. Three modes of delivery have been proposed for the way in which citizen science may influence policy (14). First, citizen science can enhance data and community knowledge to support informed community advocacy on a specific issue. For instance, community seagrass monitoring contributed to datasets that supported implementing ecofriendly moorings in the Bay with Healthy Land and Water in order to reduce damage to seagrass beds. Second, through co-created/cooperative policy change, citizen science can help identify and address an informational need with managers or policymakers. For instance, inshore reef maps and habitat inventories created through a collaborative partnership with Reef Check Australia, the Remote Sensing Research Centre (University of Queensland) and Healthy Land and Water are used in the annual Healthy Land and Water report card. They are also expected to provide some key information used by the Department of Environment and Science for reviewing zoning plans, preparing management plans or standard operating procedures, assessing applications and preparing permit conditions for activities that require permission to occur in Moreton Bay Marine Park (pers. comm. Carley Kilpatrick). Third, citizen science is used as a pathway to monitor the effectiveness of state and federal government management regimes. For instance, Grey Nurse Shark Watch aims to determine whether the management initiatives enacted to date are effective and result in population recovery (12). Further, programs that build local understanding about ecological values and management may also help communities provide informed comment and influence legislative change, such as during the review of zoning plans for Moreton Bay Marine Park.

Citizen science is increasingly recognised as a cost-efficient approach to inform natural resource management and support adaptive management (36). It has also been shown to increase the speed at which environmental decisions are made in resource management (37). For example, data collected by citizen scientists as part of the annual Glossy Black-Cockatoo Birding Day has been used to map the biology and distribution of this threatened species in the South East Queensland bioregion. These records, along with high precision records from other databases, have been used to develop Essential Habitat maps for the South East Queensland bioregion (38). This mapping contributes to protection of Essential Habitat as Regulated Vegetation under the *Vegetation Management Act 1999*. Data collection and creating this essential habitat mapping would not have been possible within the short term without the input of data collected by citizen scientists.

Career benefits

Volunteers can gain new knowledge and experiences through educational, social and collaborative activities. Potential areas of skill development include developing program leadership, fundraising, networking, fieldwork planning, data collection and analysis, species identification, mapping, modelling, photo and video skills, public education, project presentations, mapping and modelling. For undergraduates, recent graduates and those investigating a career change, the experience gained is limited only by their availability and dedication. Many professionals also engage in citizen science as an avenue to make more meaning out of what they do day-to-day (e.g. IT/database, social media, dive instructors).

Challenges of citizen science

Along with the notable potential benefits of citizen science, there are challenges and barriers to developing, undertaking, maintaining, delivering and using data collected from citizen science programs. In addition, citizen science programs often need to identify priorities and strike a broad balance of objectives for research, education and policy outcomes (2). Identifying and maintaining this balance can be challenging, especially with diverse stakeholders.

Applying citizen science data

Whether or not data from citizen science projects is accepted and applied will be limited by how valid it is perceived to be (11, 39, 40), knowledge of its availability (41) and how accessible it is. Research indicates that stakeholders are using only a small percentage of citizen science-generated data for management decisions and research (42, 43). Many citizen science programs aim to address this through better quality assurance and control in their volunteer training and project planning, data collection methods and analysis, and program evaluation (44).

To increase the uptake and application of citizen science data for research or management applications, it has been suggested that end data users should be integrated in program development, and that projects should follow accepted data collection methods, use industry-standard quality assurance and control procedures, and follow existing data standards (20). In addition, global initiatives such as the PPSR CORE Metadata Standards (https://www.wilsoncenter.org/article/ppsr-core-metadata-standards) seek to improve citizen science data standardisation and interoperability. Citizen science associations encourage project leaders to adopt data and metadata standards to ensure data is more accessible to other stakeholders.

Volunteer engagement

There appear to be many volunteers interested in coastal and marine citizen science (11), but volunteer retention can be a significant challenge in the long term (45, 46). Volunteer management, support and communication are critical, but inconsistent funding or resources as well as small and fluctuating support teams can limit these. Giving feedback and regularly communicating with existing and new volunteers is essential (11). However, these activities are resource intensive and may not be given adequate priority.

The skill level required in citizen science can range considerably — taking a photo to upload (e.g. Redmap), identifying a species (e.g. Reef Life Surveys) or calibrating a technically complicated instrument (e.g. water quality monitoring). The training, support and supervision must be aligned with the skills required and needs ongoing evaluation and support for volunteers to ensure that high quality data are collected.

Practitioners often identify ownership, feedback, ongoing learning, and recognition as important factors for continued volunteer engagement (31, 47). Field activities are the most common form of citizen science engagement; however, most volunteers want to see demonstrable outcomes from the data collection.

Workplace health and safety is a significant consideration for projects using volunteers. The diversity of participants may require programs to adapt methodologies to ensure they are suitable (e.g. different data collection protocols depending on training level), or to have specific safety criteria depending on the risk factors (e.g. health and medical condition criteria for fieldwork). For example, scuba diving surveys are restricted to volunteers with the appropriate diving experience and only go to specified depths. The cost of liability insurance and/or volunteer management can be a barrier for smaller community groups wanting to engage citizen scientists.

Funding and resources

As programs often receive inconsistent funding, available resources and the current level of funding may limit program activities. This can make stated project objectives difficult to achieve and also presents the challenges of continually engaging volunteers and collecting consistent monitoring data across space and time. It is clearly disempowering for volunteers to have invested time and effort into learning and contributing to a long-term project, only to find that the program ends due to lack of funding or cannot support consistent engagement activities. Experiences such as these can reduce a volunteer's willingness to participate in future citizen science programs. To enable citizen scientists to collect high-quality data requires ongoing, long-term investment in training and capacity building of both volunteers and program managers.

Discussion

Citizen science for the future

Citizen science programs have provided and continue to provide valuable scientific, educational, social and policy contributions across Moreton Bay's natural land and seascapes. The past decade, in particular, has seen phenomenal growth in citizen science activities and this is helping to strengthen the connection between science and society. Further growth and interest in citizen science appears to be secure, following significant support and encouragement by governments in Australia and overseas (45, 48–50).

How can we strengthen programs to build opportunities for citizens to contribute to sustaining the Bay?

Citizen science can help to address environmental questions and challenges, but there is a need to amplify this capacity in order to strengthen strategic outcomes and positive impacts. Potential pathways to help achieve this for the Moreton Bay region include:

- Foster platforms and opportunities that constructively bring together citizen science, Traditional Owners, natural resource managers, government and other partners to share information, discuss priorities and collaborate;
- Construct an inventory of citizen science projects as relevant to natural resource management priorities, including for Report Card applications;
- Use case studies to build understanding of successful citizen science projects, bearing in mind that 'success' needs to be defined upfront as it will differ from project to project (51), and identify characteristics and situations that are shared across successful projects (8);
- Secure consistent investment for long-term programs that meet science or management needs to allow for long-term planning, which will in turn facilitate best-practice volunteer capacity building, community engagement and robust data collection; and
- Conduct research into potential and existing volunteer interests, barriers and drivers for participation (9) to strengthen volunteer recruitment and retention, and to better understand the benefits of citizen science programs in terms of education, social dynamics and conservation.

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Building an understanding of Moreton Bay Marine Park's reefs through citizen science

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Abstract
Moreton Bay Marine Park (MBMP) hosts a variety of subtropical reefs, including inshore reefs and offshore rocky reefs. These habitats provide refuges, nursery grounds and food sources for a diverse variety of flora and fauna. Monitoring of these reefs by local marine authorities is limited; hence, contributions from citizen science can help to fill spatial and temporal gaps. This paper will: provide an overview of known citizen science monitoring of reef in the MBMP; discuss the approaches used; and applications. In the MBMP, Reef Check Australia has conducted annual ecological monitoring at fixed sites since 2009 and mapped inshore reefs with a high level of detail. Coral Watch has conducted monitoring as part of citizen science initiatives and capacity-building workshops that track the level of coral bleaching in the Bay over time. The University of Queensland Underwater Club (Unidive) has created detailed maps and ecological assessments of the Flinders and Point Lookout offshore reefs of the MBMP. These examples demonstrate how citizen science groups record information that can be used to support the conservation of reefs in the MBMP.

Keywords: reef monitoring, reef mapping, Reef Check Australia, CoralWatch, Unidive

Introduction
Moreton Bay Marine Park (MBMP) reefs, provide a refuge, nursery ground and food source hosting a diverse variety of flora and fauna (1). These reef include inshore reefs in central Moreton Bay *Quandamooka* such as around Peel Island, and offshore rocky reefs such as Flinders Reef (2). Although academic studies have provided some insight into the factors affecting coral assemblages in Moreton Bay and the flora and fauna distributions within them (3, 4, 5), local marine authorities do not routinely monitor these reef. Hence citizen science is valuable to help fill spatial and temporal gaps. This paper will provide an overview of known citizen science monitoring programs in the reef in the MBMP, and provide a discussion on the approaches and applications used. The citizen science groups that focus on reef area monitoring

in the MBMP include Reef Check Australia (Reef Check), CoralWatch and the University of Queensland Underwater Club (Unidive). The diversity, distribution and ecological condition of reef communities in the Moreton Bay region are addressed in more detail in Pandolfi *et al*., Olds *et al*. and Gilby *et al.*, 2019, this volume.

The MBMP reef communities include both inshore and offshore reefs (2), with inshore reefs found around Mud, St. Helena, Green, King, Peel, Goat, Russell and Macleay islands (4), as well as a patch reef at Myora (6) and some fringing areas along the mainland between Manly and Redland Bay (7). The reef areas are mostly hard substrate composed of a carbonate platform and while a few areas have highly concentrated coral growth (such as Myora (8) and Flinders Reef (9)), many areas have patchy or sporadic coral growth (10). The hard coral community is dominated by massive hard coral growth forms (8), alongside soft corals, sponges (1), and a variety of algae (11). The shallow waters of the MBMP are affected by the discharge of freshwater, pollutants and sediment from adjacent rivers (8). Hence, turbidity in Moreton Bay is often high, with visibility averaging 1 to 2 m. This limited light availability means that coral growth is more common in areas less than 5 m deep (7, 12).

Offshore rocky reefs are found along the eastern side of Moreton and Stradbroke islands, mostly around the northern points. The rocky reefs near Moreton Island are Henderson, Cherubs Cave, China Wall, Gotham City, Smith Rocks, and Flinders Reef north-east of Cape Moreton, with Flinders the only exposed reef. Stradbroke Island's rocky reefs are Flat Rock, Boat Rock, Shag Rock, Middle Reef and The Group (includes Manta Ray Bommie)(2, 13). All these are emergent and above the low tide except Middle Reef. The rocky reefs of both Moreton and Stradbroke islands are mostly basalt substrate suitable for coral growth (10), with the highest coral cover and most diverse coral assemblages found at Flinders Reef (9). These offshore reefs can be exposed to the prevailing swell and variable tidal or ocean currents, making them regularly inaccessible for boats or for snorkelling or diving. Visibility is greater outside of the Bay, therefore coral growth is found in the deeper water surrounding these rocks, with some reaching down to 40 m (14).

Citizen science monitoring on MBMP reefs

Government and academic organisations conduct detailed research studies and monitoring on the reefs in the MBMP, but consistent long-term reef health monitoring is limited. For example, Queensland Parks and Wildlife conducts annual Reef Health and Impact Surveys (RHIS) at sites throughout the MBMP. In RHIS surveys, a trained observer assesses an area within a 5 m radius, in which substrate composition and impacts are visually estimated (15). Additionally, researchers at the surrounding universities and research institutes conduct a variety of research projects in the MBMP that are discussed in other papers.

Importantly, citizen science organisations including Reef Check (16), CoralWatch (17) and Unidive (18), engage community volunteers in a diverse array of monitoring and mapping activities in the Moreton Bay region which are discussed below.

Reef Check Australia (Reef Check)

General

Reef Check is an environmental charity dedicated to protecting Australia's reefs and oceans by engaging the community in hands-on citizen science research, education and conservation activities (16). Since 2001, Reef Check has trained and coordinated volunteers to conduct globally-standardised reef health surveys along the Queensland coast. In 2007, the program expanded to monitor subtropical reefs in South East Queensland. Teams actively monitor 35 sites annually in the region from the Sunshine Coast to the Gold Coast, including multiple sites inshore and offshore in the MBMP (19).

Annual ecological surveys

Reef Check scientific methods have been peer reviewed to create a consistent global protocol for community-based reef health monitoring (20, 21, 22, 23). A set of biological indicators (site description, reef health impacts, substrate type, invertebrates, fish identification) was chosen for Reef Check, to serve individually as indicators of specific types of human impacts, and collectively as a proxy for ecosystem health (22). A four day course trains volunteers to conduct surveys, use survey materials and identify Reef Check indicators. Surveys are conducted along a transect line divided into four 20 m sections and laid along a constant depth and reef habitat (Fig. 1). Invertebrate abundance, reef impacts and fish data (when feasible) are recorded along a belt transect, whilst benthic composition of 25 substrate categories is recorded using point intercept transects to assess percent cover (Fig. 1a). A recent study demonstrated that the point

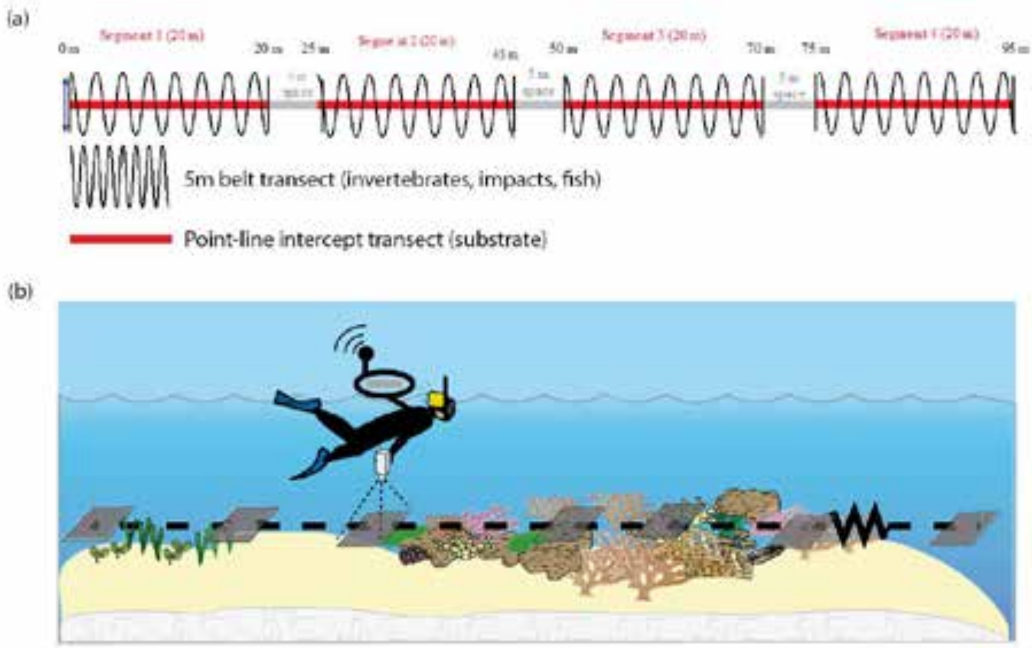


Figure 1. Conceptual model of Reef Check (22), CoralWatch (24) and Unidive Survey methods (25). (a) Invertebrates, reef impacts, fish and CoralWatch surveys are performed along a belt transect (U-shaped search pattern), whilst substrate observations are recorded at 50 cm intervals along the transect tape. (b) For benthic photography and the mapping of significant features and major habitat, georeferenced photographs are collected in the survey area (26).

intercept method for recording substrate data, despite observer and tape deployment biases, was highly accurate and capable of reliably documenting moderate changes in benthic cover (23). All Reef Check data are available as summaries and raw data through an online database, and an annual report is created to inform stakeholders on the status of reef health (https://www.reefcheckAustralia.org/data; www.reefcheckAustralia.org/publications).

Reef mapping
In 2015 and 2016, a collaborative project to inventory benthic reef habitat in the inshore MBMP was undertaken by Reef Check, The University of Queensland (UQ) Remote Sensing Research Centre, and Healthy Land and Water. This project generated a multipurpose dataset to revise a critical natural resource management dataset from 2004 for the spatial extent and condition of key reef areas (7).

For this project, more than 20 volunteer surveyors and staff conducted 610 georeferenced spot check surveys across fringing reef areas and eight inshore Moreton Bay reef areas to assess benthic composition by snorkeller, viewing bucket or using a drop camera. For these surveys, substrate percentage cover was estimated through visual inspection in an approximate 10 m diameter spot area. Each spot check survey was inventoried and the georeferenced data was overlaid on ZY-3A satellite imagery (5 m x 5 m pixel) by UQ Remote Sensing Research Centre staff. Boundaries of reef areas were manually digitised and labelled on the satellite imagery based on interpretation of the georeferenced field data, water depth and the underlying texture and colour of the satellite imagery (7). The largest reef was located around Peel Island, with smaller fringing reefs occurring around the islands of inshore Moreton Bay, and the coastline between Wellington Point and Coochiemudlo Island. Only areas of relatively dense coral cover (>20%) were digitised. Using the spot check data, reef areas could be clearly distinguished from algae-dominated areas. This, taken in conjunction with the higher resolution satellite imagery and advanced mapping software, enabled more refined habitat assessments than the 2004 baseline maps. As such, areas of soft coral on sand/rubble, and algae on sand/rubble+patchy coral, could be clearly distinguished from coral-dominated areas. The 2016 revised spatial dataset offers a practical tool for supporting management decisions relating to marine park zoning and conservation in the catchment and the Bay.

CoralWatch Surveys

General
CoralWatch is a not-for-profit citizen science program based at The University of Queensland (UQ) in Brisbane, Australia (17). CoralWatch integrates global monitoring of coral health with education about coral reef conservation, and helps non-scientists around the globe to understand and support effective reef management by using survey and educational tools that provide ready access to information and hands-on-experiences collecting scientific data about the health of corals (24, 27). Currently there are 5,861 active CoralWatch survey members that have contributed data for 1,899 reefs globally (17).

Coral Health Chart surveys

The Coral Health Chart was developed in 2002 and is a validated method to monitor coral bleaching as an indicator of coral health (24). The chart standardises changes in coral colours, and provides a simple way for people to quantify coral health and contribute to the CoralWatch global database. Dive centres, scientists, school groups and tourists use the Coral Health Chart. The colour charts are based on the actual colours of bleached and healthy corals (27). Each colour square corresponds to a concentration of symbionts contained in the coral tissue. The concentration of symbionts is directly linked to the health of the coral. It allows the user to easily match the lightest and darkest colour of a coral with one of the colours on the coral health monitoring chart and record the matching codes along with coral type (growth form). The collected data is uploaded onto the CoralWatch database, which is publicly available (https://www.coralwatch.org/web/guest/map). The simplicity of the CoralWatch approach to gather information on coral health means that it requires less than an hour of training and any volunteer can collect field data.

In the Moreton Bay region, Coral Health Chart surveys have been conducted haphazardly as part of educational workshops for local and international students that raise awareness on 'Corals at your Doorstep', and by local divers and snorkellers on the various reefs (>350 corals surveyed inshore Moreton Bay; >1,300 surveyed offshore Moreton Bay) (17). In conjunction with Reef Check surveys, CoralWatch data are recorded via a belt transect along the length of each transect (Fig. 1a). The existing field data for a site are compiled and graphs are generated automatically to provide an overview of the health status of each reef and an indication of coral bleaching (27).

The University of Queensland Underwater Club

General

Unidive, is a recreational dive community located in Brisbane and open to all divers (18). Unidive has been involved in volunteer conservation projects that include clean-ups, ecological assessments and mapping of popular local dive sites within the MBMP.

As a result, some members of Unidive have gained skills, knowledge and experience in diving, marine conservation surveys, project organisation and logistics, data collection and analysis, report and scientific writing, videography, photography and presentations (13). This is further supported by members who focus their professional research and studies on the marine environment, whilst many members are also trained and involved in Reef Check and CoralWatch surveys.

Ecological surveys

Intensive ecological surveys were conducted with a focus on substrate, invertebrates, fish and reef impacts, using the same methodology utilised for Reef Check surveys (Fig. 1) (13). Indicator categories and survey methods closely aligned with Reef Check and CoralWatch protocols to enable valid comparisons. Survey methods included transect-based and quadrat surveys and, along with indicator categories, are described in detail in the methods manuals (25, 28, 29).

Unidive conducted seasonal (winter, autumn, summer and spring) ecological surveys in 2001, 2003 and 2014 at Flat Rock (2 sites), Shag Rock (2 sites), and Manta Ray Bommie (1 site), the latter as part of the Point Lookout Ecological Assessment (PLEA) (13, 28, 29). In 2003 one-off surveys were conducted at one site at each of Henderson Reef, Cherubs Cave, China Wall and Gotham (28), and then in 2017 to 18, as part of the Flinders Reef Ecological Assessment (FREA), at 10 sites at Flinders Reef (30).

Mapping
For both the PLEA and FREA projects, water depth, significant features and major habitat were mapped according to methods developed by Unidive in collaboration with the UQ Remote Sensing Research Centre. Feature mapping was undertaken on each transect by two divers. This buddy pair conducted a roving survey of each site to a maximum depth of 20m, and recorded characteristic features (Fig. 1b) (13). Feature location was mapped by cross-referencing the time each feature was recorded or photographed with Global Positioning System (GPS) data recorded by a floating receiver towed by one of the two divers. Water depth surveys using single-beam echo sounders were conducted throughout the study areas to create contour lines. Satellite imagery was used to outline rocky areas, sandy patches and exposed rock (31).

What did citizen science find out about the reef areas in the MBMP?

Reef citizen science-based projects in Moreton Bay have resulted in a wealth of data, including: the first detailed habitat maps of Moreton Bay offshore reefs (31, 32); updated habitat maps of the main inshore reef areas in the MBMP (7); annual monitoring of many reefs (16); and intensive seasonal assessments of popular tourist dive sites (13, 28, 31, 33).

Reef monitoring
Annual reef surveys conducted since 2009 by Reef Check resulted in a better understanding of trends in coral cover or changes in impacts for reefs in Moreton Bay. Summary reports are created at the end of each survey season. For the 2017–18 season, more than 30 volunteer surveyors and staff were involved in the surveys (19). Figure 2 shows an example of the survey results for an individual reef depicting the levels of hard coral (HC), soft coral (SC), bleached coral (BC), recently killed coral (RKC), rock (RC) nutrient indicator algae (NIA), sponge (SP), other benthic (OT), silt (SI), rubble (RB), and sand (SD). Overall for the 2017-2018 survey season, inshore Moreton Bay reefs recorded an average of 12% hard coral cover, whilst outer Moreton Bay reefs recorded an average of 27% hard coral cover. More specifically, for the inshore Moreton Bay reefs, an increase in coral cover (17.5%) was observed at Myora Reef coincident with low levels of coral bleaching (1%), whilst higher bleaching was recorded at sites closer to the mainland (37.5% at Green Island), as were low levels of coral cover (0 to 2% at Mud Island). Of the outer Moreton Bay reefs, however, most sites recorded a decrease in hard coral coverage with the exception of Shag Rock, while Flinders Reef recorded the highest level of bleaching (10%) as well as the highest coral cover (79%).

Many sites monitored by Reef Check appear to have been relatively stable over the course of monitoring. However, poor reef health indicator signs were also documented during the

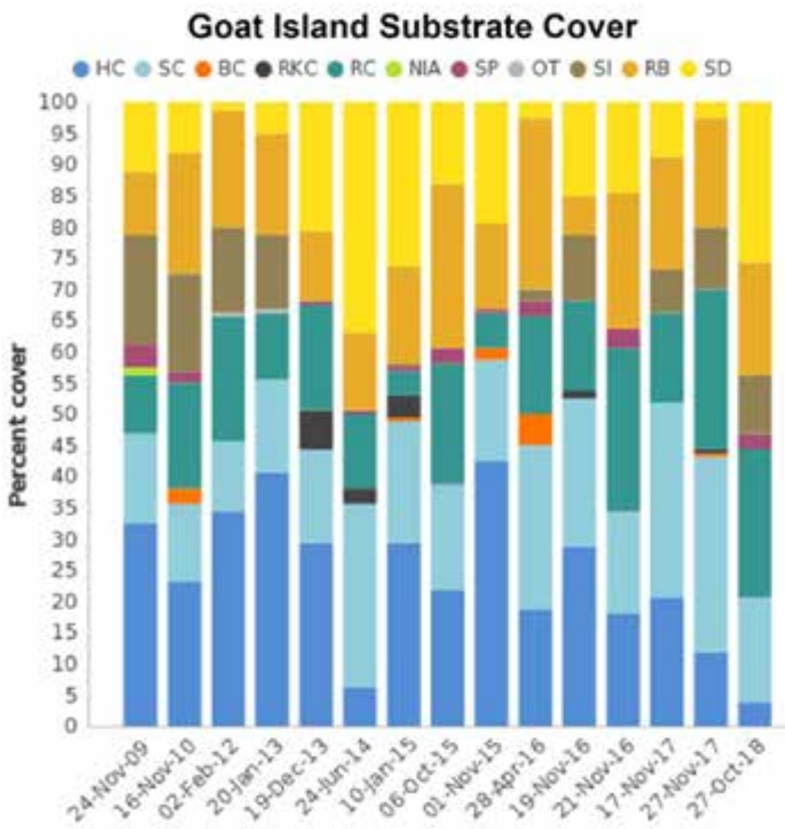
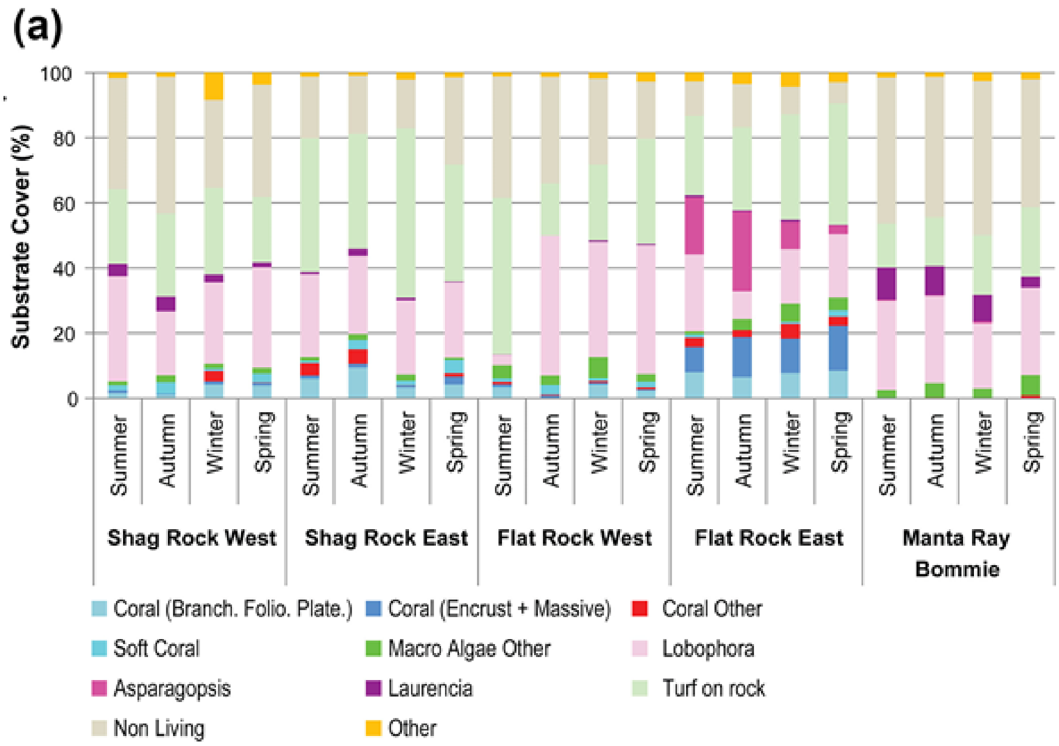


Figure 2. Nine years of Reef Check annual coral cover surveys for Goat Island indicating trend in benthic cover (16).

surveys. These indicated high coral bleaching at Peel and St Helena islands (20% and 55% respectively), algal overgrowth at St Helena and Shag Rock West, and high coral damage at Flinders Reef from unknown sources (19). Invertebrate surveys indicated that the most abundant invertebrate was the long-spined urchin (*Diadema* spp.), with 356 individuals recorded predominantly at Shag Rock, Myora and Amity Point. Collector urchins (*Tripneustes* spp.) and anemones (various species) were recorded at all survey sites, with only one crown of thorns starfish (*Acanthaster planci*) recorded (Shag Rock). Butterfly fish (Chaetodontidae) were the most abundant target fish species with the greatest proportion observed at Myora Reef. Additionally, many animals considered as rare by Reef Check were recorded including:wobbegong sharks (Orectolobidae); tawny nurse sharks (*Nebrius ferrugineus*); turtles (*Chelonia mydas*); and stingrays (Dasyatidae) (19).

Unidive has been contributing to inventories and detailed site assessments since 2003, including a baseline ecological assessment of Point Lookout dive sites (29) and the follow-up PLEA study (13). In 2016, Unidive initiated the FREA project, and expects results to be published in 2019. For the Point Lookout sites, seasonal changes were visible for macroalgal cover based on the 2014 Unidive Point Lookout surveys (30)(Fig. 3a), and the largest amount of hard coral cover was observed at Flat Rock. A high degree of coral damage was recorded at all Shag Rock sites (where anchoring is permitted) relative to all other sites (13). This study identified the long-spined urchin (*Diadema* spp.) as the most abundant urchin, as well as a high frequency of collector urchins (*Tripneustes* spp.; Shag Rock), whilst pencil urchins (*Phyllacanthas parvispinus*) were more prevalent at Manta Ray Bommie. Additionally, all sites surveyed exhibited a diversity of fish families with damsefish (Pomacentridae) and wrasse (Labridae) being in highest abundance, however, seasonal variation was observed for subtropical fish groups. CoralWatch seasonal Coral Health Chart surveys at Point Lookout in 2014 showed that the corals were relatively stable with no obvious bleaching detected (a score of 3 or more indicates a healthy reef; Fig. 3b, (13)).



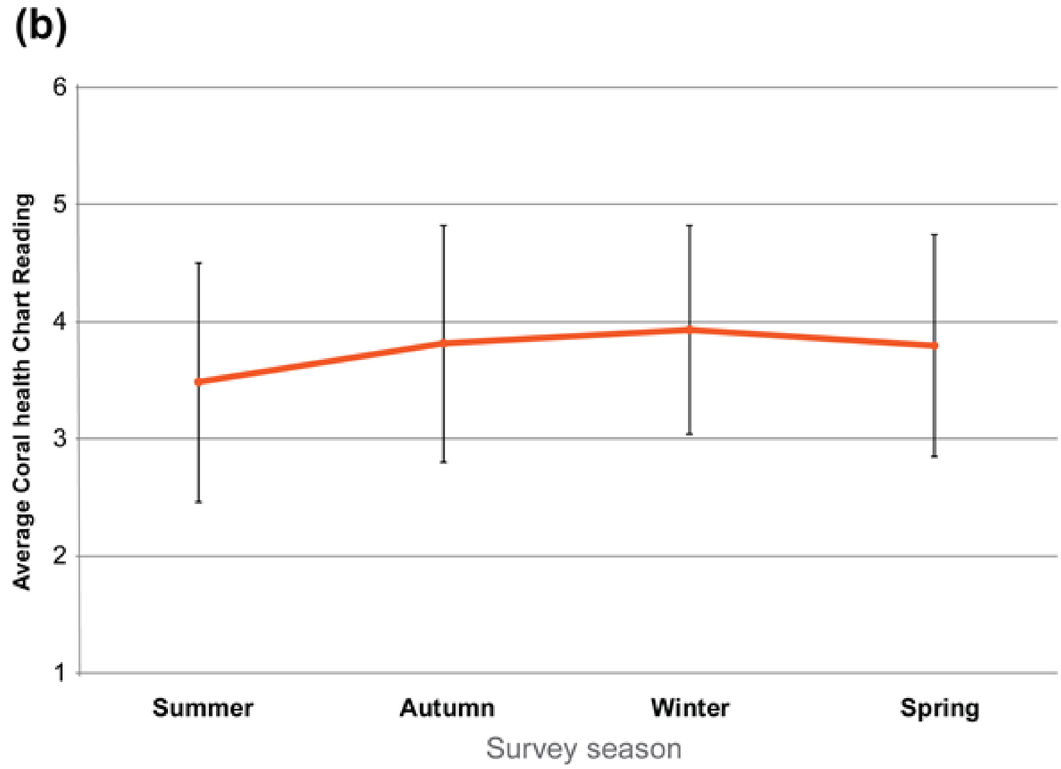


Figure 3. (a) Seasonal coral cover surveys for the Point Lookout dive sites during the 2014 Unidive Project, and (b) averaged seasonal CoralWatch Coral Health Chart readings indicating the average difference between lightest and darkest coral colour (Coral Health Score) for the five sites surveyed during the 2014 Unidive Point Lookout Ecological Assessment Project (13).

Mapping

Multiple types of maps have been supported through regional citizen science initiatives. These maps have been used for: grey nurse shark monitoring; 2009 marine park zonation; and monitoring design and/or management (2, 13, 28).

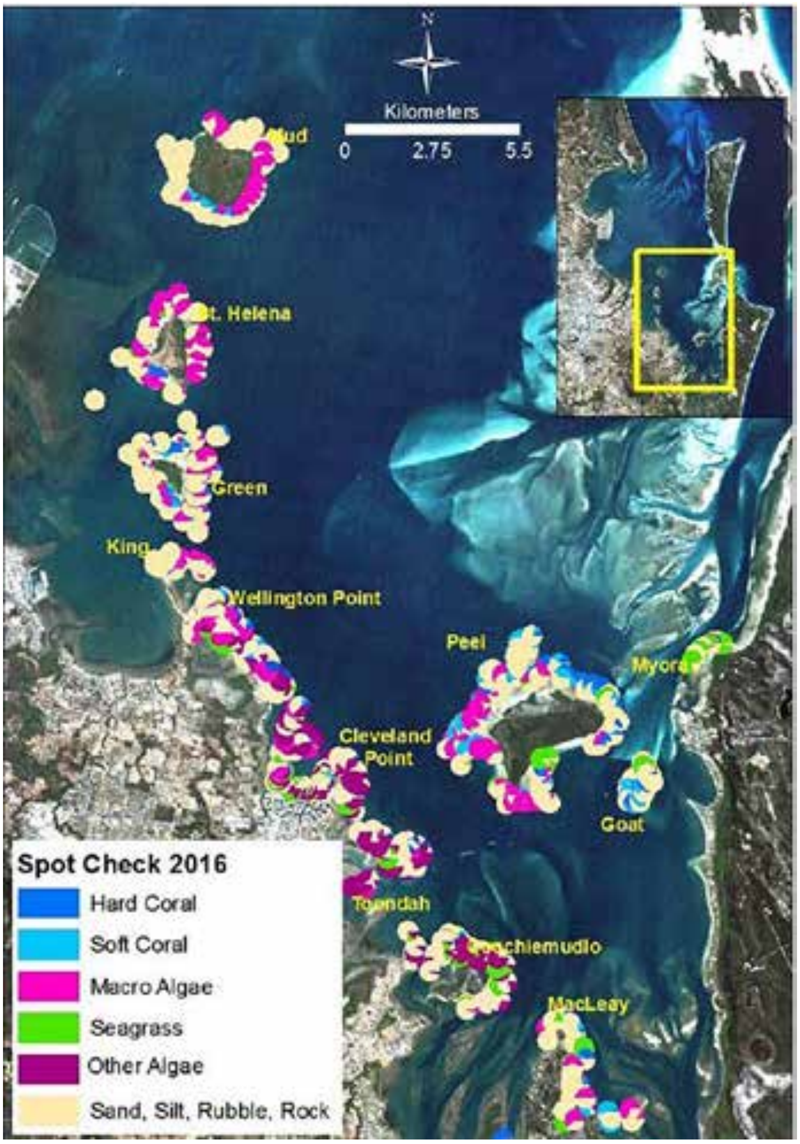


Figure 4. Citizen science reef mapping. Benthic habitat mapped for inshore Moreton Bay reefs by Reef Check, location indicated by the yellow box (7).

In 2015–16, Reef Check worked with the UQ Remote Sensing Research Centre and Healthy Land and Water to revise reef habitat maps for inshore Moreton Bay for the first time in 10 years (7)(Fig. 4). The map provides a detailed and updated inventory of the coral habitat in Moreton Bay and was to contribute directly to the 2018 Healthy Land and Water Report Card (34). This would assist with evaluation of the environmental condition of South East Queensland catchments, and management actions to reduce pollution and maintain or restore key habitats.

Habitat maps created through multiple Unidive projects provided a level of detail not mapped before for local reefs (Fig. 5a, b). These maps describe: different substrate cover types; significant features and depth; and include habitat mapping for the Critically Endangered grey nurse shark (28, 31, 32) (Cherub's Cave; Fig.5b).

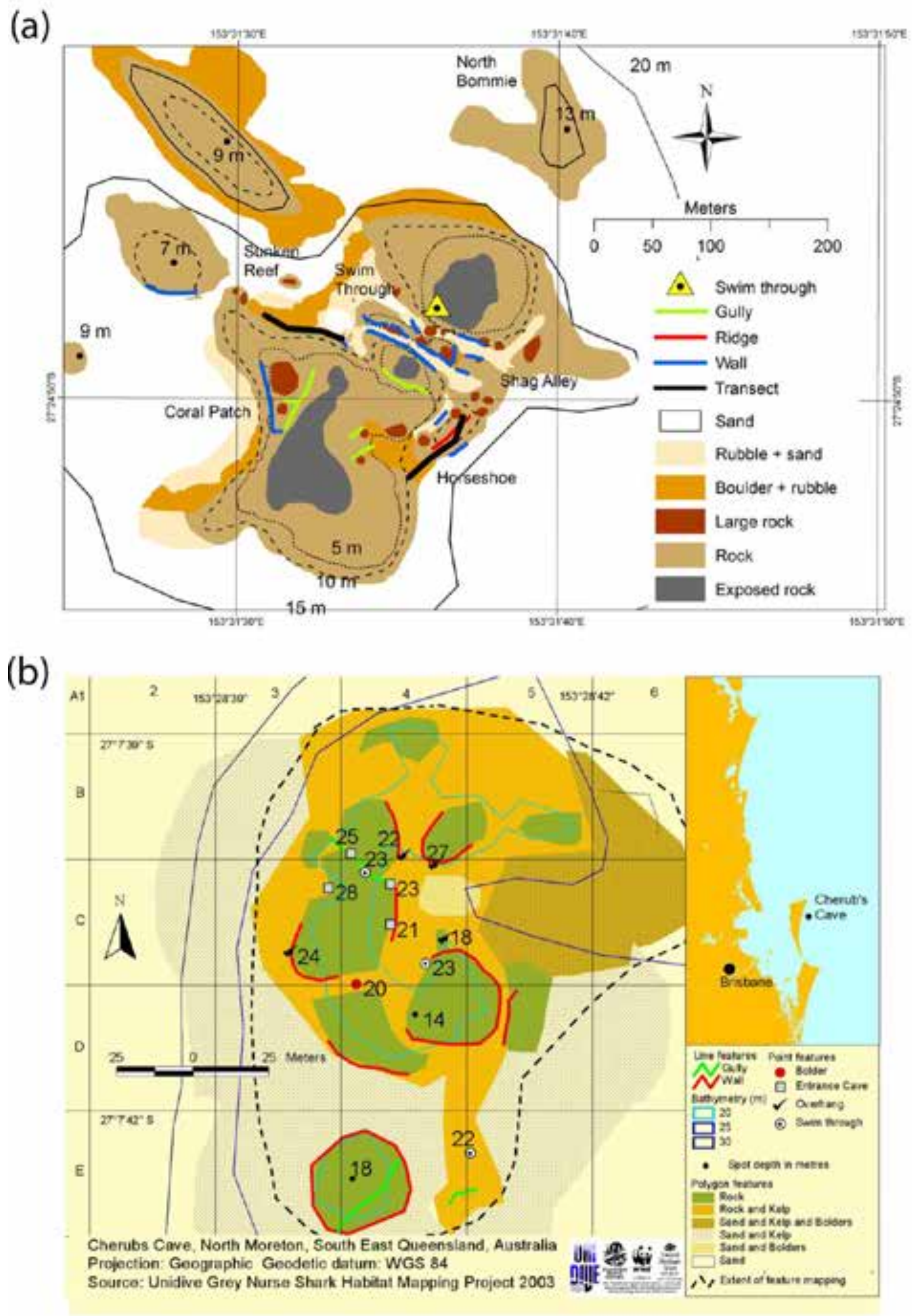


Figure 5. (a) Habitat map for Shag Rock, Point Lookout, surveyed during the 2014 UniDive Point Lookout Ecological Assessment Project (13), and (b) habitat map for Cherubs Cave, North Moreton Island surveyed by UniDive as part of the habitat mapping for the Grey Nurse Shark (GNS) Project 2003 (28).

Impact of MBMP reef citizen science

Citizen science projects have resulted in a broader ecological understanding of MBMP reefs, particularly with respect to abundance, composition and impacts, providing valuable information for marine authorities which they would otherwise not have accessed. Citizen science supports conservation actions through, for example, the mapping of critical grey nurse habitat in accordance with the Australian Government's recovery plan (35), and influencing marine park zoning and resource management (7, 36). Many citizen science datasets help fill gaps in spatial and temporal knowledge.

Citizen science has contributed notable data for (7, 13, 19, 24, 28, 29, 30, 31, 32, 33):

- substrate cover - annual (Reef Check) and intensive (Unidive)
- invertebrate and fish composition - annual (Reef Check) and intensive (Unidive)
- invertebrate and fish abundance - annual (Reef Check) and intensive (Unidive)
- human and natural impacts - annual (Reef Check) and intensive (Unidive)
- spatial composition and characteristics of habitats - intensive (Reef Check; Unidive)
- photographic records - annual (Reef Check) and intensive (Unidive).

Citizen scientist volunteers provide commitments of time that would not be possible through government agencies. In addition to science and monitoring contributions, citizen science initiatives have increased community awareness through publication and presentation of results and data in: reports, websites, brochures, videos, coffee-table books, scientific publications, workshops, conference presentations, media, online data portals and/or inclusion in government-developed publications (Fig. 6) (7, 19, 25, 26, 28, 29, 31, 32, 33). Additionally,

Figure 6. Examples of awareness-raising products generated by citizen science projects.

these initiatives have supported increased educational and capacity-building opportunities focused on the MBMP through trainin volunteer divers, workshops, and presentations at local dive clubs and high schools

Beyond regional data and awareness-raising, citizen science is contributing to positive policy and natural resource management outcomes on the international stage. In 2016, citizen science directly facilitated international recognition for the MBMP through an application to support a Mission Blue Hope Spot award (https://mission-blue.org/2016/12/citizen-science-supports-protection-in-the-moreton-bay-hope-spot/). Hope Spots are marine habitats recognised for their unique and critical value (biodiversity and important habitat) through a competitive assessment process managed by Mission Blue and International Union for Conservation of Nature (Sylvia Earle Alliance/Mission Blue; https://mission-blue.org). In addition to the unique natural environment, the Hope Spot reviewers stated that assignment of the MBMP as a Hope Spot was due to the active citizen science networks within the region.

Challenges and limitations for citizen science programs on reef areas

Marine environments are challenging areas to conduct research for any organisation. The challenges are a result of the submerged and exposed nature of the reefs, often only accessible by boat, which determines the number of passengers that visit a site. In general, travel to a site takes a long time and can be affected by environmental conditions such as water depth, wind, waves and currents, all of which can reduce ease and regularity of access.

Volunteers participating in underwater research need to be relatively fit and often need to be trained and experienced divers or snorkellers, which can limit the number of eligible volunteers. Additionally, divers and snorkellers are limited to a certain depth and dive time in order to conduct surveys safely. Environmental conditions such as wind, waves, swell and temperature, also greatly impact data collection activities, as was experienced during the FREA surveys (30). Annual sea temperatures in the MBMP vary from 15 to 27°C, and underwater visibility varies from centimetres to tens of metres.

Collecting data underwater often requires specialised and costly equipment, such as dive gear, waterproof paper forms, slates and underwater camera gear. As GPS signals don't penetrate the water, positioning relies on towing a GPS receiver directly above the diver. This assures that the recorded location is within GPS error, and it is a well-documented method for determining survey location (26).

Summary of how citizen science is helping to monitor and understand the reef areas of the MBMP

Reef citizen science data in the MBMP has provided additional ecological information about these areas that complements and augments data collected by government agencies, consultants and academic researchers. In some locations, they are the only available datasets. The information gathered has proven to be useful and it has been integrated into government and non-government programs to provide additional temporal and spatial information, as well as novel types of data (13, 28, 29, 30, 31, 32, 34, 37).

The range of citizen science programs, from casual observations to in-depth bio-inventories, opens up opportunities for wide-scale participation for a range of interests and at many levels of skill and experience. Increasingly there are chances for volunteers to get involved in other activities that do not involve fieldwork, through identification, validation, reporting and outreach. The opportunities will continue to grow as increased access to survey methodologies that can be transferred to citizen science teams, along with ease of access to online repositories of manuals, tools and publicly accessible data, amplify data sharing and validation. This will continue to boost citizen science reef data collection and integration.

The citizen science programs presented here, build science literacy and capacity in the community by training and including volunteers, and through increased communication about the condition and/or location of these reef areas. Citizen science brings together multiple stakeholders to discuss how the scientific and broader community can improve partnerships that can help generate positive science and management outcomes.

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Citizen science photographic identification of marine megafauna populations in the Moreton Bay Marine Park

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Abstract

Marine megafauna such as cetaceans, sea turtles and elasmobranchs attract considerable public attention. Despite their popularity relatively little is known about their populations in Australia. This is due to inherent challenges faced in researching megafauna in the wild, including the difficulty of locating and tracking species, their often remote distribution and elusive nature. The advent of photo identification techniques and the engaging of citizen scientists have contributed to research outputs and increased general understanding of many marine megafauna populations. We present three case studies about how citizen scientists contribute to research in the Moreton Bay Marine Park: 'Project Manta';'Grey Nurse Shark Watch'; and 'Dolphin Watchers'. Based on our comparative assessment of the case studies we identify several benefits of using photo identification (photo-ID) techniques on marine megafauna for this region. These include: (i) the extra data provided by citizen scientists substantially **increases research effort** and coverage in time and space; (ii) citizen scientists are self-funded or funded through tourism programs and substantially **reduce the costs of data collection** for research while supporting local tourism ventures; (iii) citizen science programs help disseminate research results to participants through increased contact with researchers, thereby **increasing public education** outcomes; and (iv) citizen science programs have had tangible downstream **outcomes for conservation efforts** including participation in stakeholder groups, data being used for threatened species assessments, and monitoring of sick and injured animals over time. We identify several challenges with marine megafauna citizen science programs including: (i) raising awareness of projects and accessing photos; (ii) limitations of image-matching

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software; (iii) development of online database structures that are transferable across projects; (iv) maintaining engagement with public participants; and (v) long-term funding. We make recommendations to address these challenges and propose future directions to improve citizen science programs in the region.

Keywords: photo-id, reef manta ray, cetacean, bottlenose dolphin, humpback dolphin, grey nurse shark

Introduction

The Moreton Bay Marine Park (MBMP) contains diverse and abundant marine megafauna, including marine mammals, elasmobranchs, and sea turtles. A subtropical embayment (1), Moreton Bay and its adjacent reefs which comprise the marine park host a range of substrates and bio-regions that provide habitat to a distinctive assemblage of resident and transient megafauna. Resident marine mammal species include: the Indo-Pacific bottlenose dolphin (*Tursiops aduncus*); the most southerly population of dugongs (*Dugong dugon*) on the east Australian coastline (2); and the recently-described Australian humpback dolphin (*Sousa sahulensis*) (3). Transient cetaceans include several whale species, the most conspicuous being the humpback whale (*Megaptera novaeangliae*), which has a seasonal migration that passes mostly within 10 km of Point Lookout, North Stradbroke Island (4). The Bay is an important feeding ground for all six species of sea turtles inhabiting Australian waters (5). It is also home to a diverse assemblage of resident and transient shark and ray species, with shallow habitats providing refugia for resident elasmobranchs as well as important nursery grounds for migratory species (6). Offshore rocky reefs are visited by seasonally transient species, including reef manta rays (*Mobula alfredi*) (7) and leopard sharks (*Stegostoma fasciatum*) (8) that have southerly range-extensions during summer and autumn coinciding with the strengthening of the warm East Australian Current. By contrast, more temperate species such as the white shark (*Carcharodon carcharias*) migrate north and into the Bay as southerly waters cool during winter and spring, whereas the grey nurse shark (*Carcharias taurus*) uses the MBMP waters year round with numbers peaking throughout winter and spring (9, 10).

The MBMP is adjacent to the rapidly developing urban hubs of South East Queensland. Human activities in the region have had pronounced impacts on the Bay through: nearshore habitat loss; declining water quality from pollutants; sedimentation; and increased boating and fishing (2). Given that these pressures are ongoing, it is important to assess and understand their potential impacts on marine megafauna within the MBMP.

Obtaining data on large marine animals can be challenging because of their elusive behaviours, sparse populations and wide ranging habitat preferences (11). As many species of megafauna are considered ‘threatened’, it is preferable to collect data using minimally-invasive approaches. Photographic identification (photo-ID) is one such method for tracking individual animals based on unique body patterns (12). Photographs of animals showing identifiable patterns that are stable over time provide information about when and where an individual animal was sighted. Photo-ID studies in the ocean initially focused on marine mammals (13). They have rapidly expanded to incorporate fin shapes and body patterns in other groups including sharks (36), rays (12), sea turtles (14) and bony fishes (15) (see examples for case studies: Fig. 1). Photo-ID methods have been used to: examine patterns of site-fidelity to, and movement between, key habitats (7, 10); resolve biological parameters such as reproductive periodicity (16); identify behaviours including social interactions with conspecifics (17); and estimate population size and other demographic parameters (18).

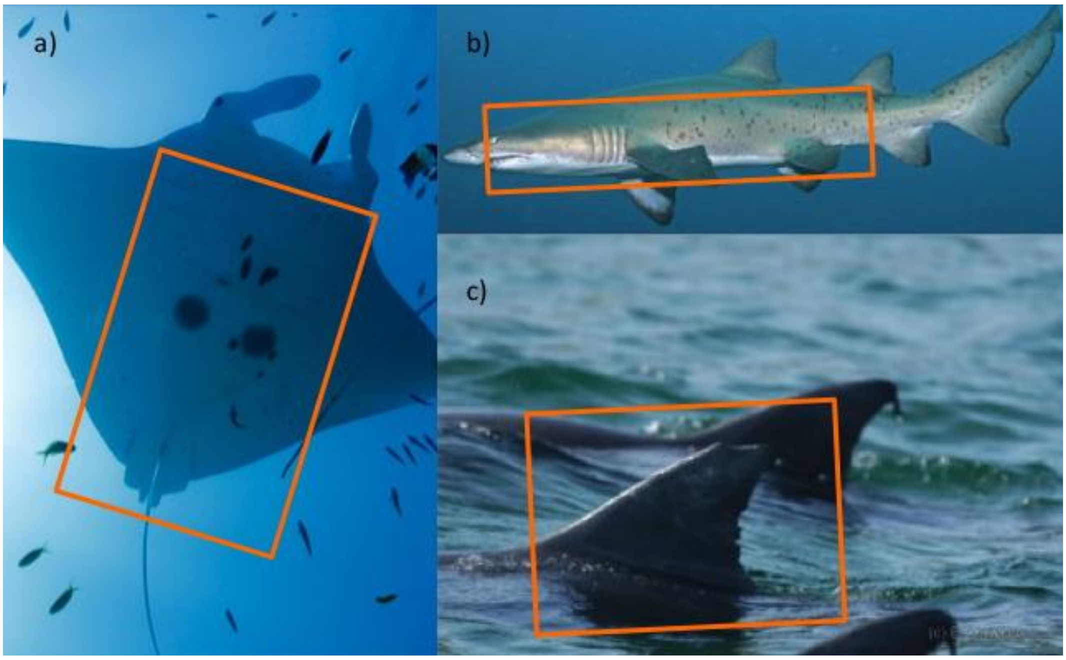

Figure 1. Representative photo-ID images of the three case study species. Orange boxes highlight the areas for identification of the: (a) reef manta ray, (b) grey nurse shark, and (c) Australian humpback dolphin.

With the increasing accessibility of digital camera technology, the past decade has seen more citizen scientist involvement in marine photo-ID projects. This contributes to knowledge acquisition while simultaneously educating participants and increasing awareness. Programs that involve citizen scientists range from opportunistic sighting reports to highly structured, hypothesis-based research projects (19). Citizen scientists generate important data for studies on distribution, movement and abundance of large, mobile species such as bottlenose dolphins (*Tursiops* spp.) (20). Mark–recapture population size estimates based on citizen science data have shown strong congruence with results from dedicated researcher surveys for whale sharks (*Rhincodon typus*) in the Maldives, indicating that citizen science data can be suitable for estimating abundance (21).

Citizen science programs are hosted by non-government organisations, universities, businesses and government agencies. These programs are motivated by the need to connect the public with science, increase conservation awareness, and encourage environmentally-beneficial behavioural change (19). With the growing challenges of funding research, projects are increasingly reliant on the participation of citizen scientists as a cost-effective option (19). In some cases, fee-based citizen science programs are embedded in the expanding voluntourism industry (e.g. Earthwatch) and contribute financially to research (22).

Several photo-ID studies within the MBMP have estimated population sizes for various dolphin and shark species (18, 23, 24). While these studies used a dedicated researcher survey approach, Couturier et al. (2011) also combined citizen science surveys with those of researchers to investigate movements of reef manta rays along the east Australian coast (7). There are now several ongoing megafauna photo-ID studies in the region that incorporate citizen science contributions of photographs, including 'Project Manta', 'Grey Nurse Shark Watch', 'Dolphin Watchers', 'Humpbacks and Highrises' and 'Spot the Leopard Shark'. Here we present three case studies from the MBMP that demonstrate different ways of using citizen scientist contributions in marine megafauna research programs. We discuss benefits of the approaches used, challenges faced, and recommendations for the future.

Case studies

Project Manta

Project Manta is a multidisciplinary research collaboration[1] investigating the population biology and ecology of reef manta rays (*Mobula alfredi*).

The project has four main aims:

- investigating connectivity and movement between populations within Australian and neighbouring waters;
- estimating population size and variation through time;
- understanding biological and environmental drivers of population dynamics; and
- providing management recommendations for populations in the region.

Reef manta rays are listed as 'Vulnerable' on the IUCN Red List of Threatened Species (25). They are captured at multiple locations around the world as target species for their gill rakers and flesh, and as bycatch. As they are slow growing, late to mature and have low reproductive output, they have low recovery potential from exploitation (26). These conservation concerns have spawned research efforts at manta ray aggregation sites globally. These multiple citizen science projects collect data about these rays to feed into larger research initiatives such as those led by Manta Trust, Marine Megafauna Foundation and Project Manta.

Individual manta rays are born with a unique 'spot' pattern on their ventral (belly) surface that is retained throughout life, enabling individual identification (Fig. 1a) (27).

[1] Collaborators and participants can be found on the Project Manta website at https://biomedical-sciences.uq.edu.au/project-manta

Many manta rays aggregate seasonally in particular locations. While feeding at the surface or visiting 'cleaning stations' they are easily approached by breath-hold or scuba divers. This provides opportunities for underwater photography of the manta rays, and engages tourism operators and the public in scientific research.

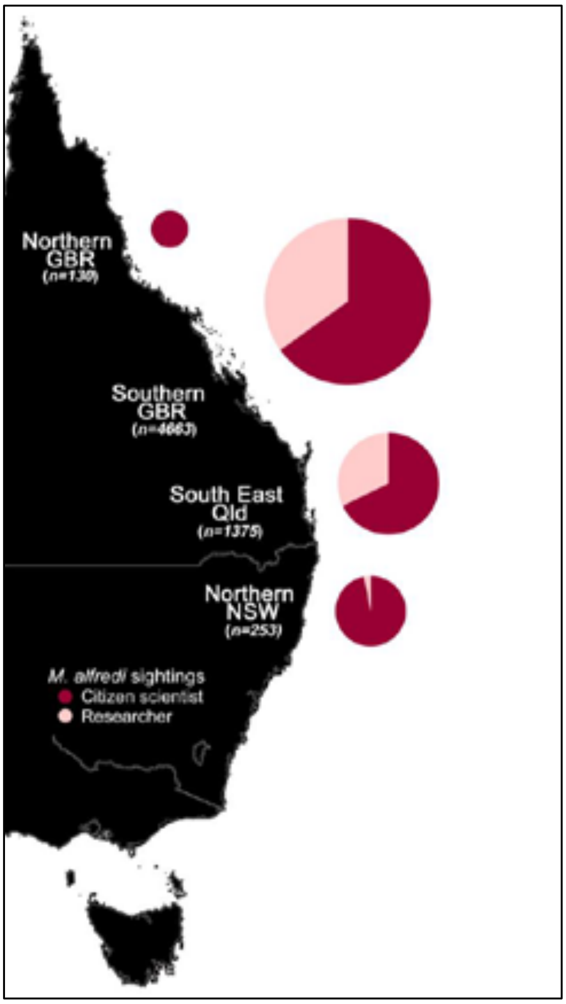

Figure 2. Proportion of reef manta ray (*Mobula alfredi*) sightings along the eastern Australian coast contributed by citizen scientists and researchers. Pie chart size represents relative number of contributions at different locations. GBR – Great Barrier Reef, Qld – Queensland, NSW – New South Wales.

Research groups use photo-ID of manta rays to investigate biological characteristics such as reproductive periodicity and behaviour (16) and to estimate population size (28, 29, 30). Public submission of images to the web has been invaluable in generating large photographic catalogues of manta ray individuals, increasing our ability to examine aspects of their ecology such as movement patterns among sites (7).

Since Project Manta began in 2007, its citizen science program has contributed photo-ID records of reef manta rays along the east coast of Australia. As of November 2017, over 1200 individual reef manta rays had been identified from 6380 records with 65% of individuals being sighted on more than one occasion. Citizen scientists have provided the original photographic record for approximately 67% of the manta rays, as well as 53% of the re-sighting records (Fig. 2). Along the Australian east coast, the reef manta ray is distributed from the Torres Strait in tropical Queensland to the South Solitary Islands, NSW. The MBMP contains 'Manta Bommie', a key reef manta ray aggregation site in the southern half of its range, located offshore from Point Lookout, North Stradbroke Island. Around 20% of the photographic contributions to Project Manta come from 'Manta Bommie'. Citizen science contributions to the Project Manta photo-ID database have assisted with identifying manta ray aggregation hotspots in eastern Australia, obtaining baseline population numbers, as well as demonstrating seasonal movements of individuals between the MBMP and Lady Elliot Island on the southern Great Barrier Reef (7).

Public participation in Project Manta is encouraged through an online presence, personal interaction with dive centres, advertising material (including promotional stickers and posters), and by disseminating results using posters and web-sites. In particular, Manta Lodge Scuba Centre on North Stradbroke Island organises twice-yearly 'Manta Fest'; a scuba-dive festival run over two weekends during the manta ray aggregation period, and contributions of images to the citizen science program is encouraged. Researchers attend the festival to give educational presentations about Project Manta, demonstrate to divers best practice underwater interaction and encourage diver participation in data collection.

Various incentives encouraged citizen science participation in Project Manta, including:

- a well-maintained and regularly-updated social media presence (Twitter, Facebook with >15,000 followers, email newsletters);
- manta ray 'naming rights' for participants who discover an animal new to the database;
- Project Manta branded t-shirts awarded for major contributions, such as provision of large numbers of photographs or important historical photographs; and
- social media competitions such as the one held to identify the 1000th manta ray for the east Australia database.

A regular media presence has also increased the project's profile. Press releases on research findings, including quality imagery and video, have ensured high levels of uptake by media outlets domestically and internationally. Appearances in high-profile documentaries (e.g. David Attenborough's BBC Series 'Great Barrier Reef' and Nat Geo WILD's 'Manta Mystery') have also provided an avenue to attract prospective citizen scientists. Following each new documentary's premier there is a spike of hundreds of new followers on the social media page. These strategies have been integral to maintaining a public presence in the citizen science space to encourage participation in the project and generate greater awareness and understanding.

However, the success of the citizen science aspect of Project Manta presents a major challenge. Comparing and matching individual images to those in the master database is time consuming. There are a number of computer programs, including MantaMatcher (31), that automate image-matching using specialised algorithms. However, the successful matching of images using this software is often hindered by poor image quality. Consequently, a large number of images require matching by eye, necessitating a dedicated part-time project officer to manage the citizen science program, maintain community engagement, and educate new project participants about types of images suitable for manta ray pattern recognition. Other specialised software is used to identify key features on a manta ray (32), speeding up manual identification.

In conclusion, the contribution of citizen science to Australian manta ray research has been invaluable. Citizen scientists extend the coverage in time and space of the Project

Manta research trips that are limited to a few key aggregation sites each year. Public contribution of archival images, some taken decades ago, help Project Manta investigate important questions about longevity, changes in habitat use and population structure. Engaging with citizen scientists has also provided an ideal platform for disseminating research findings to a broad audience.

Grey Nurse Shark Watch

Grey Nurse Shark Watch (GNS Watch) is a citizen science research and community education program that aims to improve the conservation management of the Critically Endangered (IUCN Red List, (33)) grey nurse shark (*Carcharius taurus*) in Australia. Historically, grey nurse sharks were hunted for their oil, flesh, skin and fins, and were the target of recreational fishers (34). Although protected in Australia, they remain threatened by ongoing incidental capture in recreational and commercial fisheries, as well as shark control programs. Information on population size and trends is necessary for their effective management (35, 36).

GNS Watch, including the database, webpage and Facebook page, was launched in 2011 and is hosted by Reef Check Australia. Citizen scientists contribute photographic records of grey nurse sharks to research projects to address six of the ten objectives of the 2014 National Recovery Plan for this species:

i. to monitor numbers of the Australian east coast population of grey nurse shark and determine its trend;
ii. to provide information on distribution and movements at different stages of grey nurse shark life history;
iii. to provide data to quantify interactions with commercial and recreational fishing gear, along with associated injuries and recovery;
iv. to identify new aggregation sites;
v. to increase public awareness; and
vi. to provide accurate data for management.

Individual grey nurse sharks can be identified by unique spot markings on their flanks (Fig. 1b) as well as any other key identifying features (e.g. jaw wounds, missing fin sections). Photographs of grey nurse sharks are taken during biannual surveys (January to February and July to August) and opportunistically throughout the year at several aggregation sites along the Australian east coast. The biannual surveys accounts for the seasonal variation in their distribution and movement patterns (10).

GNS Watch uses a variety of training materials and methods to educate volunteers and to help ensure that photos suitable for photo-ID are taken without disturbing the sharks. Volunteers who participate in scheduled surveys read the ‘Volunteer Methods Manual’ and to view the ‘GNS Watch Volunteer Training Video’ prior to undertaking surveys. In addition, several divers are trained each year at the annual ‘Shark Fest’ scuba diving festival on North Stradbroke Island, and additional training sessions are conducted as required. Most volunteers that contribute to scheduled surveys are ‘regulars’ who are very experienced and communicate regularly with the GNS Watch team. This helps to maintain a level of consistency in survey effort between volunteers during scheduled survey periods.

GNS Watch project officers match images to those already in the database by using ‘key identifying features’, returning a subset of existing identified sharks. If a match is not found, the shark is checked by eye against the full catalogue for that particular sex, size and view orientation (e.g. left side of the body photos of all mature male sharks). The online database provides key summary results for reporting (e.g. the maximum number of sharks counted during a survey period or year). Mark–recapture analysis is used to assess population trends. Each month, GNS Watch posts an article on their Facebook page and a story in the Reef Check Australia E-newsletter. Targeted public engagement prior to and during the biannual surveys includes:

- at least two public presentations to dive clubs/shops;
- additional Facebook posts (>1160 followers) and website updates;
- emails and distribution of printed education materials and dive slates to dive businesses, clubs and key volunteers; and
- prizes awarded to several survey participants and volunteers publicly recognised within six weeks of each survey period.

Since the start of GNS Watch in 2011, over 600 registered members have conducted 40 surveys at key locations at regular intervals, and 66 opportunistic surveys. Over 6500 photographs have been submitted to the project of which 3822 are approved photographs for the database, based on appropriate metadata, clarity and orientation of the shark. At least, 1271 individual sharks have been identified from these photographs comprising 168 sharks identified from both sides plus 539 females and 564 males identified by their right side only. The number of sharks identified by their left side only was slightly less with 529 females and 508 males. The sex ratio in all photographic categories was almost even. Of the 168 sharks identified from both sides, approximately 80% have been sighted on more than one occasion. In contrast, for the sharks identified from one side only, approximately 25 to 27% have been sighted on more than one occasion. The field methods encourage photographs to be taken of both sides of each grey nurse shark and it is therefore probable that individuals are represented in the database by both their left and right sides. However, it is very difficult to match them as the markings are not identical on both sides. One example of how a shark can be matched to its left and right sides is when features such as dorsal or caudal fin damage have been photographed from both sides during a dive.

GNS Watch faces several challenges. First, considerable time is spent applying for funds and investigating fundraising opportunities to cover costs of the webpage, interactive database, online photo-library, and a program coordinator. Second, it is time consuming to train and retain volunteer project officers to assist with processing the photographs and other behind-the-scenes program outreach. The consequent delay to disseminating results can lead to disengaged volunteers. Third, poor weather conditions can reduce survey coverage and affect survey timing. Lastly, volunteer divers do not visit some critical grey nurse shark aggregation sites during scheduled survey periods. GNS Watch encourages diving at these sites by offering prizes or relying on research divers or partners such as Sea World, Underwater World, and state government agencies.

Despite these challenges GNS Watch has proved to be a successful partnership between researchers and citizen scientists that generates important data for assisting with the recovery of the grey nurse shark along the east coast of Australia. Citizen science contributions include identifying new grey nurse shark aggregation sites. This information is provided to relevant researchers and management agencies to facilitate further investigation about the importance of aggregation sites to the population. Citizen scientists also report on and provide photos of grey nurse sharks with retained fishing gear and in some instances morbidity is probable without intervention. GNS Watch liaises with the relevant conservation management agency (i.e. Queensland Parks and Wildlife Service) and Sea World to attempt rescue and rehabilitation. Subsequent photographic contributions by citizen scientists of these sharks help to inform all partners and the community about the sharks' condition, movements and reproductive events post intervention (i.e. mating and pregnancy).

Dolphin Watchers

Dolphins and whales (cetaceans) are iconic marine megafauna that attract considerable public attention. Cetaceans play vital ecological roles as high-order predators and are under pressure from numerous human activities. Species with locally-resident populations that inhabit coastal zones and estuaries adjacent to urbanised centres, such as Moreton Bay, are among the most vulnerable to human activities resulting in pollution, encroachment, boat strikes and other disturbances (24, 37). These include the Indo-Pacific bottlenose (*Tursiops aduncus*) and Australian humpback dolphins (*Sousa sahulensis*). Cetacean research surveys are expensive and detection rates are typically low, so citizen scientists play a vital role in filling knowledge gaps about population sizes through their sightings (19).

'Dolphin Watchers' is a program of Dolphin Research Australia Inc., a not-for-profit marine conservation, education and research organisation. This program was initiated in 2009 to provide opportunities to engage, connect and empower the public to assist in the conservation of regional dolphin populations and support research efforts. The program entails: (i) opportunistic sighting reports from the public; and (ii) broad-scale land-based observation surveys with trained volunteers. The latter has been established in the Northern Rivers of NSW and during 2015to 16 engaged 15 volunteers in monthly land-based surveys. Dolphin Watchers also offers an 'eco-volunteer' program with the Moreton Bay Dolphin Research Project. This is a fee-based program whereby volunteers are trained to participate in hypothesis-driven research during intensive annual surveys.

Photographs of dolphin dorsal fins are used to identify individuals from the patterns of nicks and notches on the trailing edge that create a 'natural tag' (Fig. 1c) (13). Photo-identification of individuals from opportunistic sightings and dedicated surveys enable estimates of the population abundance, trends and status, along with individual life histories, movement and residency patterns. As part of the opportunistic sighting reports contributed to Dolphin Watchers' online platform, members of the public are encouraged to report the location, behaviour, species and photographs of dolphins observed during their marine-based leisure activities (38). Between 2012 and 2015, over 263 opportunistic sighting reports of dolphins from around Australia were received from 34 people through the online reporting platform. Twenty percent of these sighting reports included photographs and four reports included images for photo-ID.

Despite the limitations of opportunistic sighting data of cetaceans for inferring demographic and ecological parameters (39), there are numerous benefits to collecting these data through citizen science. These include establishing baseline information, identifying previously unknown populations, reporting unusual behaviours, and attaining information about the welfare and health of injured, entrapped or stranded individuals.

Dolphin Watchers promotion has focused on southeast Queensland and northern New South Wales to coincide with Dolphin Research Australia's long-term research projects in Moreton Bay and the Gold Coast, Queensland, and Tweed Heads and Byron Bay in New South Wales.

Public participation in the project is encouraged through various methods including:

- specialist training sessions;
- multi-media promotions through press releases, social media (> 2000 Facebook followers) and advertising (e.g. leaflets and posters); and
- direct community outreach through market stalls in target areas.

Although promoting Dolphin Watchers has resulted in a steady stream of opportunistic reports, there have been numerous challenges. The most prominent are: maintaining public engagement and interest; allocating organisation resources (including volunteers to handle reports); funding to continually promote the program; and acquiring quality sighting information (including photographs).

As human populations and demands on coastal zones increase, pressures from human activities on coastal dolphins are expected to intensify. Citizen science programs assist in knowledge acquisition and monitoring the status of dolphin populations. Such programs also promote and advocate for environmentally positive behavioural change in participants by providing experiences that can incite a sense of stewardship and meaning to participants. This in turn leads to increased conservation awareness and protection of vulnerable populations such as those in Moreton Bay.

Discussion

Citizen science contributions to photo-ID studies in the Moreton Bay Marine Park have and will continue to contribute to monitoring marine megafauna populations. However, developing citizen science programs poses several challenges.

i. **Engaging the public and accessing photos.** Each project has to independently develop its online and print-based engagement pathways. Each project has different means of contributing photographs including email, Facebook and directly on USB sticks.
ii. **Limitations with photo-ID matching.** Photographs provide useful data, but can be time consuming and difficult to match. Automated software options are available, but suffer from false negatives (real matches are not identified) and are generally unable to cope with wide ranges in photo quality. Volunteers are often sought to assist with photo-ID matching, but considerable training is needed and it can be tedious work that volunteers tire of easily.
iii. **Database limitations.** Most databases for photo-ID collection are custom made to facilitate the research, but are generally difficult for other researchers or interested parties to access.
iv. **Maintaining engagement with the public.** Engagement is time consuming and the lag between public contributions and the longer-term scientific outcomes makes it challenging to maintain motivated volunteers.
v. **Long-term funding.** While citizen science projects can reduce costs associated with data collection, there are still considerable costs including advertising, training and organising volunteers, online presence, data processing, and disseminating findings through public outlets. A critical role that requires funding across citizen science programs is that of project coordinator. Traditional scientific funding sources are not always amenable to funding such costs.

Based on the comparative analysis of case studies, there are several recommendations that help to ensure active and effective citizen science programs.

i. **Improve networking** – create centralized websites, social media outlets and advertising material to enable participants to learn about the suite of citizen science projects and potential contributions. Many citizen scientists have photographs to contribute for more than one target species but may be unaware of the full range of applicable projects. A central platform for photo-ID projects would produce an economy-of-scale, enabling a greater reach for individual projects to engage new participants cost effectively, as well as disseminate findings.
ii. **Develop online photo-ID encounter databases** – a generic platform could be adapted to specific requirements for each study. Enabling search functions so participants can find their personal sightings would engage the public and help disseminate results. GNS Watch is an example of a project with such an online database, although this was developed at considerable cost, and was not designed with other photo-ID projects in mind.
iii. **Create funding consortiums** – strategies to promote philanthropic donations to citizen science projects to assist with running costs could be centralized. Centralized campaigns could sell merchandise, organize joint voluntourism

trips, and target fundraising (such as 'Adopt a …' campaigns targeted over Christmas) and so raise revenue for multiple programs. Centralised consortia could also support and promote long-term industry interactions.

While each species has unique requirements, there are commonalities across the case studies that highlight several benefits of citizen science:

i. **Increasing research effort.** Research surveys only capture a small portion of patchy marine megafauna populations. Extra data provided by citizen scientists substantially increase data collection and coverage in time and space.
ii. **Reducing research costs.** Boat and scuba diving-based field-work for marine megafauna is expensive. Citizen scientists are self-funded or funded through tourism programs. This substantially reduces data collection costs and also supports local tourism businesses.
iii. **Increasing public education.** Citizen science programs help disseminate research results to participants through continual interaction with researchers. This is also of benefit to researchers, as funding bodies now typically request that results are disseminated more broadly than through specialist journals.
iv. **Tangible impacts of research and outcomes.** Citizen science programs on marine megafauna in the MBMP have had tangible downstream outcomes for conservation efforts. These programs have engaged a wide-range of stakeholder working groups, as well as informed conservation assessments, recovery plans or zoning reviews. For instance, GNS Watch is a key contributor to the grey nurse shark stakeholder group, who collectively supported the recovery plan review process and wrote to all relevant state and federal ministers providing their recommendations for the conservation management of this critically endangered species. Citizen science contributed to the revised classification of manta rays as 'Vulnerable' on the IUCN Red List (25, 40) and their inclusion for trade restrictions under CITES Appendix II listing (41). Trained volunteers and program coordinators distribute and discuss codes of conduct or legislative requirements to field volunteers, tourism operators and more widely to the public outlining behaviour that minimises disturbance to the animals. Photographs have enabled monitoring of sick or injured animals. Our local megafauna citizen science programs also play an important role in engaging citizen scientists and educating the broader community. They deliver numerous talks and distribute updates and educational material online and through other media about the importance of conserving these ecologically and economically important megafauna.

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Chapter 7 – Industry and Planning

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Professor Rod Connolly is Director of the Global Wetlands Project at Griffith University. He is an experienced marine scientist with expertise in automated monitoring of marine ecosystems and in the ecology of coastal habitats including coral, seagrass, mangroves and saltmarsh. He uses chemical tracers to determine carbon pathways and sequestration of blue carbon in estuaries and coastal waters. Rod lives and works on Moreton Bay and its estuaries and his lab has published widely on fisheries and their habitats. His projects incorporate the science and monitoring of ecosystem health into adaptation strategies. Through his work on resilience and ecosystem protection in Moreton Bay he is helping to find sustainable solutions to the issues of urbanisation, food security, ecosystem services and climate variability. He is adviser to several scientific panels overseeing wetland conservation and water quality in Queensland.

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Tourism in the Moreton Bay Region

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Abstract

Tourism is of growing importance to the Moreton Bay regional economy with increasing numbers of international and domestic visitors, as well as local day-trippers. The Moreton Bay Region has well-developed infrastructure with a range of natural and built resources that have seen Moreton Bay form an important part of the Brisbane region's tourism product and market appeal. However, the increasing use of the Bay and the surrounding coastline by tourists and recreational users has wide-ranging impacts on the sensitive host ecosystems which are already under pressure from surrounding urban development. This is one of the key challenges for the sustainable development of the region. Opportunities exist to further develop the Indigenous tourism products and event sector to further differentiate the region from its competitors in South East Queensland. This chapter reviews key tourism statistics and visitor markets for the Moreton Bay Region, as well as the tourism governance arrangements and key policies and strategies for tourism. Opportunities and challenges for sustainable tourism in the region are considered, including marine recreation and tourism, tourism impacts and sustainability, Indigenous tourism and events. We also provide an audit of the region's tourism infrastructure, products and experiences, as well as accommodation.

Keywords: visitors, governance, marine tourism, Indigenous tourism, events

Introduction

Moreton Bay is one of South East Queensland's most diverse areas. From a tourism perspective, it is a rapidly growing region that offers visitors a variety of distinct coastal and hinterland experiences, together with a range of special-interest events and attractions. The region's core appeals are its diverse natural assets — islands, beaches, coastal Bay towns, a marine park and hinterland mountain retreats. As a tourism region, one of its strengths is its location within an hour's drive of a major capital city; however, this proximity also presents many challenges by placing pressure on its natural assets.

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The Moreton Bay area primarily targets South East Queensland 'short-breaks'[1]. Therefore its brand positioning aims to differentiate it from other Queensland Bay and island destinations, such as the Gold Coast (including South Stradbroke Island), the Sunshine Coast, the Fraser Coast (including Fraser Island), the Whitsundays, and Townsville (including Magnetic Island). This paper provides an overview of tourism in the Moreton Bay Region and assesses opportunities and challenges through a review of documents related to tourism in the Bay, such as visitor statistics and Council tourism strategies.

Importance of tourism to the Moreton Bay Region

Tourism is of growing importance to the Moreton Bay Region (encompassing both the Moreton Bay Regional Council and Redlands City Council areas), accounting for approximately 2.7% of the Moreton Bay Regional Council's gross regional product ($313 million) and 1.2% for the Redlands City Council area ($46 million) (1–4).

While tourism statistics for the Moreton Bay Region are contained within the broader Brisbane tourism region (which consists of the local council areas of Moreton Bay, Redlands City, Brisbane City, Logan City, Ipswich City and the Scenic Rim), it is estimated that 20.6% of visitors (overnight and daytrips) to the Brisbane tourism region between 2009 and 2012 visited the Moreton Bay Region (3,831,000 visitors), and 13.4% of visitor nights were spent in the Moreton Bay Region (4,352,000 visitor nights) (5, 6). Only 7% of visitors to Queensland visited Moreton Bay, with 3.8% of total Queensland visitor nights spent in the Moreton Bay Region (5, 6).

Tourism employment statistics are also difficult to define because the Australian Bureau of Statistics does not classify tourism as a separate industry. However, it is possible to estimate tourism-related employment through other industry classifications, in particular, 'Accommodation and food services' (close to a third of tourism-related jobs in Queensland) and 'Retail trade' (one in six tourism-related jobs in Queensland) (7). For instance, Tourism and Events Queensland estimate direct employment in tourism-related services equates to more than 1 in 20 jobs in Queensland (7). For Moreton Bay, tourism-related employment is estimated to account for approximately 4% of total employment in both the Moreton Bay Regional Council and Redlands City Council areas, equating to approximately 6,562 tourism-related jobs in the broader Moreton Bay Region (2, 3). Employment levels in 'Accommodation and food services' (6.8%) contribute to tourism's ranking as the fifth largest industry in Moreton Bay and fifth largest in Redlands (8.7%) (2, 3).

Visitors to the Moreton Bay Region

The Queensland tourism market is dominated by four tourism regions (Brisbane, the Gold Coast, the Sunshine Coast and Tropical North Queensland) that collectively receive more than 80% of international visits and almost 72% of all domestic trips (8, 9). While domestic tourism to the greater Brisbane region (including the Moreton Bay Region) represents a greater number of visits compared to international tourism (6,894 domestic visitors compared to 1,274 million international visitors in 2017) (8, 9), domestic tourism growth has been more subdued. Since 2000, domestic visitation has been growing at a rate of approximately 1.6% per annum (10); while Brisbane's (including the Moreton Bay Region) share of the international visitor market in Queensland grew from 33.6% to 46.2% between 2000 and 2016, representing an average annual increase in international visitor nights of approximately 3% per annum (10). This growth in the international market can largely be attributed to the emergence of new source markets and, in particular, the growth of the Chinese market, but also India and other South East Asian nations. These markets prefer to visit major cities and this has seen a shift in tourism activity towards destinations such as Brisbane (11). Such a trend provides an opportunity for the Moreton Bay Region to leverage off the growing Brisbane tourism market, perhaps by highlighting the proximity of the region to Brisbane and hence the opportunities for daytrips from Brisbane to the Bay region.

International visitors to the Moreton Bay Region are primarily from New Zealand, Asia and the United Kingdom. Compared to Queensland as a whole, the region excels at attracting visitors from New Zealand (34% vs state average of 20%) and the United Kingdom (16% vs state average of 11%), while it has not done as well in capturing the Asian market (23% vs state average of 37%) (5, 6).

Domestic visitors to Moreton Bay are largely from the greater Brisbane area (58%) and it is a more popular destination for daytrips than overnight stays — 66% of day-trippers come from the Brisbane region, while only 31% of the overnight market comes from Brisbane. For the southern end of the Moreton Bay Region (the Redlands City Council area), domestic day-trippers from the Gold Coast are an important segment (23%), whereas more domestic day-trippers from the Sunshine Coast (19%) visit the northern end of the Bay (the Moreton Bay Regional Council area). A further 31% of the overnight visitor market is from other Australian states and the remainder from other regional areas in Queensland (5, 6).

The largest proportion of visitors (international and domestic) to the Brisbane region travel to see family and friends (approx. 40%). However, a higher proportion of international tourists are visiting for a holiday. The most commonly used type of accommodation is staying with friends and relatives (69%), followed by house/apartment/unit/flat (16%) (5, 6).

The most popular activity during a visit to the Moreton Bay Region for domestic visitors (including both daytrips and overnight stays) is spending time with friends and family, undertaken by about 47% of domestic visitors. Other popular activities include eating out at restaurants (38%), going to the beach (including swimming) (18%), and general sightseeing (16%) (5, 6).

While the Moreton Bay Region is host to a wide range of visitors and recreational users, many of them would not view themselves as tourists, nor be captured in the formal tourism data. Nevertheless, all of these people are visitors to the waters of the Bay, whether local resident or not, and each places value on the resources of the Bay for recreation and enjoyment.

Supply of tourism in the region

In addition to the services and products that are typical of most urban areas (cafes and restaurants, cycling and pedestrian paths, markets, parks, and sporting infrastructure such as bowls and golf clubs), the Moreton Bay Region has a number of unique tourism assets, infrastructure and experiences (Table 1), as well as a variety of accommodation options (Table 2). While marketing of the region does indeed highlight these unique aspects, they additionally provide an opportunity to further differentiate the region and hence potentially further grow tourism to both the Moreton Bay and Brisbane regions.

Table 1. Moreton Bay Region tourism infrastructure, product and experience audit.

National Parks (NP)

- South Stradbroke (50% NP), Moreton Island (98% NP), Bribie Island (33% NP), Peel Island (100% NP), St Helena Island (100%)
- Venman Bushland National Park, D'Aguilar Ranges National Park – South D'Aguilar and Mount Mee sections, Bellthorpe National Park
- Fort Lytton National Park including historical area

Reserves, wetlands, conservation areas

- Buckley's Hole Conservation Park, Sheep Station Creek Conservation Park, Bunyaville Conservation Park, Point Halloran Conservation Area
- Bribie Island Recreation Area, Mt Glorious recreation area, Mt Nebo recreation area, Lake Samsonvale and Mt Samson recreation precincts
- Bunya Crossing Reserve, John Oxley Reserve, Victoria Point Reserve, King Island – Wellington Point Reserve, Nudgee Beach Reserve
- Egret Colony Wetlands, Glen Road Wetlands, Black Swamp Wetlands, Geoff Skinner Wetlands, Valley Road Wetlands

Marinas and water-based activities and experiences

- Fishing, beaches and beach activities, surfing, scuba diving
- Compass Marina, Newport Marina, Scarborough Marina, Cleveland Harbour and Marina, Manly Harbour
- Victoria Point, gateway to Coochiemudlo Island
- Whale-watching cruises, various cruises/boat charters, Bay and island cruises
- St Helena tours

Animal sanctuaries

- Tangalooma dolphin experience, Alma Park Zoo, Kumbartcho Sanctuary, Lyell Deer Farm

Adventure tourism experiences

- Scuba diving, 4WD driving, camel rides, sand-dune tobogganing, paragliding, quad biking, hiking
- Lakeside Park raceway, Bushy Browns Adventure Ski Park, skydiving (Redcliffe), Surf Connect Watersports Centre

Museums and culture	
• Pine Rivers Heritage Museum, Redcliffe Museum, Avicultural and Poultry Museum, Caboolture Historical Village, Caboolture Warplane Museum, Samford District Historical Museum, Woodford Community Museum, Redlands IndigiScapes Centre, Queensland Ambulance Museum, Sandgate and District Historical Society and Museum, Salt Water Murris' Quandamooka Gallery, Minjerribah Moorgumpin Aboriginal Elders in Council house	
Wineries	
• Dr Red Winery, Ocean View Estate Winery, Sirromet Winery	

Note: The summary list was compiled based on online database searches from Visit Brisbane, Moreton and the Redland and Moreton Bay Regional Councils' website. Operators without a website may not have not been included.

Table 2. Moreton Bay Region accommodation audit.

	North Stradbroke	Mainland Redlands City Council	Southern Moreton islands	Bribie Island	Mainland Moreton Bay Regional Council	Moreton Island	Total
Beds and breakfasts	1	2	4	3	16	0	**26**
Cottages and cabins	5	1	5	0	18	0	**29**
Guesthouses	1	1	0	0	7	0	**9**
Farmstays	0	0	0	0	3	0	**3**
Motels and hotels	0	11	0	2	19	0	**32**
Resorts, holiday apartments and units	14	0	3	8	8	1	**34**
Caravan parks and camping	9	0	3	10	13	5	**40**
Backpackers	1	0	0	0	1	0	**2**
Total	**31**	**15**	**15**	**23**	**85**	**6**	**175**

Note: The summary list was compiled based on online database searches from Wotif, TripAdvisor, Google, Visit Brisbane, Moreton Island Accommodation and Redland and Moreton Bay Regional Council's website as of June 2018. As there are many operators in the region who are yet to 'go online' with their tourism business, there may be operators who have not been included in this summary list. This list does not include privately owned houses that are rented out as holiday homes.

Moreton Bay Region tourism marketing

Moreton Bay is currently promoted within the broader 'Visit Brisbane' tourism campaign, whereas strategies to promote the 'Moreton Bay and Islands' as a travel destination are developed and managed by 'Brisbane Marketing'. Brisbane's tourism development plans rely on the natural features of the Moreton Bay Region — the

Moreton Bay Marine Park, D'Aguilar National Park, and three of the world's largest sand islands: North Stradbroke (Minjerribah), Moreton (Moorgumpin) and Bribie Island (Yarun) — as key assets by which the Brisbane tourism region can differentiate itself from other capital cities.

The Moreton Bay Regional Council and Redlands City Council both promote tourism through tourism information centres and their websites. Within the Moreton Bay Regional Council area, there is also a third organisation tasked with developing and executing destination marketing projects and campaigns to promote the region — Moreton Bay Region Industry & Tourism (MBRIT). This industry-led, destination management organisation focuses on tourism in only the Moreton Bay Regional Council area and promotes only those organisations that are financial MBRIT members.

State/regional tourism policy and planning

The key tourism planning document for the Brisbane tourism region is the *Brisbane Visitor Economy Strategy: A Destination Tourism Plan for Brisbane 2014–2020.* Key priorities as outlined in the Plan related to the Moreton Bay Region (Moreton Bay and Redlands) include:

- Increase economic contribution of tourism to the Bay by converting day visits to overnight trips;
- Growth and development of tourism consistent with community values and lifestyle considerations, and by promoting a collection of Moreton Bay Adventure Experiences across the region as key events and an economic strategy;
- Extend market share, length of stay and the value of tourism to the Redlands;
- Encourage investment in tourism accommodation;
- Develop a working group with industry and government representation to develop an overarching strategic plan for the transition from mining to tourism on North Stradbroke Island;
- Create new precincts (destinations) that meet the needs of locals and visitors with tourism-orientated development, facilities, infrastructure and marketing;
- Build a positive image for the region and support the local way of life while embracing our indigenous history and living culture;
- Become a year-round destination leveraging our climate and range of activities and experiences; and
- Activate public spaces for festivals and events and actively assist event organisers to hold events in the Redlands.

Other current strategies include the *Queensland Tourism Investment Guide 2016* which details the Queensland Government's key strategies to increase the attractiveness of Queensland's tourism industry, and the *Brisbane City & Hinterland Regional Tourism Investment and Infrastructure Plan 2008–2018.* They identify key infrastructure projects for the Moreton Bay Region including:

- Improving/changing the transport infrastructure to and on the Moreton Bay islands. This specifically includes ferries, piers and jetties, transportation options on the islands, and interaction between the various transport modes;
- Improvement to public transport on the Moreton Bay coast (e.g. redeveloping rail stations, creating light rail/trams on disused rail lines, and running more buses such as from Caboolture to Bribie Island);
- Providing opportunities in appropriately defined locations within the island national parks for eco-accommodation to be built; and
- Improving the management of waste water within the Bay area in order to ensure no/limited compromise to the marine environment (12–14).

Opportunities and challenges for sustainable tourism in the Moreton Bay Region

Marine recreation and tourism in the Bay

Moreton Bay has a wide range of commercial tourism operations that use the waters and intertidal areas of the Bay as their primary attraction. These operators tend to focus on attractions that are either wildlife related — such as dolphins, humpback whales (July to October), dugongs and seabirds — or on specific activities that have demand from locals and visitors. Examples include fishing, scuba diving, snorkelling, surfing and sailing. In addition, two commercial tourism resorts are based on the western shores of the islands that bound the eastern edge of Moreton Bay. Tangalooma Resort, on the western shore of Moreton Island, was established in the 1960s and in its early years primarily served local residents and visitors from southern states during school holidays and the winter months. During the 1990s, the resort transitioned from a timeshare-based model focused on the domestic Australian market to a more diverse market. Customers now include international package tourists from South East Asia, and independent travellers from the northern hemisphere and from New Zealand. Most recently, the resort has developed apartments/units and house-and-land packages which are sold to clients who then become frequent and regular visitors to the resort and the island. Couran Cove Resort, on the western shores of South Stradbroke Island, is a more recent development. In a similar way to Tangalooma, it strongly markets itself as an ecotourism-style location whereby visitors can experience a close connection to the natural environment of Moreton Bay and the surrounding islands.

Despite some significant tourism infrastructure, most of the marine tourism that occurs in the Bay area is neither resort-based nor commercial tour-led. It is instead more self-directed whereby both local residents and visitors to the region engage in recreational activities associated with the Bay. This more casual self-directed recreation is significant but quite difficult to quantify. Examples include renting four-wheel drive vehicles, camping, exploration trips on Moreton Island (which often involve sightseeing, fishing, beach walking, swimming, surfing, snorkelling and so on), transport to islands for day- or overnight trips, such as to North Stradbroke, St Helena, Coochiemudlo, Peel, Bribie and Moreton islands. Boat-based voyages are also a major use of the Bay ranging from small trailer outboard engine-powered boats to larger charter yachts. Access to the Bay for launching and retrieving vessels is via many public boat ramps and major marinas at Manly, Scarborough, Rivergate (Brisbane River) and Cabbage Tree Point (Woongoolba). Other users access the Bay from marinas based on the Gold Coast or the Sunshine Coast. In addition, a major feature of the coastal environment in South East Queensland has been the establishment of residential communities based on human-made canals. Such developments provide local residents with access to the waters of Moreton Bay via docks, boat ramps and piers built within these canal-based residential communities. As a consequence, many recreational users of the Bay are property owners or renters who see Moreton Bay as their ‘playground’.

A further significant and distinct sector of visitors who are frequent users of the Bay are those who have their primary residences elsewhere but who own holiday homes or apartments in the Moreton Bay coastal region. These semi-residents tend to use these properties as investments (both for short-term rental to visitors and for capital gain) and as places for their own vacations. Many of these semi-residents live permanently in southern states or New Zealand and use the warmer climates of South East Queensland as an ‘escape from the winter’.

Tourism and recreation impacts and sustainability

The increasing use of the Bay and the surrounding coastline has a wide range of effects on the host ecosystems and often adds pressure to locations already compromised by many other human influences. Moreton Bay has long been recognised as a special and sensitive ecosystem. Its designation as a marine park is an explicit attempt to ensure that human interaction in the park is sustainable and that ecological values are conserved. The location of the rapidly growing city of Brisbane and the associated urban development of the coastline and near-shore coastal catchment present the most significant challenges for the Bay. The effects of human activities on the Bay are numerous and include: water run-off, sedimentation, increased nutrient loads, toxins and chemicals, coastal infilling, dredging, dumping, coastal structures, canal developments and coastal current redirection, commercial and recreational overfishing, noise pollution, introduction of alien and harmful organisms, wildlife disturbance, litter and debris, eutrophication of tidal estuaries, increased water temperatures (due to climate change and the decreasing depth of the Bay and reduced current flows), growth and encroachment of mangroves, and coastal erosion. Such degradation paints a bleak future for Moreton Bay and causes many to question whether sustainability is in fact achievable.

The growth of tourism and recreational use of the Bay forms part of this wider pattern of increasing effects of human activities on the Bay and could be viewed as a further contributor to human-induced degradation. However, it is worth remembering that part of the motivation for establishing the Moreton Island National Park, Bribie Island National Park, Moreton Bay Marine Park and other protection mechanisms, which have stopped the development of these important areas, has been because of their value for recreation and tourism. Further examples of hope include the strong evidence that humpback whales (*Megaptera novaeangliae*), once hunted to near extinction off the eastern Australian coast, have made a remarkable and strong recovery. In addition, the movement to stop sandmining on the Moreton Bay barrier islands was fought and won by many residents and visitors who love the Bay region for its ecological and recreational values. Many conservation initiatives exist in the Moreton Bay Region and those who use the Bay for recreation and as visitors (whether locally resident or not) are the leaders and contributors to these initiatives. This is where the key lies for the sustainable use of the Bay.

Indigenous tourism

North Stradbroke Island or Minjerribah is the home of the Quandamooka Peoples who offer a range of Aboriginal cultural experiences, from guided headland and bush walks to boomerang painting and throwing. Visitors can experience traditional Aboriginal song and dance, discover the bush tucker trail, learn more about the art and craft of the Quandamooka Peoples, see a cultural site thousands of years old and take a whale-watching cultural tour. The Quandamooka Yoolooburrabee Aboriginal Corporation (QYAC) offers cultural experiences for tourists, school and university groups. It also helps to develop cultural tours, talks, presentations and demonstrations in line with school and university curriculums. QYAC is currently involved in the Amity Eco Project with Straddie Camping and the Australian Government's Australian Trade Commission. This project aims to improve the North Stradbroke Island camping holiday experience and to present the camping grounds in such a way that the nature and culture of North Stradbroke Island is celebrated and respected (15, 16). Each cabin will draw inspiration from traditional Australian tent styles and the quintessential North Stradbroke Island beach shacks, whilst also integrating the Quandamooka Peoples' cultural considerations in design concept and application (15, 16).

In the North Stradbroke Island town of Dunwich there are two Indigenous-operated galleries — Salt Water Murris' Quandamooka Gallery and Minjerribah Moorgumpin Aboriginal Elders in Council (MMEIC) house. The Salt Water Murris' Quandamooka Gallery is a contemporary Aboriginal visual arts and craft centre while MMEIC houses an exhibit depicting the history and culture of Minjerribah–Moorgumpin (North Stradbroke Island and Moreton Island) and a mini bush-tucker trail on the grounds. This trail is the prototype for the one being developed at Terra Bulla Luemeah Conservation Reserve. On the mainland is the Redlands IndigiScapes Centre. While the centre is primarily a botanic garden that offers a number of guided experiences, one of those experiences is the Indigi Bush Tucker Tour (17).

In addition to the Indigenous tourism experiences offered on Stradbroke Island and at IndigiScapes, the Redland City Council has plans to build on the Moreton Bay Region's significant Indigenous cultural history (4). As outlined in the *Redland City Tourism Strategy and Action Plan 2015–2020*, there are plans to create better links with the international cruise market in the area to offer combined local half-day eco tours and Indigenous products. Day excursions are also planned to tap into the local South East Queensland high-school market. With the redevelopment of the Toondah Harbour, the

Council has an opportunity to advocate for including an Indigenous Interpretive Centre (4).

Events

The broad assortment of festivals and events that are staged across Moreton Bay make a significant contribution to the diverse appeal and cultural depth of the region. The range of festivals and events that occur in Moreton Bay (i.e. concerning business, charity/fundraising, performing and visual arts, education, environment, lifestyle, health and wellbeing, sport, and markets) showcase an abundance of creativity, innovation and inventiveness synonymous with the region. Concomitantly, they also attract tourists eager to participate in the gamut of experiences offered by the variety of festivals and events staged across the Bay. For instance, each year the Quandamooka Festival, an Indigenous cultural event, is celebrated from July to September and offers activities across the Redlands, Moreton Bay and Brisbane area. Highlights of the festival include cultural tours, traditional song and dance, music, art exhibitions, workshops, film nights, traditional food, markets, storytelling, weaving, sand art, sporting events and speakers' forums (18). Additionally, Queensland Youth Week is a sporting event hosted by the Royal Queensland Yacht Squadron. This major youth yachting regatta is held over a week during the July school holidays and attracts around 200 competitors and 150 supporters and has grown to become a significant annual regatta for the Australian competitive sailing community. In addition, the Brisbane to Keppel Yacht Race, which began in 2006, is a major coastal yachting event that begins in Moreton Bay each August.

Currently, there are number of signature events in the Moreton Bay Region, including the Urban Country Music Festival, the Pine Rivers Festival, Celebrate Redcliffe Festival and the Festival of Sails. In 2010–2011, events in Moreton Bay enjoyed an overall attendance of 157,000 people (19). Along with these signature events, the Moreton Bay Regional Council is not only 'investigat(ing) the opportunity to conduct an annual arts event to showcase the region's creativity'(20 p8), but are also working to develop a range of high-profile and community festivals and events to ensure 'residents and visitors can participate in diverse community events, recreation and cultural opportunities' (19 p4).

Community events can be a unique expression of the Moreton Bay Region and increasingly represent an opportunity to grow community-based tourism. Indeed, the daytrip traveller market, the purpose of which is to participate in events and festivals, has the potential to continue to grow strongly. Therefore this sector needs to continue to be targeted as a key initiative in local tourism and economic development. However, at the same time, it is important that the region works to avoid negative social and environmental impacts that can occur as a result of events (e.g. noise pollution, crowding, waste) by embracing sustainable event-management practices.

Conclusions

Tourism is arguably of growing importance for the Moreton Bay regional economy and forms an integral part of the wider tourism product and market appeal of the Brisbane region. Tourism to Moreton Bay has increased over the past decade with growth in both international and domestic arrivals; and, at the same time, the region remains popular with daytrip visitors from South East Queensland. Tourism infrastructure in the region is growing, yet there are further opportunities to improve visitor length of stay and spending, particularly in commercial accommodation providers, as the region has such a large proportion of day trippers and visitors visiting friends or relatives. These strategies have been identified as priorities in the various state, regional and local development strategies.

While there is much opportunity for developing tourism, the region must contend with the increasing impacts of human activities on the Bay by tourist and recreational users. This presents a significant challenge for the sustainable development of the region and arguably the extent to which conservation initiatives can be maintained and extended is key for the sustainable future of the Bay and broader region. Opportunities exist in terms of developing the region's Indigenous tourism product as well as the event sector. Both have appeals for local as well as interstate and domestic visitors and present opportunities to further differentiate the Moreton Bay region from competitors.

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Aquaculture in Moreton Bay

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Abstract

Moreton Bay prawn farmers have prospered over the past 20 years, despite endemic prawn diseases, broodstock shortages, and regulations on nutrient release into the surrounding environment. The established intensive prawn farms on the Logan River sustainably expanded in the early 2000s and successfully competed with a mass of seafood imports. However, the recent outbreak of the exotic white spot disease has been a major setback for the industry. The farmed oyster industry in Moreton Bay has also been challenged. Once a dietary staple of the Quandamooka People and South East Queensland's largest and single most important fishery, production of the native Sydney rock oyster dwindled during the twentieth century. The inefficiency of oyster areas has been linked to a short harvest season, disease, competition from the exotic Pacific oyster, a high proportion of hobbyist farmers and poor water quality in the Bay. Better economic opportunities in nearby Brisbane may negate regulators' plans to attract more ambitious farmers to the industry. Currently, within Moreton Bay, oyster farming requires improvements in efficiency, prawn farms have commenced restocking after closures due to disease outbreak and there are no sea cage farms. The future of aquaculture in Moreton Bay requires proactive management that recognises the complex ways in which present-day metropolitan and catchment development challenge sustainable growth of the industry. By careful consideration of these issues and applying recent advances in Australian aquaculture technologies, aquaculture enterprises in the region could achieve sustainable growth with an effective balance between economic success and conserving Moreton Bay's unique ecosystem.

Keywords: prawn, shrimp, oyster, farm, pond, sea cage, South East Queensland, Brisbane

Introduction

Aquaculture supplied ~40% ($120 million) of the total Queensland fisheries value in 2015–16, with ~91% of aquaculture value from prawn and barramundi (1). In 2015–16, aquaculture production in Queensland was 7,783 t, of which Moreton Bay contributed 1,172 t (1). Recently, oyster areas (Sydney rock oyster, *Saccostrea glomerata*) have contributed a relatively small proportion of this, with land-based prawn farms (black tiger prawn, *Penaeus monodon*) suppling the bulk of the production.

Oyster growing occurs in four areas of Moreton Bay Marine Park: Moreton Island, North Stradbroke Island, Pimpama River and Pumicestone Passage (Fig. 1) (2). Spat, mostly sourced from NSW but also from Moreton Bay, are generally grown to maturity and fattened with tray cultivation and adjustable longline systems. Harvesting occurs between August and April (2).

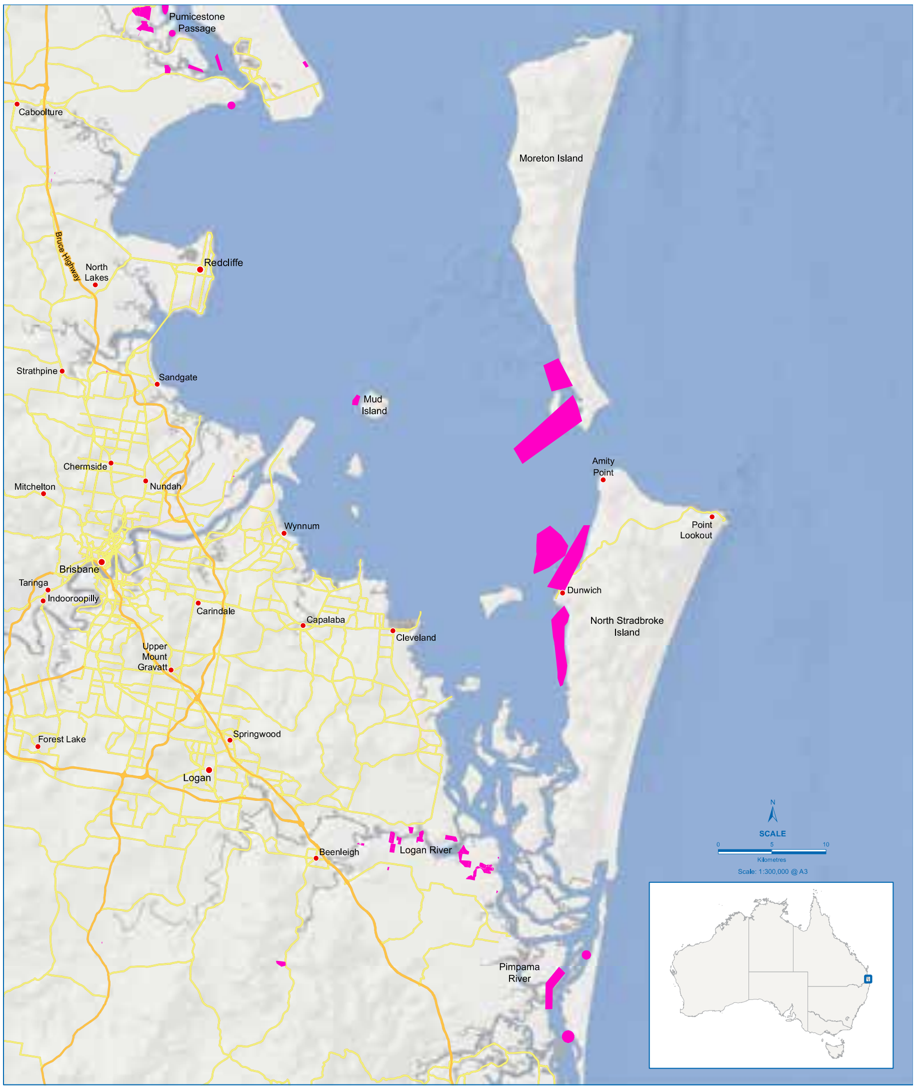

Figure 1. Aquaculture areas in Moreton Bay.

Smaller (bistro-grade) oysters have shorter grow-out times (2 to 2.5 years) and tend to be produced in Moreton Bay to reduce risk of stock loss and maintain cash flow (2, 3). Sixty-seven oyster businesses operate the 97 approved areas that cover 435 ha of the Bay (2). In 2015–16, the total annual production of oysters in Moreton Bay was 109,577 dozen, valued at $563,970 (1) (Fig. 2).

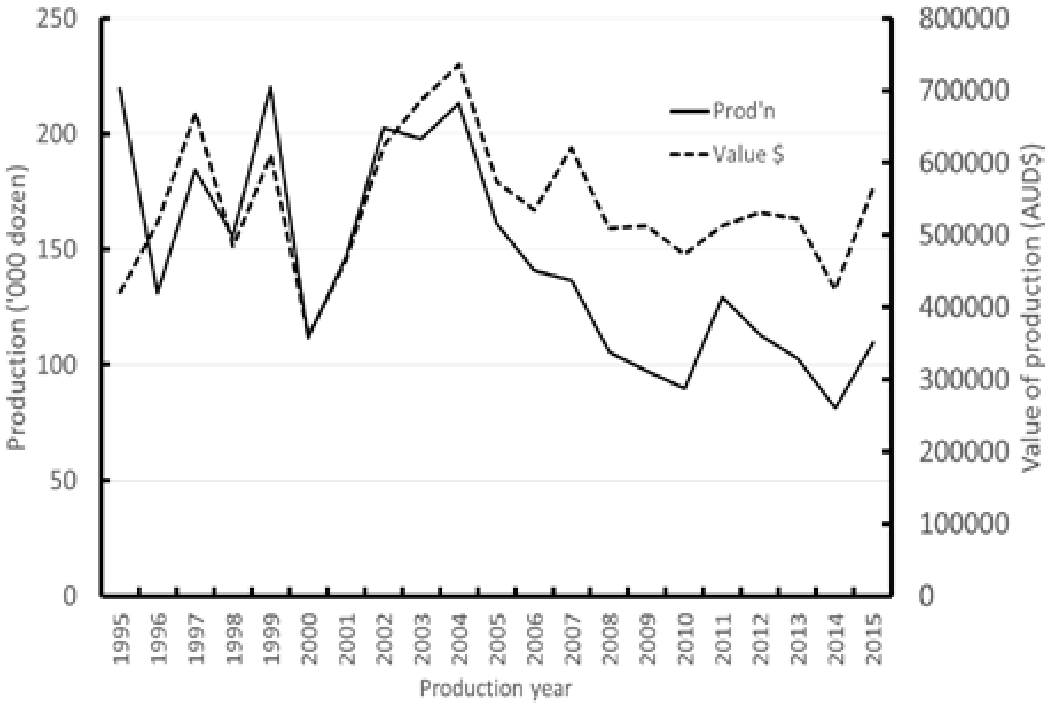

Figure 2. Production ('000 dozen) and value of the oyster industry in Moreton Bay (1995 to 2015 season).

Seven prawn farms (total ~150 ha) have seawater ponds (generally 1 ha each) on flat farmland adjacent to the Logan estuary (Fig. 1). Post-larvae from Logan estuary hatcheries are stocked in ponds (at densities of 25 to 40 per m^2) and grown on a formulated diet to market size in approximately six months (4). Stocking generally occurs in October, and harvesting and sale from April to June (4). In 2014, Moreton Bay produced 1,384 t from the 116 ha of ponded area (Fig. 3, 4) and was worth more than $20 million per annum (5). However, in the summer of 2016–17, a breach in biosecurity impacted the prawn aquaculture industry when uncooked prawns infected with the exotic white-spot disease (WSD) were imported and distributed in the Moreton Bay region (6).

Brief history and current trends

Oyster aquaculture

The presence of shell middens confirms that oysters were harvested by generations of Aboriginal people inhabiting the region now called Moreton Bay (7, 8). The Quandamooka People probably also farmed oysters in Moreton Bay, as there is evidence in nearby northern New South Wales (NSW) of Aboriginal people returning shell material to estuaries to promote settlement of oyster spat (9).

Early settlers quickly exploited existing intertidal and subtidal oysters beds both for human consumption and to manufacture construction lime (10). During this time, Moreton Bay was considered to be an excellent oyster production area and exported spat to southern colonies (10). However, natural oyster beds were over-exploited which lead to government regulation (*Oyster Acts 1863*, *1874* and *1886*) early in the industry's history. This largely failed to control pressure on the resource. In addition, land practices resulted in increased sediment inputs to inshore areas by 1870. This was the likely cause of the decline of subtidal oyster reefs that were infested by spionid polychaete mudworms after major flood events in the late nineteenth century (11).

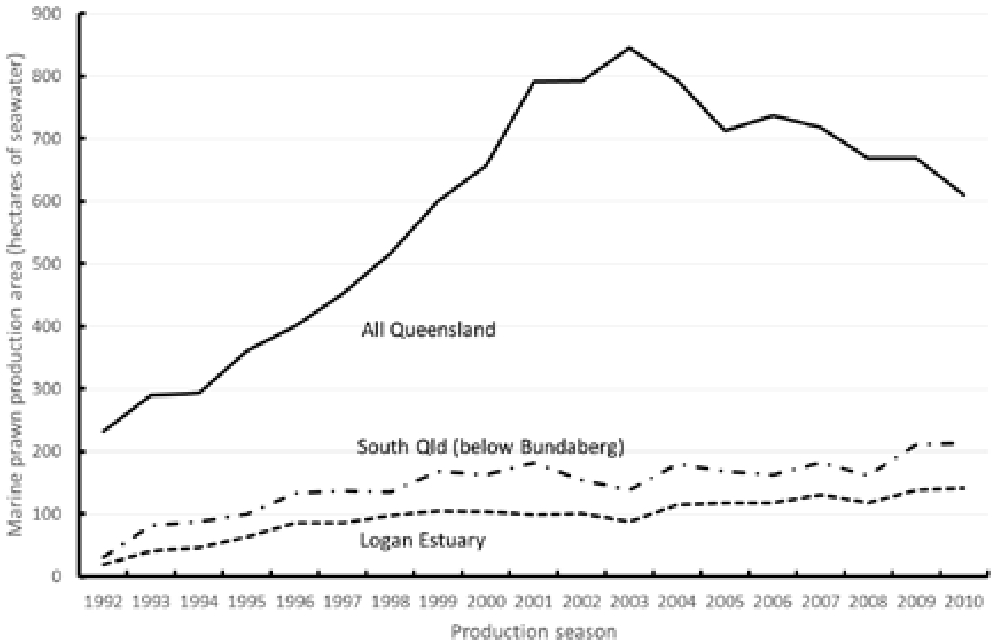

Figure 3. Area of ponds producing marine prawns in Queensland during each growing season from 1992–93 to 2010–11 (Data: Department of Agriculture and Fisheries).

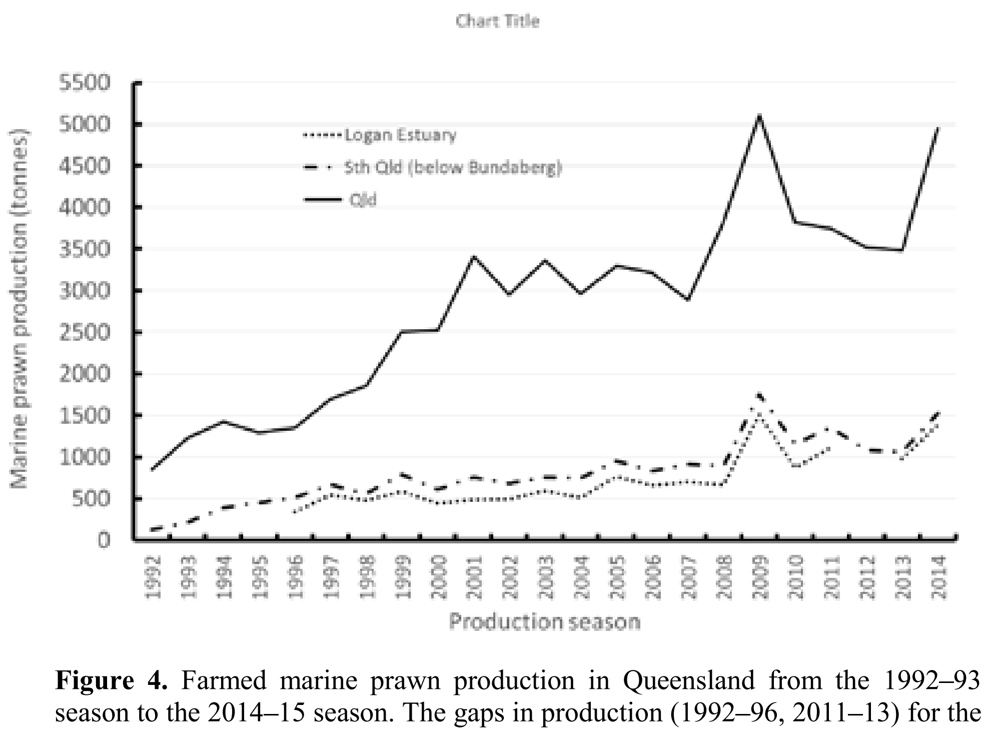

Figure 4. Farmed marine prawn production in Queensland from the 1992–93 season to the 2014–15 season. The gaps in production (1992–96, 2011–13) for the Logan area are to protect confidentiality when fewer than five farms produce that season (Data: Department of Agriculture and Fisheries).

In response to depleted natural stocks, organised farming by bank oystering began in the 1870s (3, 10). Bank oystering initially used sticks, rocks, and shells to collect spat-fall and grow out natural oysters in the intertidal (10). Oyster production in Moreton Bay escalated from ~4,500 bags (281 t) in 1870 to its peak of ~21,000 bags (1,313 t) in 1891, when the greatest production came from bank oystering (10). In the early 1900s, farming infrastructure evolved to stick and tray culture in response to bed losses to floods and oyster pathogen incursions, particularly the mudworm, *Polydora* sp. (3, 10). This involved collecting spat on sticks, removing excessive spat and leaving the remaining oysters to mature on stick and/or fattening the oysters in grow-out trays.

Oystering was considered the largest and single most important industry in the region until the 1920s (10). However, mudworm, floods, stock theft and increasing competition from NSW and New Zealand challenged the industry (3, 10, 12). Uncertain tenure also meant Moreton Bay producers were reluctant to invest in the labour and equipment required for stick and tray cultivation (10). By the early 1920s, annual oyster production in Queensland had declined to ~2,000 bags (125 t) per annum (10, 13). Production has also been heavily reliant on spat from NSW since 1936 due to low natural recruitment (3).

While the oyster industry thrived in NSW from the 1960s, production in Queensland remained low (3). The industry suffered from QX disease caused by the parasite, *Marteilia sydneyi,* competition with the exotic Pacific oyster (*Crassostrea gigas*), and food safety concerns (14). Innovations from NSW and elsewhere, such as the sale of single seed oysters (individual 'loose' spat), selective breeding hatcheries, sterile triploid Pacific oysters and recyclable plastic culture trays for oyster cultivation, have not increased Moreton Bay oyster production. Recently, annual production has fluctuated between ~100,000 and 220,000 dozen, with the annual industry value between ~$400,000 and $700,000 (Fig. 2). If a 'bag' contains 120–130 dozen whole oysters (15), then that is less than 2,000 bags per annum in the old units, and less than 10% of peak historic levels.

Since 2007, production has fluctuated between ~80,000 and 130,000 dozen, though higher prices have seen industry value hold at ~$500,000 per annum. The inefficiency of production in existing oyster-growing areas is likely due to the short harvest season, QX disease, competition from Pacific oyster, poor water quality and the relatively high proportion of hobbyist farmers in the industry (3). An oyster industry plan for the Moreton Bay Marine Park was developed in 2008 and reviewed in 2015 (16). The plan provides the tenure needed for long-term investment and is accredited under the *Marine Parks Regulation 2006*. Individual oyster growers who conduct their operations within the framework of the plan do not require a Marine Parks permit. Some growers have increased production using the provisions allowing a working platform on the area. An industry renewal policy issuing resource allocation authorities was also developed which established minimum production levels for authority holders. Some notices have been issued, but even if authorities to operate oyster areas are surrendered, attracting ambitious growers and labour remains a major challenge given the close proximity to better economic opportunities nearby in Brisbane (17).

Prawn (shrimp) aquaculture

In the early 1970s, Australian agribusinesses considered the two models of prawn farming available: intertidal farms or high-density tanks. Traditional intertidal farms in Asia had poor yield, but high-density production in tanks on land was unproven and likely expensive (18). In 1971, one corporation tried hatching brown tiger prawn (*Penaeus esculentus*) in tanks near Cleveland, but attempts there and later in Port Douglas were unsuccessful and the trials were abandoned in 1976 (19). A pilot of indoor production at Southport was also unsuccessful (19).

In Taiwan, farmers found a middle path by culturing prawns in small outdoor ponds built on coastal farmland (20, 21). Taiwan's land-based prawn farms produced so many black tiger prawn (*P. monodon*) that feeding, aeration and massive seawater changes were essential (20, 21). Even though this industry crashed in Taiwan in the late 1980s due to an epidemic of unforeseen prawn diseases (22), land-based prawn farms expanded into several other countries (23, 24). When world sugar prices crashed in the mid-eighties, a number of cane farmers on the banks of the Logan estuary (southern Moreton Bay) also diversified into prawn farming (26).

Land-based prawn farming in Australia first appeared in NSW, but farms established shortly after in tropical Queensland quickly dominated national production (25, 26). Most ponds were built in the warmer climates in the north of the state, where two crops per year were possible. The returns per hectare for prawns were better than for agriculture. Risks, uncertainties and opposition from existing seawater users (25) eventually led the Australian Government to intervene using regulations developed to ensure prawn farms had no additional impact (in terms of point source discharge) to the Great Barrier Reef (GBR) (27). The total area of prawn ponds in northern Queensland decreased as early farms closed or diversified production to barramundi (Fig. 3). Nutrient and suspended sediment restrictions were also placed on the Logan estuary prawn farms. In response to these controls, Moreton Bay prawn farms made significant contributions to advances in global research into environmental management of prawn farms (28). Despite this, at its recent peak, only a small fraction of Queensland's coastal land was dedicated to prawn farming and a small part of that was in Moreton Bay (Fig. 3, Fig. 1).

In the mid-1990s, the dependence on wild broodstock caused production to lag behind pond construction (Figs 3, 4). Farmers discovered that visibly healthy wild prawns could still pass a suite of hidden pathogens to their offspring (29, 30). In 1993 and 1994 a mid-crop mortality syndrome (MCMS) stalled production in Queensland (Fig. 4). Northern farms that dried ponds to break the infection cycle then risked having little or no crop if hatcheries could not deliver post-larvae at the crucial time (31, 32). Elsewhere, production crashes in Asia followed outbreaks of new, extremely virulent pathogens, white-spot syndrome virus (WSSV) and yellow-head virus (YHV1) (29, 30). Queensland's wild black tiger prawn already hosted the pathogen linked to MCMS (i.e. YHV2, a milder variant of YHV1), thereby softening the impact of the local pathogen (33, 34).

Farmed prawn production in southern Queensland avoided many of the issues faced further north during the 1990s (Fig. 4). Farms in northern Queensland could produce 8–10 t/ha y^{-1} in back-to-back 4–5 t/ha crops (32, 35, 36). When the disease-affected northern farms resumed production in 1997, the increasingly efficient Logan River producers grew nearly one-third of Queensland's farmed black tiger prawn, using two-thirds of the ~86 ha of production ponds beside the estuary at the time (37). These farms were sustainably harvesting 6–7.5 t/ha crops (38–41).

Australia's higher valued export brown tiger prawn (*P. esculentus*) and other species familiar to local consumers (i.e. the banana pawn *Penaeus merguiensis*) were occasionally cultured in the first few years (42), but Queensland prawn farmers ultimately chose black tiger prawn as techniques were established and feed was available (36, 40, 43). A small prawn farm near Cleveland also established live export of *Penaeus pulchricaudatus* [formerly *japonicus*], the local equivalent of Japan's prestigious prawn 'kuruma ebi' (44). By the mid-nineties, up to seven southern Queensland prawn farms were exporting live Queensland 'kurumas' (45). Overseas investors avoiding WSD in Asia built two kuruma farms, one near Bundaberg and another near Steiglitz in southern Moreton Bay, approximately 5 km south of the mouth of the Logan River (46). By then, unregulated translocation of northern hemisphere kuruma prawn amongst countries near Japan had spread WSD through nations bordering the Sea of Japan (29, 47). Queensland's kuruma production peaked at 250 t per annum in 1996 (from 60 ha), approximately half of southern Queensland's marine prawn output (Fig. 3). However, economic troubles in Asia quickly drove local prices down (48–50) and live export of kurumas from Queensland ceased in the 2005–06 season (51) due to the high costs of culture and export, and local viruses causing low stocking rates (52, 53).

Meanwhile local black tiger prawn production was impacted by another shortage of healthy breeders and post-larvae (54), resulting in insufficient broodstock to fill 800 ha of available ponds (54, 55) (Figs 3, 4). Broodstock collectors were also excluded from the best broodstock areas by the revision of the GBR marine park zones, with aquaculture competing with commercial fishing in the remaining areas (56, 57). In 2002, CSIRO started assisting one of the Logan estuary prawn farms to develop an in-house domestication and selective breeding program for black tiger prawn (58). One of Queensland's oldest farms, at Cardwell in North Queensland, also developed a domestication and selective breeding program for banana prawn, *P. merguiensis* (59). Regulated translocation of virus-tested wild black tiger prawn from prawn fisheries in the Northern Territory also began (60).

The appreciation of the Australian dollar in the mid-2000s resulted in an increase of farmed imports from South East Asia (61, 62). Disease-troubled producers in Asia switched to the relatively more bio-secure but low-value exotic prawn, *Penaeus vannamei*, using plastic-lined ponds pre-filled with seawater free of virus hosts and carriers (63, 64). The first result of increased imports was decreased domestic prices, so pond area in Australia decreased (Fig. 3), with some Queensland farms closing. Twenty-six Queensland black tiger prawn farms remained in 2006–07, eight fewer than at the peak (Fig. 4). Secondly, the imported prawns carried the same viruses that had impacted black tiger prawn production elsewhere in Asia (65).

An import risk assessment concluded that entry of uncooked, intact, farmed prawns posed the greatest risk, with surveys revealing some recreational fishers were using imported supermarket prawns as bait (66). An onerous testing regime commenced to prevent entry of WSSV and YHV-infected consignments of frozen, uncooked prawns into Australia (66); however, there was some backlash from seafood importers (67).

Domesticating and translocating broodstock from Northern Territory waters overcame the breeder bottleneck, increasing production by approximately 40% in two seasons (68) and briefly doubling production in the Logan estuary (Fig. 4). However, now that entry of exotic prawn viruses into Australian seas has been demonstrated, wild-caught breeders carry risks. By 2008, the development of domestication and breeding programs for black tiger prawn proved to be a cost-effective alternative to reliance on wild broodstock (69). Combining domestication with selective breeding enabled progressive, permanent genetic gains in growth rates and feed conversion efficiency resulting in the highest recorded yields of farmed black tiger prawn in the world (mean t/ha) (28). However, as with other agricultural sectors, production can be reduced by extreme weather events, such as the cyclones and widespread floods in coastal Queensland in 2011 (Fig. 4) (70).

In late December 2016, the exotic WSD caused a mass mortality of prawns at a farm bordering the Logan estuary (71). An eradication plan was activated in an attempt to maintain Australia's long-defended, WSSV-free status (72). By early 2017, all Moreton Bay prawn farms had been destocked and disinfected (73). The importation of uncooked prawns to Australia was temporarily suspended and a movement control order extending from Caloundra to the NSW border was put in place to prevent dispersal of the virus (74). Prawn hatcheries in this region were contained in the movement control zone. Mass importation of uncooked WSSV-infected prawns indicated a failure of Australia's biosecurity system (6). Surveillance testing in April 2018 returned positive for the virus at nine sites in Moreton Bay near Deception Bay and Redcliffe, but indicated that there had been no further spread throughout Moreton Bay or Queensland. Further surveillance testing in August and September 2018 were all negative for the virus, although testing during the same period in 2017 also returned negative results, which is likely to indicate WSSV is more prevalent in the warmer months. Three farms resumed operation in the 2018-2019 season, with additional biosecurity measures, including revised on-farm biosecurity plans, installation of water filtration for all incoming water, modified farm layouts, installed crab fencing and implementation of strict controls for the movement of equipment, staff and visitors (75).

Interaction with the environment

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Opportunities, challenges and future of the industry

Aquaculture is one of the fastest growing primary production sectors in the world, accounting for approximately 45% of aquatic animal food produced for human consumption (94, 95).

The rising demand for seafood produced through aquaculture provides a significant opportunity for the market to increase. However, industry growth faces significant challenges including water quality, diseases and competition (17).

Aquaculture is challenged by the potential environmental impacts to water quality in adjacent waterways. Each new intensive aquaculture development can add to existing diffuse pollution from the catchment (96, 97), requiring strict environmental regulations on the quality of this source of wastewater. This may be one of the reasons for the lack of any new major entrants to the Queensland industry in over a decade (98, 99). For example, the SunAqua proposal for snapper and yellowtail kingfish cages on the eastern side of Moreton Bay was refused permission to proceed by the Queensland Coordinator-General in 2004 (100). This project was refused due to concerns about nutrient discharges. A strong public campaign also objected to the project due to the potential impacts to environmentally sensitive areas (101). The rejection of this proposal has discouraged the establishment of, and investment in, Queensland aquaculture (98). Fortunately, Queensland policies have recently been put in place to support the sustainable expansion of the industry by focusing on defined Aquaculture Development Areas and adopting innovative technologies to treat the discharge wastes (102).

Currently, the major challenge for the Moreton Bay prawn aquaculture industry is the recent WSD outbreak. Prawn farms beyond Moreton Bay must also now review their vulnerability to the arrival of exotic pathogens, and consider innovations such as polychaete-assisted sand-filters and algal raceways to treat discharge water (103, 104). Accelerated adoption of filtration/remediation systems that assist in managing the WSD outbreak will be valuable additions to prawn farming environmental management technologies. Selective breeding programs producing pathogen-free prawns that are resistant to the disease are likely to assist in combatting WSD (105).

Diversifying aquaculture activities through additional species and products may also be an important risk management strategy to increase the economic viability of the aquaculture industry. Rather than resume prawn production following the WSD outbreak, one Logan estuary farm has begun trials to grow and market two new fish products, cobia (*Rachycentron canadum*) and Queensland groper (*Epinephelus lanceolatus*) (106). In Asia, replacing, supplementing or rotating prawn aquaculture with other high-value fish species has negated the risk and instability of disease outbreaks (107). In Moreton Bay, diversifying prawn farms to include finfish production to avoid WSD and/or diversifying oyster farms to Akoya pearls to negate food safety issues may enhance the economic viability of these industries. However, further research, aimed for example at supply and demand and environmental management of any new species, would be required.

Overall, the future of aquaculture in Moreton Bay requires proactive management of the whole system that recognises the complex ways in which present-day metropolitan and catchment development challenges sustainable growth of the industry. Careful consideration of these issues and applying recent advances in Australian aquaculture technologies could enable aquaculture enterprises in the region to achieve sustainable growth with an effective balance between economic success and conserving Moreton Bay's unique ecosystem.

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Fishers and fisheries of Moreton Bay

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Abstract

Moreton Bay is one of the most intensively used coastal systems in Australia and supports some of Queensland's most productive fisheries, including Indigenous, commercial, recreational and charter sectors. This paper explores the economic and cultural value of these fisheries to the Moreton Bay region and the challenges they face. Fishing is recognised as one of Queensland's oldest industries. Marine resources were harvested by Indigenous peoples long before European settlement and continue to form an important part of Indigenous culture today. Commercial fisheries operating within Moreton Bay are valued at \$24 M per annum, and target a variety of species groups including prawns, crabs, squid and finfish such as mullet, bream and whiting. Direct expenditure by the recreational sector in Moreton Bay is estimated to be ~\$194 M per annum, with fishers harvesting mud crabs, sand whiting, snapper, tailor and bream, among others. Despite the longevity of these sectors, a number of challenges exist. These include managing risks related to climate change, a growing urban population, and the need to mitigate environmental impacts from fishing and other marine activities. Interactions with other management sectors, including marine park planning and native title rights, will also need to evolve if we are to ensure a sustainable future for the fisheries of Moreton Bay.

Keywords: charter fishing, indigenous fishing, industry, prawn, recreational fishing, trawl

Introduction

Moreton Bay is one of the most intensively fished regions in Queensland. Although it comprises just 3% of the Queensland coastline, it produces about 12% of Queensland's fish catch (1) and supports some of the state's most productive commercial and recreational fisheries (2). Moreton Bay has a long history of exploitation. Archaeological evidence suggests that Indigenous fishers have harvested seafood in Moreton Bay for thousands of years, including finfish such as mullet (*Mugil cephalus*), crustaceans, shellfish (e.g. oysters, *Saccostrea glomerata*), turtles (e.g. green sea turtle, *Chelonia mydas*), and dugong (*Dugong dugon*) (3). Once Europeans settled in Moreton Bay, Indigenous peoples commercially traded fish with settlers, but many traditional methods of fishing were either eventually interrupted or halted (4).

Indigenous fisheries

Fishing (both finfish and shellfish) and marine mammal hunting form an important part of contemporary Indigenous society and practices within Moreton Bay. A number of Indigenous groups maintain strong cultural connections with this region and make use of, or have aspirations to make use of, the resources within the Bay (Pinner *et al.,* this volume) (3). For example, some of the Aboriginal people of Quandamooka, one of the Indigenous groups with cultural ties to Moreton Bay and made up of Nunukul, Ngugi and Goenpul peoples, continue to catch fish and shellfish as part of their way of life, with mullet being particularly significant, culturally and economically (3). Queensland fisheries regulations dictate that Indigenous peoples living in the vicinity of their traditional land and who wish to fish for traditional or ceremonial purposes using a commercial-sized net, must apply for a permit through Fisheries Queensland (5). Fish traps (defined as a holding area designed for capturing fish and made out of stone or organic material) can be used and, along with recreational fishing gear, do not require a licence. Seasonal closures and size and in-possession limits do not apply to Indigenous peoples who are fishing in their traditionally accessed waters or where permission has been obtained from the Traditional Owners (5).

In addition to state law, many Indigenous peoples with ties to Moreton Bay also recognise and subscribe to customary law, which governs all aspects of their traditional way of life, including communal ownership rights over their native estate (6). In 2011, the Federal Court recognised the Quandamooka Peoples' non-exclusive native title rights over 29,505ha of Moreton Bay and adjacent ocean beaches. These include 'the right to be present on the area, including by accessing and traversing the area, and take, use, share and exchange traditional natural resources and seawater for any non-commercial purpose'. This seaward boundary extends up to 200m from the high-water mark along North Stradbroke Island and the southernmost tip of Moreton Island, and encompasses an area inside of Moreton Bay (7). Because these are non-exclusive rights, the Quandamooka group exercises these rights alongside the rights of others including other Indigenous groups, and non-Indigenous recreational and commercial users.

Commercial fisheries

A number of historical commercial fisheries no longer operate in Moreton Bay, with some exhibiting a boom-and-bust pattern as a result of heavy exploitation. By the 1830s, Europeans had started fishing for dugong (which were exploited for centuries prior by Indigenous peoples) and this developed into a cottage industry for dugong oil that existed until 1920 (2). After a resurgence in the need for this oil after World War II, dugong declined in the Bay (2). Since this period, dugong numbers have increased and continued to be harvested in small numbers by Indigenous peoples, who have imposed their own moratoria in the past when they deemed the population was too low to sustain hunting (8). In the 1950s, a commercial whaling industry commenced on Moreton Island. The Australian whaling industry contributed to a rapid decline in the humpback whale population, forcing the Moreton Island operation to close in the early 1960s (2). A commercial fishery targeting turtles for meat and soup existed in Moreton Bay from the late 19th century, but declined in the early 20th century (9).

During the 19th century increasing numbers of oysters (*S. glomerata*) were extracted for food and for lime (10). By 1886, oyster banks covered 2,036ha of Moreton Bay (10), and at its peak at the turn of the 20th century this fishery harvested oysters for consumption as far away as Sydney and Melbourne (10). From the 1920s, landings from the Moreton Bay oyster fishery began a decline that continued throughout the 20th century. This resulted from a combination of factors, including flood events and poor water quality in the Bay (11), which was compounded in later decades by diseases (12) and competition from oyster growers in other regions (West *et al*., 2019, this volume) (13,14). Oyster farms (still comprising *S. glomerata*) exist today within Moreton Bay but at a reduced scale, covering 435ha in 2008 (14). Commercial fishing for prawns (Penaeidae) in Queensland commenced in the Brisbane River in the 1840s using scoop nets and scissor nets (15). However, it was not until the 1950s when a ban on otter board trawling was lifted, that a prawn trawl fishery developed in Moreton Bay (Fig. 1a). In recent years, grid W37 (a fishing area within Moreton Bay) has received more trawl fishing effort than any other coastal water in Queensland.

The ocean beach and inshore commercial fisheries have also operated since the 19th century. The Queensland Fish Board assumed responsibility for the control of statewide fish marketing in 1936 (16). After this period, and until the dissolution of the Fish Board in 1982, all fish landed for sale had to be sold through the Board and the quantities of fish sold were made available in annual reports. An unknown quantity of this catch was landed by non-commercial fishers, who for part of this period were lawfully permitted to sell their excess catch. Non-commercial fishers wanting to sell fish to Fish Board depots were required to purchase a permit, and this practice was encouraged by the government and Fish Board at the time as a means of increasing the local supply of fish. A number of distribution centres existed around Moreton Bay, which, when totalled, provide us with estimates of fish landed within the Bay. Some fish were undoubtedly landed but not processed through the Board, but these quantities are unknown.

From 1944–1981, the species landed in the greatest commercial quantities from the Moreton Bay region comprised mullet, sea bream (e.g. yellow-finned bream, *Acanthopagrus australis*), whiting (*Sillago* spp.), tailor (*Pomatomus saltatrix*), prawns and crabs (e.g. blue swimmer crab, *Portunus armatus*) (Fig. 1a). Historically, mullet was the finfish landed in the greatest quantities from the Moreton Bay region, with 651t landed per year on average, although annual landings could vary by >500t (Fig. 1a).

Quantities of fish processed by the Board were recorded by place of landing, rather than where at sea they were caught, hence the spatial resolution of these data are vague and no information on fishing effort exists. In addition, similar species were often grouped together. Despite their deficiencies, these data are the only consistent source of historical landings data for this period, and they provide a record of landings trends, year-to-year variability in landings, as well as an indication of when particular fisheries commenced.

Moreton Bay fisheries today are regulated under the *Fisheries Act 1994* (Qld), which aims for the ‘economically viable, socially acceptable and ecologically sustainable development of Queensland’s fisheries resources’. To address the limitations of Fish Board records, the

Queensland Government implemented a mandatory logbook database program for all commercial fishers to record both landings and fishing effort. Since the establishment of the logbook monitoring program in 1988, fishers have reported catches to 30-minute grids (i.e. 30 nautical miles by 30 nautical miles). Two 30-minute grids, W37 and W38, encompass the sheltered waters of Moreton Bay, as well as a limited area to the east of Moreton and North Stradbroke islands.

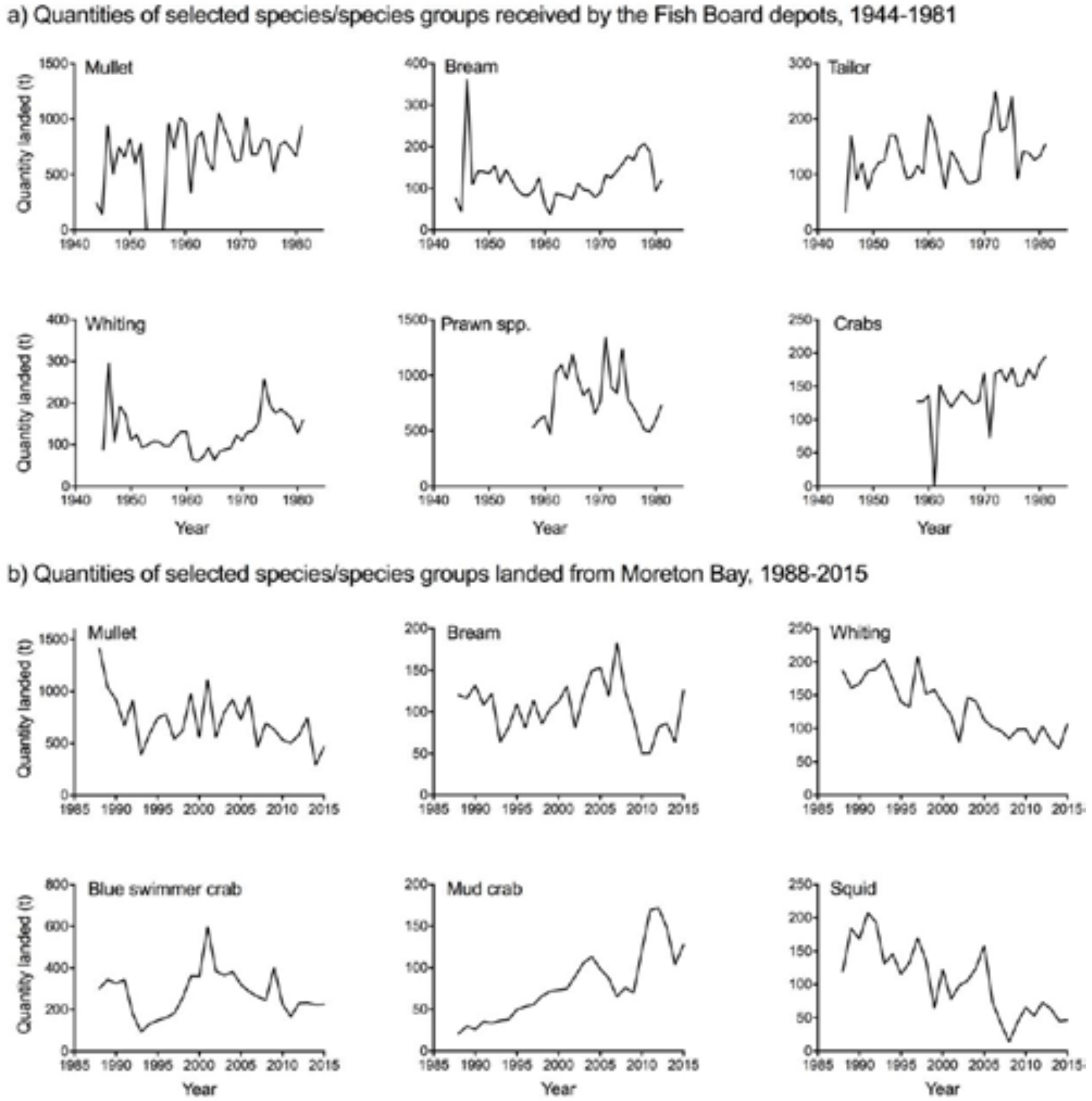

Figure 1. (a) Quantities of fish received by the Fish Board at branches and depots from fishing districts within Moreton Bay, 1944–81 (Bribie Island, Brisbane, Cleveland, Doboy Creek, Redcliffe, Sandgate, Scarborough, Wynnum). The top six species landed (ranked by total quantity throughout the time series) are shown. (Source: Queensland Fish Board reports); (b) Quantities of individual species landed from within Moreton Bay (grids W37 and W38; data sourced from the Queensland Government (1)). Note that the axes differ in scale.

Commercial fisheries are now monitored using daily catch and effort logbooks and biological data collection (e.g. length, age and sex) of key fish species. The Department of Agriculture and Fisheries (DAF) quantitatively assess the status of major fish stocks every 2 to 10 years. Where data are available, time series of catch and catch per unit effort (CPUE) are examined more frequently, although stock status is not assessed spatially at the Moreton Bay regional level. The main gear types used in Moreton Bay are otter trawl, net, pot and line (1). The commercial harvest of particular species may be regulated using a range of both input (e.g. licensing, limitations on fishing gear, limiting the time and place people can fish) and output controls (e.g. minimum or maximum size restrictions), which vary by fishery.

In 2013–14, Queensland's wild-catch fisheries produced nearly 21,000t of product with a gross value of production (GVP) of $191m (17). Moreton Bay fisheries caught 2,254t of that total (1), and prior to the 2009 rezoning of the Moreton Bay Marine Park, contributed an estimated $24–$30m per annum to the economy (18), making Moreton Bay the most important region in the state by volume and value of fish per unit area. At this time an estimated 1,000 people were employed in the commercial fishing sector (17).

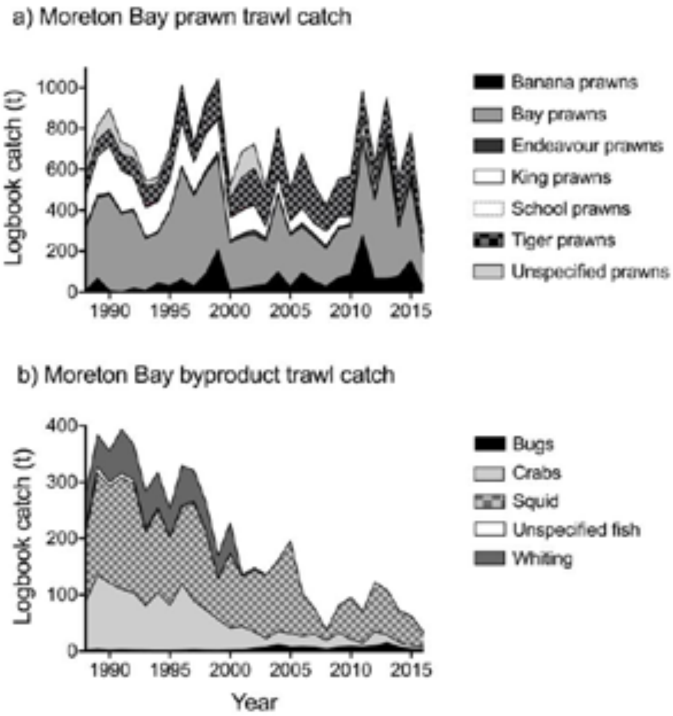

Figure 2. Reported annual catches of (a) prawns and (b) byproduct from the Moreton Bay (grids W37 and W38) otter trawl fishery, based on CFISH logbook data (1). The decline in byproduct after 2000 is largely due to the implementation of the Trawl Fishery Management Plan, which prohibited retention of whiting and introduced catch restrictions on blue swimmer crabs and other byproducts (2016 data incomplete). Note that the axes differ in scale.

Since 1988 when mandatory logbooks were introduced, the species groups caught in the greatest quantities are prawns, mullet, bream, whiting, blue swimmer (*P. armatus*), mud crab (*Scylla serrata*), and squid (1) (e.g. *Sepioteuthis* and *Ommastrephes* spp.) (Fig. 1b). In more recent years these are identified to species level, but not necessarily throughout the whole logbook time series. Bay prawns, which are mainly composed of *Metapenaeus bennettae*, have dominated prawn trawl landings throughout the available historical record (Fig. 2a). Brown tiger prawns, *Penaeus esculentus,* are the largest prawn species caught in the Bay, and because they command higher prices, account for the majority of the prawn catch value. Eastern king prawns (*Melicertus plebejus*), banana prawns (*Fenneropenaeus merguiensis*), endeavour prawns (*Metapenaeus endeavouri* and *M. ensis*) and school prawns (*M. macleayi*) are also caught in Moreton Bay.

In addition to these commercial target species, several non-target species can be retained and sold. These byproduct species can provide significant additional income for fishers. For example, the amount of byproduct retained by otter trawl fishers peaked at about 400t in the 1990s, but has declined since, mainly due to management changes (Fig. 2b).

Most bream (99%), mullet (99.5%) and whiting (73%) are landed by net, while blue swimmer (88%) and mud crabs (99.6%) are landed by pot gear. Landing trends vary across species. Mullet, whiting and squid have exhibited an overall decline throughout the time series, whereas bream is more stable. Fishing effort is not shown for individual species because the available data do not detail which species were being targeted from day to day. However, the number of fishing licences and number of days fished have declined overall, with the most marked declines occurring in the otter trawl fleet (Fig. 3). Reasons for the decline in the otter trawl fleet include reduced profitability as a result of increased operational costs (i.e. fuel and labour), the introduction of a fishing effort unitisation scheme aimed at limited trawl fishing effort, restrictions on byproduct, as well as increased imports of aquacultured prawns that have largely displaced the bay prawn market and depressed prawn prices. Based on these reasons, a recent economic study of the Moreton Bay trawl fishery concluded that it was economically unsustainable (19). Despite these issues, the decline in fishing effort since 2000 has been associated with a significant increase in annual prawn catch rate (Fig. 3). This may be attributed to smaller, less-efficient vessels exiting the fishery, or reducing their annual effort, resulting in higher mean catch rates from the remaining, larger vessels. There is also evidence to suggest that increased catch rates may be partially due to a recovery of the brown tiger prawn population from recruitment overfishing (i.e. significantly reduced recruitment to the exploitable stock) in the 1980s and 1990s (20).

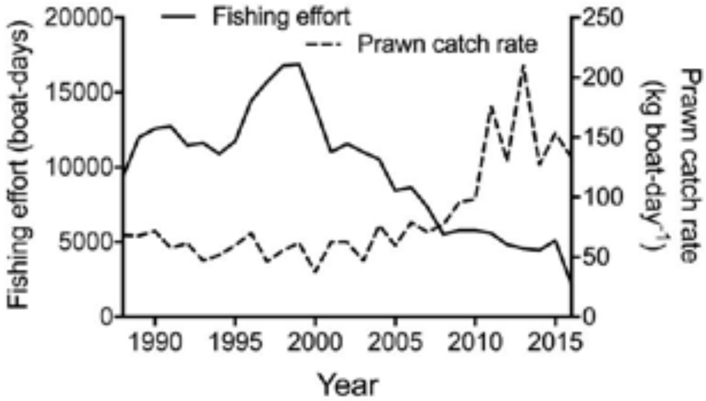

Figure 3. Annual fishing effort (boat-days) and prawn catch rates in the Moreton Bay (grid W37) otter trawl fishery, based on CFISH logbook data (1). Note the declining trend in effort and the increasing trend in catch rate since 2000 (2016 data incomplete).

Recreational fisheries

Recreational fishing has taken place within Moreton Bay for more than 130 years, when the *Queensland Fisheries Act 1877* implemented commercial licensing for fishers who wished to sell fish caught using large nets, thus clearly distinguishing commercial from recreational fishing activities. Recreational catch data are derived from fishing surveys conducted by DAF in 2000, 2010 and 2013[21]. The 2013 survey estimated there were approximately 642,000 anglers in Queensland, who harvested 8,500t of fish, crabs and prawns. Of these, approximately one-third lived in the Brisbane region around Moreton Bay (21). The economic value of

Queensland recreational fishing is $400m per year (22) and estimates of direct expenditure from this sector in South East Queensland (including Moreton Bay) range from $156m to $194m (23). Recreational fishing thus contributes significant economic benefits, especially to the local area, with boating, bait and fishing tackle industries heavily reliant on this activity (21).

Participation rates for recreational fishing activities within Moreton Bay and Queensland are unknown prior to the start of state-wide surveys in 2000. Recreational fishing was common prior to World War II, with some fishing clubs recording their fishing activities within and just outside of Moreton Bay as early as the 1870s (24). Initially, these clubs were independent of each other, but in 1949 the Queensland Amateur Fishing Clubs Association (QAFCA) was formed as a 'major representative sporting body for competitive angling', to promote recreational fishing and organise inter-club competitions (25). The post-war period saw greater participation in recreational fishing activities, due to the increasing affordability and accessibility of personal motor vehicles, powerboats and fishing technology, although participation rates are unknown. Club competition angling remained the most affordable way to fish productive areas and people increasingly joined clubs to participate in recreational fishing activities (26). Today the QAFCA acts as a parent body and representative for over 100 recreational fishing clubs throughout Queensland (27), a number of which regularly fish in Moreton Bay. The Australian National Sportfishing Association (Queensland Branch) was formed in the late 1960s and has several clubs actively fishing in Moreton Bay. Game fishing clubs and underwater (spearfishing) clubs have also been active in Moreton Bay, but to a lesser extent than sport fishing clubs. Despite the large number of fishing clubs, the vast majority of recreational fishers today do not belong to fishing clubs.

Since the start of state-wide recreational fishing surveys in 2000, participation rates within Queensland have declined. In 2000, just under 25% of Queenslanders surveyed stated that they participated in recreational fishing. By 2013 this had declined to 15% (21). Despite declining participation rates, recreational fishing is still a popular leisure activity for those residing in the Brisbane and Moreton Bay areas. With approximately 3 million people living in the area around Moreton Bay and population growth in South East Queensland expected to continue to increase to 4.4 million by 2031 (28), it can be expected that greater numbers of recreational fishers will enter the fishery over the coming years.

Recreational fishers primarily use lines to harvest finfish, but pots are also commonly used for crab fishing and cast nets to target prawns (21). In 2013, Brisbane's resident recreational anglers reported catching 74 species (harvested and/or released), with trumpeter whiting (*Sillago maculata*), yellow-finned bream and sand whiting (*S. ciliata*) the most commonly harvested finfish. For many species, similar numbers of individuals are released as are harvested, with significantly greater quantities of yellow-finned bream, snapper (*Pagrus auratus*) and mud crab released than harvested (21). The most recent survey estimated that recreational anglers fished 240,000 days over a 12-month period in the Moreton Bay catchment fishing region, and that they expended more boat-based fishing effort than shore-based (21). Trumpeter whiting and yellow-finned bream were the most commonly caught fish species within the Moreton Bay catchment region, with >200,000 individuals of each species estimated as being harvested or released by recreational fishers throughout 2011. Over 100,000 snapper and mud crab were estimated to have been either harvested or released. From these surveys, it is thought that the recreational harvest of snapper and yellow-finned bream by weight (throughout Queensland) is similar to that of the commercial sector (21).

Recreational fishing is open access in Queensland and fishing licences are not required; however, size, in-possession limits and gear restrictions have been applied to a range of target species since the late 19th century. Major innovations to recreational fishing controls in Queensland occurred in 1993, when recreational in-possession limits were applied to a number of species, a recreational fishing code of practice was formed, and increased enforcement and penalties were introduced for fisheries infringements, among other changes. Since 1877, when minimum size limits were first introduced for eight species and a further eight species groups, there are now size restrictions on 31 species and 18 species groups, and recreational in-possession limits on 18 species and 24 species groups in Queensland, the majority of which occur in Moreton Bay. There are no restrictions on the number of people allowed to enter the recreational fishery and hence no restrictions on total recreational catch. The 2009 establishment and expansion of green (no-take) zones in the Moreton Bay Marine Park has removed recreational fishing effort from 16% of Moreton Bay, but since 2009 seven artificial reefs have been established to provide additional opportunities for recreational and charter fishers, with several of these artificial reefs allowing spearfishing (29).

Research and monitoring of Queensland recreational fisheries and fishing activities is undertaken by the state government, university researchers and recreational fishing bodies. For example, the DAF Keen Angler Program encourages fishers to supply fish frames for age-frequency analysis and subsequent stock assessments. The Queensland branch of the Australian National Sportfishing Association started tag and release activities in the 1970s; recaptures of tagged fish are recorded and the information on movements and growth made available to researchers and managers (30,31). During the past four years, Sunfish Queensland, the state's peak recreational fishing group, and its affiliated members have undertaken scientific studies within Moreton Bay, including incidences and causes of fish injury (32), fish reproductive biology (33), fishery range shifts (34) and management history of recreational fishing.

Traditionally, communication among members of the recreational fishing community, research scientists and fisheries managers has occurred through popular media platforms (e.g. weekly newspaper columns) and formal organisations such as fishing clubs and peak bodies. However, today, communication and monitoring activities are increasingly undertaken via social media. Recreational fishers use a variety of social media platforms to post photographs of their catches and to share information with other fishers; over one-third of Queensland recreational fishers surveyed in 2011 identified government internet sites and social media as their primary methods of finding out about fishing regulations and other fisheries-related information, a proportion which is likely to increase into the future (35). Some researchers have used social media platforms to engage recreational fishing participants in ecological and fisheries sustainability research. For example, Redmap (Range Extension Database and Mapping project) (36) aims to document range shifts in marine species, while studies that aim to understand the survivability of caught and released fish and inform best practice catch-and-release fishing have also engaged recreational fishers via social media (37). The recently launched Queensland Sustainable Fisheries Strategy (2017–2027) highlights the potential of social media platforms and government–social media partnerships for collating more comprehensive monitoring data on fishing activities into the future (38).

Charter fisheries

Charter fishing is defined as a trip where an operator takes paying passengers to a site to fish. Only offshore charter operators (i.e. those operating beyond sheltered waters) are required to hold a charter fishing licence. Since 1996, offshore operators have been obliged to record their daily fishing activities using the same grid locations as commercial fishers (1). All fishers on board are required to abide by recreational in-possession and size limits.

Charter fishing is popular in offshore areas adjacent to Moreton Bay and in particular around Moreton Island (1). From 1996–2015, logbook records of licensed charters operations fishing this region show the top six species (retained by quantity) to be snapper, flathead (*Platycephalus* spp.), tailor, teraglin (*Atractoscion aequidens*), pearl perch (*Glaucosoma scapulare*) and bream (Fig. 4). On average, these species comprised 76% by weight of the total quantity of fish landed by licensed operators, with snapper caught in the greatest quantities, averaging 30% of total landings (1).

The number of charter licences and days fished within Moreton Bay peaked in 2003 at 44 licences and 2,036 days. As a result of fleet restructuring, both the number of licences and days fished were reduced in 2007 to 21 and 506 respectively. In recent years, the number of charter licences has continued to decline, with 17 licences registered in 2015, but since 2009 the total number of days fished has stabilised at around 600 days fished per year (1).

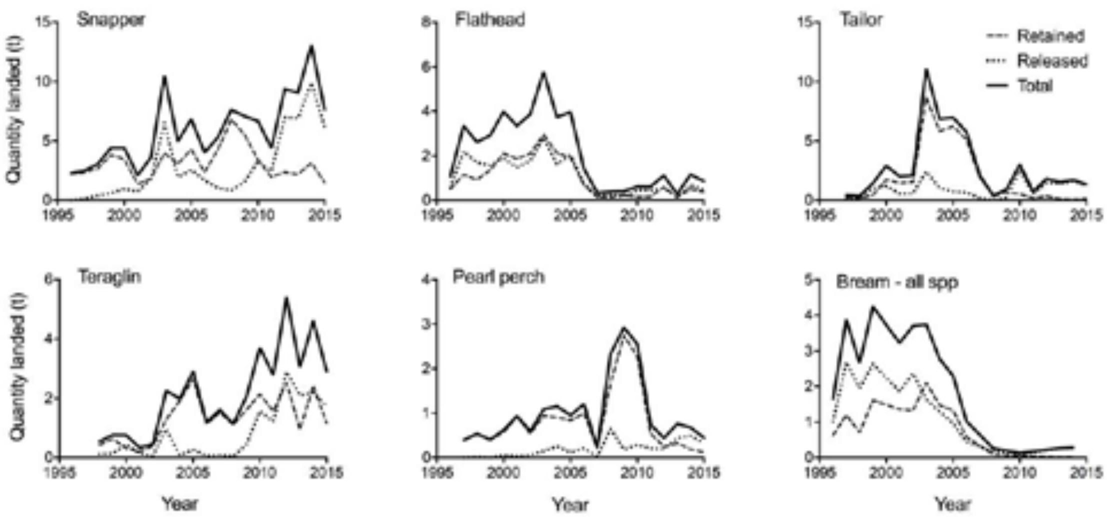

Figure 4. Total landings (retained and released) of the top six species retained by quantity by charter fishers operating within Moreton Bay (grids W37 and W38; data sourced from the Queensland Government (1)). Note that the axes differ in scale.

Discussion

Looking to the future, a number of challenges exist for the fisheries of Moreton Bay. These include managing risks related to climate change and disease outbreaks, a growing urban population, conflict among sectors and competition from imported seafood products, mitigating environmental impacts from fishing, and navigating a changing regulatory landscape.

Risks to fishing activities

Potential risks to fishing activities in Moreton Bay exist from other industries and activities. The population of South East Queensland continues to grow (28), which will not only increase the number of people directly relying on the marine environment for food and leisure (through participation in recreational fishing activities, non-fishing activities or increased demand for seafood products), but will also likely present additional pressures on habitat and water quality through coastal and catchment development.

Destruction of inshore habitats and reductions/alterations in estuarine water flows are known to affect fishery nursery grounds and/or recruitment success (39). In the longer term, commercial and recreational fishing practices will also need to be capable of adapting to the impacts of climate change (40). For example, it is possible that a rise in coastal water temperatures, as predicted for South East Queensland, would depress recruitment of eastern king prawn (41). Extreme or changing weather events may also influence or increase the variability of fishery recruitment patterns, as well as access to fishing grounds, thereby putting the economic viability of current fisheries at risk. Changing conditions and shifting distribution of species may reduce populations of some species but could also encourage the development of new fisheries within Moreton Bay over the longer term.

Infectious diseases can also affect the growth, survival rates and economic value of commercial and recreational marine species (42). While such impacts are more commonly reported in aquaculture, wild populations can also be affected (42). In 2018, prawn and crab samples from Moreton Bay tested positive for white spot disease (*Whispovirus*), a highly contagious viral infection that affects crustaceans and is primarily spread by contaminated water and movement of affected animals (43). While white spot-infected crustaceans remain safe to eat, the virus causes rapid mortality of affected individuals. The potential spread of white spot disease throughout Queensland and the associated biosecurity risks has necessitated ongoing mitigation efforts including restrictions on fishing and aquaculture activities, restrictions on the movement of certain marine animals, and additional interstate importation requirements (44). To date, significant state and commonwealth resources (tens of millions of dollars) have been invested towards compensation, monitoring and mitigation of white spot disease (45).

In 2015 the Australian Labor Party made an election commitment to sustainable management of Queensland's fisheries through its Sustainable Fishing Policy that was taken to the state election (46). This policy proposed to improve the economic value of Queensland's fisheries resources. To achieve this, the Labor Government committed to adopt a fisheries resource allocation policy based on maximising economic value, recognising tourism-related fishing as a distinct activity, and developing the economic value of tourism-related fishing. In addition, they committed to review the regulatory structure of commercial fishing, including exploring the establishment of net-free fishing zones within Moreton Bay. While these actions are likely to boost support for the charter industries, at this stage it is unclear to what extent these actions will impact commercial operators within the Bay.

Rising disposable income, together with awareness of the health benefits of seafood, has increased Australian seafood consumption from an estimated 13kg per capita per year in 2000–01, to 15kg per capita per year in 2012–13 (47). Fish consumption is projected to continue to rise, however, competition with aquaculture and cheap imported fish products (currently ~70% of Australian seafood is imported) poses continued challenges to the economic sustainability of Australia's commercial fishing industries (47).

Mitigating the environmental impacts of fishing

Fishing impacts on the marine environment have occurred, but the level of impact varies greatly depending on the fishing gear used, locations fished (in terms of specific habitat and species interactions) and intensity of use. There also remains a lack of effective catch or effort limits across most of the commercial and recreational sectors. Since 2009, an increase in protective marine park zoning has spatially restricted both commercial and recreational fishing activities in Moreton Bay. Active gears such as those used by the commercial sector have the potential to alter and degrade marine habitats, and capture non-target species (48). However, the magnitude of changes to habitats and fish populations from fishing is often unknown due to a lack of baseline data and the compounding effects of activities such as coastal development (49).

In recent years, regulations and fishery-specific mitigation practices have been implemented to reduce impacts such as bycatch and interactions with protected species. For example, the inclusion of turtle excluder devices has been mandatory for East Coast Otter Trawl fishery vessels since 2002, while commercial interactions with protected species are monitored through records of commercial fishery interactions with 'Species of Conservation Interest' in commercial logbooks. Commercial fishing industry associations, such as the Queensland Seafood Industry Association and Moreton Bay Seafood Industry Association, have also worked with the government to reduce bycatch and interactions with vulnerable species, and have developed codes of best practice e.g. the Moreton Bay tunnel net fishery (50) to reduce the environmental issues relating to fishing activities.

Fishing lines and pots, commonly used by the recreational and charter sectors, have minimal impacts on the structure and functioning of marine habitats (21). However, such gear can become broken off or lost, potentially interacting with marine animals and habitats for years afterwards. Bycatch of small individuals of target species or non-targeted incidentally caught species also occurs across all fisheries, and while these fish and invertebrates are often released, poor handling practices may increase their risk of injury and premature death (51,52). In 1995, a non-mandatory National Code of Practice for Recreational and Sport Fishing was developed by recreational peak bodies, supported by the Australian Government (53). This code addresses the need to fish responsibly, treat fish humanely and protect the wider environment.

Fisheries management and the future

An independent review of Queensland fisheries management approaches was undertaken in 2014, with the aim to deliver a policy framework for consideration by government that would, among other things, achieve simplified fisheries management systems, and maintain and improve environmental sustainability. The review provided a number of recommendations, including that the Queensland Government clarify its approach to future management, revise the decision-making framework, be more strategic and transparent in allocating and managing access to fisheries resources, and improve data collection and monitoring protocols (54).

In 2017 the Queensland Government implemented the Queensland Sustainable Fisheries Strategy 2017–2027 (38), which sets out a reform agenda for fisheries management in Queensland. Among other ambitions, the strategy aims to develop sustainable harvest strategies for all Queensland fisheries and set clear harvest limits, improve sustainability and profitability, clarify the regulatory framework, and move to a best practice system of fisheries management and decision-making that is responsive to change and stakeholder needs (38). Major areas for reform include setting catch limits of target stocks at maximum economic yield (generally around 60% of the unfished biomass) by 2027, ensure that no Queensland fisheries are overfished, developing a simpler and more responsible system of fishery regulations for users and improving compliance rates across sectors (54).

The 2014 independent review touched on the interaction between fisheries and marine park planning, highlighting that marine parks have the potential to strongly influence fisheries management goals, both in terms of effecting wider ecosystem functioning and altering resource user behaviour. However, the 2017 strategy did not discuss marine parks. Additionally, while fisheries legislation currently contains provisions for Indigenous fishing activities, this may not be adequate given the recent recognition of native title rights in Moreton Bay and how legal recognition of these rights may evolve in the future. This is a complex and emerging regulatory landscape and it is not yet clear how the legislation will be reconciled, although the Resource Reallocation Policy, which will deliver on the action under the Sustainable Fisheries Strategy, does state that Indigenous sector allocations will be considered as part of this policy (55,54).

Conclusion

Fishing in Moreton Bay has a long history and is one of the oldest Queensland industries. Today, the economic and cultural value of fisheries, and their related industries, to the Moreton Bay region are immense. The next ten years will likely see major reform of Moreton Bay fisheries. If a sustainable future for these sectors is to be assured, these reforms will need to balance demand to access fishery resources with conservation drivers, Indigenous fishing rights, other marine-based activities and increasing demands upon coastal space.

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Marine transport infrastructure development in Moreton Bay: Dredging, monitoring and future directions

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Abstract
Marine infrastructure development throughout southeast Queensland is fast-paced, with the ongoing expansion of our major ports and harbours, airports and road infrastructure. Our cities and regional centres continue to expand along the Queensland coastline and into the marine environment through dredging and land reclamation. These activities are managed from an environmental protection perspective at the local, State and Commonwealth government levels. Here we examine the maintenance and capital dredging works undertaken by the Port of Brisbane Pty Ltd (PBPL), Department of Transport and Main Roads (DTMR) and Brisbane Airport Corporation (BAC), which are necessary for maintaining ports and marina infrastructure, roads and runways. A variety of methods has been adopted over the past few decades for managing potential marine environmental impacts from these dredging activities. This chapter explores the different monitoring tools implemented by the PBPL, DTMR and BAC for managing potential impacts from port and harbour maintenance, capital works programs and operational activities. We consider the regulatory environment and how this influences port and harbour works, road and airport infrastructure development within the Bay. We also explore new technology and approaches to monitoring and the areas of future research and investigation to help contribute towards a sustainable future for Moreton Bay.

Keywords: ports, dredging, transport, marine, Gold Coast, turbidity, light, seagrass.

Introduction
Early development
Regional exports of coal, rural products and manufactured goods into and out of the Brisbane River began in the mid to late 19th century. The first exports from Ipswich and Brisbane were timber from local forests, where the product was transported down river and across Moreton Bay to Dunwich on North Stradbroke Island (Fig. 1).

The development of two oil refineries at the mouth of the Brisbane River in the 1960s boosted the local economy and the first container terminal was built in the late 1960s. The Port of Brisbane was formed in the mid-1970s and the Port of Brisbane Authority Act 1976 was introduced and the first contract awarded to the Port in 1977 (1).

Air travel was first established in Brisbane in the early 1920s, when a site at Eagle Farm was chosen for development of a government aerodrome (Fig. 2). This aerodrome was used by the Royal Australian Air Force in World War II and formally established as the principal airport for Brisbane in 1947.

Figure 1. Left: Brisbane's first exports in the late 19th century. Right: Recent image of the Port of Brisbane (images from Port of Brisbane (2)).

A new international terminal was built in the 1990s and today Brisbane Airport Corporation Pty Ltd (BAC) owns and operates two major terminals (domestic and international) accommodating 35 airlines flying to 84 domestic and international destinations and is the third largest airport in Australia (3).

Figure 2. Left: Eagle Farm Airfield in 1925. Right: Brisbane Airport (domestic terminal) today (3).

Shipping channel maintenance

The Port of Brisbane is a major source of import and export into and out of southeast Queensland. Approximately $50 billion worth of international cargo is shipped each year and 33.2 million tonnes of trade goods. The Port of Brisbane is managed and developed by the Port of Brisbane Pty Ltd (PBPL) under a 99-year lease from the Queensland Government. It is Queensland's largest multi-cargo port and the closest major container port to export markets in Asia, where more than 30 shipping lines service the Port of Brisbane (4).

To maintain its shipping channels, the Port of Brisbane Pty Ltd (PBPL) has undertaken annual maintenance dredging in and around the Port, where the dredge material is either deposited in the Fisherman Island reclamation areas, or in the Mud Island Dredge Material Disposal Area, which is a designated offshore disposal site (Fig. 3). Dredging at the Port of Brisbane has occurred since 1862 due to siltation and sediment buildup and the need to bring in deep draft vessels.

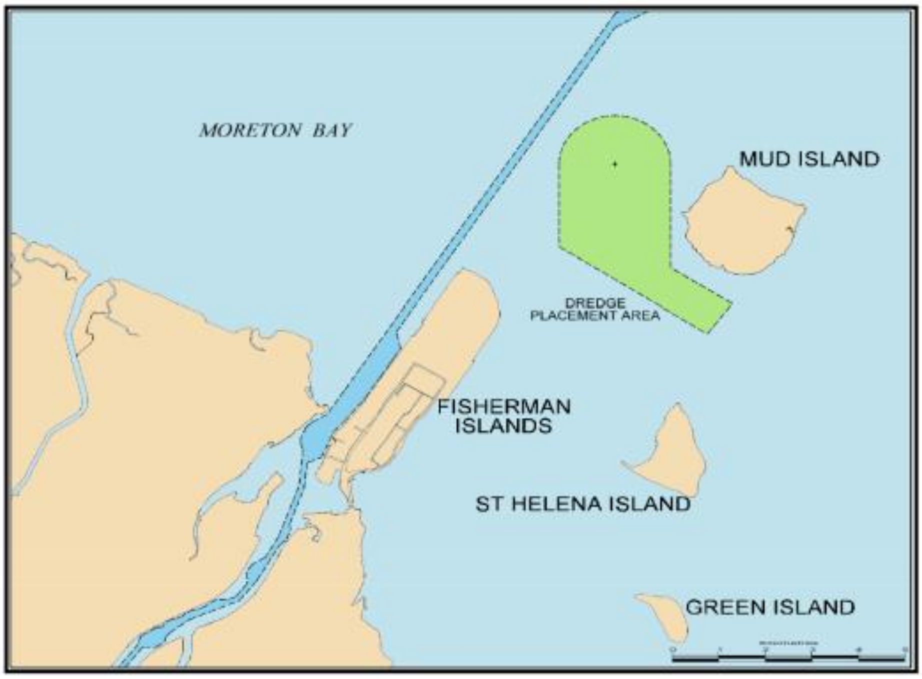

Figure 3. Mud Island Dredge Material Disposal Area (5).

PBPL are responsible for maintaining the declared depth of 14 m below lowest astronomical tide level for 90 km of navigational shipping channel from Bribie Island, southwards inside Moreton Island, across Moreton Bay and into the Brisbane River as far as the Hamilton Reach. To this end, maintenance dredging is carried out between Fisherman Island and the Hamilton Reach of the Brisbane River and within the channels of Moreton Bay (6).

Figure 4. Port of Brisbane Pty Ltd trailer suction hopper dredge, Brisbane (image from Dredgepoint.org).

Each year the trailer suction hopper dredge (TSHD), *Brisbane*, removes up to 1 M m^3 of sediments from the Port's berths and shipping channels (Fig. 4). These works are undertaken to maintain the shipping channels into the Port of Brisbane. These channels are in naturally deep areas of the Bay, which minimises the extent of dredging required.

Periodically, larger capital dredging works (areas not previously dredged) occur at the Port. PBPL is constructing a new $100 M cruise ship facility at the mouth of the Brisbane River, which will require localised dredging to be undertaken. These works will accommodate cruise vessels more than 270 m in length. There was no dedicated cruise facility in southeast Queensland able to accommodate mega-cruise ships.

The new facility is considered the 'missing link' in Brisbane's tourism infrastructure. This facility aims to ensure the city can attract and support the world's largest cruise ships and act as an important gateway to the south-east Queensland region (4). The contracts for construction of the wharf and terminal facilities were awarded in early 2019 and the new cruise terminal is scheduled to open in late 2020 (Fig. 5).

Figure 5. Proposed Port of Brisbane Limited Cruise Terminal (7).

Brisbane Airport Expansion

A large infrastructure project recently completed by the Brisbane Airport Corporation (BAC) was the New Parallel Runway project (Fig. 6). This project involved the dredging of 11 M m^3 of sand from the Bay and reclamation of 360 ha of soft marshland.

Dredge material was transported onto the site over a 4-year period and the weight of the sand is being used to create a solid base for the runway. The sand was extracted from the Bay's Middle Banks by the Jan de Nul Group's TSHD, ***Charles Darwin***.

In addition to the large-scale projects throughout Queensland that involve maintenance and capital dredging works, the Department of Transport and Main Roads (DTMR) has committed to a $30 million, 2-year extension of the Marine Infrastructure Fund from July 2016, for additional facilities and upgrades to existing facilities (8), which include boat ramps, jetties and seawalls.

DTMR has undertaken recent maintenance and/or capital dredging programs at Cabbage Tree Point and Cabbage Tree Creek. These involved dredging between 10,000 m^3 and 50,000 m^3 of material from the seabed. Other projects include the Manly Boat Harbour public channel deepening and maintenance dredging, and Raby Bay (east) maintenance dredging projects (Fig. 7).

Figure 6. New Parallel Runway Project (3).

Figure 7. Small maintenance dredging locations in southeast Queensland (image from Google Earth Pro).

There are small to medium-Local Councils that also undertake routine maintenance dredging programs. For example, Redland City Council recently commissioned a 5-year dredging program in Aquatic Paradise, involving the removal of approximately 180,000 m^3 of sediment (Fig 7). These works were completed by the PBPL dredger, ***Brisbane*** to ensure ongoing vessel access into this canal estate.

Gold Coast Waterways and the City of Gold Coast undertake routine maintenance dredging and beach nourishment activities. Gold Coast Waterways recently completed maintenance dredging at Biggera Creek and Tipplers Passage and Cabbage Tree Point in the Gold Coast Broadwater (Fig 7).

The City of Gold Coast recently completed the Northern Beaches Shoreline Project (NBSP), which involved offshore dredging and beach re-nourishment along the coastline from North Burleigh to Main Beach. The works by RN Dredging were completed in the second half 2017 and enhanced the condition of beaches for a wide variety of uses including the 2018 Commonwealth Games (Fig. 8).

Figure 8. Before (left) and after (right) beach nourishment works at Narrowneck (image from City of Gold Coast website).

As evidenced by these small, medium and large-scale projects throughout southeast Queensland, dredging plays an important part in maintaining our shipping channels, waterways and coastline, as well as provides a valuable resource (i.e. sand) for infrastructure development. However, how these works are managed from an environmental protection perspective remains a key issue.

Environmental management of dredging

The dredging works described above are guided by the various State and Commonwealth Acts, Regulations and Guidelines; namely the Commonwealth Environmental Protection and Biodiversity Conservation Act 1999, the Commonwealth Environment Protection (Sea Dumping) Act 1981 and Queensland Environment Protection Act 1994 (EP Act).

In Queensland, dredging and land reclamation activities require an Environment Authority (EA) (under the EP Act), as they are traditionally classed as environmentally relevant activities (ERA) and a Tidal Works permit. The EA and Tidal Works permit have a series of environmental management monitoring and mitigation measures (i.e. water quality monitoring) that the proponent (persons/company/government body that undertakes the dredging) needs to follow to manage the environmental risks associated with each respective project.

For large scale projects such as the New Parallel Runway, the environmental responsibilities employed and reported by the Brisbane Airport Corporation included demonstrating that the sand was uncontaminated in accordance with the National Assessment Guidelines for Dredging (NAGD) and contained negligible levels of fine clay/ silts.

The Brisbane Airport Corporation (BAC) implemented a continuous, real-time monitoring program to ensure that project-specific water quality criteria were not exceeded. In accordance with best practice, temporary sediment ponds were constructed by BAC to manage suspended sediments and turbidity in return waters. The water was contained on site within the primary reclamation bund and tail water ponds and was then released back into the Kedron Brook floodway via the airport's new major drainage system. No water was released until it met the agreed water quality discharge requirements. This approach is now standard practice for managing return waters from onshore disposal and dewatering activities.

For smaller-scale dredging projects in southeast Queensland, the dredging contractor or the proponent who has contracted the dredging works, is required to undertake an acceptable form of monitoring of dredge plumes to ensure that they are contained and do not either extend beyond the agreed dredge plume footprint or negatively impact sensitive marine communities. This generally requires qualitative observational monitoring, but can also involve collection of turbidity and other physico-chemical parameters at set distances from the dredge and disposal site.

In some instances, and where there is a medium to high risk of impact to the marine environment due to the presence of sensitive species (e.g. seagrasses), the Environment Authority or Tidal Works permit will also specify a requirement for habitat surveys before and/ or after dredging to demonstrate that dredging has not impacted the environment (Fig. 9).

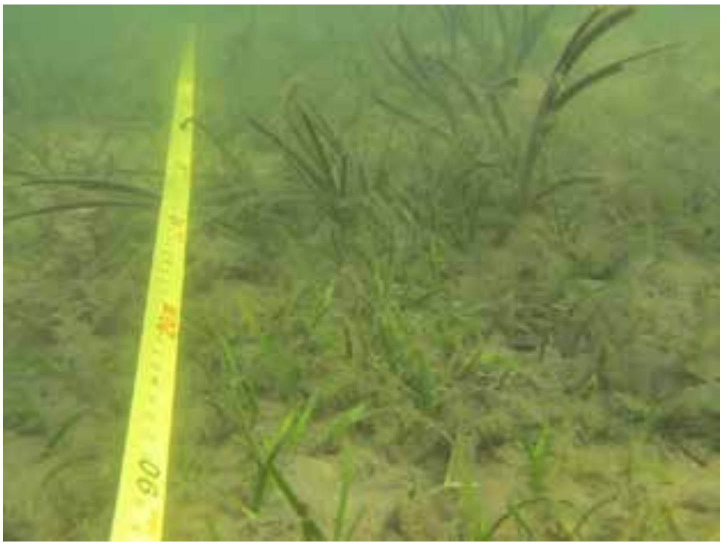

Figure 9. Habitat surveys are used in some cases to demonstrate impacts of dredging on sensitive communities such as this seagrass (*Zostera* spp) meadow.

Current Monitoring Methods and Novel Approaches

Given the location of the major transport infrastructure to the Bay, there should be a continued emphasis on monitoring and managing impacts to sensitive marine communities, particularly in western Moreton Bay. The chief tools used for monitoring water quality in marine waters throughout southeast Queensland are telemetered fixed site instruments, which report on physico-chemical parameters such as pH, dissolved oxygen (DO), temperature, turbidity, suspended solids, light attenuation and salinity/ conductivity in real time.

Elsewhere in Australia other approaches are used, some of which might be applied in the Moreton Bay context. For example, the Port of Melbourne (PoM) in 2008 and 2009 looked at 'cutting edge' statistical analysis methods to better understand short-term biological response to dredging and increased turbidity and generated 6-hourly Exponentially Weighted Moving Average and 2-week moving average control charts for turbidity (9). This provided an early warning trigger and assisted the Port in ensuring that seagrass light requirements were maintained throughout the project.

The traditional method of measuring sedimentation using sediment traps and taking water samples for measuring suspended sediment concentrations (SSC) has also been upgraded in recent years with the adoption of *in-situ* instruments which monitor optical backscatter. This is because sedimentation monitoring with sediment traps does not provide monitoring data over time frames that are relevant to the affected organisms (10).

Taking water quality measurements and waiting for the laboratory to report on SSC is also unrealistic in terms of reporting timeframes and trying to monitor potential changes in organism and ecosystem response. Other recent technological advances in measuring suspended sediment concentrations *in-situ* includes the Laser In Situ Scattering Transmissometer-Stream Lined profiler (LISST-SL), which is designed to provide real-time data on sediment concentrations and particle-size distributions.

In addition to real time water quality monitoring, there has also been a change in the type of parameters monitored. The mining company BHP, in Port Hedland in 2011, focussed on active light monitoring, to better understand how seagrasses responded to turbidity and sedimentation. Application of lethal, sub-lethal and non-measurable change (% surface irradiance (SI) thresholds) compared to the dredge plume modelling outputs, was used to define the Zones of High Impact, Moderate Impact and Influence for corals and seagrasses (11).

A shift to monitoring incident light on the seabed was also adopted by Gladstone Ports Corporation (GPC) in 2013 and 2014, for monitoring potential impacts to seagrass from dredging, where GPC used telemetered benthic photosynthetically active radiation (BPAR) monitoring and applied a PAR limit over a 14-day rolling average to manage light availability to seagrass (12). This approach was again utilised on the INPEX Ichthys Project in 2014, where the company adopted a 28-day moving average of benthic PAR to assist in understanding seagrass and coral responses to dredging activities (13).

In summary, what has been learnt by transport-related entities from dredging and land reclamation activities is the need to better understand, in 'real time', how the marine species and communities respond to increases in suspended solids concentrations in the water column.

Opportunities and Constraints

There are a number of new infrastructure projects proposed in the near future along the Moreton Bay foreshore, which include: the Brisbane Cruise Ship Terminal; Toondah Harbour; and Manly Boat Harbour Channel Deepening, amongst others. One of the key challenges for managing the marine environment, considering this new infrastructure, includes gaining a thorough understanding of the sensitive marine organisms present in the Bay. In addition, understanding the threshold tolerances of these species and implementing monitoring programs that allow the dredge contractor/dredge proponent to respond quickly to any negative biological responses will also be a key challenge for the future.

There is also the need to better understand the type of dredge plant and the potential impacts from dredging and disposal activities. Cutter suction dredges and trailer dredges tend to be the preferred method of dredging in Queensland. However, these dredges have the potential to generate significant turbidity during disposal of dredge material to beaches as part of beach nourishment activities, especially when there is a high silt content.

The regulators who are preparing the Environment Authority or writing the Tidal Works permits, as well as the proponents who are undertaking these works, should consider undertaking a thorough evaluation prior to dredging of the type of equipment available and the potential impacts to the environment. This is highly relevant to the smaller dredging projects up to 50,000 m^3, where a bucket, clam shell or auger dredge may be the more appropriate equipment, as they are relatively efficient up to this dredge volume, do not generate as much excess water and therefore generate less turbidity during both dredging and disposal activities.

Another important area of investigation for transport development would be on the fate and remobilisation of sediments in the Bay. Understanding of how the finer sediments present in the lower estuaries are recycled and whether this material influences ecosystem function is essential. This understanding is important to gain a better appreciation of how the ecosystem responds to change, and whether it is from natural or anthropogenic sources, such as dredging activities.

Future research and investigation that helps contribute towards a sustainable future for Moreton Bay, may include undertaking sediment transport modelling to better enhance our understanding of the fate of sediments and how they are recycled in the environment, which are either naturally deposited in Moreton Bay from catchment inputs or deposited at Mud Island from dredge material disposal activities.

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Charting a course by the stars: a review of progress towards a comprehensive management plan for Moreton Bay 20 years on

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Abstract

Twenty years since a course towards a comprehensive management plan for Moreton Bay and Catchments was charted by Low Choy, what has been achieved and are we heading in the right direction? This paper chronicles the actions taken by a galaxy of diverse stakeholders to enhance the management of the catchments that collect the water that flows into Moreton Bay. The role of community movements such as Landcare and catchment management will be outlined to ascertain the ongoing contribution of these social enterprises to the management of Moreton Bay landscapes. Peak industry groups have also put an increasing focus on the health of the Bay to address catchment issues of priority to the socio-economic fabric of many industries, such as agriculture. The history of the repeated introduction and withdrawal of various strategies and programs by all levels of government will be examined to isolate the successes and shortfalls of these largely short-term commitments to long-term landscape change. The wave of social and scientific collaboration that has been generated by these programs is one of the great success stories in the recent history of natural resource management in the region. The roles played by high profile programs such as the Healthy Waterways Report Card and related planning and implementation initiatives, such as the SEQ Natural Resource Management Plan, in raising awareness and connection to the Bay will also form a central theme of this paper. Significant achievements have been made particularly in raising a broader awareness and understanding of the regional water cycle; however, the necessary social and political capital required to make a transformational change has not reached a critical mass. Progress towards the goal of each principle of the comprehensive management plan for Moreton Bay and Catchments charted by Low Choy is assessed and awarded stars; five stars indicating very significant travel in the right direction.

Keywords: integrated catchment management, natural resource management, community, partnership, collaboration, governance, Landcare, planning, Indigenous landscape values.

Introduction

In 1998 Low Choy identified 10 principles required for a comprehensive management plan for Moreton Bay and Catchments (1) (Table 1). Here we examine the catchments component of the proposed future planning framework, in particular the roles and experience of the community/non-government sector in working to develop and implement a comprehensive SEQ management plan.

Table 1: Principles of the management framework proposed for future planning in South East Queensland (Low Choy, 1998).

Principle 1.	It [the planning framework] should embrace a regional setting that allows the inclusion of all elements and issues of regional significance.
Principle 2.	The scope of the study should be comprehensive and multidisciplinary and it should embrace the biophysical and socio-cultural elements of the marine and the terrestrial environments of the Bay.
Principle 3.	Planning considerations need to be based on scientific knowledge.
Principle 4.	The underlying planning philosophy should embrace the environmental planning principles of diversity, sustainable development, environmental carrying capacity, equity and the precautionary principle.
Principle 5.	The planning study area should approximate a natural area, and be delineated on the basis of an ecosystems or biophysical approach, without regard to the existing legislative and administrative arrangements.
Principle 6.	It should be a democratic and participatory process that facilitates the maximum involvement of all stakeholders.
Principle 7.	Future planning should promote a cooperative approach that involves the community at all levels of government in partnership arrangements.
Principle 8.	It must be capable of resolving conflicts but more importantly managing potential conflicts before they arise.
Principle 9.	It should be an open and transparent planning process that achieves and retains the confidence of all participants.
Principle 10.	It should be capable of producing a viable range of alternative options.

In his paper, Low Choy defines planning as the means of deriving and delivering policies and actions as part of a coordinated strategy or plan, to address a range of environmental problems and issues relevant to an agreed planning study area. It should be both transparent and participatory (i.e. provide opportunities for the active participation of all recognised stakeholders) and holistic (ranged across the biophysical and the socio-cultural environments). Transparency and the active participation of the community in catchment management is at the higher end of the collaborative planning spectrum. The 10 principles enshrine equity and collaboration as central themes.

Over the past 20 years, various levels of government, community groups, industry organisations and individuals have all undertaken actions and strategies, either singularly or collectively, to sustainably manage the catchments of the Bay. It is now widely held that these actions have not been fully effective because the condition of natural resources continues to decline (2). Has the lack of lasting improvement been a symptom of the lack of a comprehensive management plan that effectively involves the community in the planning, implementation and ownership of catchment management activities?

This paper does not critique the original principles espoused by Low Choy nor does it propose enhancements based on this high level review. The objectives of this paper are to provide an overview of past and current planning activities undertaken by the community in collaboration with government and review how effectively these initiatives have steered the region in the direction charted by Low Choy in 1996. Progress towards the goal of each principle is assessed and awarded stars; five stars indicating very significant travel in the right direction.

Background

To understand where we have got to since the last Moreton Bay and Catchments Conference in 1996, we must briefly explore changes in the social, economic, political and environmental landscapes as related to the management of the Bay's catchments. These changes (or in some instances a lack of change) have impacted heavily on the availability and continuity of the required capacity, resources and governance to promote Low Choy's 10 principles.

The past 20 years of planning, administration and funding arrangements have had a considerable impact on the capacity of the community, government and industry to sustainably manage the Bay's catchments. In fact, so much has occurred that there is neither time nor space here to chronicle the full history. Thus key initiatives and associated outcomes will be the focus of discussion which inevitably glosses over other laudable initiatives, and the authors apologise for this.

In 1996 there were approximately 30 catchment coordinators, Landcare facilitators and Waterwatch officers operating in the catchments of South East Queensland. By 2005 there were nine regional partnership managers employed by one regional entity called SEQ Catchments Ltd. (SEQC).

The original catchment coordinators and facilitators were employed on an individual basis by a number of incorporated associations overseen by either a board or management committee. These associations were non-government entities with a range of working relationships with local and state governments. During this time the majority of project funding was delivered through the Australian Government's National Landcare Program (NLP). The SEQ Regional Assessment Panel (a committee comprising government and community representatives) recommended the funding of projects that had been submitted by groups to the Australian Government for the investment of approximately $2.5 million per annum to the SEQ region (3).

Planning was principally on a catchment scale with varying degrees of awareness of the SEQ regional scale water cycle. The principal non-statutory tool to inform land use planning and resource management was the Integrated Catchment Management (ICM) strategy. The Queensland Government instigated a pilot ICM program across three demonstration catchments in Queensland in the early 1990s. The Lockyer Catchment was the focus of one of these pilots on the back of the work done by the Lockyer Watershed Management Association (LWMA) since the early 1980s.

By 2000, ICM strategies existed in various forms across the region. Extension officers from the then Department of Natural Resource Management (NRM) had the task of equipping staff and groups with the capacity to develop and implement these strategies and acquit the funds invested through the NLP.

NRM extension officers organised regional 'get togethers' for both coordinators and groups to promote information sharing, professional development and regional coordination. This culminated in the development of the Strategic Guide to Natural Resource Management in South East Queensland: December 2000 (4) (the Strategic Guide), which had two key objectives: (i) to provide information for local government planning schemes; and (ii) to aid community, local and State governments in obtaining information on natural resource management in South East Queensland, and in managing natural resources in an integrated manner.

The Strategic Guide was based on the principle of ecologically sustainable development and key principles from the South East Queensland Regional Water Quality Management Strategy (5) and the South East Queensland Regional Coastal Management Plan (6). It also contained half a page on the links with the Integrated Planning Act 1997 (Qld) and local government planning urging that the range of NRM issues identified be considered in development/statutory land use planning. The Strategic Guide was a major achievement in synthesizing the regional aspirations of the NRM community in support of an agreed collective vision for the region; however, the lack of a comprehensive planning framework that subscribed to Low Choy's 10 principles made the achievement of the agreed collective vision problematic and well-nigh impossible.

Monitoring and evaluation of the outcomes of the government investment in SEQ during the 1990s occurred as a requirement for project funding. However, in 1997, the Australian National Audit Office (ANAO) concluded that, after some five years since the then Prime Minister's Statement on the Environment and nearly eight years into the Decade of Landcare, the Commonwealth was still unable to indicate in any detail the outcomes that had been achieved from any of the programs examined (7). The challenges of issues of scale, establishing causal links and time scales involved in quantifying progress towards the landscape scale change required to achieve the objectives of land care cannot be underestimated.

The establishment of the Healthy Waters monitoring and report card program in the early 2000s (8) informed by the water quality and ecological health monitoring network, made a positive contribution to capturing the outcomes of land use planning and management, albeit with limited assessment of the causal links to local projects such as those highlighted in the Strategic Guide. Work is ongoing to enhance this understanding (9).

Establishment of the National Action Plan for Salinity and Water Quality (NAPSWQ) in 2000 and Natural Heritage Trust (NHT) program in 2001 saw the move to a more regional focus for planning, delivery and monitoring via the "Regional Arrangements" (10). This significant change saw the unravelling of the catchment coordinator network and many of the community networks they supported. At the core of these new arrangements was the signing of the Trust Bilateral Agreement between the Commonwealth and State Governments (10).

The first component of these regional arrangements was a focus on salinity and water quality under the NAPSWQ. The Lockyer was identified as a catchment of national significance due largely to the saline nature of large parts of its ancient marine sandstone-derived landscapes. There was also a heightened awareness of the impacts of sediment on water quality in the Bay, as a culmination of work led by Healthy Waterways and local governments including the Brisbane River and Moreton Bay Wastewater Management Study (11) and the subsequent SEQ Regional Water Quality Management Strategy.

The NHT program covered the whole of SEQ and saw the creation of a separate regional body for the eastern coastal catchments. In many instances this was accompanied by the gradual removal of financial support for local Catchment and Landcare officers, particularly in the less populated western catchment areas, and a move to centrally funded staff. A number of high profile groups with a sustainable business model, under-written by support and funding from a larger more affluent urban population, were still operating in 2016.

Separate regional NRM Plans were developed for the eastern and western catchments of SEQ by the two regional groups. The SEQ Western Catchments Group (SEQWCG) oversaw NRM planning and investment for the Lockyer, Bremer and Brisbane Catchments. Natural Resource Management SEQ (NRMSEQ) operated in the Noosa, Maroochydore, Mooloolaba, Pine and Pumicestone, Lower Brisbane, Redlands, Logan Albert and the Gold Coast catchments. These two NRM Plans underpinned the regional investment strategy for the region and formed the funding agreement with governments. A sum of money similar to that received by the region under the NLP program ($2.5 M) was made available to the regional body in what was termed bulk funding. This funding was tied to regional priorities identified and agreed upon by the community. These priorities, actions and targets reflected national priorities set by the Commonwealth Government. SEQWCG and NRMSEQ merged in 2006 and the strategies were combined in 2009. The SEQ Healthy Waterways Strategy 2007-2012 (12) provided targets for inclusion in the subsequent SEQ NRM Plan 2009-2031 (13).

Nine sub-regional Community Partnership Managers supported by project and administration staff were employed by the regional body South East Queensland Catchments Ltd. (SEQC) by 2006. Further changes to the regional mode of delivery have occurred since 2009 with funding, and therefore capacity to address water quality issues, declining in real terms. The ability to coordinate activity to address key issues is further exacerbated by the competitive nature of the funding process, which does not subscribe to the road map promulgated by the regional NRM plan.

The most recent and significant event has been the merging of Healthy Waterways and SEQC to form Healthy Land and Water (HLW) in 2017. To many observers this was an obvious development too long in the making. For those more nuanced in the history of NRM in SEQ and the complicated nature of power and regulation in one of the fastest growing and biodiverse regions in the world (14), this was never a foregone conclusion. This amalgamation can be seen as a positive step towards more coordinated monitoring and evaluation of water quality in the Bay and on ground action in the catchments. This new non-government entity continues to be a critical link between land managers and the pursuit of a comprehensive management plan for the Bay.

Review of progress

The comprehensive planning framework envisioned by Low Choy in 1998 had not materialised by the time of the second Moreton Bay and Catchment Forum in 2016, at least not as a cohesive framework promulgated at a single point in time. The 10 principles were not adopted as a collective response when first described 20 years ago. The reason for this lack of uptake has many dimensions; some will be discussed in this paper. A more forensic investigation is required to adjudicate on the lack of commitment to a comprehensive framework. Suffice to say the complicated nature of the planning, development and governance framework in the region creates unpredictable currents which are hard to navigate.

Distinct and important components of the framework have existed in a disparate temporal and spatial fashion, generating hope and expectations of opportunity, only for potential elements of a comprehensive framework to either suffer from their own success or be starved of the necessary resources to grow and prosper. It is now timely to identify these components and explore the role they have played in achieving the principles identified by Low Choy (Table 1). Progress towards the goal of each principle is assessed and awarded stars, with five stars indicating very significant developments in the right direction.

Principle 1. It (the planning framework) should **embrace a regional setting** that allows the inclusion of all elements and issues of **regional significance.**

Issues of regional significance have been identified and described (15); however, the complex nature of the water quality and other pressures on landscapes, ecosystems and the people of SEQ requires a genuine commitment to a regional governance framework. This must allow for a dynamic approach to planning and management that has the clear support of the dominant institutional frameworks of the region.

Many forums have contributed to this process including the Regional Landscape and Open Space Advisory Committee (RLOSAC) whose members worked to identify and raise the profile of regional landscape issues in the regional planning process over the last twenty years. RLOSAC championed the fact that the catchments provide the majority of greenspace and recreational opportunities for the urban population, along with scenic amenity and the fundamentals of life such as food, water and air (16).

The SEQ NRM planning process (2004) was instigated to prepare a regional plan for natural resource management, an important component of a comprehensive plan for the catchments. Subsequent iterations of the SEQ NRM Plan (2009 and 2014) pursued a joined up planning approach to the delivery of regional natural resource management. This was achieved through the alignment of non-statutory NRM targets and the desired regional outcomes in the statutory SEQ Regional Plan (2009-2031). This regional planning architecture provided a ‘line of sight’ for the community, especially those undertaking on ground works, to the achievement of regional goals that was in tune with a range of other approaches including land use regulations and policies. This also facilitated the coordination of effort and conversely the weeding out of duplication which maximised the impact of available resources including funding.

The catchments of SEQ are first and foremost Indigenous cultural heritage landscapes that have provided the physical and spiritual connection to Country for Traditional Owners for thousands of years. These values have a history of not adequately being included in regional planning processes particularly given the cultural significance of waterways and their connections to the Bay through creation stories (17). The SEQ Traditional Owners Alliance (SEQTOA) formed and mobilised to produce a Cultural Resource Management Plan that identified regional issues that could be broken down into sub regional issues of importance for individual groups (18). Indeed, Traditional Owners have continued to play an active role in regional planning, most recently in the development of ShapingSEQ – SEQ Regional Plan 2017 (19). This involvement was informed by the Native Title process which, since the last Moreton Bay and Catchment Conference in 1996, has facilitated the recognition of continuous connection to Country by groups across most of the region. ShapingSEQ commits the government to at least two Aboriginal and Torres Strait Islander Planning forums per year to progress the recognition of indigenous values in planning.

Progress towards Principle 1 receives three stars.

Principle 2. The scope of the study should be **comprehensive and multidisciplinary** and it should embrace the biophysical and socio-cultural elements of the marine and the terrestrial environments of the Bay.

Disparate biophysical and socio-cultural studies have occurred in the history of catchment management in SEQ but have never become a solid fixture on which an ongoing cohesive research contribution could be built. The NRM regional body process of the 2000s, as described earlier, included a large number of both biophysical and socio-cultural studies. A major impediment to a comprehensive and multidisciplinary approach was the way in which funding was made available for research largely along single disciplinary lines. This was further compounded by institutional barriers between state agencies and the challenges of a consolidated approach to research and implementation.

The Cooperative Research Centre for Coastal Zone, Estuary and Waterway Management (the Coastal CRC) created new tools and processes to enhance knowledge-sharing, knowledge-brokering and effective and democratic communication (20). The Coastal CRC sought to improve cooperation and communication amongst the scientists and involve the community in the development, sharing and implementation of tools for enhanced NRM. The CRC operated from 1999 to 2006 when funding was withdrawn.

Progress towards Principle 2 receives 3 stars.

Principle 3. Planning considerations need to be based on **scientific knowledge.**

The one fixture in this discussion has been the Healthy Land and Water science expert panels for water quality; however, the cross fertilisation of planning with this information has been haphazard. The Healthy Waterways program has provided the bulk of scientific knowledge that links the catchments to the Bay. This knowledge, informed by the annual monitoring of waterways, is used to produce the Healthy Waterways Report Card (now the Healthy Land and Water Report Card), which successfully engages the community to recognise their connection to the Bay and the role they can play in enhancing water quality on a regional stage.

Again there have been flashes of hope where the significant body of scientific knowledge available has connected with planning, management and investment in catchment management. However, the lack of direction, clarity of roles, the nurturing of effective relationships with stakeholders at the local level, and a lack of long term commitment to maintaining and investing in on ground activities, has dulled the effectiveness of these initiatives. The Healthy Land and Water scientific and community engagement programs continue to play a pivotal role in enhancing this situation. Furthermore, many other scientific studies have greatly advanced our knowledge of ecological processes in SEQ catchments (see Chapter on Freshwater wetlands (Arthington et al. this volume (21).

Progress towards Principle 3 receives three stars.

Principle 4. The underlying planning philosophy should embrace the **environmental planning principles** of diversity, sustainable development, environmental carrying capacity, equity and the precautionary principle.

Managing predicted population growth is the starting point for regional planning in SEQ. The regional planning framework is dedicated to providing the required number of dwellings and the hard infrastructure to accommodate this accepted growth. The fact that there is a regulatory planning approach to land use in the region as part of a legislative planning framework that subscribes to ecologically sustainable development, is a tick in the box. However, the philosophical discourse promoted by Principle 4 finds no legitimate space within the dominant political and soci-economic construct of the region, despite the urgency of the need for this debate and resultant action.

The Local Government Association of Queensland (LGAQ) has played a pivotal role in promoting the integration of NRM into planning schemes including the production of generic code provisions for local governments and the pilot training course for integrating NRM into planning schemes (22). Both were produced with funding from the National Landcare Program and Caring for Our Country. With the changing nature of the planning system and funding priorities, these initiatives have lost their currency or been starved of resources.

Consequently there continues to be a chasm between rigid statutory process and the need for dynamic land use planning that involves true partnerships between agencies and collaborative engagement with catchment communities.

Progress towards Principle 4 receives two stars.

Principle 5. The planning study area should approximate a **natural area**, and be delineated on the basis of an ecosystems or biophysical approach, without regard to the existing legislative and administrative arrangements.

The SEQ planning area is a patchwork of jurisdictions with the resultant legislative and administrative arrangements frustrating any chance of planning on the basis of an ecosystems or biophysical approach. The two major regional land use planning approaches, i.e. ShapingSEQ and the SEQ NRM Plan have been linked in writing, but not since the regional arrangements broke down has there been any tangible framework to bring out the best of this recognised nexus.

The SEQ Ecosystem Services framework engaged over 100 academic and citizen experts to gauge and map the level of goods and services provided by the landscapes of SEQ.(23, 24) Many of the ecosystems of Moreton Bay were identified as the highest producers of ecosystem services for the growing population of SEQ (25). The framework was supported by the SEQ Regional Plan with the desired outcome to manage the region as an organic entity cognisant of where life giving services were being generated.

Progress towards Principle 5 receives two stars.

Principle 6. It should be a **democratic and participatory** process that facilitates the maximum involvement of all stakeholders.

The lack of meaningful engagement and capacity building as part of a truly collaborative planning approach by those that hold the planning power in the region continues to disconnect the community from the planning process. The SEQ Citizen Senates, the formation of Healthy Land and Water and the ongoing commitment from key stakeholder groups has shown promise for this principle and creates a precedent and an opportunity to progress this ingredient.

The conduct of the SEQ Citizen Senates for NRM in 2004 and 2005 provided the opportunity for the community to interact with scientists and regulators to prioritise action and investment in the catchments. This alternative approach to planning and investment was borne from the more independent context rich regional arrangements for NRM which allowed such innovation to flourish. Support for this democratic jury process was withdrawn as the NRM funding program abruptly changed from a bespoke regional funding model to a Canberra driven competitive grants program.

Native title was recognised in the region in 2011 for the Quandamooka People of Moreton Bay. The issues and opportunities this creates are not truly understood by governments and land managers at this point in time. However, there are encouraging signs that this fundamental recognition will enhance the involvement of Traditional Owners in land use planning and management and progress towards improved relationships.

During this period the catchments of SEQ also experienced rapid peri-urbanisation. Peri-urban regions are those areas on the urban periphery into which cities expand or which cities influence. SEQ has experienced closer subdivision and fragmentation of lot sizes that has resulted in a large number of new land managers on a wide range of rural residential lot sizes. The diverse nature of these peri-urban areas presented numerous challenges of both a socio-economic and landscape management nature. Landscape management challenges include loss of biodiversity, pest animal and weed infestation, loss of scenic amenity, water quality decline, changes to hydrological regime, impacts to groundwater resources, increased prevalence of bushfire and landscape management capacity (26). The players in this very significant change to the demographic of the catchment can be typified based on their available skills, time and other resources. This new management context has made enhancing the capacity of new land managers to respond to the challenge of enhancing water quality a difficult task for Landcare groups, councils and others. Despite clear recommendations from a number of studies to address this situation, only small areas of success have eventuated (27).

Progress towards Principle 6 receives two and a half stars.

Principle 7. Future planning should promote a cooperative approach that involves the community at all levels of government in **partnership** arrangements.

As Hardy et al. (2003) (28) posit, a partnership requires: (i) recognition and acceptance of the need for a partnership; (ii) highly developed clarity and realism of purpose; (iii) commitment and ownership; (iv) trust; (v) clear and robust partnership arrangements; and (vi) a process to monitor, measure and learn. However, the rigid nature of bureaucracies with their many rules and regulations means that a partnership with community or between departments that meets these requirements is hard to achieve. This is not unique to the SEQ Region. The required devolution of power to local communities has occurred from time to time, but there has been no degree of permanence and longevity to these arrangements. The development of the SEQ NRM Plan 2009-2031 under the guidance of the SEQ Regional Coordination Group (SEQRCG) chaired by the then Department of Environment and Resource Management (DERM) ushered in a new era of governance. The Chief Executive Officers Committee for NRM, which reported to the Regional Coordination Committee, oversaw the operations of various technical and science panels that worked with the SEQRCG to support implementation, reporting and evaluation. The implementation of the SEQ NRM Plan was identified as a key activity towards achieving a number of desired regional outcomes in the SEQ Regional Plan.

A change of state government in 2012 saw the end of these arrangements and a far less proactive focus on ecologically sustainable development overall. An evaluation of the SEQ Healthy Country Partnership concluded that a strategic management group with an independent chair was required to undertake strategic and long range planning and program management of river restoration (29). The group requires adequate resourcing with a program director and operational staff and enhanced Indigenous engagement and inclusion in implementation.

Progress towards Principle 7 receives two stars.

Principle 8. It must be capable of resolving conflicts but more importantly **managing potential conflicts** before they arise.

Statutory land use planning across the region and within the catchments is embedded in the legal system, hence land use conflicts tend to be resolved through the legal system with varying opportunities for mediation before such matters reach the courts. Whilst scientific evidence has been injected into this process to varying degrees, there is clearly room to improve the employment of a science-based and participatory approach to land use planning in order to assist in managing conflicts before they arise.

In many respects this principle also calls for a move towards a proactive planning process as opposed to the reactionary processes that currently dominate most planning practices. Improved planning practices that embrace higher levels of citizen engagement and collaboration can serve to assist in identifying and managing potential conflicts before they arise. These levels of engagement also enhance the community's capacity to understand the planning process and the trade-offs that sometimes need to be made to achieve regional outcomes such as enhanced water quality in Moreton Bay. Whilst statutory land use planning has some way to go towards these standards of engagement, recent NRM planning practices are designed to manage potential conflicts before they arise and have achieved improved levels of community engagement.

Progress towards Principle 8 receives two and a half stars.

Principle 9. It should be an open and **transparent** planning process that achieves and retains the confidence of all participants.

The sheer weight of consultation processes and change that occurs in a heavily populated and dynamic region such as SEQ not only exhausts the community but contributes to vision fatigue. This can stem from the lack of a clear understanding of what a consultation process can actually achieve given that those in power are often driven by an outcome that meets the objectives of legislation or departmental strategic goals. The community's trust in consultation and planning processes has been eroded as a result of the perceived lack of ownership and transparency.

The development of progressive versions of the SEQ NRM Plan over time employed a variety of engagement tool kits depending on the available funding and governance arrangements. As communities became more comfortable with the knowledge of the role their communities and sub-catchments played in the regional water cycle, input became more informed. The SEQ NRM Plan process conducted community and industry roundtables in each sub-catchment, which provided a vehicle to recognise local issues in the context of the regional jigsaw puzzle. Citizen science and local knowledge were actively sought and valued as an input to the evidence that drove planning and investment through this process.

Progress towards Principle 9 receives two stars.

Principle 10. It should be capable of producing a viable range of **alternative options**.

Traditional approaches to NRM and catchment management should not be the only pathway to achieving our vision for the Bay. Viable alternatives consistent with the vision should be nurtured and allowed to take shape. Despite a framework as mapped by Low Choy (1) not materialising in the past 20 years, there have been a number of significant routes charted to get us back on course. Many including the SEQ Citizen Senates have been described in this paper.

A number of recent business cases for "saving" the Bay have focussed on economic analysis to substantiate the viability of investment in catchment management (30-32). The quantification of the benefits to community and industry lends support to a payment for ecosystems services approach to amassing the investment required to address water quality issues in the Bay. A number of pilot nutrient offset projects that recognise the services ecosystems provide are now underway involving water utilities and will require further planning and regulatory support to maximise the commensurate reduction in nutrient and sediment loads in the Bay. The recently launched Building Catchment Resilience project aims to showcase how to tackle the problems at their source in the upper catchment where the greatest enhancements can be achieved (31). Scenario planning and systems thinking have also been trialled and are tools that could be employed to identify alternative approaches to planning and implementation (32, 33). Systems planning and adaptive management should be the hallmarks of alternative approaches because, as we have seen in this paper, the route to a comprehensive plan for the Bay is by no means a linear one.

Progress towards Principle 10 receives three stars.

Conclusions

This paper has sought to show that the comprehensive management of the catchments of the Bay has proven to be difficult to resolve because of the complex social, economic and environmental interdependencies that characterise the SEQ region. A single focus on one issue has often revealed a multitude of others and exposed the lack of knowledge or contradictions in our understanding of the social and environmental landscape. These awkward relationships are aggravated by sharp, unpredictable changes such as extreme weather events, changes in the political landscape and global economic shocks.

Many stakeholders are involved and it is becoming increasingly obvious that resolution will depend, not so much on more or better governance but on new forms and systems of governance for catchment management. It is widely recognised that past ways of operating will not necessarily assist in solving new challenges, as the new challenges overlain with climate change present issues very different from the past (34, 35) It is important to reinforce the central role of Traditional Owners and their knowledge in managing Country in such a comprehensive planning framework.

A solution to a "wicked problem" such as this can only be found in a truly collaborative planning approach. This immutable fact must provide the foundation on which to analyse progress in the region towards a comprehensive management plan. True collaboration requires recognition of the power structure and a framework to rebalance this power to provide equity in participation, decision making and an equitable sharing of the responsibilities for implementation, monitoring and improvement. It also needs resources and appropriate funding that is ongoing and not subject to short-term investment and policy programs so often promulgated by the election cycle.

For Low Choy's 10 principles to exist as the constituents of a comprehensive planning framework, we must first acknowledge the fact that there is a serious problem on our doorstep. From there we must actively create a true partnership approach that is based on highly developed clarity and realism of purpose, commitment and ownership, particularly to implementation and a process to fill important knowledge gaps, monitor, measure, learn and adapt. A successful partnership can build trust leading to a collaborative approach to a comprehensive management plan for Moreton Bay and its catchments.

The need for application of Low Choy's 10 principles still resonates in the catchments of Moreton Bay. The large body of work and effort described in this paper are testament to the passion, commitment and vision of individuals and organisations in the quest to activate a comprehensive framework. For this journey to continue this commitment must be matched by a coordinated, adequately resourced and uninterrupted program of science, community engagement and implementation. This paper's analysis suggests that despite some peaks in achievements we are only halfway along on the journey. Given the scale of landscape and community change required to rebuild catchment resilience this should not be seen as pessimistic but rather a solid springboard (not plank) in support of the community's unwavering commitment to the cause. The underlying planning philosophy must embrace the environmental planning principles of diversity, sustainable development, environmental carrying capacity, equity and the precautionary principle as key ingredients for collaborative catchment planning, research, implementation, monitoring and evaluation.

Acknowledging and understanding these challenges allows us to remain positive about pursuing a number of suggested pathways to enhance the health of Moreton Bay. It is now a matter of boarding the same boat and all rowing in the same direction guided by what the stars in this review have told us.

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Chapter 8 - Moreton Bay Marine Park

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Managing for the multiple uses and values of Moreton Bay and its catchments

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Abstract

Managing Moreton Bay involves a complex set of organisations and regulations which broadly reflect the historical build-up of Aboriginal customary uses and meeting of cultural obligations followed by a set of uses of this marine space for fishing; shipping and transport; maritime safety; conservation of marine ecosystems, birds and marine species; and water quality. Until now, management has been focused on regulating uses and managing their co-existence and potential conflicts, with some acknowledgement of 'rights'. While this is important, utilitarian and ecological values are only two of a potential set of values the public may hold towards waterways. This paper summarises the history of management of Moreton Bay, then considers how Moreton Bay and relevant aspects of the catchments are managed. It suggests new ways in which a wider set of values can be considered in management, and opportunities for communication with the interested public.

Keywords: governance, collaboration, partnership, history, communication, stewardship, shared responsibility

Introduction

Moreton Bay is managed as the sea country of the Quandamooka, Kabi Kabi/Gubbi Gubbi and Kombumerri (members of the Yugambeh peoples), under Aboriginal customary law, and since 2011 some of it has had formal recognition under the Quandamooka native title decision (1). Meanwhile it is managed as a marine park, and as a fishery, a Ramsar site, as well as for shipping, recreation, and multiple other uses. We argue that prior to policies for and regulation of these uses, Moreton Bay was a 'commons', to which the non-Indigenous public had open access and unrestricted use. Alongside formally recognised organisations with policies and management responsibilities, there are numerous citizen science groups, environmental education centres, and 'care' groups.

Its catchments, similarly, have overlays of management from the many original owners–custodians to governments with responsibilities for urban planning, environment, agriculture and water supply, to the 11 catchment management committees belonging to the Brisbane Catchments Network, to numerous Landcare and other groups, and to the individual landholders and industries adopting 'best management practices' on land they control (2).

This paper explores the many forms of management of this complex marine and freshwater system. In doing so it takes an expanded view of 'management' that goes beyond the formal perspective based on legislation, policies and plans formed by governments, to incorporate the actuality of Indigenous management and many voluntary activities by community organisations and NGOs. In doing so, we suggest that voluntary efforts (Nasplezes *et al*. (2), this volume), underpinned by people's values towards waterways (Ross *et al*. (3) and Pinner *et al.* (4), this volume), should be recognised for the significant contribution they make towards the management of Moreton Bay and its catchments.

Management is not a straightforward matter of governing 'functions'. It involves managing people as well as their activities and impacts. Yet we know very little about how people value waterways and marine spaces, what they mean in their lives, and their activities in marine spaces. This information is important for management, demonstrating voter support for formal management levers such as legislation and policy relating to the protection and restoration of waterways, the extent of voluntary stewardship, and the public's priorities. A river, or marine park and its coastline offer many opportunities for people to enjoy these settings—from good places to experience nature, walking, reflecting, canoeing, surfing, fishing, hang-gliding, jetskiing, bird watching and meditation, to having wedding photos taken. Different cultural groups, ages and genders may relate to these places in different ways. People may value marine and waterway spaces in multiple ways including through capture and use of their resources, through feelings of affection and care, in aesthetic appreciation and inspiration, for learning and exploration, in spiritual reverence, or for physical and mental challenges (3–5). On the basis of the multiple values held towards the waterways, and the many government, Indigenous and community interests involved in their management, we argue for a more integrative approach to waterway management.

We thus interpret 'management' broadly to include policies, plans and programs intended to influence environmental outcomes over an area or resource or human behaviour (the conventional 'government' view of management), and tangible actions directly affecting that area or resource by any party, not necessarily a government. It can include managing public information and understanding (e.g. awareness raising), as well as stewardship by landholders and voluntary groups (2). Campaigning by lobby groups aims to influence management, and should also be considered part of the management system.

Managing Moreton Bay and its catchments

We can view the management of Moreton Bay in terms of changes over time (Table 1). As new forms and purposes of management have been added to preceding ones, a series of 'overlays' has arisen in which different management regimes exist over the same set of waters. In this view, Moreton Bay began and continues as an Aboriginal-managed domain. It is also a former commons that has been transformed through legislation limiting public access and use, a set of fisheries for a range of species ranging from whales to mud crabs, a marine park that includes an internationally recognised Ramsar site, as well as a marine space requiring management of shipping and boating. Moreton Bay is an important element of the regional economy with continual growth and expansion of infrastructure to accommodate increasing international trade. Privatisation of government-owned assets, such as the port and airports, as well as substantial recreation-based commerce and tourism, has resulted in the private sector being an instrumental player in the management of the Bay. Additionally, the proximity of the Bay to Australia's third-largest city has resulted in challenges to water quality and increased the interaction of a range of business and industries with the catchment and Bay. Across all of these are mixes of Aboriginal, local government, state and federal government jurisdiction, community-based stewardship and citizen science groups, and advocacy groups, sometimes acting in combination. The catchments similarly are domains of Aboriginal management, and under multifunctional and overlapping management regimes embracing planning, urban and regional management, mainly under local and state governments. The waterways are managed for water supply (urban and irrigation), water quality, and as transport corridors. Because water is regarded as a public good, seldom subject to property rights, management often has to rely on collaboration (6). From the late 1990s, a unique collaboration of government, non-government and science organisations, Healthy Waterways[1], developed to improve water quality in Moreton Bay and its catchments. In 2016 this joined with another collaborative body, SEQ Catchments (one of Australia's 56 regional bodies for natural resource management) to form Healthy Land and Water. This collaboration combines strategic initiatives with on-ground opportunities for working across land to sea. The SEQ Regional Plan 2017 provides a blue-print for the sustainable development of the SEQ region for the next 50 years and includes substantial recognition of Moreton Bay and its stakeholders, and a range of strategies to support sustainable outcomes.

Evolution of management

Throughout its history, Moreton Bay, its islands and its catchments have been managed by a set of Aboriginal Traditional Custodians according to customary arrangements based in a holistic belief system in which humans and the natural world are closely related. Environmental management is a customary responsibility and informed by deep traditional ecological knowledge. For example, the peoples of Moreton Bay were active stewards of oyster beds (7). Table 1 provides a timeline of significant events in the management of Moreton Bay.

Moreton Bay and the Brisbane River were critical to the early and continuing settlement of South East Queensland. Following non-Indigenous incursion into the region, Moreton Bay appears to have been treated as a 'commons', that is, under open access (Aboriginal ownership and management arrangements not being formally recognised at the time). There was a strong utilitarian focus on the Bay with animals and fish being exploited for commercial and recreational purposes, and other recreation especially yachting. Following the near extermination of dugong under unrestricted hunting from the 1850s, restrictions commenced in 1881 (commercial dugong hunting was prohibited altogether in 1969). Commercial whaling occurred from 1952 to 1962, with a base at Tangalooma on Moreton Island. The closure was a commercial decision, related to over-exploitation, not a policy decision.

Fisheries management in Queensland, including Moreton Bay, commenced with the *Oyster Fisheries Act 1863*, which licensed the cultivation of oysters (17). Habitat protection commenced in 1951 with the closure of Coombabah Lake (Coomera catchment, Gold Coast area) to fishing. From 1969, the mechanism of declaring fisheries habitat reserves was adopted to protect fish habitats: seven were declared that year and a further four in 1971. A further four were declared in 1983, and a distinction introduced between fish habitat, and wetlands, reserves. It is important to note that these protections were put in place by fisheries managers with the goal of sustainable management of fish stocks rather than protection of biodiversity more generally, and they have a single purpose, that is, protecting fish habitat.

Coastal planning commenced under the *Coastal Protection and Management Act 1995*. This assisted the development of plans to protect coastline habitat and prevent impact from coastal

[1] with a variety of predecessor names

processes. The coastal plans, however, were not integrated with habitat protection measures with many components operating with different specialisations and at different scales or marine parks.

Table 1. A timeline of significant events in the management of Moreton Bay

Date	Law/Regulation
1862	Regulation of oyster cultivation (*Oyster Fisheries Act 1863*)
1888	Regulation of dugong fishing (*Queensland Fisheries Act 1887*)
1952	Coombabah Lake closed to taking of fish
1959	Swan Bay closed to taking of fish
1962	Commercial whaling ceased at Tangalooma
1968	Commercial turtle fishing ceased. Turtles designated as protected under Queensland Fisheries Act by order of Council.
1969	Commercial dugong fishing ceased. Hunting continued for recreational, subsistence and ceremonial purposes.
1969–1971	11 ‘fisheries habitat reserve’ declarations in Moreton Bay
1982	*Marine Parks Act 1982* provided for the declaration and management of marine parks.
1983	All fisheries habitat reserves re-declared as either fish habitat reserve or wetlands reserves; Coomera, Coombabah and Bribie Island wetlands reserves declared.
1986	Pumicestone Passage Marine Park declared
1988	Northern Moreton Bay Marine Park proposed
1990	Marine Parks Regulation made
1991	Second Draft Moreton Bay Strategic Plan released (the first document to specify a need for a marine park over the whole area)
1992	*Nature Conservation Act 1992*
1992	Myora Extension Fish Habitat Reserve declared
1993	Moreton Bay Strategic Plan gazetted
	Moreton Bay Marine Park gazetted
	Moreton Bay Ramsar site declared
1994	Maritime safety included under the *Transport Operations (Maritime Safety) Act 1994*
1995	All fish habitat reserves and wetland reserves re-declared under new Fisheries Regulation 1995 as ‘fish habitat areas’
1997	Pumicestone Passage Marine Park revoked and Pumicestone Passage included within Moreton Bay Marine Park
	First zoning plan for Moreton Bay Marine Park implemented
1998	Pumicestone Channel Fish Habitat Area declared (amalgamated Pumicestone Passage and Bribie Island Fish Habitat Areas)
1999	*Environment Protection and Biodiversity Conservation Act 1999*
1992	Myora-Amity Banks Fish Habitat Area declared (amalgamated Myora and Myora Extension)
2003	Grey Nurse Shark areas declared under the *Fisheries Act 1994* and Marine Parks (Moreton Bay) Zoning Plan 1997
2009	Second Zoning Plan for Moreton Bay Marine Park implemented

Protection of migratory birds commenced in 1981, through an agreement with Japan, and agreements with China (1988) and Korea (2007) followed. A Partnership for the Conservation of Migratory Waterbirds and the Sustainable Use of their Habitats in the East Asian–Australasian

Flyway was launched in 2006 and enables sharing of information, and collaboration between all sectors with an aim to protect migratory birds, their habitats and the livelihood of people dependent on them. Ramsar protects wetlands and their resources, an important component of bird habitat. These various agreements recognise the global dynamics of migratory shorebirds, but there is a long way to go, and numbers of several migratory birds utilising Moreton Bay have declined (8).

Nature conservation was broadened under the *Nature Conservation Act 1992*, which sought conservation through a variety of mechanisms, including establishing protected areas, protecting wildlife and habitat, and the sustainable use of wildlife and habitat areas. It affects tidal areas overlapping the Moreton Bay Marine Park, and fish habitat areas, such as the southern Bay islands (an example of inter-related management responsibilities). This Act was also important in recognising the interests of Aboriginal and Torres Strait Islander peoples in nature conservation, and the 'co-operative involvement' of Indigenous peoples and landholders.

There was no systematic protection of Moreton Bay's waters prior to 1993. A marine park over the northern part of the Bay was first proposed in 1988, and strategic planning commenced in 1989. The first Moreton Bay Marine Park, with minimal protection by today's standards, was declared in 1993. Much tighter zoning was introduced in 2009. Public acceptance was difficult in both periods, with mixed public support and some sharp divisions between viewpoints favouring conservation versus unrestricted access to recreational and commercial fishing and related pursuits. This may be a legacy of the periods in which Moreton Bay was a commons with open access. The public has been obliged to accept and adapt to new regimes involving losses of former freedoms, and attitudes may be slow to follow the legislative changes. Indigenous people throughout Australia have always treated their estates – land and sea – as common (shared) property, operating under specific cultural rules, rather than as open access.

From 1994, maritime safety became part of the mixture of management arrangements under the *Transport Operations (Maritime Safety) Act 1994*. There were antecedents in some legislation promoting navigation safety under the *Harbours Act 1955*.

Aboriginal management over a large part of the Bay has been strengthened with a new level of formality under the 2011 native title settlement providing Quandamooka (Stradbroke Island, Moreton Island, the southern Bay islands and associated waters, and parts of the mainland coast south from the Brisbane River) with a combination of exclusive and non-exclusive (use) rights over land and water. The Australian and state governments, two city councils (Brisbane and Redland), and a range of commercial interests, including mining, fishing, infrastructure providers and oyster growers, participated in the negotiations. This determination places the Quandamooka peoples (Dandrubin Gorenpul, Ngugi and Noonucal) in a much stronger position for managing their country; in many cases other organisations must now negotiate with the native title holders over particular issues of land and water use. The native title parties have formed an association, The Quandamooka Yoolooburrabee Aboriginal Corporation, to coordinate their decision-making and activities, and provide a point of liaison with other organisations.

The current management situation

We argue that there are two types of management over Moreton Bay and the waterways of the catchments. There is an overt and official type, focused on legislation and formally appointed bodies, as well as an unofficial and overlooked set of contributors focused on Indigenous, voluntary non-Indigenous, and advocacy efforts. There is some overlap between these roles, where governments offer funding to voluntary organisations. The formal, government-led, management focuses on Moreton Bay Marine Park; fishing (traditional, recreational and commercial); shipping, navigation and marine safety; and meeting water quality objectives. Here the state and local governments are prominent, though their responsibilities require regulation and management of others.

The overlooked, unofficial, dimensions of management include the contributions of Aboriginal Traditional Custodians, activist organisations and peak bodies, stewardship and citizen science groups, science organisations, and some recreational groups. Blending across these are two former collaborations, now merged as Healthy Land and Water. Healthy Waterways focused on strategy, monitoring, and encouragement of implementation partners towards improving water quality in Moreton Bay and the catchment rivers. SEQ Catchments, as a regional body for natural resource management, had a broader natural resource management brief, and by mutual agreement focused more on on-ground works, including support of local stewardship organisations. It also gained influence over urban and regional planning by having its natural resource management plan adopted as the regional plan's natural resource management component. This represents a shift towards a governance approach for managing Moreton Bay whereby collaborative relationships are sought among government and non-government actors to work effectively to manage natural resource systems. Table 2 shows the many forms of management extant over the waters and coastal land of Moreton Bay and the catchments.

Formal management

Formal management is framed by a range of legislation and associated regulations, in which three levels of government—federal, state and local— play interacting roles alongside aspects of Aboriginal management that enjoy legal force under native title legislation. While the Australian Government's role is seldom overt, the Ramsar Convention and migratory bird agreements can trigger Commonwealth environmental impact assessments under the *Environment Protection (Biodiversity Conservation) Act 1999* (e.g. the Wyaralong Dam assessment, (9)). While much of the legislation and hence formal management arrangements affecting the Bay and catchments is state legislation, it often requires local governments and industry to act as well. These parties are prominent in the collaborative organisation Healthy Land and Water described below.

Despite recent arrangements to bring fisheries habitat managers and marine parks in Queensland under a single authority (in 2012)[2], the reality of management over Moreton Bay

[2] Fisheries habitat administration and marine park management first came together in 2012 in the then Department of National Parks, Recreation, Sport and Racing; they are now in the Department of Environment and Science. Formally, this means that under the Administrative Arrangement Orders, one minister is responsible for the *Marine Parks Act 2004* and the *Fisheries Act 1994* as they relate to 'fish habitat areas'. The other 'fish habitat' parts of the Fisheries Act (marine plants and fish passage) are the responsibility of the Department of Agriculture and Fisheries.

is that it remains highly divided according to specific functions managed by a number of separate authorities. Although applying to the same waters, fisheries, marine park management, the Ramsar site, shipping and maritime safety, are all under separate legislation, policy and organisations.

Recognising native title over much of the Bay and islands means that those native title holders represented by the Quandamooka Yoolooburrabee Aboriginal Corporation are now part of the formal decision-making. Other Traditional Custodian groups are not yet brought under formal management, other than some provisions that apply in certain circumstances through cultural heritage and native title legislation, such as the ability to form cultural heritage management plans and Indigenous Land Use Agreements.

There are further management interests in water quantity and quality. The official responsibility for meeting water quality standards in the rivers and Bay rests with the Department of Environment and Science (Queensland), but the practical actions required draw in local governments and a wide range of land and water users. A collaboration of state government, local governments, science organisations, water utilities, commercial organisations and community groups formed in the late 1990s. This was originally under the name of the Moreton Bay Waterways and Catchments Partnership, followed by a number of subsequent name changes including Healthy Waterways, and more recently Healthy Land and Water (6). This began with a focus on the Bay and lower catchments, and extended to the entire catchments of Moreton Bay in the 2000s. Significant achievements of this collaboration are a strong water quality monitoring process, an evidence-based approach with close scientific participation in the collaboration, and significant improvements to water quality in the Bay following upgrades to sewage treatment plants. The Ramsar site ensures Australian Government interest in activities within the Bay. An example is the approvals process for the construction of the Wyaralong Dam, which required consideration of the changes in flows on mud crab populations within Moreton Bay (9).

Below we briefly outline the process for evaluating and adjusting the boundaries and zoning of the Moreton Bay Marine Park. This process is different to other management processes in the Bay. It illustrates challenges of achieving an integrated approach and associated whole-of-Bay outcomes. The range of management frameworks and approaches increases the complexity of the management system, and can be challenging for managers and other stakeholders alike.

While we will not attempt to document the complexity of the management of land areas, it is important to note that catchment management, including cities and rural areas, is separated from marine management. Rivers flow into the Bay, yet there is no statutory or formal connection in their management. Marine park and fisheries legislation and management arrangements have no formal influence beyond their respective aquatic boundaries. This means there is no formal mechanism for guiding land-based activities in the catchments that affect the water quality and other environmental integrity issues in the Bay. This must be achieved through non-statutory collaboration, one of the main functions of Healthy Land and Water.

Table 2. Managing parties, foci and forms of management over Moreton Bay and its catchments. Note: Organisation names are presented by type rather than specific name, given the occurrence of organisational changes.

Geographical scale	Managing party(ies)	Focus or function	Nature/type of management
Aboriginal			
Local	Aboriginal Traditional Owners and their organisations e.g. incorporated Traditional Owner associations; native title representative bodies	Holistic care for their country, including land and marine areas, and species	Customary stewardship activity, following cultural responsibilities and using traditional ecological as well as local knowledge Managing specific areas (e.g. native title lands and waters, and one Indigenous Protected Area) Being involved as partners in a wide variety of programs and actions (e.g. the Moreton Island oil spill in 2009) Specific land and water initiatives (e.g. restoring Myora Springs on Stradbroke Island) Can involve campaigning Associations provide capacity and logistical ability for the management actions
Governments			
Federal	Federal ministers, government departments (environment, heritage responsibilities)	Specific international conservation agreements: *National habitat management agreements* Ramsar agreement: governs wetlands (including any area of the Bay and surrounding areas with depth of less than 6m) *Bilateral migratory bird agreements*: • CAMBA (China Australia Migratory Bird Agreement) • JAMBA (Japan Australia Migratory Bird Agreement) • RKMBA (Republic of Korea Migratory Bird Agreement)	Signatory to international agreements Practical management delegated to state governments, which must report, and deal with threats Declaration of species and habitats for protection
		National conservation legislation *Environment Protection and Biodiversity Conservation Act 1999*: governs nationally recognised threatened species and habitats	Environmental impact assessments over certain types of development with international implications (e.g. Toondah Harbour development)
		Airports	Air navigation, infrastructure (airports), air safety

			Brisbane's airport adjoins and has impacts on Moreton Bay and designated wetlands (e.g. expanding runways involve sand extraction, local aquatic impacts)
State	Minister, department, responsible for fisheries Note: In 2012 fish habitat areas and marine parks were brought under a single portfolio.	Commercial fisheries (specific types) Recreational fisheries (including charter fishing boats)	*Fisheries management legislation*: • *Fisheries Act 1994*, Fisheries Regulation 2008 (except for fish habitat areas) Policies, resource access rights and quotas, allowable technologies (types of gear etc.), management of bycatch, science and monitoring
State	Minister, department, responsible for the environment	Marine park	*Marine park legislation* and implementation roles: • *Marine Parks Act 2004*: governs establishment and management of Moreton Bay Marine Park (established 1992 though with low levels of protection). • Moreton Bay Marine Park Zoning Plan 2009 (rezoned the marine park to increase the level of protection) Management activities include zoning and enforcement; behaviour codes (e.g. boat speeds); science and monitoring; commercial activity (e.g. sand extraction)
		Environmental protection; water	*Environmental protection legislation*: • *Environmental Protection Act 1994* • *Environmental Protection (Water) Policy 2009*
		Coastal management and development	Sustainable development of water in rivers, streams, wetlands, lakes, aquifers, estuaries and coastal areas; monitor water quality and ecosystem health • *Coastal Protection and Management Act 1995* • *Coastal Protection and Management Regulation 2017*
State	Water resources, supply and treatment	Bulk water supply	Infrastructure and logistics towards water supply system, including dams
		Water supply (retail, to some but not all local government areas)	Implications for water quality including sediment delivery affecting dams, water treatment, Moreton Bay
		Sewage treatment	Water management in catchment
		Recycled water	Implications for water quality in rivers and Bay
State	Minister, department, responsible for maritime safety	Shipping and maritime activity	Ports, shipping routes and channels, navigational beacons, pilots Regulate use of waterways including speed limits, boat licences, vessel registration
		Boat-sourced pollution	Maritime safety (e.g. smaller boats) Manage vessel-sourced pollution

State	Minister, department, responsible for planning		• *Planning Act 2016*, Planning Regulation 2017 Land-use planning and development assessment, towards ecological sustainability Implications for Marine Park, coastal zone, water quality in catchments
Local	Elected councils and staff for councils adjoining and covering waters and islands for Moreton Bay, and for inland areas of the catchment	Planning, development approvals Services including waste management	Planning, development application of building codes etc. Sewage treatment plants (some councils) Manage stormwater Encourage public engagement with waterways Infrastructure including boat ramps, public access to water Health standards of recreational waters
		Collaborations	
	Healthy Land and Water (non-government but collaboration includes government bodies; part of nationally endorsed system of regional bodies for natural resource management)	Water quality in rivers and Moreton Bay, from urban and rural sources Multiple environmental functions including biodiversity Community engagement	Coordination (through collaboration), supporting the partners to fulfil their roles effectively; facilitating on-ground actions Science and monitoring Public awareness and engagement Strategies for solving sources of sediment and pollutants (targeting, best practices) Coordination (through collaboration) Public awareness and engagement Strategies for solving sources (targeting, best practices) No regulatory powers but, by agreement, provides the natural resource component of the statutory SEQ Regional Plan 2009–2031
Advocacy organisations			
National	• WWF Australia • Australian Marine Conservation Society • Greenpeace • The Nature Conservancy Australia	Conservation, wildlife, including marine animals, fish and birds	Advocacy roles and processes Influence governments, directly through lobbying or by mobilising the public via campaigns. Involves exploring and summarising the science, a degree of public education.
State	• Environmental Defenders Office (Qld) • Queensland Conservation Council • Wildlife Queensland	Support the public to bring public interest cases Conservation Wildlife	As above These organisations may have combined roles (e.g. member services, building public awareness, advocacy)

	• Sunfish Queensland	Represents recreational fishers	
	• Queensland Seafood Industry Association	Represents commercial fishers	Note: Birdwatching associations, stewardship groups (e.g. Seagrass Watch, catchment bodies) may conduct some advocacy.
Regional – local	• Moreton Bay Eco Alliance • Save Moreton Bay • Moreton Bay Seafood Industry Association • Brisbane Region Environment Council	As above, with regional foci	As above
Stewardship/community action groups			
All local, though some may connect with national networks	• Catchment management bodies (11 coordinate as the Brisbane Catchments Network, covering the Brisbane River, principally in the Brisbane metropolitan area)	Community-based management of catchments, local areas	Approaches differ, but these organisations tend to focus on on-ground action and building community awareness through those activities. All are voluntary organisations, run by committees of their members. They also rely heavily on volunteer labour (their members and others), and applying for small grants. A degree of endorsement and cooperation comes from federal, state and local government funding for certain activities. Many activities involve multiple partners.
	• Landcare and Coastcare groups. (voluntary organisations focusing on on-ground works to rehabilitate environments)		
	• Citizen science/community-based monitoring groups, including birdwatching groups (e.g. Queensland Wader Studies Group), MangroveWatch, Seagrass-Watch, Reef Check	Monitoring, public awareness	
	Environmental education centres	Environmental awareness, often with schools and families	All of these centres are coastal, open to the public, often run programs with schools

Moreton Bay Marine Park

The first Moreton Bay Marine Park Zoning Plan was implemented in 1997 (Marine Parks (Moreton Bay) Zoning Plan 1997). The marine park had five zones and provided for green zone protection of 0.5% of the Bay. This 0.5% area did not include representation of all habitat types in the Bay. The 1997 Zoning Plan expired on 1 September 2008, and following a substantial review during 2007/2008, a new zoning plan came into effect on 1 March 2009. The new zoning plan was based on research that had become available over the past 10 years, and on expert advice from an independent panel. The revised zoning plan protected 16% of the Bay, including a minimum of 15% of each habitat type. To support the transition to the new zoning, a structural adjustment package was implemented to buy out licences of commercial fishers who were impacted by changes. The new zoning plan had four zones: green zones (the highest level of protection), yellow zones (highly protected), blue zones (habitat protection), light blue zones (general use), and a series of go slow areas to reduce potential for boat strikes on turtles and marine mammals. These zones were similar to those used in other marine parks, including the Great Barrier Marine Park, and improved consistency in marine park management along the Queensland coast. The zoning plan also includes designated mooring areas allowing for environmentally friendly moorings. A monitoring program assessed social, ecological and economic changes in and around Moreton Bay.

We note that formal management is more focused on 'top-down' control and compliance through regulation than on encouraging desired behaviours. An indicator is the number of signs along the Moreton Bay coast listing forbidden actions, and very few enjoining positive engagement with the coastal and marine environment (Fig. 1). Formal management is also understood in a limited way- other than the native title determination over some two-thirds of the Bay's waters, there is low recognition of Aboriginal custodianship, and of the activities and commitment of stewardship and citizen science groups. Similarly there is little role for the general public, who are treated as users of the environment (often being viewed principally in terms of their damaging actions) rather than positive contributors to its care. Yet a study exploring how people value Moreton Bay and its tributaries (3–5, 10) suggests a strong desire among waterway users throughout the region to protect and look after waterways in South East Queensland to maintain their ecological integrity and ensure people can continue to derive

Figure 1. Signage on Moreton Bay coastline showing different styles of communication which can invoke either positive or negative responses.

cultural, recreational and economic benefits. (This does not necessarily translate into general public willingness to manage actively, according to surveys conducted on behalf of Healthy Land and Water).

Overlooked and unofficial dimensions of management

In a holistic picture of what constitutes 'management', a number of other roles and highly committed organisations and members should be recognised.

Traditional Aboriginal Custodians take a holistic and social–ecological perspective over managing their land and sea country that contrasts sharply with the sectoralism of government. Native title rights are transitioning the Quandamooka peoples into formally recognised governance roles, though the level of effective interaction with government arrangements is yet to be determined. Unfortunately, interaction between Traditional Custodians and other organisations is sporadic. A celebrated exception is the cooperation between Traditional Custodians, state government and other organisations in the clean-up effort following an oil spill off Moreton Island in 2009 (11).

Activist organisations and peak bodies concentrate on political and social influence and educational roles to mobilise public opinion in favour of changes, or influence political decisions directly. Examples are the organisations promoting conservation of Moreton Bay over the decades and those representing fishing interests.

Stewardship groups generally focus on on-ground work in local areas (Landcare and similar groups) or on a wider scale (catchment management bodies, the Brisbane Catchments Network). The catchment management bodies often coordinate, and offer support to, the more local organisations. These organisations are particularly active in restoration, as well as social influence and educational roles.

*Science organisation*s, involving formally qualified scientists mainly working for universities, government and the CSIRO, influence management through research providing an information base, and the design and oversight of environmental monitoring procedures. At times they may assist cautiously in advocacy, especially on behalf of conservation. Citizen science organisations contribute to monitoring particular habitats and species (e.g. reefs (12), seagrass (13, 14), mangroves (13), marine megafauna (15), and birds).

Recreational groups, such as surfers, divers, birdwatchers and fishers, also conduct some stewardship activities and monitoring (e.g. Birds Australia, Carpbusters).

Education organisations such as environmental education centres and the University of Queensland's marine research station on North Stradbroke Island play a role in the capacity building of future generations, increasing stakeholder knowledge of the Bay. This is likely to foster potential for stewardship and improved management in the future.

Media organisations take initiatives in promoting certain information and stories, and are used by other actors such as activist organisations, lobbyists and government for informal influence. For instance, media can be used to influence public opinion, and hence gain support for a policy, leverage in an advocacy campaign, or votes for a local government to commit more strongly to waterway protection.

These organisations and their efforts influence formal governance and sometimes political decisions, contribute constituent support for policies and investment, build and contribute local knowledge, and contribute significant and unpaid effort to on-ground management. They are recognised and supported to varying degrees, for example stewardship groups have been supported under federal–state programs since the 1990s (2, 16), and advocacy organisations and peak bodies are periodically consulted at times of policy change. Funding for Aboriginal custodial activity is less clear-cut. In general it is not supported in the same way as non-Indigenous stewardship organisations, but periodically specific funds are available to those organisations conducting specific on-ground activities.

The different actors and types of management also influence one another. For example advocacy organisations seek to achieve policy change, directly by lobbying governments and mobilising the public to support (or resist) the proposed policy changes. In the process of their advocacy, they may undertake–or indirectly achieve–public awareness activity (e.g. recognising the importance of ecological process or threatened species, or of the activities, livelihoods, and sustainable practices of fishers). This can mobilise campaigning in support of their cause. On-ground stewardship groups build community awareness and achieve tangible effects. Governments foster the activities of the stewardship groups, at least to some degree, through programs such as the National Landcare Program, and through part-funding of the regional bodies for natural resource management.

Effective management of Moreton Bay and its catchments as a complex system will depend not only on the involvement and commitment of diverse actor groups, both formal and informal, but also collaboration among them. This will require a 'new governance' approach whereby unofficial management actions receive greater recognition. 'New governance' involves tackling problems in a way that is collective and decentralised, and therefore depends on principles of inclusivity and networked actors (21). Dedicated effort is needed to build relations between the diverse actors operating in natural resource management of Moreton Bay in order to foster and build a new governance approach, whilst also acknowledging the challenges associated with legitimising new roles and responsibilities of different actor groups (22).

Conclusions and implications

Our inclusive analysis suggests that Moreton Bay and its catchments are managed by a system that is part-formal and part-informal, with many specialised components operating at different scales. Their interactions change perpetually as trajectories and outcomes shift according to the land and seascapes being managed. Members of the public harbour awareness, interests and values towards these environments. They need to be acknowledged within this management picture as people who care about the outcomes, are willing to contribute their efforts, and who will vote to achieve them.

This suggests some new directions for the management of waterways in South East Queensland. A more expansive view of management would recognise the important customary and often voluntary stewardship roles played by Traditional Custodians, stewardship organisations, such as catchment management bodies and Landcare groups, and voluntary monitoring organisations, such as creek and Waterwatch organisations. The collaboration Healthy Land and Water is already well recognised and connects some of these organisations. The role and uses of collaboration could be more strongly formalised, which would extend the basis for coordination and inclusion, for example by better connecting between land and sea similarly to the way Indigenous people view their coastal estates.

The more holistic view of what constitutes 'management', and who contributes to it, also opens opportunities to move from a dominant reliance on a 'control' way of thinking, focused on preventing damaging activity (e.g. limiting fishing activity, boating speeds through zoning and regulation), to incorporate the positive dimensions of caring and collaboration. A collaborative narrative may foster new opportunities for building relationships between formal and informal organisations that value waterways in South East Queensland in similar ways, and that hold shared objectives to manage these aquatic environments and/or resources sustainably. Monitoring and evaluation can expand from biophysical threats and damage, to social, economic and cultural benefits and contributions, as Healthy Land and Water has been doing since 2015.

The wide range of people's values towards waterways has management and communication implications (3-5). It expands the set of considerations from the past trade-offs between uses and protection, to incorporate love of nature, aesthetic appreciation, and spiritual and symbolic connections. As the region's local governments are already recognising, members of the public have some interests in the Bay and rivers that differ from those that have been the focus of past management. They like some areas to be protected, or restored to a relatively 'intact' state, so as to enjoy and learn from nature firsthand, and other areas to be controlled and maintained in a modified state to allow convenient access for recreation and enjoyment. Others want to see waterways and marine spaces managed to a condition that they know will allow populations of species such as fish, turtles and dugongs to remain viable so close to a high-growth urban area. Expectations in the upper catchments show that local waterway management should be focused on local issues and needs, not necessarily for the benefit of the Bay (16). While the need to control potentially damaging uses will continue, as will purely moral and ecological reasons for protecting areas and species, engaging public interest and cooperation through appeal to the specific ways in which they appreciate and use waterways offers a wider repertoire of management options.

Recognising the way in which formal and informal management is conducted will help all stakeholders to engage more effectively and to work to achieve mutual outcomes. Such empowerment is important and will help to ensure that Moreton Bay and catchments are managed for all users into the future, not just for user groups that are well versed in working within a complex management environment.

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Performance of marine reserves for fish and associated ecological functions in the Moreton Bay Marine Park

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Abstract

No-take marine reserves in Moreton Bay were established to conserve and restore the structure and function of marine ecosystems and ensure sustainable social-ecological systems (Ross et al. 2019, this volume). Here, we review published literature to determine our current understanding of how no-take marine reserves (i.e. green zones) benefit fish, and shape ecological functions in numerous ecosystems within the Moreton Bay Marine Park. Over the past decade, 16 peer-reviewed studies have examined 'reserve effects' for fish and associated ecological processes in Moreton Bay; this work was mostly conducted in the central part of the Bay in coral reefs and seagrass meadows. Most studies showed enhanced fish abundance, diversity, or both, inside reserves and increases in the levels of functions performed by fish (e.g. greater grazing rates). The degree to which reserves enhance the abundance of fish and their functions was contingent on two key conditions. Reserves that were better connected (i.e. those in proximity to complementary habitat types and situated in a more complex seascape) and those located in clearer water typically perform better and may also be more resilient. Therefore, these two factors must be strongly considered during future deliberations about expanding or modifying reserves in Moreton Bay. We identify a number of information gaps that are likely to impede improvement to the current network of no-take reserves, namely, research on sandy and muddy bottoms, ocean beaches, fishing outside of reserves, and pivotal ecological functions other than herbivory. Reserve design and future rezoning can take advantage of the considerable body of evidence gathered on factors governing reserve performance for fishes, but reserve effects need to be examined for the numerous habitats that have been overlooked. How reserves shape a broader range of functions, productivity, habitat and ecological resilience needs to be investigated.

In: Tibbetts IR, Rothlisberg PC, Neil DT, Homburg TA, Brewer DT, Arthington AH. (Eds). 2019. Moreton Bay *Quandamooka* & Catchment: Past, present and future. The Moreton Bay Foundation. Brisbane, Australia. pp. 579 - 592 https://moretonbayfoundation.org

Keywords: conservation planning, coral reef, disturbance, fisheries, habitat, offshore, seagrass, spatial ecology, water quality

Introduction

No-take marine reserves (i.e. green zones) are widely used to conserve habitats and species in the face of human threats, particularly fishing (1). Many studies have assessed the efficacy of no-take reserves for fishes over the past two decades. Reviews of the global literature show that strategically placed and well-enforced marine reserves can benefit populations and assemblages of fishes, especially species that are heavily harvested (2, 3). Importantly, marine reserves can in some instances promote the recovery of overfished apex predators and herbivores towards their pre-fished biomass, thereby reversing trophic cascades (4, 5), restoring ecological functions (e.g. herbivory, predation, recruitment), and the condition of some benthic ecosystems (3, 4, 6).

Historically, research on reserves mainly asked whether they enhanced the biomass of fished species or restored food webs (7, 8). Recent work has expanded in scope, asking *inter alia*: (i) whether reserves can benefit surrounding fished areas (i.e. spillover) (9, 10), (ii) how effective reserves are compared with other management interventions (11), and (iii) whether and how reserves can increase ecological resilience (i.e. the capacity of ecosystems to resist, or recover from, disturbance). It is also increasingly acknowledged that reserve effects extend beyond fishes and other mobile animals (12). The key ecological functions of herbivory, predation and scavenging can be significantly modified in intensity and spatial extent within reserves, and might improve the capacity of ecosystems to withstand disturbance (13-15). For example, in Kenyan marine reserves, the recovery of keystone predators reduced the abundance of their sea urchin prey (16), and promoted recovery of calcifying algae (17). These are critical advances in our understanding of reserve effectiveness for ecosystems (18, 19).

Research on reserves within the Moreton Bay Marine Park, has contributed measurably to the global literature on the topic (3, 20, 21), and in the past decade, has helped to progress our understanding of how reserves influence fish communities (22, 23), ecological functions (24, 25), and the structure and resilience of ecosystems (26–28). The quantity and quality of published outputs from Moreton Bay on these topics is comparable to the Caribbean (4), Kenya (29) and Tasmania (30), which are widely regarded as prime research areas on this topic (3). In this study, we review the peer-reviewed, published literature for studies that quantify how no-take reserves influence fish assemblages and ecological functions performed by fishes in Moreton Bay. We identify the habitats where these studies were focused, the types of factors the studies considered in their analysis that might modify overall effects, and whether the study concluded that the reserves were overall 'effective' for their target groups, species, or functions within Moreton Bay.

Summary of research on reserve effectiveness

Individual species and specific habitats in Moreton Bay have been provided various forms of protection since the late 1800s, and the first marine park with formalised zoning was implemented in Moreton Bay in 1993 (Ross *et al.* (31), this volume). Despite this long history of protection, research into conservation performance was not published until 2005 (32), and did not focus on fish until 2007 (33). Since then, 16 studies have examined reserve effectiveness for fishes and/or ecological functions in Moreton Bay (Table 1). Each of these studies sampled multiple no-take reserves and compared them with multiple reference sites that were open to fishing. Only one article charted how assemblages in reserves changed relative to their condition prior to reserve establishment (34).

In terms of ecosystem coverage, studies can be grouped broadly into those focusing on one or two of the six main ecosystem types (Figs 1, 2). Coral reefs were the most researched ecosystem in Moreton Bay, with eight studies overall, followed by seagrass meadows (four studies). Outside of these ecosystems, estuaries (three studies), mangroves (one study), deep reefs (>20 m water depths) in areas offshore of bordering sand islands (one study), and unconsolidated soft sediments in the nearshore surf zones of sandy beaches (one study) have also been assessed (Figs 1, 2). For the purposes of this study, ‘estuaries’ were defined as the tidal mouth of a creek or river, where the tide meets the stream (which can often include mangroves), whereas mangroves were defined as any areas outside of this definition which surveyed ‘mangrove’ ecosystems. Most research (11 of 16 included studies) has been conducted in the heterogeneous seascapes of central Moreton Bay (Fig. 1). Here, the close proximity of mangroves, seagrasses and corals allows for research on both ecosystem-specific responses to marine reserves, as well as determining how connectivity between ecosystems modifies reserve effects.

Thematically, studies have focused on either one or a combination of four main topics: (i) fish communities (fish abundance and assemblage composition), (ii) ecological functions (herbivory, scavenging), (iii) benthic ecosystems (seagrasses and corals), and (iv) reserve effects in the context of disturbance and complementary management interventions (water-quality effects, disturbance from floods, spatial effects of seascape connectivity on reserve performance) (Fig. 2, Table 1). A sizeable fraction (40%) of studies examined various facets of reserve effects on fishes, mostly on coral reefs and in seagrass meadows (Fig. 2). The main metrics measured were spatial contrasts (i.e. inside versus outside reserves) in the abundance of species that have commercial value, or are of conservation significance (14 studies). Eight studies compared differences in the diversity and species composition of fish assemblages between reserves and fished locations.

Work on the ecological roles and functions of fishes inside and outside of reserves is centred on herbivory, either on coral reefs (six studies) (25), or in seagrass meadows (one study) (26). Enhanced grazing of algae by fishes within reserves has significant effects on benthic habitat structure of corals and the physiology of seagrass species (26, 27). The fish species most frequently identified as a functionally important herbivore is the dusky rabbitfish *Siganus fuscescens*. This is a harvested species (35), which varies in abundance seasonally (24), and is strongly affected by the proximity of coral reefs and seagrass meadows to other ecosystems, especially mangroves (e.g. seascape connectivity effects) (27, 36). The effects of reserves on other ecological functions (e.g. scavenging, carbon processing, predation) have not been sufficiently studied, but there is an indication that estuarine reserves might promote scavenging and carbon processing (15), whereas soft-sediment reserves do not appear to modify predation pressure (37).

Table 1. Summary of studies on reserve performance in Moreton Bay, grouped by ecosystem type. UVC: underwater visual census, BRUVS: baited remote underwater video stations. 'Reserves effective?' is an assessment of whether the study in question shows positive effects of marine reserves on either assemblages or ecological functions (Y, effective; Y*, somewhat effective; N, not effective).

Reference	Survey method	Focal species/group	Focal function	External factors	Reserves effective?
Coral reefs					
Olds *et al.* 2012 (27)	UVC	Fish assemblage	Herbivory	Seascape	Y*
Olds *et al.* 2012 (22)	UVC	Fish assemblage	-	Seascape	Y*
Olds *et al.* 2014 (28)	UVC	Fish assemblage	Herbivory	Water quality, seascape	Y*
Gilby *et al.* 2015 (11)	Benthic quadrats, algae deployments	Benthic macroalgae	Herbivory	Water quality	N
Yabsley *et al.* 2016 (25)	UVC, algae deployments	Fish assemblage (herbivores)	Herbivory (grazing and browsing)	Seascape	Y*
Gilby *et al.* 2016 (23)	Benthic quadrats, BRUVS	Fish assemblage	Predation	Water quality, seascape	N
Gilby *et al.* 2016 (24)	BRUVS	Fish assemblage (herbivores)	Herbivory (browsing)	-	N
Gilby *et al.* 2016 (50)	Benthic quadrats/BRUVS	Fish assemblage	Predation, herbivory (grazing and browsing)	Water quality, seascape	N
Seagrass					
Pillans *et al.* 2007 (33)	Seine net	Nekton	-	-	Y
Henderson *et al.* 2017 (36)	BRUVS	Fish assemblage (harvested)	-	Water quality, Seascape	Y*
Henderson *et al.* 2017 (26)	Algae deployments, BRUVS	Fish assemblage (harvested)	Herbivory (browsing)	Seascape positioning	N
Henderson *et al.* 2017 (43)	Acoustic telemetry	Giant shovelnose ray (*Glaucostegus typus*)	-	Seascape positioning	N
Mangroves					
Olds *et al.* 2012 (22)	UVC	Fish assemblage	-	Seascape	Y*
Estuaries					
Pillans *et al.* 2007 (33)	Seine net	Nekton	-	-	Y
Olds *et al.* 2017 (57)	BRUVS	Fish assemblage	Scavenging	Seascape positioning, urbanisation	N
Gilby *et al.* 2017 (40)	BRUVS	Fish assemblage	-	Seascape positioning, urbanisation, water quality	N
Offshore rocky reefs					
Terres *et al.* 2015 (34)	BRUVS	Pink snapper	-	Habitat type and positioning	Y
Unconsolidated soft sediments					
Ortodossi *et al.* 2018 (41)	BRUVS	Fish assemblage	-	Seascape positioning	Y*

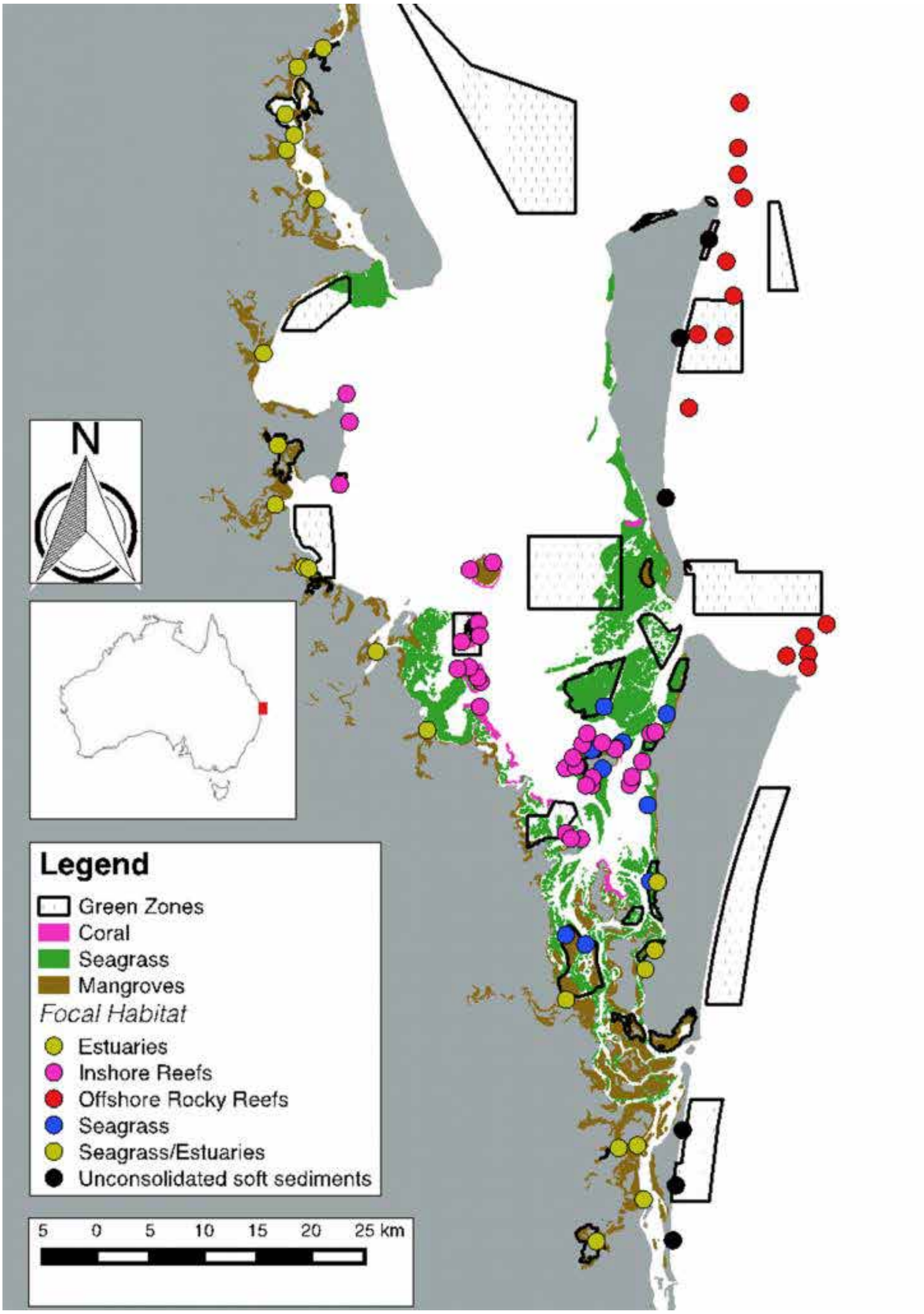

Figure 1. Spatial distribution of research effort on no-take marine reserve (i.e. green zone) effects within the Moreton Bay Marine Park. Points indicate individual sites surveyed since 2009, with colours corresponding to the ecosystems studied.

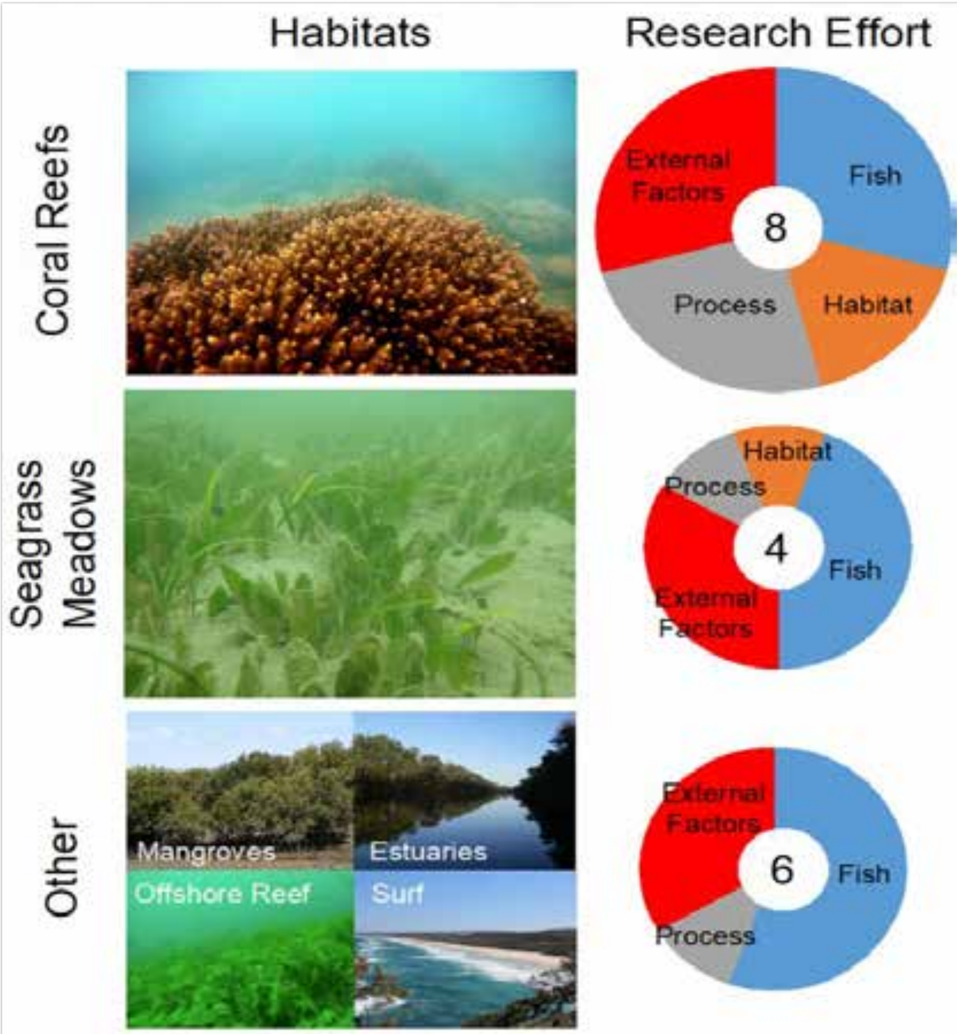

Figure 2. Summary of research effort on marine reserve effects for fish, ecosystems, ecological functions, and the external factors that alter reserve performance in Moreton Bay. Pie charts are scaled in size according to the number of studies, which are given in white circles. 'External Factors' indicates studies that assessed which factors external to reserves most affect reserve performance. 'Ecosystem' indicates studies that assess the relationship between a given ecological function and ecosystem condition. Note that groups are not mutually exclusive as many studies assessed multiple attributes across multiple ecosystems. Photos courtesy B. Gilby, D. Burfeind, Wikepedia Commons.

Changes to ecological functions performed by fishes that are associated with reserves, are also predicted to propagate to effects on the condition of benthic ecosystems. For example, reserves that conserve both coral reefs and nearby mangroves contain more roving herbivores (22), which consume more algae (i.e. higher herbivory) and promote coral recruitment on reefs (27). Macroalgal blooms on reefs in response to high nutrient loads can smother corals in Moreton Bay (11). However, abundant herbivorous fishes rapidly consume algae in some marine reserves; a function that enhanced the resilience of protected reefs to the impacts of flood disturbance in 2011 (28). Herbivorous rabbitfish are also important herbivores in seagrass meadows (24, 38), and are more abundant in marine reserves than in similar fished locations (36), but it is not clear whether these reserve effects also modify herbivory in seagrass meadows

(26). No studies in Moreton Bay have addressed questions about reserve-associated changes to ecological functions, or the condition of benthic communities for ocean beaches, mangroves, and soft-sediment ecosystems within Moreton Bay (Fig. 2).

Ecological features that shape conservation performance

A recurrent question in conservation planning is 'What factors determine the effectiveness of marine reserves?' (Fig. 3). In Moreton Bay, several studies have sought to identify the ecological factors that contribute most to making reserves effective. The effects of seascape context (i.e. the spatial attributes of ecosystems within heterogeneous seascapes, including their position, isolation and size) (39) for reserve performance feature prominently in the literature from Moreton Bay. Effects of seascape context on reserve performance have been examined for coral reefs (22), seagrass meadows (36), estuaries (40) and surf zones (41). Across each of these ecosystems, marine reserves that conserved prominent features and seascape connections were more effective than those that did not. For example, reserves that conserved both coral reefs and mangroves in close proximity were more effective for fishes than those that did not (Fig. 3a, b) (22).

Similarly, reserves that conserve seagrass meadows, which are close to the open ocean, perform better for fishes than reserves that are farther from the sea (36). By contrast, reserves in estuaries perform poorly for fishes (i.e. abundance does not differ between reserves and fished waters) because they conserve locations with limited habitat values (i.e. narrow estuaries with weak connections to mangrove habitats and the open ocean) (40). Small reserves that protect the surf zones of ocean beaches in Moreton Bay were not found to be effective for fishes in their current positions (41). We know, however, from other regions along the Australian east coast that surf-zone reserves perform better for fishes when they conserve large areas that distinct gradient in water quality, characterised by turbid, nutrient-rich waters towards the western and southern margins where estuaries discharge, and cleaner, oceanic waters in the east and north (11, 42). These water-quality effects influence the composition of some fish communities (23, 36). They do not, however, modify the strong effects of seascape context on fish assemblages on coral reefs, and in seagrass meadows (23, 36). By contrast, variation in water quality is particularly important in shaping the composition of benthic communities on coral reefs, and in seagrass meadows, which are frequently dominated by macroalgae in areas distinct gradient in water quality, characterised by turbid, nutrient-rich waters towards the western and southern margins where estuaries discharge, and cleaner, oceanic waters in the fish assemblages on coral reefs, and in seagrass meadows (23, 36). By contrast, variation in water quality is particularly important in shaping the composition of benthic communities on coral reefs, and in seagrass meadows, which are frequently dominated by macroalgae in areas that receive higher nutrient concentrations (11, 42) (Fig. 3c, d). Coral reefs that are within reserves, however, recover from eutrophication more quickly than reefs that are open to fishing, because they support more herbivorous fishes (28).

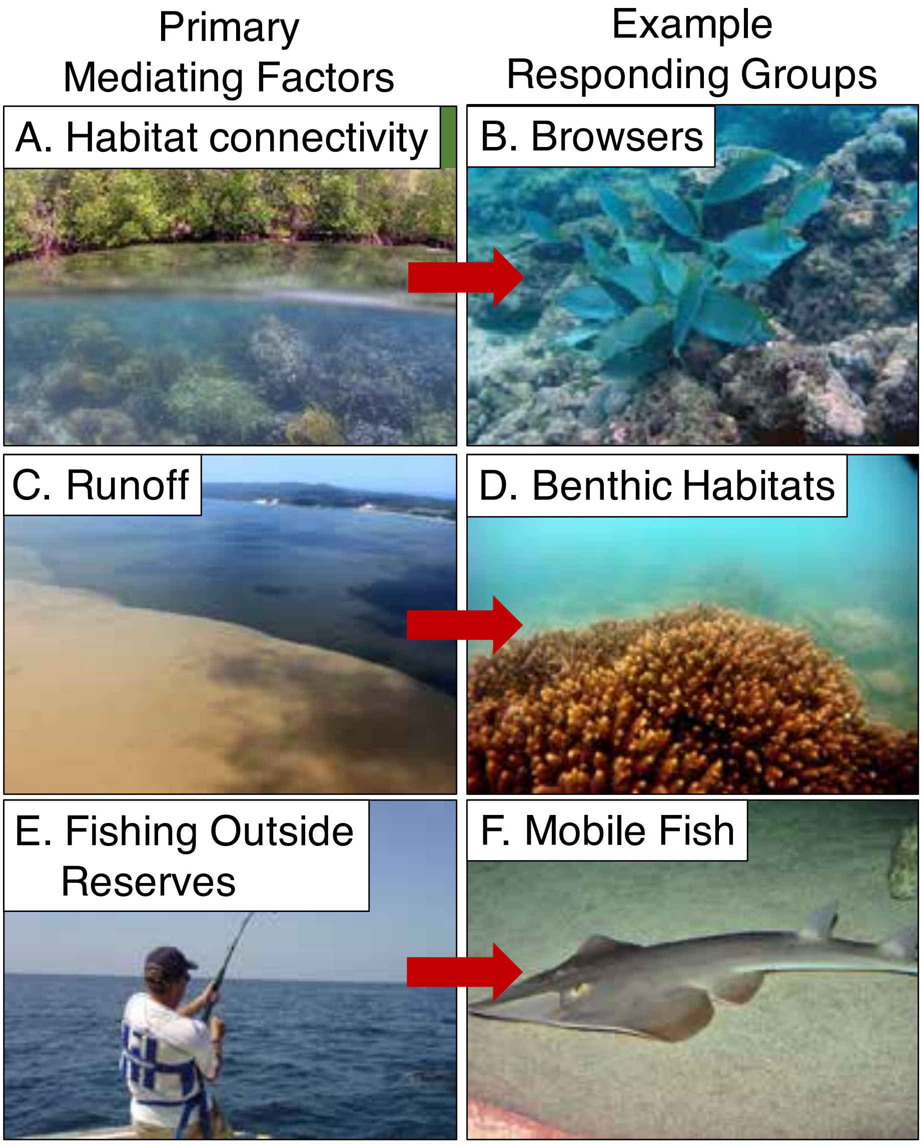

Figure 3. Key examples of factors that alter reserve effectiveness for fish and ecological functions in the Moreton Bay. Habitat connectivity (i.e. the distance between different habitats in heterogeneous seascapes) shapes fish assemblages in all ecosystems examined (A). On reefs in Moreton Bay, macroalgal browsing rabbitfish are more abundant on reefs near mangroves, resulting in greater herbivory on these reefs (B). Moreton Bay experiences a strong south-north and west-east water quality gradient, with southern and western regions being increasingly influenced by estuarine water runoff from rivers (C). This runoff gradient modifies the composition of fish assemblages on coral reefs, and in seagrass meadows (D). Fishing outside reserve boundaries (E) can significantly affect the abundance of large, mobile species, such as shovelnose sharks (F) Photos courtesy A. Olds, B. Gilby, Healthy Land and Water, Wikimedia Commons, OzCoasts.

The effects of fishing outside reserves, and movement of species beyond reserve boundaries, is also a crucial consideration for conservation in Moreton Bay given the spatial scale of the current reserves in the Bay (23, 43). Many fish species might migrate across the boundaries of marine reserves during tidal, diel or seasonal movements, thereby increasing their risk of being caught by fishers (44, 45); however, further research into these effects needs to be conducted specifically for reserves in Moreton Bay (Fig. 3e, f). We suggest that large, highly mobile species (e.g. elasmobranchs) are particu-larly susceptible to the effects of fishing outside of reserves, but this prediction has not been tested in Moreton Bay. Empirical data are therefore needed to determine whether, and how, the distribution and intensity of fishing effort in Moreton Bay influences reserve performance.

Synthesis and future directions

This review demonstrates that reserves can be effective for restoring fish assemblages, key ecological functions and some key habitats in Moreton Bay. This is, however contingent upon the reserves being appropriately large for the species being protected, on the reserve being connected with nearby alternative habitats (especially if these functional linkages are also preserved), and the reserve being placed strategically along a gradient (such as riverine run-off). In unison, these findings, whilst important for Moreton Bay specifically, reflect the findings of several broader reserve effectiveness studies globally (2, 46, 47). Consequently, the effects of no-take reserves in Moreton Bay are highly variable. They can have positive effects on numerous ecosystem components in some locations, but might have little, or no, detectable effect in other settings. We found that reserves in Moreton Bay were effective for fish, ecological functions and benthic communities in some ecosystems (i.e. coral reefs, seagrass meadows), and less effective for others (i.e. surf zones, rocky reefs). Whilst the performance of marine reserves broadly across Moreton Bay is principally shaped by: (i) the level of connectivity between habitat patches, and (ii) the position of reserves along the ambient water-quality gradient, the intensity of these effects varies among ecosystems. The effects of reserves on benthic assemblages, ecological functions and resilience have only been comprehensively examined for coral reefs, and more research is needed to determine whether these reserve effects occur in other ecosystems. These types of reserve effects are complex and can be difficult to measure, partly because disturbances that occur outside reserve boundaries (e.g. eutrophication, sedimentation, pollution, fishing) also influence the composition, and trophic ecology, of fish assemblages within reserves. The magnitude of reserve effects can, therefore, vary within and among ecosystems depending on the level of external disturbance (e.g. the gradient of water-quality degradation from west-to-east across Moreton Bay), and the spatial properties of local seascapes (e.g. ecosystem context, connectivity, size).

These findings are analogous to results from other parts of the world, where the spatial connections between functionally linked habitats have been found to be principal determinants of marine reserve success in many coastal seascapes (21, 48), and where exogenic unmanaged pressures are considered as one of the most important threats to effective management of marine ecosystems worldwide (49). Because data on reserve effectiveness are lacking for some habitats, we cannot determine whether reserve effectiveness differs among ecosystems, but comparison is probably far less important than having a network of reserves that is representative, sufficiently enforced and monitored, across all ecosystem types.

Because a number of external factors (e.g. connectivity and water quality) govern the effectiveness of no-take reserves, it is important to diversify management and conservation interventions in Moreton Bay, beyond simply creating additional reserves or expanding existing ones (50). It has been demonstrated in other systems that reserve implementation is not always sufficient for conservation, and that a broader approach that tackles catchment-borne sedimentation, water quality and habitat loss is necessary to manage the full suite of impacts affecting coastal ecosystems (50, 51). For example, the success of reserves in Moreton Bay could be significantly modified by the outcomes of catchment management activities (50, 52). Consequently, one strategy could be to purposefully place some reserves in parts of the Bay where flood impacts are lower (28, 42). Numerous authors have stressed the importance of accounting for reserve size and the movement of species when designing new reserves (53). Given our current understanding of fish movement in Moreton Bay (23, 24, 43), some existing reserves may not be large enough to encompass the daily home ranges of species that move among mangroves, seagrasses and coral reefs (22). Any new reserves should, therefore, be designed to conserve focal habitats for the species or assemblages of interest, and include all connections with adjacent habitats that these taxa use regularly for feeding, sheltering, or breeding purposes (22).

There are several sizable gaps in our understanding of reserve performance in Moreton Bay. Research effort has primarily focused on three ecosystems in the central and southern portions of Moreton Bay (i.e. coral reefs, mangroves, seagrasses), whereas the performance of reserves in other ecosystems has not been sufficiently studied. For example, subtidal soft-sediments, sandbanks and mud flats are the most widespread, and common, ecosystems in central Moreton Bay. Trawling closures can modify the epi-benthic communities of subtidal soft-sediments in the central Bay (54), but it is not clear whether these effects also propagate to fish assemblages and ecological functions. Similarly, coastal reserves modify the fauna of ocean beaches, and their surf zones, in Queensland; sometimes for the better in terms of increasing targeted fish species, and other times negatively in terms of increasing invasive species along sandy beaches (41, 55, 56), but these effects have not been explicitly tested in Moreton Bay.

The effects of reserves on ecological functions and benthic communities have been reasonably well-studied on coral reefs, and in seagrass meadows, but we do not know whether these functional effects of reserves are common, or widespread, in other ecosystems. Within Moreton Bay, there has been significant focus on how reserves influence herbivory and some work to measure reserve effects on predation and scavenging, but other critical processes remain poorly studied. For example, it is not clear whether reserves in Moreton Bay also influence larval recruitment and settlement, nutrient budgets, or productivity (either primary or secondary). Because the performance of reserves usually improves over time, continued monitoring will be critical to determine whether trajectories differ among ecosystems. Finally, to determine the potential effects of fishing on reserve performance, we suggest that data are needed test how variation in fishing effort outside marine reserves correlates with fish movement across reserve boundaries. This might be particularly important for large, highly mobile species with home ranges that are larger than reserves, such as elasmobranchs (43).

Conclusions

Reserves in Moreton Bay are effective for enhancing the abundance of harvested fish species, and improving ecological functions in some ecosystems (i.e. coral reefs, seagrass meadows), but might not be particularly effective in others (i.e. estuaries, surf zones). The performance of reserves has not been studied sufficiently in many ecosystems (subtidal soft-sediments, ocean beaches, offshore reefs). The most important considerations given research to date in terms of maximising the effectiveness of reserves in Moreton Bay are how well ecosystems are spatially connected within reserve seascapes, and their resilience to variable water quality from catchment and estuarine runoff. Significant progress has been made to understand the effects of no-take reserves over the last two decades, but there are numerous gaps in our ecological knowledge of how reserves function. To better understand conservation performance in Moreton Bay, and help optimise future management decisions, studies of reserve effectiveness must be broadened to investigate how reserves shape fish assemblages and ecological functions across all ecosystems in Moreton Bay. Finally, the success of reserves in Moreton Bay could be significantly modified by the outcomes of catchment management activities that govern the water quality gradient across the Bay.

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Changes in fish and crab abundance in response to the Moreton Bay Marine Park rezoning.

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Abstract
The 2009 Moreton Bay Marine Park Zoning Plan increased the level of no-take protection from 5 to 16% of the total area of the Moreton Bay Marine Park. Whilst the primary motivation for increased protection was the conservation of the various representative habitats within the Marine Park, another expected outcome of restricting fishing activities was to increase the abundance and biomass of target species. In order to determine whether there had been any changes in the abundance and biomass of targeted species within the areas closed to fishing, we examined the catch rates, size structure and sex ratios of mud and sand crabs and catch rates and biomass of a number of species of selected line-caught fish species at seven Marine National Park Zones (MNPZ; no-take) within the inshore areas of the Marine Park. We also used Baited Remote Underwater Video (BRUV) to examine the relative abundance and biomass of fish at three MNPZs in the offshore area of the Marine Park. Survey sites were located within the newly established no-take zones (hereafter termed New green zones), nearby areas open to fishing and in areas that had been closed to fishing since 1997 (hereafter termed Old green zones). Catch rates and the size of mud crabs and yellowfin bream were higher within the two Old green zones compared to the New green zones or Open areas. However, sand crabs did not show any significant responses to zoning in any of the MNPZs surveyed. Catch rates and mean weight of snapper increased rapidly in the New green zone at St Helena Island. In the offshore areas of the marine park, the average biomass of the fishing target species: snapper, spangled emperor, redthroat emperor, blackspot tuskfish, Maori rock cod and goldspot wrasse, all increased in the New green zones. In contrast, there was no significant change in the abundance of targeted aquarium species. Overall, there was evidence of a trend towards increased numbers and biomass of some targeted species within the New green zones

within three years of their implementation. However, this is insufficient time to determine the full impacts of the zoning changes, particularly for long-lived species and further regular monitoring is required to make a comprehensive assessment.

Keywords: fish, crab, BRUV, Marine Protected Area, no-take marine reserve, fishing

Introduction

No-take marine reserves or Marine Protected Areas (MPAs) have long been used by management agencies to conserve biodiversity, habitats and increase the biomass of fishery targeted species (1, 2). Provided MPAs are designed and managed appropriately (3) they have been demonstrated to be effective in increasing the biomass and abundance of target species and may also impact other taxa indirectly through trophic cascades (4). They are also considered an important tool for ecosystem-based management to assist in mitigating threats to marine ecosystems (5).

The original Moreton Bay Marine Park (MBMP) was established in 1997 (6) and covered an area of approximately 3400 km^2 and extended from between 3 to 20 km offshore to a maximum depth of about 150 m (7). The park was classified into five zones in order to manage the activities within the park. In order of ascending level of protection, they were: general use, habitat, conservation, buffer and protection. The highest level of protection was afforded by the protection zones whose purpose was: "…to provide for the permanent preservation of the zone's biological diversity and natural condition to the greatest possible extent, while allowing the public to appreciate and enjoy the undisturbed nature of the zone" (6). In effect this meant the protection zones were classified as no-take zones. The area of the marine park classified as protection zone under the 1997 Zoning Plan was approximately 0.5% of the total area of the Marine Park. This constituted the lowest level of protection of any Queensland marine park and was not considered adequate to satisfy contemporary standards of protection for marine conservation.

The Queensland Department of Environment and Science (known at the time as the Queensland Environmental Protection Agency) conducted a broad-scale benthic mapping program that identified 16 broad habitats within the Moreton Bay Marine Park. The habitats ranged from shallow, turbid, mud-bottom estuarine waters to deep, clear-water reef environments. Following a review of the 1997 MBMP zoning plan in 2007, it was recommended that a minimum of 10% of the area of each of the 16 major habitat types (7) identified within the MBMP were to be classified as no-take zones. These recommendations were implemented in the 2009 Marine Park Zoning Plan with 16% of the marine park being classified as Marine National Park Zones (MNPZ; no-take) (Table 1, Fig. 1).

No-take zones are seen as fulfilling many objectives. Among these are the conservation of biodiversity, protection of habitats and conservation of fish stocks. In order to test whether the increased level of protection from fishing within the MBMP had an influence on fish and crustacean populations, CSIRO and the Queensland Department of Environment and Science conducted a study to compare the abundance of fish and sand and mud crabs in on similar habitats both inside and outside ten of the MNPZs comprising a range of habitats throughout the Marine Park.

Methods

In order to assess the impacts of the zoning plan on fish and crabs, a series of sampling sites were selected on similar habitat types, both inside some of the original Old green zones (established in 1997), in the New green zones (established in 2009) and in areas open to fishing (hereafter referred to as 'Open' areas) (Figs 1, 7). Site selection was performed using an approach known as Generalised Random Tessellation Stratified Sampling (GRTS; (8) The GRTS method selects sites from a spatially referenced sampling frame in a manner that achieves spatial balance with randomness but less clustering than conventional random sampling. The relative probability of selection in different parts of the sampling frame can be varied according to a pre-defined weighting scheme. In our case, sites for line fishing and BRUV close to or on reef were allocated 5 times the weight of non-reef sites, since sandy, non-reefal areas have a much lower abundance of fish compared to areas on reef. Sampling was conducted twice annually (winter [June to August] and summer [December to February]) to incorporate seasonal variation in abundance, biomass and composition of the fish and crustacean assemblages.

Table 1. Areas of the Moreton Bay Marine Park sampled during this study. Codes, names and areas of the Marine National Park (MNP) zones are as declared by the Queensland Environmental Protection Agency (EPA) in 2008. N.B. the EPA is now known as the Queensland Department of Environment and Heritage (DEH). BRUV = Baited Remote Underwater video.

Code	Name	Area (ha)	Sampling Method
MNP02	Tripcony Bight-Long Island	1151.9	Crab pots & line fishing
MNP04	Flinders Reef	75.9	BRUV
MNP09	Deception Bay	1674.2	Crab pots & line fishing
MNP10	Cherubs Cave-Henderson Rock	2984.0	BRUV
MNP17	St Helena Island	903.6	Crab pots & line fishing
MNP19	Flat Rock	448.4	BRUV
MNP20	Wanga Wallen Bank	360.9	Crab pots & line fishing
MNP26	Price Anchorage	374.0	Crab pots & line fishing
MNP27	Lamb Island	198.9	Crab pots & line fishing
MNP29	Willes Island	209.9	Crab pots & line fishing

The new zoning came into effect in December 2008, however any responses to the zoning would not be detectable until sometime after that. Data collected during the first two sampling sessions (Winter 2008 and Summer 2009) provided the baseline "Before" data against which subsequent data, collected after the new zoning plan was implemented, were compared (see below for statistical methodology). Bi-annual sampling continued for two years after the new zoning was implemented (Winter 2009 to Winter 2011). The same sites were sampled each season. The range of environments and species found throughout the MBMP required that a variety of techniques be employed in order to sample them effectively. We used potting for crabs within Moreton Bay (9), line-fishing (bait and lure) for fin fish within turbid estuarine and inshore waters, and stereo BRUV (10) for fish in the clear waters outside the Bay.

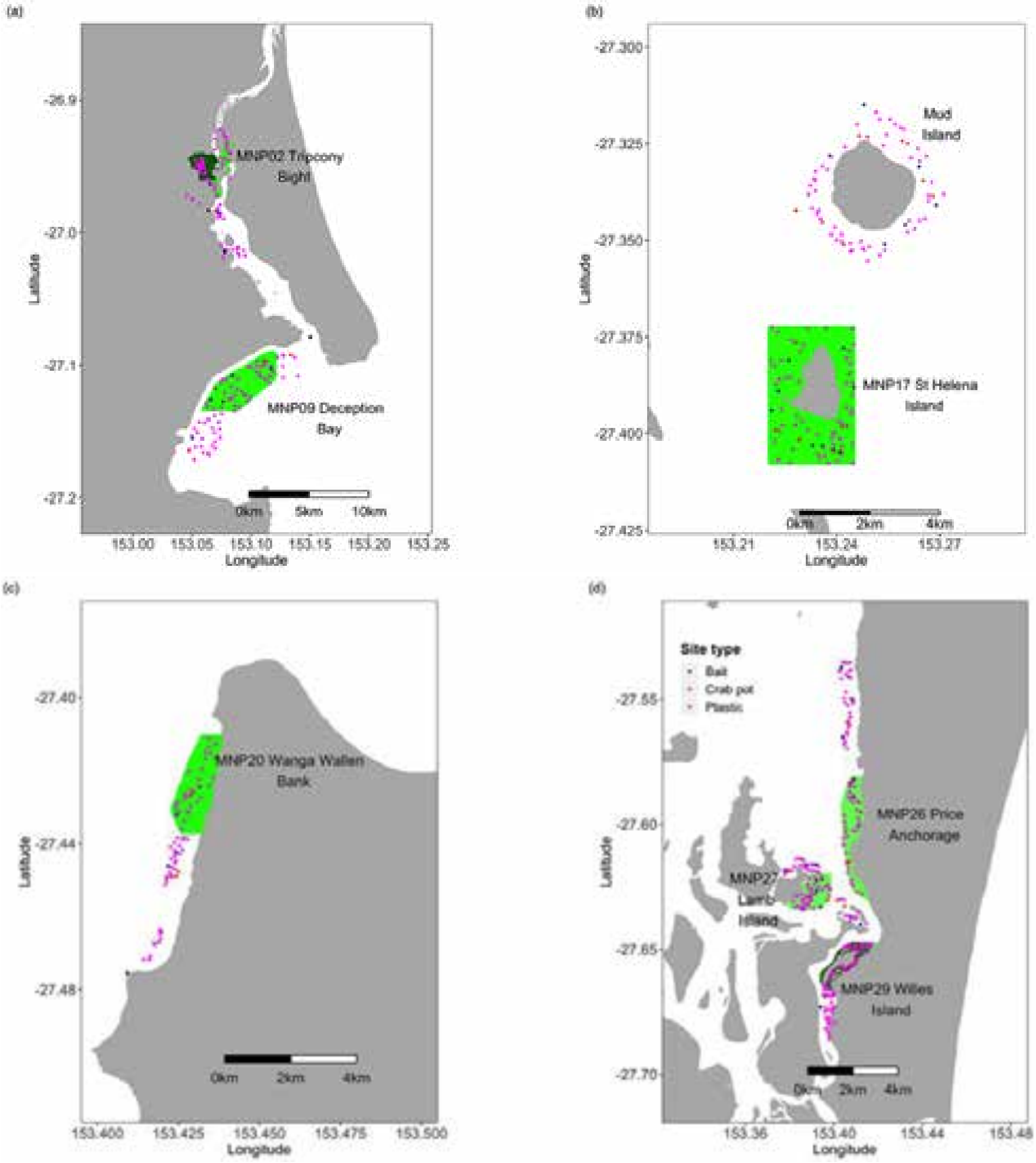

Figure 1. Locations of crab potting and line fishing sites inside and outside green zones at (a) MNP02 (Tripcony Bight) and MNP09 (Deception Bay), (b) MNP17 (St Helena Island), (c) MNP20 (Wanga Wallen Bank) and (d) MNP26 (Price Anchorage), MNP27 (Lamb Island) and MNP29 (Willes Island). Areas shaded dark green indicate the Old green zones, light green indicates the New green zones.

Crab potting

Crab pots were of similar design to those used in the commercial fishing industry being made of dark green trawl mesh (outer walls and entrances) with four entrances and 900 mm diameter and 300 mm in height (0.11 m3). Floats with identification and permit number were attached to all pots. Pots were deployed and recovered with the assistance of the Queensland EPA vessel "Spoonbill" and her crew. In instances where the water was too shallow, pots were deployed using the 5 m CSIRO Naiad. Pots were baited with a whole mullet (*Mugil cephalis*) and a single pot was deployed at each site. Pots were set in the same location each season throughout the study period with the aid of a GPS. Pots were generally deployed during high tide in the day, and checked the following day with set and check times recorded. All crabs, fish and elasmobranchs captured in the crab pots were identified, measured, sexed and released alive at the site of capture. Female crabs were also checked for eggs and missing legs and chelae were recorded for all crabs.

Bait fishing

To standardise bait fishing CPUE estimates, all fishing was done with 1/0 circle hooks baited with prawn (Penaeidae). The rig consisted of a 1/0 circle hook attached to a small swivel with 6 kg monofilament fishing line. The swivel was attached to the main fishing line and a small sinker placed above the swivel. Sinker size was determined by water depth and current. Each bait fishing event was done at anchor in a pre-defined location and lasted 30 min. Sites were located accurately using portable GPS units. During the 30 min sampling period, all captured fish were placed into an aerated tub of water from the site of capture. At the end of the 30 min period, all fish were identified, measured and weighed. Bait fishing was generally undertaken to target yellowfin bream, snapper and whiting.

Lure fishing

Fishing with soft plastic lures was carried out during 30 minute intervals while the boat was drifting with wind or tide. The position at the start and end of the 30 min period was recorded. Fishing with soft plastic lures involves repeatedly casting a small lure in front of the drifting boat. The lure is allowed to sink to the bottom and is then erratically retrieved to imitate a small fish. This method is commonly employed by recreational fishers in South East Queensland. Any captured fish were treated the same as those captured by bait fishing with individual catch rates of the two anglers also recorded. Lure fishing was done on the same days as bait fishing and lures were used to target dusky flathead and snapper. All fish were identified, measured and weighed.

Baited Remote Underwater Video (BRUV)

We used stereo Baited Remote Underwater Video (BRUV) units supplied by SeaGIS Pty. Ltd (11). These systems consist of a pair of digital video cameras (Panasonic NV-GS330) with 0.5× wide-angle lenses in waterproof PVC housings mounted on a galvanised steel frame. The frames were fitted with breakaway legs in the event of fouling on the seabed and were able to be loaded with a variable amount of ballast if required under high current conditions. A rotating flashing diode mounted on a pole such that it was visible from both cameras facilitated synchronisation of the two stereo images during video analysis. A bait bag (220 × 150 mm; 10 mm mesh size) made from plastic gutter guard was mounted on a PVC conduit pole and fixed approximately 1.2 m in front of the cameras.

Prior to deployment each video camera was loaded with a new mini DV tape and the bait bag was filled with pilchards (approximately 750 g). The pilchards were crushed in order to maximise dispersal of the fish oil and flesh. Once the skipper had positioned the vessel on site, the BRUV was deployed from the stern. Each BRUV had a surface buoy attached with 8 mm rope to facilitate recovery. BRUVs were deployed for 45 min as previous research in Western Australia has demonstrated that a deployment time of at least 36 min is necessary to record the majority of the fish species (12). Once the BRUVs were recovered, tapes were replaced, batteries checked and bait replaced before the subsequent deployment. Using four BRUV units generally permitted us to conduct between 20 and 25 deployments each day. Adjacent replicate sites were usually separated by a minimum of 250 m to avoid the possibility of the same fish visiting adjacent BRUVs during the sampling period. In some cases, due to a paucity of the appropriate habitat, it was necessary to locate sites ~ 100 m apart; in these cases the deployments were not done on the same day.

Stereo video analysis
The video tapes were digitised to 720 PAL 16:9 interlaced and converted to .avi format (using the Xvid codec) at the Cleveland laboratory using Adobe Premiere Elements. Video analysis was conducted in two stages. Initially one of the stereo pair of videos was analysed for species composition and abundance using EventMeasure software (SeaGIS Pty. Ltd., (11)). Fish species identification was confirmed using a number of texts: (13-19) and websites (e.g. FishBase (20)). To avoid counting the same fish more than once as they move into and out of the camera's field of view, we recorded relative abundance counts of each species of fish as the maximum number of individuals of each species sighted at any one time during the video deployment; this statistic is termed MaxN (21).

Following the identification and enumeration of fish, the file output from Event Measure was loaded into a second software package: PhotoMeasure (SeaGIS Pty. Ltd.(11)) in order to measure the fish. This software utilises imagery from both the left and right cameras of the stereo pair to make accurate measurements of fish length. The accuracy and precision of these measurements is reliant on the calibration of the stereo cameras and so we calibrated each stereo pair both before and immediately following each sampling season using Cal software (SeaGIS Pty. Ltd. (11)). A second calibration was necessary each season in case the cameras were jarred out of alignment during deployment or recovery.

The Photo Measure software gave an estimate of the precision of each length measurement as they were being made permitting the operator to discard the measurement if the precision was >5% of the length estimate. The operator was then able to scroll forward or backwards within the video to locate a clearer image and try again. The software also recorded the distance of each measured fish from the camera system (range). We used highest value of the range for each BRUV deployment as an index of the visibility for each deployment; this was then added as a covariate to the statistical models described later. Fish lengths were converted to weights using published allometric relationships of the form $W = a \times FL^b$ (, where W = weight (g), a and b are estimated coefficients and FL is the Fork Length (mm) (20).

Data analysis
The analysis of the BRUV and line-caught fish presented a problem as the data contained a large percentage of zeros. We used zero-inflated models to accommodate this problem. Zero inflated models are two component mixture models combining a point mass at zero with a count distribution that we define here to be a negative binomial. Due to the sparsity of data, only a linear trend term was fitted to the zero-inflation component. The zero inflation component accounts for any trend in the number of sites each species was caught at across the

five sampling seasons. The crab pot data did not suffer the zero-inflation problem and so were analysed using the generalised linear model function of the MASS library of the R programming environment (22, 23).

Our initial hypothesis was that, all other factors being equal, if the New green zones were acting to protect targeted species populations, then the trend in their abundance and biomass would increase following the establishment of the 2009 zoning plan whereas the trends for abundances in the Open areas and Old green zones would not change. Given this, the model terms we were interested in were: status (Old green zone, New green zone and Open area) and linear trend within each of the Old green zones, New green zones and Open areas.

In Queensland, recreational and commercial fisheries are managed by size limits (fish and crabs), bag limits (recreation fish and crabs) and male-only take of mud and sand crabs (24) Minimum size and any sex related regulations for key recreational and commercial target species are shown in Table 2. There are no bag limits for commercial fisheries. Lengths are in carapace width (CW) for crabs and total length (TL) for line-caught fish.

Table 2. Minimum and maximum size limits and sex-specific regulations for selected target species in Queensland.

Species	Minimum size	Maximum size	Sex specific regulations
Sand crab	11.5 cm CW	n/a	Male only
Mud crab	15 cm CW	n/a	Male only
Bream	25 cm TL	n/a	n/a
Snapper	35 cm TL	1 fish over 70 cm TL	n/a
Dusky flathead	40 cm TL	75 cm TL	n/a
Blackspot tuskfish	30 cm TL	n/a	n/a
Venus tuskfish	30 cm TL	n/a	n/a
Maori rockcod	45 cm TL	n/a	n/a
Redthroat emperor	38 cm TL	n/a	n/a

Results and Discussion

Inshore fish and crabs

A total of 3522 crab pots were set at 671 sites during this study of inshore areas of Moreton Bay. During the study we captured 1777 mud crabs and 1507 sand crabs that were measured and sexed and released. We surveyed 136 line-fishing sites that were sampled 539 times during the study (approximately 4 times per site), with over 1570 fish comprising 53 species being captured, measured and released (Table 3). The most commonly caught fish were yellowfin bream (*Acanthopagrus australis*) and snapper (*Pagrus auratus*) (Table 3).

Table 3. Number of fish representing each species caught at bait sites, including the cumulative number of sites over three years of the study. Species are listed in descending order of abundance.

Species	Common name	Number of fish	Number of sites
Acanthopagrus australis	Yellowfin bream	447	192
Pagrus auratus	Snapper	328	118
Rhabdosargus sarba	Tarwhine	72	48
Lethrinus genivittatus	Threadfin emperor	46	18
Sillago maculata	Trumpeter whiting	40	31
Neoarius graeffei	Blue catfish	36	19
Lethrinus laticaudis	Grass emperor	29	19
Choerodon cephalotes	Purple tuskfish	22	16
Dasyatis fluviorum	Estuary stingray	21	19
Platycephalus fuscus	Dusky flathead	18	16
Pomadasys kakaan	Grunter	18	12
Pentapodus paradiseus	Paradise threadfin emperor	13	6
Tragulichthys jaculiferus	Long-spinned porcupinefish	12	10
Aptychotrema rostrata	Eastern shovelnose ray	11	11
Sillago ciliata	Sand whiting	11	10
Pseudolabrus guentheri	Gunther’s wrasse	9	7
Terapon jarbua	Cresent grunter	9	8
Pelates sexlineatus	Six-line trumpeter	8	8
Dicotylichthys punctulatus	Threebar porupinefish	6	4
Euristhmus lepturus	Longtail catfish	5	3
Lagocephalus sceleratus	Silver toadfish	5	5
Sillago analis	Goldenline whiting	5	4
Himantura astra	Blackspotted whipray	4	4
Platycephalus indicus	Bartail flathead	4	2
Polydactylus sp - small	Threadfin	4	4
Halichoeres margaritaceus	Pearly wrasse	3	3
Lutjanus russelli	Russell’s snapper	3	3
Polydactylus multiradiatus	Australian threadfin	3	3
Gnathonodon speciosus	Golden trevally	2	2
Himantura toshi	Coachwhip ray	2	2
Lutjanus argentimaculatus	Mangrove jack	2	1
Neotrygon kuhlii	Bluespotted maskray	2	2
Parapercis nebulosa	Pinkbanded grubfish	2	2
Pseudorhombus jenynsii	Smalltooth flounder	2	2
Rhizoprionodon acutus	Milk shark	2	2
Saurida undosquamis	Largescale saury	2	2
Tripodichthys angustifrons	Yellowfin tripodfish	2	2
Tylosurus crocodilus	Crocodile longtom	2	2
Acentrogobius gracilis	Bluespotted mangrove goby	1	1
Argyrosomus japonicus	Mulloway	1	1

Chelinus trilobatus	Tripletail maori wrasse	1	1
Diagramma pictum	Painted sweetlips	1	1
Epinephelus coioides	Estuary cod	1	1
Hemigaleus australiensis	Weasel shark	1	1
Himantura fluviourum	Estuary stingray	1	1
Monacanthus chinensis	Fanbelly leatherjacket	1	1
Platycephalus endrachtensis	Northern sand flathead	1	1
Pomatomus saltatrix	Tailor	1	1
Portunus armatus	Sand crab	1	1
Rhinobatus typus	Giant shovelnose ray	1	1
Rhizoprionodon taylori	Australian shovelnose shark	1	1
Sphyraena obtusata	Stripped barracuda	1	1
Upeneus tragula	Bartail goatfish	1	1

Old green zones

As part of the 2009 Marine Park Management Plan the Old green zones at Tripcony Bight (MNP02) and Willes Island (MNP29) were increased in area by 47 and 85% respectively. Catch rates of legal-sized male mud crabs (Queensland Fisheries regulations protect all female mud crabs) in these Old green zones were 4–18 times greater than the catch rates in the adjacent Open areas. However, they did vary over time with factors such as the season and the impact of the floods in January 2011. At Tripcony Bight, catch rates of legal-sized male mud crabs in the Old green zone were 1.6–9 times greater than the New green zone except in the summers of 2010 and 2011 when catches were not significantly different as they were influenced by floods (Fig. 2).

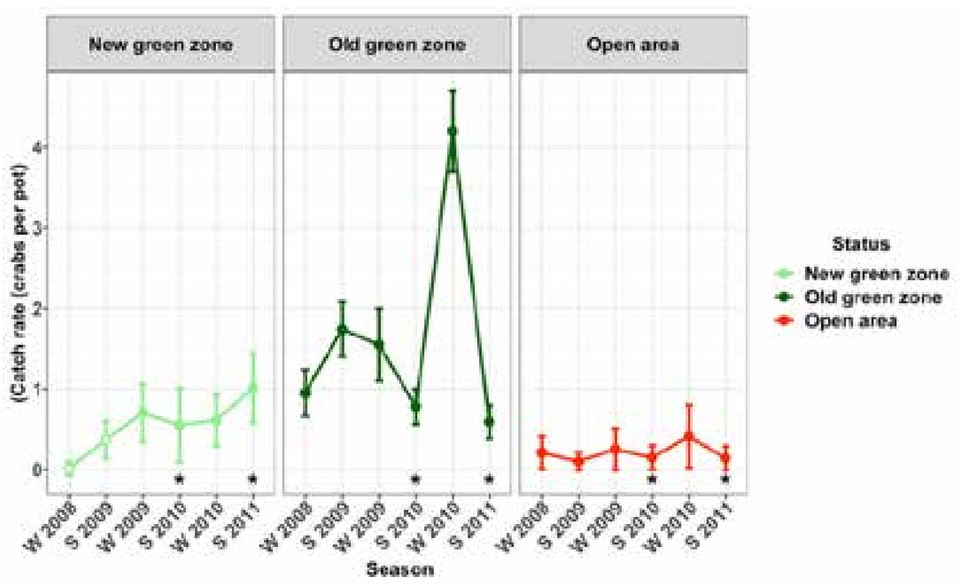

Figure 2. Mean catch rates of legal-sized male Mud Crabs (*Scylla serrata*) in the Tripcony Bight (MNP02) study area. Empty circles indicate New MNP zones prior to the implementation of the 2009 Moreton Bay Marine Park Zoning Plan. Asterisks indicate years when catches were influenced by floods. Data are means ±1SE. 'W' = winter, 'S' = summer.

The sex ratio of mud crabs in the two Old green zones (Tripcony Bight and Willes Island) was heavily skewed towards males (5 – 18 times greater than adjacent Open areas). In contrast, in the Open areas and New green zones, the sex ratio was dominated by females. The markedly different sex ratio in the Old Green zones suggests that no take zones protect the mud crab population within these zones from male only harvesting, thereby allowing the mud crab sex ratio to return to unfished levels where males dominate in almost all size classes. The implications for long term sustainability of crabs in sex biased fisheries and the potential for sperm limitation are currently unknown. However insufficient sperm supply from males due to the smaller average size of males, reduced number of males and female-biased sex ratio are capable of leading to a reduction in the reproductive success of female crustaceans in several studies (25-28).

Yellowfin bream (*Acanthopagrus australis*) catch rates in the Old green zone at Tripcony Bight were highly variable but up to seven times greater than in the Open areas (Fig. 3). Similarly, biomass of yellowfin bream was up to 2.5 times greater in the Old green zone than in the Open area, but it was also highly variable. Within the New green zone at Tripcony Bight, catch rates of bream in the New green zone trended strongly upwards over the period of the study (Fig. 3).

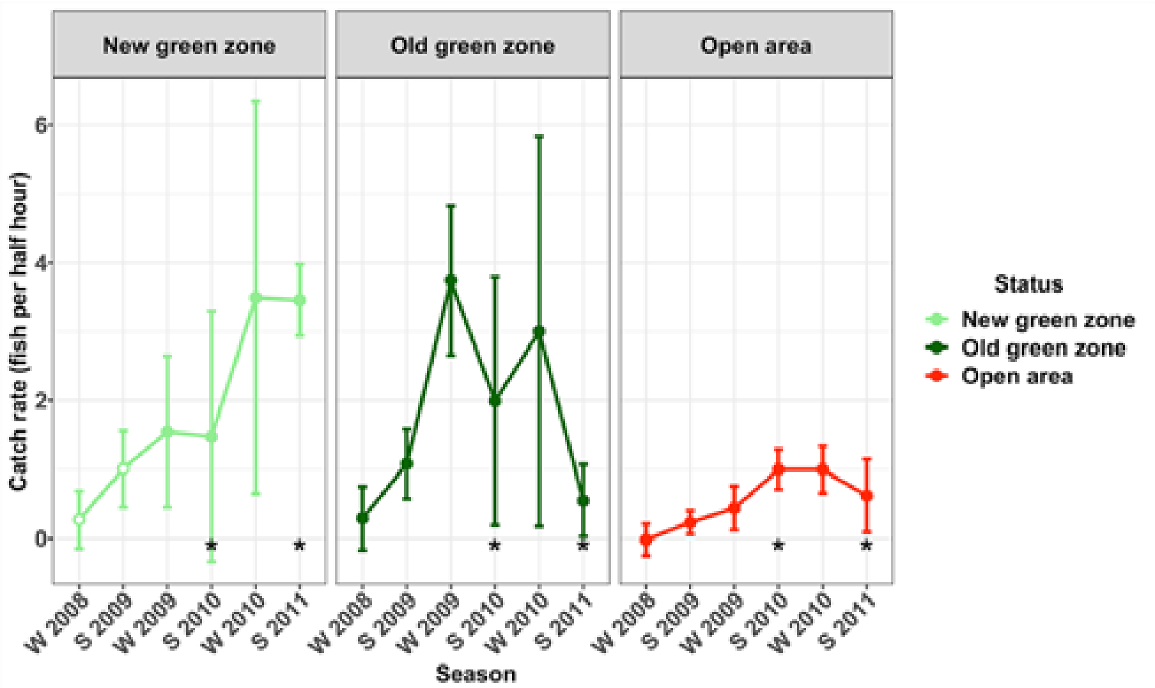

Figure 3. Mean catch rates of yellowfin bream (*Acanthopagrus australis*) in the Tripcony Bight (MNP02) study area. Empty pale green circles indicate New Green Zones prior to the implementation of the Moreton Bay Marine Park Zoning Plan in autumn 2009. Asterisks indicate years when catches were influence by floods. Data are means ±1SE. 'W' = winter, 'S' = summer.

On average, catch rates of dusky flathead (*Platycephalus fuscus*) were highest in the Old green zone at Tripcony Bight. Within the Old green zone, they were consistently highest in winter. However, there was no seasonal pattern in the Open areas. In winter surveys the catch rates of flathead were up to 20 times higher in the Old green zone. However, in summer, 2010 catch rates in the two areas were similar (Fig. 4). Catches of legal-sized flathead were considerably higher within the Old green zone (78% of fish ≥ legal size) compared to the Open area (58% of fish ≥ legal size).

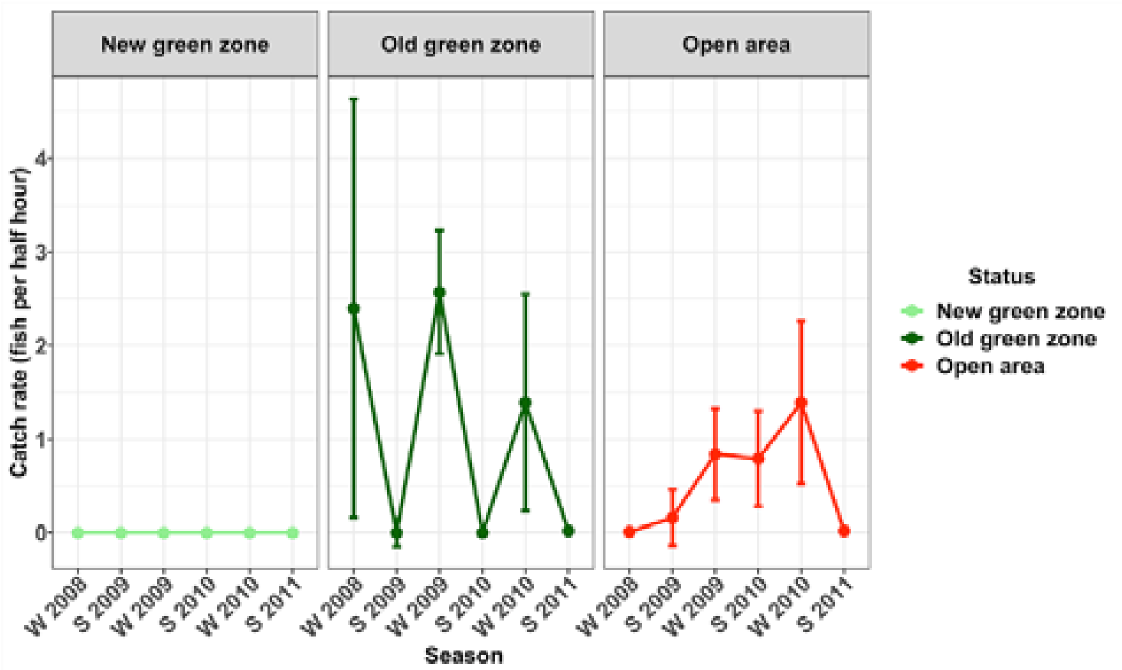

Figure 4. Mean catch rates of dusky flathead (*Platycephalus fuscus*) in the Tripcony Bight (MNP02) study area. Data are means ±1SE. 'W' = winter, 'S' = summer.

New green zones

Significant increases in the catch rates of mud crabs were only detected in two of the five surveyed newly established green zones (MNP02 and MNP26) during the course of the study. Catch rates of legal-sized male mud crabs at Tripcony Bight (MNP02) increased steadily over time in the New green zone and were 2–6 times greater than catch rates in the Open areas.

In the winter of 2008 when sampling began, mud crab catch rates at the Price Anchorage New green zone (MNP26) were very low and similar to those obtained at the adjacent Open area. During the period of the study, catch rates within the Open area remained relatively unchanged, whereas those from the New green zone steadily increased to be approximately four times greater than those within the Open area (Fig. 5). Concurrent with this increase, there was a significant decrease in the catch rate of sand crabs, the only significant MNPZ effect measured for sand crabs. Lower sand crab catches may have been the result of increasing competition with mud crabs resulting in fewer sand crabs entering the pots.

There was no change in the sex ratio of mud crabs in the New green zones at MNP02, MNP26 or MNP27 following the rezoning. There was however, an increase in the proportion of males at MNP09, although there was no change in the proportion of legal-sized males. In contrast, at Price Anchorage (MNP26), although there was no change in the overall sex ratio, the proportion of legal-sized males increased over the period of the study.

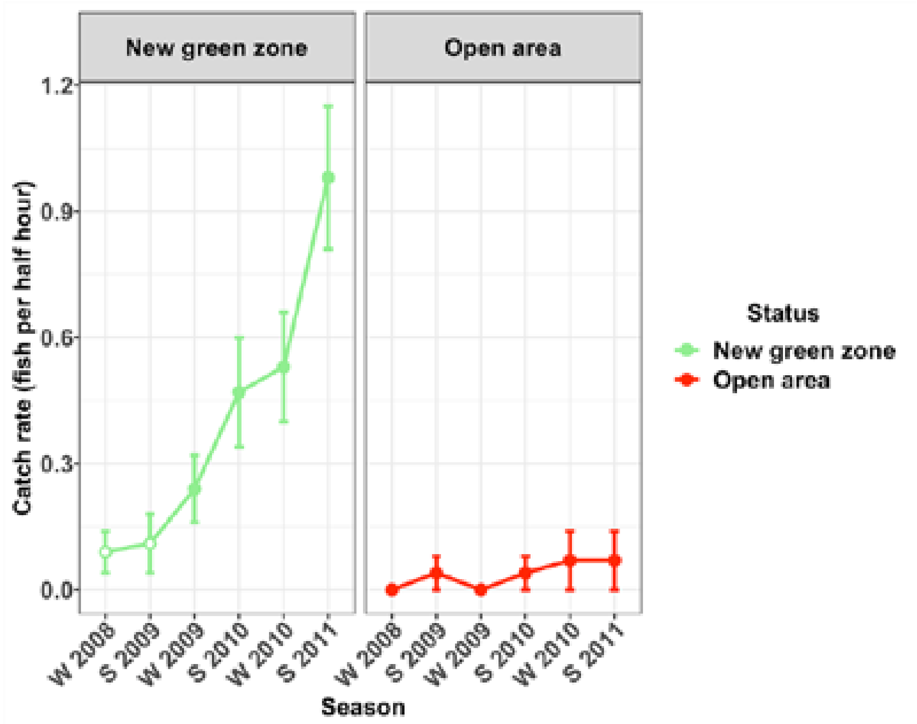

Figure 5. Catch rates of legal-sized male mud crabs (*Scylla serrata*) in the Price Anchorage (MNP26) study area. Empty pale green circles indicate New Green Zone prior to the implementation of the 2009 Moreton Bay Marine Park Zoning Plan. Data are means ±1SE. 'W' = winter, 'S' = summer. NB there was no Old green zone at Price Anchorage.

The average size of females in the New green zones and Open areas were similar and there were no temporal trends. Similarly, there were no consistent changes in the average size of males in the New green zones at MNP02, MNP09 and MNP27. However, at MNP26 the average size of males in the New green zones increased significantly and was equal to or greater than minimum legal size in all surveys after rezoning. The lack of response in the size of males or catch rates of legal-sized male mud crabs in the New green zones at MNP09, MNP17, MNP20 or MNP27 is likely due to habitat at these sites as they predominantly consist of sand, rubble and in the case of MNP17, rocky reef. These areas are unlikely to ever support large numbers of mud crabs and future sampling at these sites will probably not detect any changes. The fact that the highest rates of illegal fishing recorded within the Moreton Bay Marine Park were at the New green zone at Lamb Island (MNP27; (29) may also explain the lack of response of legal-sized male mud crabs

In the New green zone at St Helena Island (MNP17) snapper (*Pagrus auratus*) responded strongly. Catch rates of snapper on soft plastic lures prior to rezoning were similar in the New green zone and Open areas. However, after rezoning the catch rates in the New green zone were approximately 10 times greater than Open areas. Because of the seasonality of snapper movements in Moreton Bay this trend was most pronounced in winter (Fig. 6).

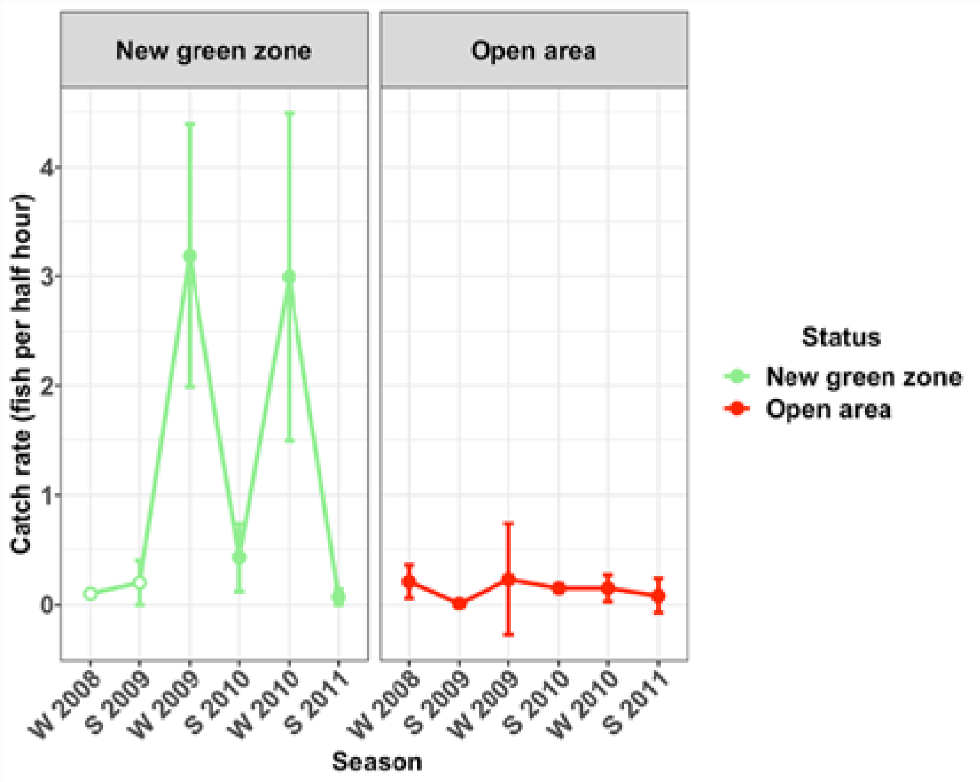

Figure 6. Catch rates of snapper (*Pagrus auratus*) in the St Helena Is (MNP17) study area. Catch per 30 minute standardised fishing session (plastic lures) in a New green zone (St Helena Island) and an Open area (Mud Island) are shown. Empty pale green circles indicate New Green zone prior to the implementation of the 2009 Moreton Bay Marine Park Zoning Plan. Data are means ±1SE. 'W' = winter, 'S' = summer. NB there was no Old green zone at St Helena Island.

There was a significant increase in the mean weight of snapper in the New green zone, with approximately an 18% weight increase per annum. Mean weight of snapper in the Open area increased by approximately 1% per annum and was not statistically significant. The number of legal-sized snapper captured in the New green zone was approximately seven times greater than the Open area with most legal-sized fish captured 12–18 months after rezoning.

At St Helena there was no response observed in catch rates of other fish, mud crabs or sand crabs. The size of male sand crabs increased significantly in the New green zones at St Helena (MNP17) and Price Anchorage (MNP26). However, the reasons for this increase are uncertain given there was no trend. Sand crab numbers did not show any direct positive response to zoning at any of the MNPZs surveyed, potentially because of the high rates of movement in this species.

Offshore Fish

Three of the offshore rocky reefs within the marine park were chosen for this study: Flinders Reef, Henderson Rock and Flat Rock. Flinders Reef had the only Old green zone in the offshore region of the marine park. However, grey nurse shark protection zones had been established around Henderson Rock and Flat Rock since December 2003. Since bottom fishing had been banned in these areas since that time, we chose to classify them as Old green zones for the purpose of this study. The BRUVs were deployed at 175 sites inside the Old and New green zones, and at similar surrounding areas where fishing was permitted (Open areas), at Flinders Reef (MNP04), Henderson Rock (MNP10) and Flat Rock (MNP19) twice yearly during winter and summer from 2008 to 2010 (Fig. 7). A total of 63,654 fish comprising 442 species and 77 families, and 52 turtles were identified from 605 hours of BRUV footage taken as part of this study.

At the time this study was conducted, the New green zones had only been in place for approximately two years. Nevertheless, the study found encouraging results for several fish species targeted by anglers, including an increase in the average biomass of snapper, spangled emperor, redthroat emperor, blackspot tuskfish, Maori rock cod and goldspot wrasse in the New green zones, in the offshore areas of the MBMP.

While these results are encouraging, it should be noted the changes to the marine park were still new at the time of sampling and many of these species are long-lived (e.g. snapper and spangled emperor live for up to approximately 30 years). Therefore the responses of populations within the New green zones may take many years to become fully evident. Any responses will also vary among species depending on their range of movement, as well as the size and the types of habitat that are prevalent within each green zone.

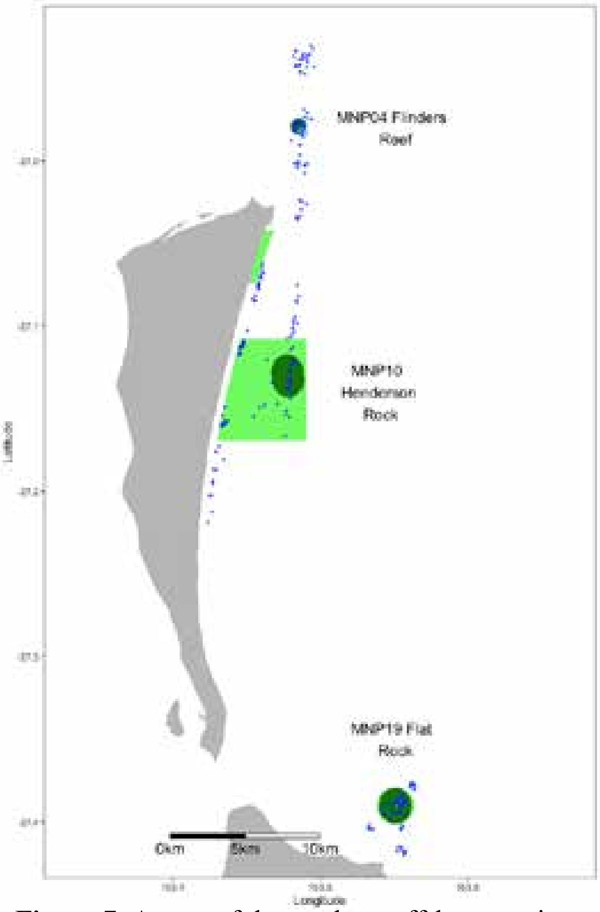

Figure 7. A map of the northern offshore section of the Moreton Bay Marine Park showing the location of the green zones and areas open to fishing surveyed using Baited Underwater Video (BRUV) systems. Areas shaded dark green indicate the Old green zones, light green indicates the New green zones.

It should also be noted that although the numbers of people fishing in green zones has declined, fishing has not stopped completely (29, 30). A companion study measuring the influence of the 2009 zoning plan on human use, showed that fishing activity in green zones declined by a little over half, from 6.3 to 2.6% of the observed fishing activity (29, 30). Although low, this activity has the potential to reduce or nullify any positive results within green zones (3).

Snapper (Pagrus auratus)

Snapper were present at all of the surveyed MNPs and their corresponding Open areas. Their numbers varied seasonally, with more snapper being recorded during the winter surveys. The trend term in the model was marginally significant (p=0.059), indicating the numbers of snapper (Figs 8, 9) increased during the study in the Open (14.8 ± 14.8 [mean ± 95% CI] % per season) and Old green (19.7 ± 17.5 % per season) zones, but not in the New green zones. The average biomass of snapper increased during the study period across all zones (Fig. 10).

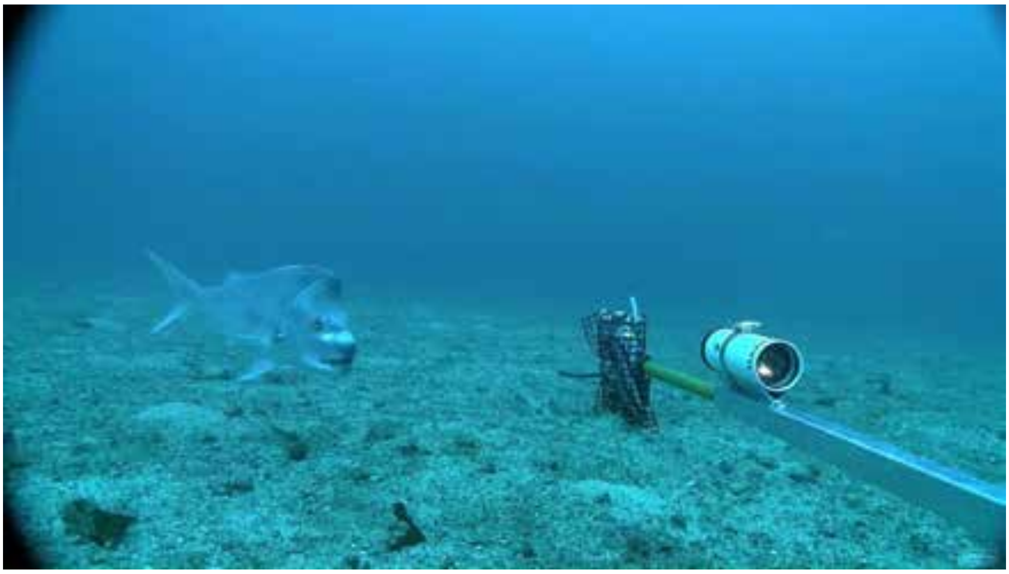

Figure 8. A large snapper (*Pagrus auratus*) at 42 m depth approaching the BRUV bait bag at Flat Rock (MNP19).

However, the increase was only significant in the New green zones, where on average, biomass increased by 13.6 ± 12.5% per season suggesting that whilst the number of snapper remained stable within the New green zones, they increased in size.

Spangled emperor (Lethrinus nebulosus)
Numbers of spangled emperor were generally low throughout the study area. The highest numbers were found on rugose areas around Flinders Reef (MNP04). The trend term in the model indicated an overall decrease in the abundance of spangled emperor over the course of the study. However, further investigation revealed that this was driven by an estimated decrease of 83 ± 82.5 % per season in the Old green zones, with no detectable change in numbers in the other zones (Fig. 11).

The mean biomass of spangled emperor in the New green zones increased significantly during the study (33.9 ± 34.0%) whilst there was no significant trend in biomass in either the Old green zones or the Open areas. This suggests that the protection from fishing provided by the New green zones was effective in allowing spangled emperor within these zones to increase in size through the period of the study.

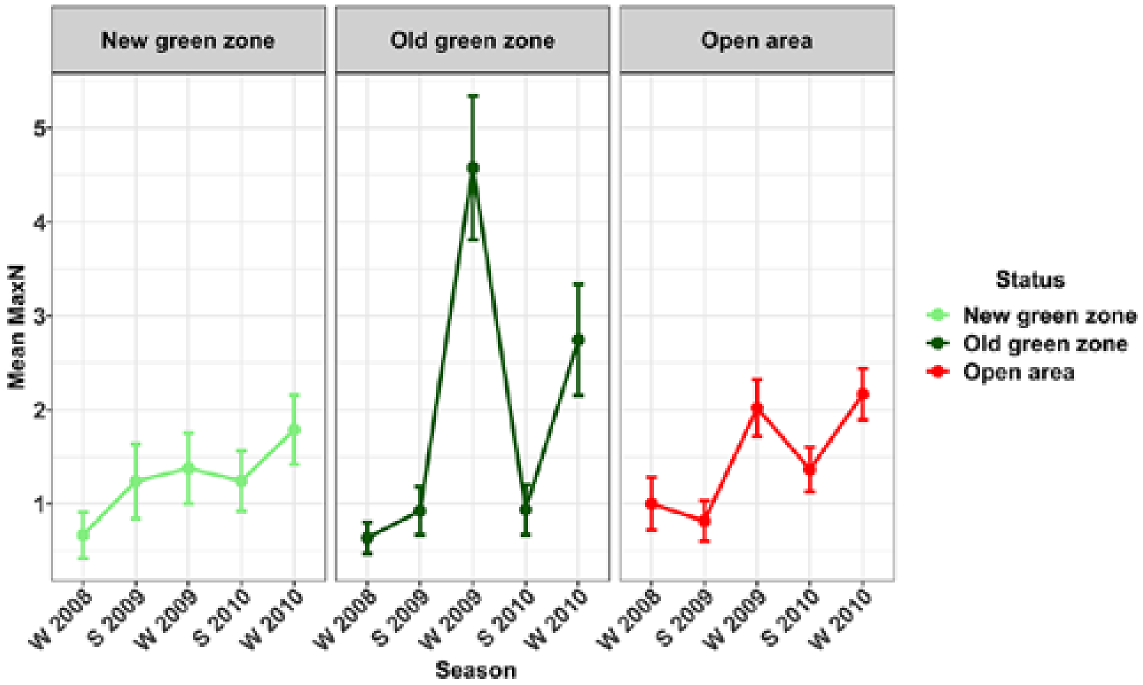

Figure 9. The mean relative abundance (MaxN) of snapper (*Pagrus auratus*). All three study areas (MNP04, MNP10 & MNP19 pooled) per season ±1SE. 'W' = winter, 'S' = summer.

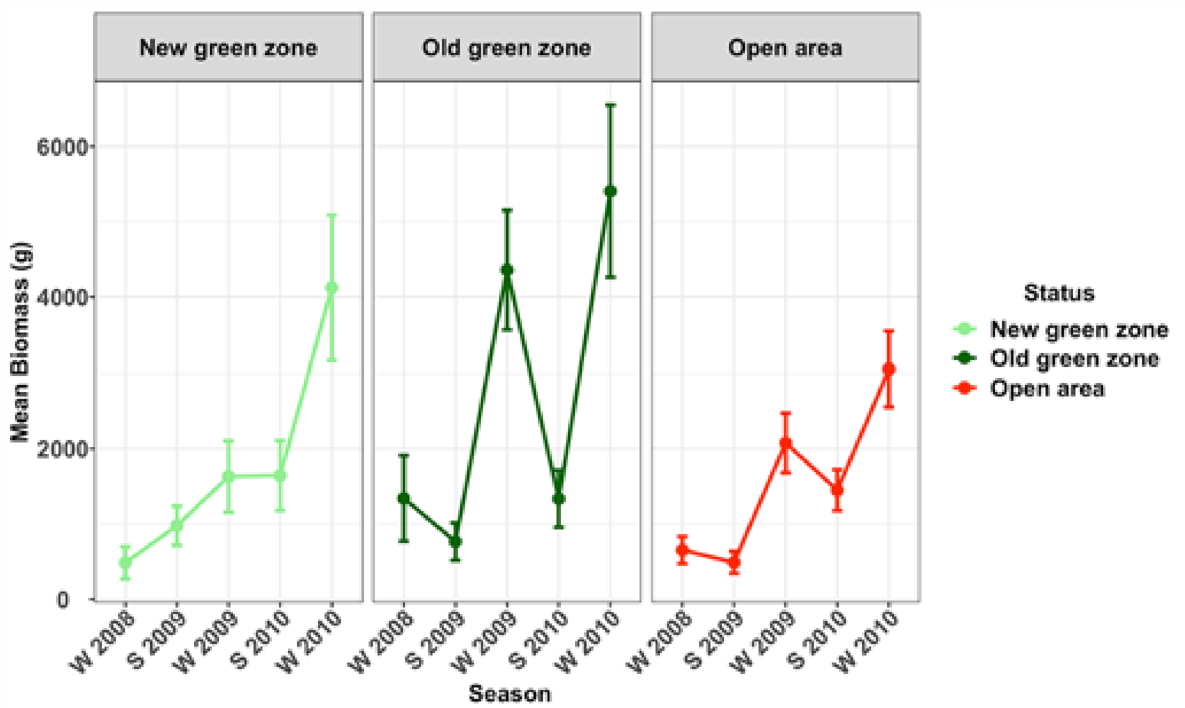

Figure 10. The mean biomass of snapper (*Pagrus auratus*; all three study areas (MNP04, MNP10 & MNP19 pooled) per season ±1SE. Biomass estimates are based on summed estimated weights of fish per BRUV recording. 'W' = winter, 'S' = summer.

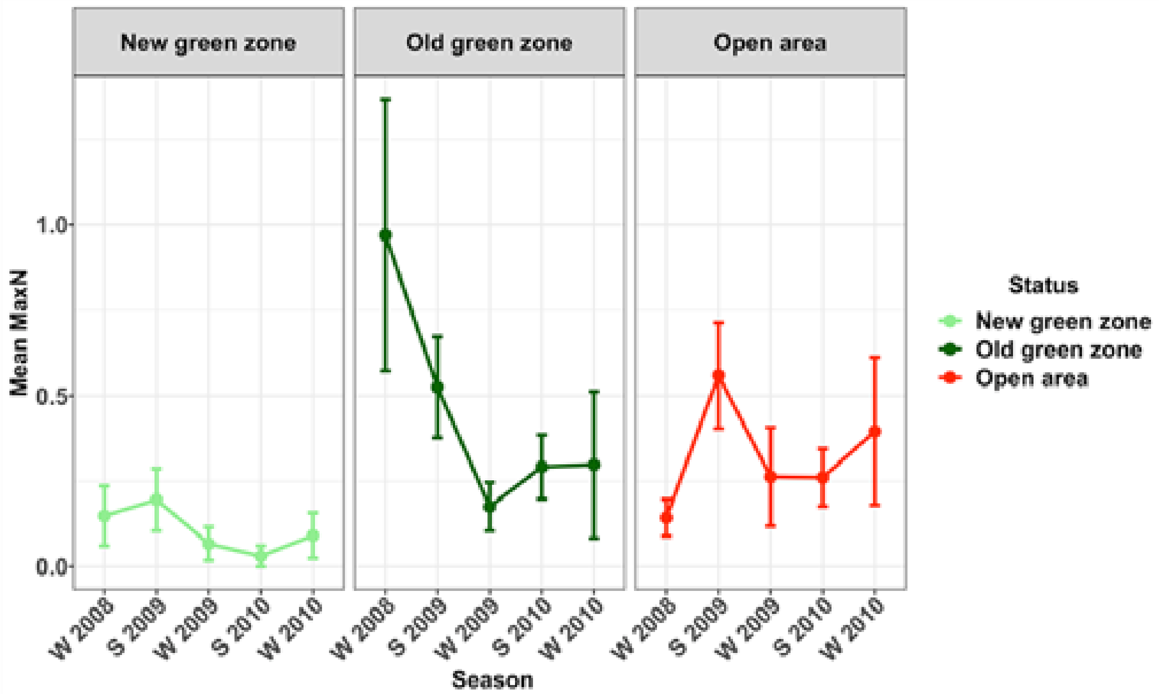

Figure 11. The relative abundance (MaxN) of spangled emperor (*Lethrinus nebulsosus*). All three study areas (MNP04, MNP10 & MNP19 pooled) per season ±1SE. 'W' = winter, 'S' = summer.

Redthroat emperor (Lethrinus miniatu*s*)
Redthroat emperor were observed throughout the study area, but they were consistently more abundant within the Old green zone at Henderson Rock (MNP10). This is unlikely to be due to habitat preference alone since both the New green zones and Open areas at MNP10 had similar habitat to that within the Old green zone and so the difference is likely to be due to lower fishing pressure in the Old green zone.

There was a significant decrease in the relative abundance of redthroat emperor in both the Open (36.1 ± 17.0%) and Old green (15.7 ± 12.5%) zones and no change in the relative abundance in the New green zones. The mean biomass of redthroat emperor increased significantly in all zones over the period of the study, with the greatest increase occurring in the New green zones (Open: 18.0 ± 12.5% per season; New green: 33.0 ± 17.0% per season; Old green: 17.9 ± 10.0% per season). This was despite a decrease in relative abundance suggesting that although numbers decreased the size of the remaining fish increased in all zones.

Venus tuskfish (Choerodon venustus)
Venus tuskfish were observed almost exclusively at Flat Rock (MNP19) and were rarely recorded at either Flinders Reef (MNP04) or Henderson Rock (MNP10). The relative abundance of venus tuskfish increased significantly in the New green zone at Flat Rock (41.1 ± 28.5% per season), whereas there was no change in their abundance in either the Old green or Open areas (Fig. 12). The mean biomass of venus tuskfish decreased by an average of 23.5 ± 21.5 % per season only in the New green zones throughout the study period. This indicates

that the New green zone at Flat Rock may be protecting venus tuskfish through enhanced survival of new recruits but perhaps not through higher survival of older fish.

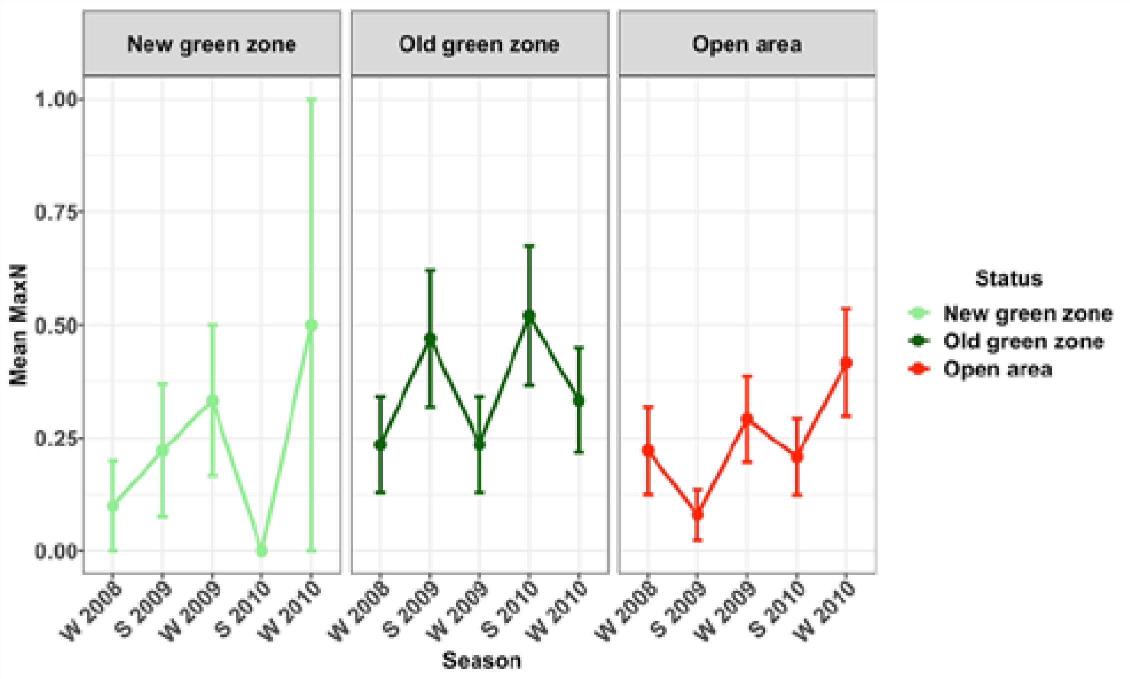

Figure 12. The relative abundance (MaxN) of Venus tuskfish (*Choerodon venustus*) recorded from Flat Rock (MNP19) per season ±1SE. 'W' = winter, 'S' = summer.

The relative abundance of blackspot tuskfish was highest at Flat Rock (MNP19) compared to either Henderson Rock (MNP10) or Flinders Reef (MNP04). Mean relative abundance of blackspot tuskfish increased significantly over the period of the study in the New green (42.8 ± 42.5% per season) and Open zones (19.6 ± 20.5 % per season) with no statistically significant change within the Old green zones (Fig. 13). Mean biomass of blackspot tuskfish increased over the period of the study in the New green zones (44. 1 ± 44.0 % per season) with no statistically significant change in mean biomass detected in either the Open areas or Old green zones, suggesting that the New green zones are beginning to protect the existing populations of blackspot tuskfish through enhanced survival.

Blackspot tuskfish (Choerodon schoenleinii)

Maori rock cod were most common at the New green and Open zones in the region around Henderson Rock (MNP10) and were rarely observed at either Flinders Reef (MNP04) or Flat Rock (MNP19). The trend term in the model for relative abundance was not significant indicating there was no change in abundance of maori rock cod since the introduction of the 2009 Moreton Bay Marine Park Zoning Plan. There was however, a significant increase in the mean biomass of maori rock cod in the Open and New green Zones over the period of the study (by 28.9 ± 34.5% and 30.6 ± 42.0% respectively). This result is difficult to interpret given there was no increase in biomass in the Old green zones, but a significant increase in both the New green zones and Open areas. It may suggest a reduction in overall fishing pressure on this species.

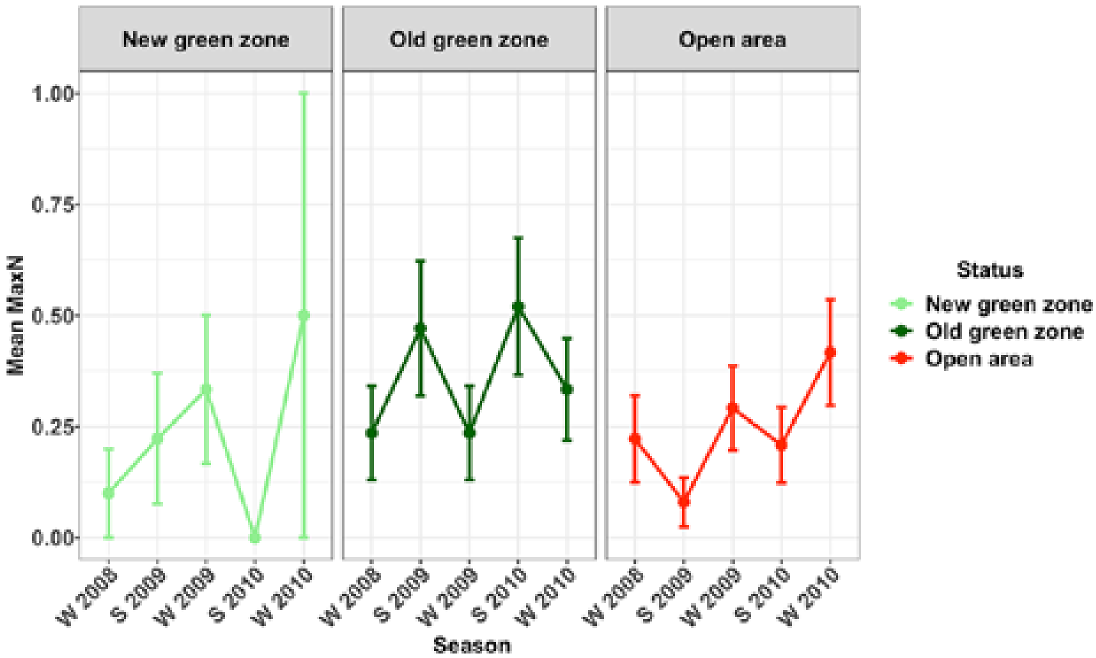

Figure 13. The relative abundance (MaxN) of blackspot tuskfish (*Choerodon schoenleinii*) recorded from Flat Rock (MNP19) per season ±1SE. 'W' = winter, 'S' = summer.

Goldspot wrasse (Bodianus perditio)
Goldspot wrasse were consistently most abundant in the Old green zones at Henderson Rock (MNP10). The trend term for the model of relative abundance of goldspot wrasse was not significant indicating no change in relative abundance over the study period. There was however, a statistically significant increase in mean biomass in the Open (14.8 ± 13.5%) and marginally statistically significant increase in the New green (22.0 ± 22.0%) zones throughout the period of the study. Similar to the result for Maori rock cod, this is difficult to interpret, except to suggest that there may be low and variable fishing pressure on this species.

Aquarium target species
Six species of fish targeted by the aquarium fish industry were observed on the BRUVs in sufficient numbers for analysis: pencil surgeonfish (*Acanthurus dussumieri*); keyhole angelfish (*Centropyge tibicen*); Guenther's butterflyfish (*Chaetodon guentheri*); neon damselfish (*Pomacentrus coelestis*); moon wrasse (*Thalassoma lunare*); and green moon wrasse (*Thalassoma lutescens*). However, there was no significant change in the relative abundance of any of these species during the study. We did not expect to detect significant changes in the relative abundance of fish targeted by the aquarium fish industry since the levels of collection pressure have historically been relatively low (50 to 200 days effort in the region in 2003; (31)), however we collected the data to provide a robust baseline for future monitoring.

Conclusions

The MNPZs in the offshore reef areas of Moreton Bay Marine Park were beginning to impact populations of fish and crabs within two years of their establishment. During these early stages, the changes were primarily through the increased biomass of most targeted fish species in the offshore region of the park. Increases in relative abundance would only be evident in fish following several years of protection from fishing. In contrast, both catch rates and average size of the shorter-lived mud crabs and the average size of sand crabs increased in several of the New green zones, indicating they are effective for these species where there is appropriate habitat available. In the inshore New green zone at St Helena, snapper responded strongly with increases in both catch rates and mean weight recorded. However, it is important to continue monitoring key green zones in order to understand their long-term effectiveness and to detect any unforeseen changes that may arise from the greater level of protection afforded to MNPZs in Moreton Bay. Furthermore, the full value of these no-take zones as benchmarks for ongoing evidence-based management of the broader marine park can only be realised by regular monitoring and assessment, as per the water quality monitoring programs in Moreton Bay, for example. Maintaining such a program will present significant challenges.

Presently, the full potential of these areas for conservation of fish populations has not been realised due to two principal factors: time since establishment and non-compliance by some Bay users with no-take regulations.

More time is required for the full potential effects of New green zones to be achieved. This is a fundamental consequence of many fish species' biology. For example, many targeted fish species are relatively long-lived (e.g. spangled emperor: 14 (32) to 28 (33) years) and in the case of protogynous hermaphrodites such as the spangled emperor, may not mature as females until 6 years of age (34). Consequently, significant changes in relative abundance would not be expected within 3 years. Repeat surveys over the coming years are required in order to evaluate the rates of change and variability in fish populations as well as the size of any effect.

Although the level of non-compliance quantified in both Old green and New green zones has declined since the implementation of the 2009 Moreton Bay Marine Park Zoning Plan it remains a concern since it has the potential to seriously erode the effectiveness of the MNPZs. Levels of education and enforcement need to be increased if conservation outcomes are to be achieved.

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Non-extractive human use and vessel characteristics in Moreton Bay Marine Park following rezoning

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Abstract
The Moreton Bay Marine Park (MBMP) is a multiple-use marine park in eastern Australia that was established in 1993 and rezoned in 2009 by Queensland's Environmental Protection Agency, thereby increasing the total no-take area of marine national park from 0.5 to 16%. In conjunction with measured trends in the human use of no-take areas before and after rezoning (previously reported by the authors (37)), we documented vessel use and characteristics of vessels in MBMP by way of on-water and aerial surveys. About 35% of vessel-based activity in the marine park was non-extractive use. Fishing was the dominant activity in the MBMP (65%), both within Moreton Bay itself and on nearby offshore waters, and recreational fishing comprised 97% of all fishing activity. Despite a thirty-fold increase in no-take area in the MBMP, there was minimal change in the spatial distribution of all on-water activities, including recreational fishing.

Vessels with overnight accommodation capacity (lifestyle vessels) comprised about 20% of vessel activity in the marine park. Sailing, sightseeing, jetskiing, paddling and camping made up significant proportions of other vessel-based activity. Small vessels < 5m in length made up 50% of all vessel length classes. The largest vessels encountered in MBMP were not found offshore; they were 'weekender' lifestyle vessels frequenting the many safe anchorages within the Bay. Vessels in the 5–8m length range were the most common vessels operated offshore. The majority of vessels (80%) had one or two people onboard, while offshore three to four people per vessel was common. Available leisure time and weather impacted the use of the marine park; all vessel types were observed more often on weekends and when forecast wind speed was low.

Keywords: spatial management, no-take zones, on-water observations, vessel operation, fishing, fishing gear, leisure time, weather forecast

Introduction

Marine protected areas (MPAs) are spatial management tools used extensively worldwide, primarily to conserve marine biodiversity (1–6). They include ‘no-take’ zones that prevent human extractive uses and displace extractive users to other fishing locations. Management by input controls, such as ‘no-take’ zones, reduces the effort deployed spatially or temporally in the fishery; as opposed to output controls that do not restrict effort but restrict ‘take-home’ catch by means such as bag limits. MPAs affect fishers’ behaviour by permanently reducing effort in selected areas (7, 8). Input controls are more conservative than output controls in that they reduce incidental mortality caused unintentionally, such as catching undersize fish that are returned to the sea, but the fish may perish due to barotrauma and handling (9).

In addition to conserving biodiversity, MPAs may have positive effects for non-extractive uses such as recreation, education (10) and aesthetics (3, 11, 12). They also can be valuable tools for research and adaptive management (13). However, quantitative studies of the benefits or costs of MPAs for non-extractive purposes are not common.

Non-extractive activities may be more highly valued by visitors to MPAs than extractive-use values (14) and command an economic premium. For example, scuba divers are more willing to accept restrictions to their activity if they can expect to see more marine life in an MPA (15, 16). Given a high willingness to pay for non-extractive values, no-take marine reserves may add significantly to a local economy by enhancing the perceived enjoyment of a natural feature.

At a regional scale, the economic performance of coastal cities and communities adjacent to the Great Barrier Reef Marine Park (GBRMP) is underpinned by tourism. Thus, marine conservation and marine parks are key components of the economy. In 2017, the Great Barrier Reef’s (GBR) economic, social and iconic value to Australia was estimated at $56 billion. In the GBR region, tourism was worth $6.4 billion per year and it supported 64,000 jobs (17). At the same time, commercial fishing and aquaculture was worth $199 million (17). Historically, the value of tourism among the GBRMP regional industries has been a far larger component (28%) of gross value of production than fishing (1%) (18). The sustainability of the GBR was strengthened by the creation of no-take zones; introduced and expanded by the Australian Government through the Great Barrier Reef Marine Park Authority, but broadly supported by the general public via the definition of conservation objectives, data-supported substantiation, community education and social licence (19). Likewise, at ‘single-site’ spatial scales, tourism at the Leigh Marine Reserve (New Zealand) was estimated to bring 100,000 visitors per year, contributing substantially to the local economy (20).

Considering the competing uses of marine park resources, it makes economic sense to carefully evaluate the balance between extractive and non-extractive uses. Specific examples of economic input to Australia from non-extractive use of the GBRMP include the direct and indirect economic values of tourism (17), the visitor experience in dwarf minke (*Balaenoptera acutorostrata*) whale tourism in the northern GBR (21), and changing visitor perceptions (22).

Internationally, the evaluation of the non-market resource value of MPAs, in particular, and marine ecosystems, in general, demonstrates a direct economic benefit that often surpasses value to the region measured in more traditional ways (23–28). The high non-market value reflects an estimate of the value of global ecosystem services and 'natural capital' that is about double the global gross national product; mainly through the MPA's contribution to human wellbeing (29, 30). To give a specific example, the value of extractive commercial fishing in the Florida Keys was dwarfed by the non-market value of recreational activities within an MPA which was established to maintain and improve the value of the coral reef ecosystem, particularly coral and fish abundance and biodiversity. MPA non-extractive users were 40–80% more likely to visit the Keys and enjoyed a 69% more valuable experience on a reef ecosystem where reef quality was protected by the MPA (23). These trends mimic those measured in the GBR, Australia (17). Even in the planning of MPA boundaries and zoning categories, experiential expectation of MPA use demonstrates subtle differences. For example, in British Columbia, the prospect of non-extractive use by boaters operating sail or motor vessels in a proposed MPA was investigated by face-to-face questionnaires (31). Sailboaters valued the natural environment; they rated a pristine environment more highly, and valued access to built facilities and fishing less highly than motorboaters (31). The targeted use of pristine MPAs will enhance the economy of a region and offer non-market benefits that are even more difficult to differentiate than most measures of non-market value in comparison to the traditional economic indicators, such as market value of landed fish and crustaceans. Differences in experiential expectation as boaters use waterways could be used to better plan the zoning of the MPA (31). In the case of Moreton Bay, the contrast between the high value of conservation benefits from MPAs close to a major urban population, and the opportunity cost associated with historical use for extractive commerce (e.g. the oyster growing industry) is evident (32). Aquaculture must operate with maximum efficiency to compete with the maintenance of ecosystem services and biodiversity outcomes supported by MPA conservation, if commercial activity was not to be displaced.

The Moreton Bay Marine Park (MBMP) was established in 1993 and includes 3400km^2 along the southern Queensland coast (Fig. 1). The management of the park was reviewed in 2007 to protect a greater percentage of marine habitats with a stated objective to 'provide for the ecologically sustainable use of the Moreton Bay Marine Park and to protect its natural, recreational, cultural heritage and amenity values' (33). Park managers analysed data, gathered scientific advice and consulted stakeholders to minimise impacts on users. Simultaneously, an alliance of commercial and recreational fishers, fishing retailers and wholesalers and others undertook a similar socioeconomic/biological analysis and developed an alternative plan, aspects of which were adopted (34, 35). The new zoning plan came into effect in March 2009, increasing no-take marine national park (MNP) zones from 0.5% to 16% (36). The design of the rezoning was successful in minimising the impact of rezoning on extractive users (37). Despite the 300% increase in the aerial extent of MNP zones, just 6.7% of fishers in MBMP were displaced (37). The low displacement of extractive users was due to an informed placement of no-take zones relative to locations of high extractive use and realignment of some no-take zone boundaries following public consultation (38), including the Minister for National Parks personally speaking to conservation, commercial and recreational fishing stakeholder peak bodies.

We sampled the MBMP, observing non-fishing activities, fishing and vessel characteristics in MNP and conservation park zones (CPZs), compared with habitat protection zones (HPZs) and general use zones (GUZs) as control areas using both on-water and aerial surveys, both before and after rezoning. HPZs do not exclude recreational and commercial fishing, apart from trawling, so they were included in our control areas. Importantly, we gathered data on the suite of usage types of Moreton Bay and the non-extractive use by recreational and commercial users. Though MPAs are used as a tool for biodiversity conservation, their amenity and attractiveness to non-extractive users has economic value and social impact (17, 19). This study investigates the potential for significant value to accrue to non-extractive users of Moreton Bay due to the increase in MNP zoning.

Methods

Study area

The MBMP is located in South East Queensland, Australia, including Moreton Bay and adjacent offshore waters (3 to 20 km offshore, maximum depth of about 150 m) (37). It stretches 125 km from 26° 48.5' S to 27° 58.0' S encompassing the Bay's tidal waters, including many estuaries, and extends seawards to the limit of Queensland state territorial waters (Fig. 1).

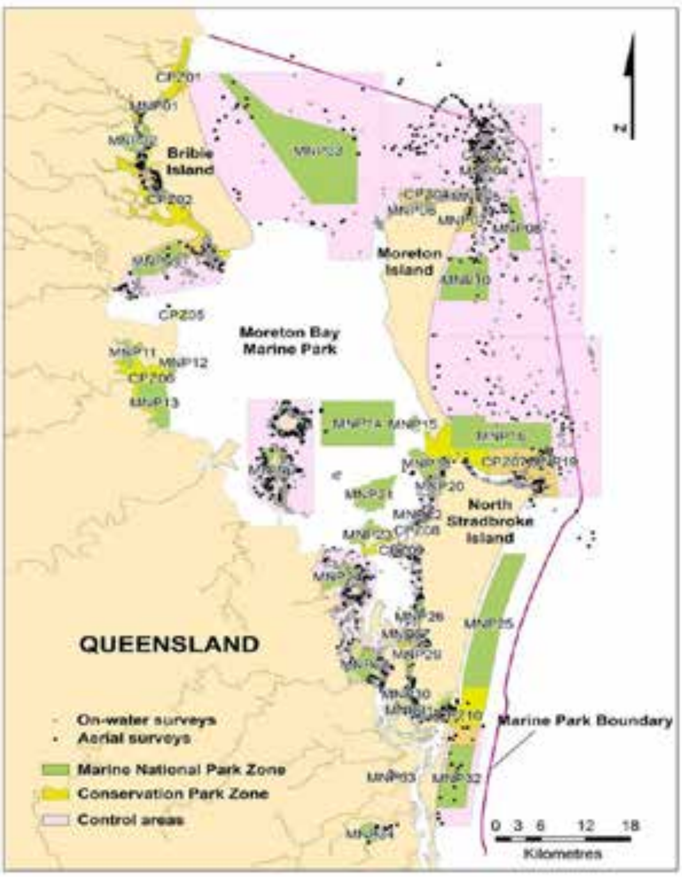

Figure 1. Map of the Moreton Bay Marine Park area showing the marine national park zones (MNP), conservation park zones (CPZ), corresponding control areas, and location names used in this study. The reference control areas are adjacent to or surrounding their respective marine national park zones. The map shows vessel locations observed in survey areas during on-water surveys (grey dots) and aerial surveys (black dots) undertaken on Moreton Bay from August 2008 to February 2011.

Four levels of zoning were implemented in the MBMP impacting the activities of recreational and commercial fishers, and possibly other park users. MNP zones are the most restrictive for fishers, with no extractive activity allowed. CPZs allow fishing and some collecting, but trawling and the majority of commercial netting are not allowed (recreational bait netting and a specific N11 commercial net endorsement are allowed, though whiting (*Sillago* sp.), bream (*Acanthopagrus* sp.) and flathead (*Platycephalus* sp.) may not be retained). HPZs allow netting, but not trawling. Trawling and all other legal activities are allowed in the GUZs. Here we restrict our analysis to the MNP zones as 'impact' areas and adjacent GUZs and HPZs as control areas.

Data collection
We recorded non-extractive activities, extractive use and vessel characteristics in the MNP and adjacent control areas (areas with similar habitat and bathymetry to the MNP) of the MBMP using both vessel and aerial surveys. The extractive use and impact of MPA zoning on fishing activities were reported by Kenyon *et al.* (37). The categories of human use and vessel descriptors used are detailed in Table 1.

The on-water sampling program was based on the proposed zoning plan using a BACI-pairs experimental design (38). The statistic analysed was the proportion of vessels in the MNP as a percentage of all vessels within the MNP and control area. Thus it was independent of area surveyed, time-of-day, weather etc., as all factors affecting the MNP also affected the paired control area (37).

Boat-based surveys
Prior to MNP implementation, there were six rounds of surveys conducted monthly between August 2008 and January 2009. After MNP implementation (1 March 2009), sampling was conducted every two months for 12 surveys between April 2009 and March 2011. Due to the timing of the rezoning, it was not possible to fully balance the sampling design for the season before and after rezoning. Prior to MNP implementation, review of the MBMP, including public information sessions and submissions, was well advanced (33). We have presumed that the behaviour of fishers was not changed during the public consultation process prior to implementation of the new zoning plan.

The on-water monitoring sampled both vessel- and land-based fishing activities as well as all vessel-based non-fishing activities such as passive anchoring, tow-sports, sailing, diving, or transiting the survey areas. Twenty-one of the 34 MNPs were regularly surveyed. The MNP zones, distributed along the length of the Bay, included a range of habitats from shallow, inshore bays and estuaries to offshore rocky reefs (Fig.1). The greatest numbers of survey days were undertaken on weekdays, and 53% of MNPs were visited during mornings, 47% during afternoons. Thirty-three per cent of surveys were done on weekends. For a series of MNPs, the survey vessel track was predetermined and recorded by GPS on each survey.

On-water monitoring was completed in sets of observations over consecutive days. We observed, located and inventoried all vessels in each MNP and associated control areas. If required, we deviated from our path to ascertain details of distant vessels before returning to the track. During each on-water survey, vessel locations (recorded by GPS), vessel descriptions and activities were annotated on data sheets.

Aerial surveys
The aerial surveys provided coverage of the entire study site in one day (refer to (37)). Aerial surveying covered the 21 MNPs that the on-water surveys covered, as well as additional study areas at South Stradbroke Island (MNP32), McCoys Creek (MNP33) and Coombahbah Lake (MNP34) (Fig. 1). For the pre-zoning period, the three surveys were conducted once a month from November to January 2008–09. After rezoning of the MNPs, aerial surveys were conducted monthly from November to January 2009–10 (three surveys). Each flight lasted about 2.5–3.5 hours, depending on vessel density. Flights were conducted from an over-wing

aircraft at low-level (~125m) and low-speed (90 to 100 knots) and a GPS recorded the aircraft flight path.

Table 1. Vessel type and activity classifications that were collected during on-water surveys. Lifestyle vessels supported day- or overnight trips, usually with cooking facilities and sleeping accommodation onboard. Similar vessels were lived on permanently by some Bay users. Note that it is possible for a single vessel to fall into two or more categories (e.g. fishing and lifestyle vessels).

Categories	Activity classification/characteristics
Vessel type	
Dinghy	Small outboard vessel: aluminium, fibreglass, timber
Canopy dinghy	Small outboard vessel: aluminium, fibreglass, timber – with canopy
Cabin runabout	Outboard vessel with fo'c'sle not used for sleeping
Cabin	Fo'c'sle or cabin designed for sleeping accommodation
Walk-through	Passenger seating placed forward of steering position
Walk-around	Central cabin accommodation with full deck access fore and aft
Centre console	Steering from a central pod; limited or no passenger seating/accommodation
Speedboat	Outboard or inboard vessel with minimal passenger accommodation built for watersport (e.g. waterskiing)
Bass boat	Low freeboard, flush-deck vessel designed as a calm-water fishing platform
Yacht sailing	Yacht deriving propulsion from sail power (active sailing experience), possible engine thrust engaged
Yacht under motor	Yacht being propelled by engine power, not sail
Houseboat	Vessel designed for calm-water conditions with maximum cabin space
Kayak	One or two person paddle craft
Jetski	Personal powered watercraft
Vessel in transit	Type as per category above, speed and heading estimated
Vessel size	<5m, 5–8m, 8–10m, 10–15m, >15m
Propulsion type	Inboard motor, outboard motor, sail
Hull design	Planing, Displacement
Activity	
Fishing	Primary activity in Moreton Bay Marine Park is fishing; e.g. line, pot or spear (recreational/ commercial)
Diving	Primary activity is diving; SCUBA (recreational/ commercial)
Whale watching	Primary activity is whale watching, usually from a commercial tour vessel
Sightseeing	Primary activity is less well defined, but specific appreciation of a component of the natural environment (no overnight accommodation),
Lifestyle	Primary mode of transit an engine-powered vessel with overnight accommodation, but general appreciation of the natural environment a significant component, vessel operators may fish.
Live-aboard	Vessel is the permanent primary residence.
Yachting	Primary mode of transit is wind-propelled vessel operation (pleasure activity)
Jetskiing	Primary activity is the operation of personal watercraft for pleasure alone
Fishing gear	Baited line-anchored, baited line-drifting, trolling, casting lures, casting soft plastic lures, pots/dillies, yabby pumping, bait netting, cast netting, beach fishing (land based), beach fishing (initial vessel transit), spear fishing (boat based), spear fishing (land based), searching, resting
Vessel type	
Dinghy	Small outboard vessel: aluminium, fibreglass, timber
Canopy dinghy	Small outboard vessel: aluminium, fibreglass, timber – with canopy

Cabin runabout	Outboard vessel with fo’c’sle not used for sleeping
Cabin	Fo’c’sle or cabin designed for sleeping accommodation
Walk-through	Passenger seating placed forward of steering position
Walk-around	Central cabin accommodation with full deck access fore and aft
Centre console	Steering from a central pod; limited or no passenger seating/accommodation
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During each flight, vessel descriptions and locations were annotated on maps noting vessel activities and nearby geographical features and man-made markers. The maximum error of near-shore position estimates was approximately 50m and in open bay and offshore areas approximately 200m. Vessels operating in featureless open water were plotted using the handheld GPS with a maximum 50° arc of lateral observation from vertical. The maximum error of these position estimates was approximately 600m.

Vessel size and people per vessel

The vessels described by size and occupancy include all vessels observed: vessels in transit, vessels for which activity could be categorised, and vessels for which activity was unable to be categorised but for which size could be reliably estimated. The total number is higher than those vessels for which analyses of vessel activity were undertaken. Data for both on-water and aerial surveys are combined.

Spatial processing and data analysis
Spatial processing
Spatial data were mapped using GIS (ESRI ArcGIS versions 9.3 and 10). The positions of observed vessels and tracks of survey boats and airplanes were mapped on shapefiles to an accuracy of ±15m. The precision of vessel location mapped on shapefile was dependent on the method of vessel position recording (37). As mentioned above, the locations of on-water vessel observations and the tracks of survey vessels were mapped precisely. However, position estimates during aerial surveys had lower levels of precision relative to the precisely mapped track of the survey aircraft, though geographical features and navigation marks were used to improve the precision of location estimates (37). Control area boundaries were created by manually positioning nodes or subtraction of MNP polygons where overlap with a control area existed.

Statistical analyses of human use data
For each of the surveyed MNPs, the average number of vessels per survey, day-of-the-week, season and vessel activity were included in the analysis. Generalised linear models (GLMs) (40) were used to compare the mean proportions of vessels (total vessels, fishing vessels, non-fishing vessels) in MNP and control areas, accounting for day of week or season.

As the data are over-dispersed, the models were fitted based on the negative binomial distribution in the MASS package in R (41). The GLMs for fishing vessels were fitted separately to 'in-MNP' and 'control' data with fixed-effects estimated for each MNP and paired control area, season ('summer', 'autumn', 'winter', 'spring'), type of day ('weekend' or 'weekday') and time of sample ('before rezoning' or 'after rezoning'). Similar models were also fitted for 'all vessels' and 'vessels not fishing'.

The similarity of MBMP zones and paired control areas based on proportions of various types of boating activity observed during the boat-based surveys was investigated using Bray–Curtis similarity ordination (CLUSTER routine in PRIMER software) (42).

To investigate vessel use in relation to environmental factors (weather) and available leisure time (weekends vs weekdays), we used a simple GLM model incorporating several variables: marine national park (MNP), day type (weekend day vs weekday), rain prior day (the observed average rainfall over five locations adjacent to Moreton Bay the day prior to the survey), rain survey (the observed average rainfall over the five locations adjacent to Moreton Bay the day of the survey), wind forecast (the upper limit of the forecast wind range provided by the Bureau of Meteorology (BOM)), wind direction (as forecast by the BOM), and maximum temperature (as forecast by the BOM). The five rainfall locations were Bribie Island (gauge # 40978), Redcliffe (gauge # 40958), Brisbane Airport (gauge # 40842), Steiglitz Wharf (gauge # 540295) and Gold Coast Seaway (gauge # 40764).

The upper and lower limits of the forecast wind range were highly correlated so only one measure was modelled. The same protocol was applied to maximum and minimum temperature. A quasi-poisson distribution was used in the model due to the large amount of variability in the data (partly due to our observations of vessels in a range of diverse MNPs both within and outside Moreton Bay during each survey).

Results

Boating activity in Moreton Bay Marine Park

We completed 75 days of on-water sampling in Moreton Bay Marine Park (25 pre- and 50 post-zoning) collecting 4411 vessel observations, together with 1854 aerial survey observations of stationary vessels (Fig. 1). During the on-water surveys prior to the March 2009 rezoning, 914 vessels were observed (during 6 surveys), whereas after rezoning 3497 vessels were encountered during 12 surveys. Before rezoning, approximately 30% of on-water sample days were conducted on weekends, and about 34% on weekends post-MNP declaration. During aerial surveys, we observed 763 vessels prior to rezoning and made 1091 observations post-declaration. Two hundred and twenty-three vessels observed during aerial surveys (9.9%) were unable to be assigned to activity type. In addition, 1304 vessels were 'in-transit' to a destination and were not engaged in an activity that could be categorised. However, their size and number of people onboard could be documented.

The effect of the increased area of no-take zones on the spatial displacement of vessels or change in activity has been described previously by the authors (37); including change to the spatial location of fishing activity in Moreton Bay and offshore adjacent to Moreton and Stradbroke islands. The most common human use by vessel operators was extractive use: fishing (recreational or commercial) (66%). Recreational fishers made up the greatest proportion of all fishers (~97%).

However, as observed during both on-water and from aerial surveys, about 34% of the human use of the marine park from vessels was non-extractive use (37). All vessel-use categories are shown in Figure 2. The most common non-extractive activity on Moreton Bay was being aboard a 'lifestyle' vessel (~20%) and this was the second-most common activity of all use types. Lifestyle vessels are large-cabin vessels with food storage and preparation facilities and sleeping quarters. The aim of their operators was to spend time relaxing on Moreton Bay, including non-extractive use. If fishing activity was observed from a lifestyle vessel, the vessel was categorised as 'fishing'. Observed both on-water and from the air, sailing, sightseeing, jetskiing, paddling, resting and camping made up significant proportions (each <5%) of these non-extractive, on-bay activities (Fig. 2). On about 100 occasions (~2%), the vessels encountered were occupied by people who live permanently on Moreton Bay. These are usually on reasonably large 'cabin-cruiser' style displacement hull vessels, as determined by obvious vessel characteristics, from interviews and multiple encounters. Commercial whale-watching vessels operated offshore from June to October (we saw two whale- watching vessels prior to rezoning and seven post rezoning), and offshore fishing charter vessels operated year round (we saw 4 charter vessels prior to rezoning and 23 post rezoning). Some land-based fishing was observed, mostly from Moreton and North Stradbroke islands. The categories of vessel type observed and the activities undertaken in Moreton Bay are summarised in Table 1.

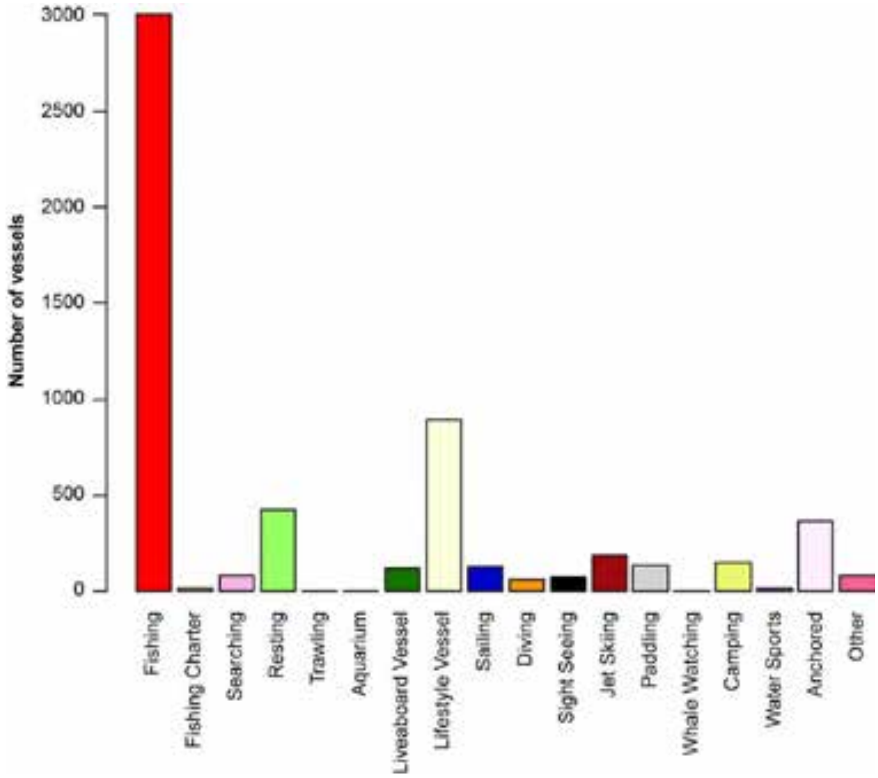

Figure 2. Vessel-based activities as observed from the boat-based surveys (4,411 vessel observations). 'Resting, live-aboard, lifestyle, sailing, diving, sightseeing, jetskiing, paddling, whale watching, camping and water sports' are non-extractive uses.

Small vessel operation and characteristics in Moreton Bay Marine Park

Boat-based surveys

Patterns of human use were discerned based on similarity in the types of activities carried out in each MNP area. The majority of MNPs and paired control areas fell into five groups which corresponded to environmental classifications: offshore reefs, offshore open water, lifestyle anchorages, sheltered bay waters, and open bay waters (Fig. 3). Human activities in the control areas of the offshore reefs and open-water habitats were characterised by high proportions of fishing at >75%, as well as diving, sightseeing and whale watching. Fishing activity in the offshore open-water habitats targeted deeper hard-bottom reefs. Diving and sightseeing were prevalent at the offshore reef sites. Several of these reefs are attractive as they have shallow portions accessible to divers (SCUBA and free divers) and visible intertidal sections.

(NP)Vessel anchorage sites located on the western shores of North Stradbroke Island were characterised by higher numbers of lifestyle vessels than any other vessel type, 30–40%. Fishing was common within anchorages that were outside no-take zones, but so were activities such as resting and reading. Waters inside Moreton Bay were characterised by higher levels of fishing than any other activity. A range of other activities such as paddling, jetskiing and resting-at-anchor were observed at similar frequencies. Open bay sites had higher proportions of sailing vessels (142 sailing vessels observed) than the sheltered bay waters (27 sailing vessels observed), although 126 sailing vessels were observed in anchorages some of which were adjacent to open bay waters.

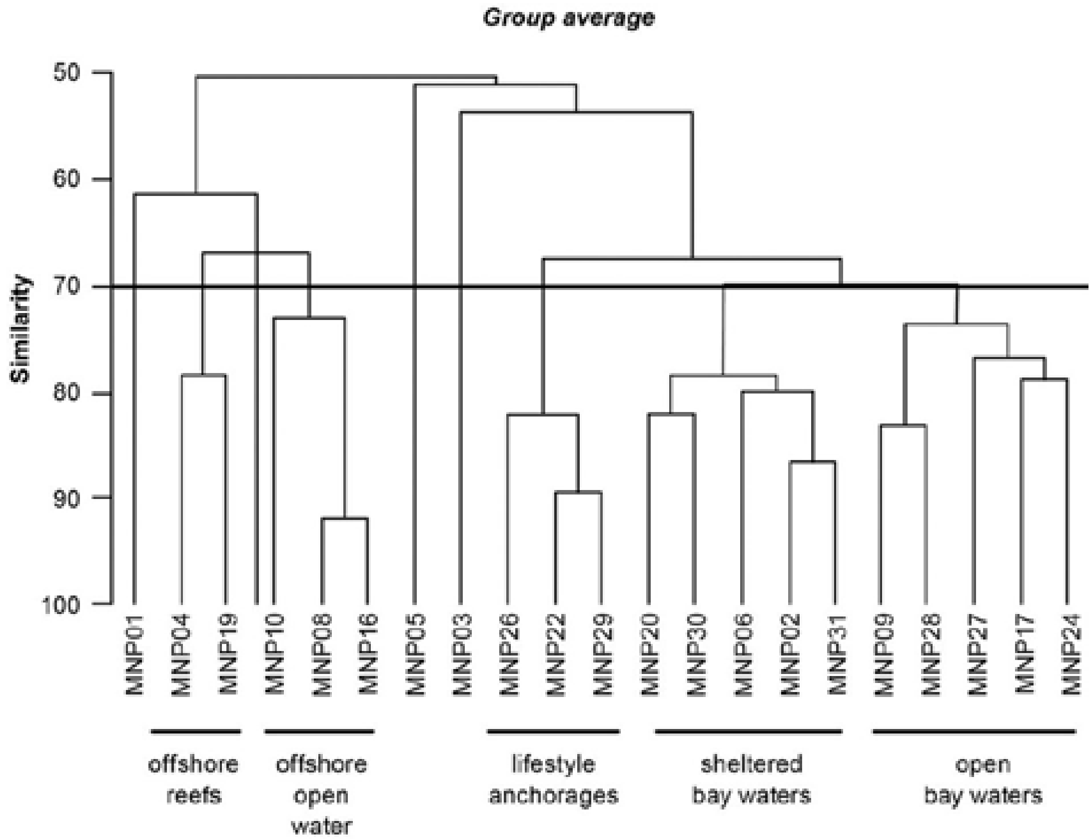

Figure 3. Clustering dendrogram showing the similarity of Moreton Bay Marine Park zones and paired control areas based on boating activities observed therein.

A few atypical outlier MNPs and control areas did not fall into any of the categories above (i.e. Westaways Creek (MNP01), Wild Banks (MNP03) and Cape Moreton (MNP05)). Fishing and whale watching dominated activities at Cape Moreton, while only a few fishers and sailing vessels were seen on Wild Banks, and fishers and jetskiers were common in the vicinity of Westaways Creek.

The average number of vessel observations made in a day was greatest on the weekend days than weekdays. Roughly double the numbers of vessels were encountered on a Saturday or Sunday than on a weekday (Table 2). The highest median number of vessels was recorded on summer days and the lowest in winter (Fig. 4). Autumn showed the greatest variability with 173 vessels on one day and only 14 on another. Spring showed comparatively small variability excluding one large outlier of 208 vessels (Sunday 7/11/2010). Figure 4 emphasises the large amount of variability in the data and the need to include season as a term when modelling the data as they are highly unbalanced.

Vessel type and size and number of people per vessel
Vessels < 8m make up the great majority of the vessel observations within Moreton Bay and adjacent offshore waters. Vessels < 5m in length were the most common vessels in use on the MBMP, especially within the sheltered waters within Moreton Bay (3891 of 8087 vessels). Five- to eight-metre vessels are the next most common vessel operated (n=2020). Both of these length classes of vessels were dominated by outboard-powered vessels; usually open dinghies, centre console runabouts or cabin runabouts. They are mainly day-use vessels. Vessels in the

10–15-m size class are the next most common vessel class (n=1153). These vessels are dominated by lifestyle vessels that support overnight on-water experiential activity, and yachts. Both of these vessel types have a galley and bunks for food preparation and sleeping, respectively.

Table 2. Number of observations (vessels encountered) and mean per day for each day of the week

Day	No. of observations	No. of sample days	Mean no. of observations per day
Sunday	981	10	98
Monday	295	5	59
Tuesday	473	9	53
Wednesday	661	11	60
Thursday	482	10	48
Friday	723	14	52
Saturday	1652	14	118

Vessels > 5m dominate the vessel size characteristics at four offshore MNPs: Flinders Reef (MNP04), Deep Tempest (MNP08), Mirapool (MNP16), Flat Rock (MNP19); and at two inshore MNPs: Myora (MNP22) and Willes Island (MNP29) (Table 3). However, the vessel types differ between the inshore and offshore MNPs. The offshore MNPs and control areas require a larger plaining-hull vessel to access them safely. The numerically dominant offshore vessel favoured by fishers was a 5–8-m vessel of either cabin or centre console configuration, usually fibreglass (glass reinforced polyester) or plate-aluminium hulled. In contrast, the typical large vessels at inshore anchorages were lifestyle vessels supporting overnight operation.

Though not numerically dominant, large cabin vessels (>8m) with capacity to sustain overnight or longer operation were sometimes common offshore, but usually they were engaged in seasonal game fishing, often trolling (i.e. day fishing – not staying out overnight). Some vessels > 15m were also common offshore, especially commercial dive vessels and whale-watch vessels operating north of Moreton Island (e.g. Flinders Reef).

Annually, large vessels (>10m) were not numerically dominant offshore (Table 3). Vessels > 10m were common at inshore MNPs and control areas within Moreton Bay; they were the ‘weekender’ vessels (vessels in the lifestyle category) or yachts anchored in known anchorages overnight. The Myora anchorage (control area near MNP22) was a typical location frequented by lifestyle vessels, as was the anchorage adjacent to the Royal Queensland Yacht Squadron facility on the north-east tip of Russell Island, Canaipa Passage (control area near MNP29).

About 80% of the vessels observed during the boat-based surveys had one or two people onboard, 12% had three people and 8% of vessels had four or more people onboard (Fig. 5). One or two fishers in a < 5-m or 5–8-m vessel were very common.

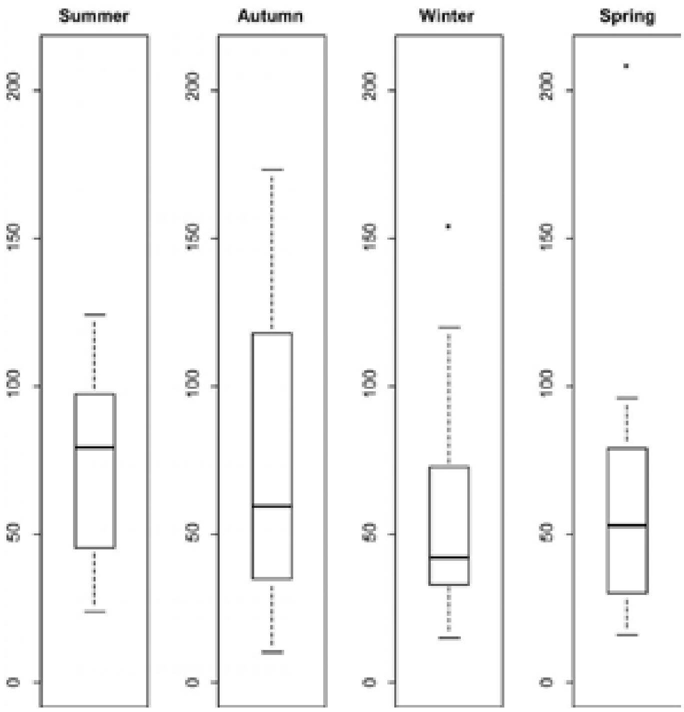

Figure 4. Seasonal variation in number of vessels recorded on each boat-based survey day. Box plots show the median number of observations (line within each box), the first and third quartiles (box range) and full data range (dotted line).

A few vessels had 20–50 people onboard, usually commercial dive vessels or chartered vessels engaged in sightseeing or whale watching. Yachts and day-vessels not fishing may have three or more people onboard.

The average number of people per vessel was highest in Wild Banks (MNP03 and control area), Henderson Rock (MNP10 and control area) and Mirapool (MNP16 and control area) where the average was > 2.5 persons per vessel. These MNPs are offshore locations accessed by large vessels with more occupants (including charter vessels with >10 passengers). Similarly, an average of 2.4–2.5 people per vessel were observed elsewhere offshore (Flinders Reef, Cape Moreton and Deep Tempest). Inshore, fishers often took their vessels on the Bay alone. Vessels with two people onboard were observed throughout the survey area.

Impact of weather

There were significantly fewer vessels using Moreton Bay when the upper limit of predicted wind speed was high (~15–20 knots) (Table 4). As shown in a previous analysis, a greater number of vessels were observed on the weekends than on weekdays. No other variables (e.g. rainfall or temperature) contributed significantly to the model, due to variability in the data attributed in part to the large number of MNPs sampled in various combinations (Table 4).

Discussion

In the Moreton Bay Marine Park, one-third of on-water users were engaged in non-extractive activities that rely of the geophysical, biological and cultural values of the marine environment to attract their visitation. Being aboard a weekender ‘lifestyle’ vessel was the most popular non-extractive activity; yachting, jetskiing, scuba diving, paddling, sightseeing and whale watching were also enjoyed. Recreational fishing made up the remaining two-thirds of popular activities undertaken both within Moreton Bay itself and on nearby offshore waters, comprising 66% of all activity (37). Elsewhere in Queensland, fishing is also the most popular activity by vessel operators using coastal waters (17, 43); yet regional quantitative comparisons with non-extractive use are sparse. Approximately 35% of recreational fishing in Queensland occurs in the Moreton Bay Region (43) and about 57% in South East Queensland (Brisbane, Sunshine Coast, Wide Bay Burnett).

Table 3. Breakdown of vessel size (in metres) by marine national park (MNP) (including paired control area) as encountered by boat-based surveys. The high numbers of 'unknown' vessels at Heath Island, Amity, Point Halloran (Coochiemudlo Island) and Swan Bay are land-based beach fishers.

		VESSEL SIZE (M)					
	MNP	≤5	5.01–8	8.01–10	10.01–15	>15	Unknown
MNP01	Westaways Creek	38	1	0	5	0	0
MNP02	Tripcony Bight	373	49	13	25	0	4
MNP03	Wild Banks	4	6	7	4	1	0
MNP04	Flinders Reef	29	140	23	25	11	2
MNP05	Cape Moreton	3	3	0	0	0	5
MNP06	Heath Island	32	12	9	3	1	31
MNP08	Deep Tempest	2	39	4	9	2	0
MNP09	Deception Bay	193	45	11	9	0	1
MNP10	Henderson Rock	4	18	1	5	3	1
MNP16	Mirapool	2	45	3	8	6	1
MNP17	St Helena Is	269	96	30	54	22	8
MNP19	Flat Rock	36	63	5	0	2	2
MNP20	Amity	86	48	9	12	2	159
MNP22	Myora	34	22	18	83	29	1
MNP24	Point Halloran	284	71	20	61	9	17
MNP26	Price Anchorage	72	27	28	42	4	1
MNP27	Lamb Is	12	6	3	4	2	0
MNP28	Pannikin Is	89	17	4	9	2	0
MNP29	Willes Is	69	36	58	112	19	8
MNP30	Cobby Cobby	116	47	40	46	6	1
MNP31	Swan Bay	468	133	30	45	10	22
	TOTAL	**2215**	**924**	**316**	**561**	**131**	**264**

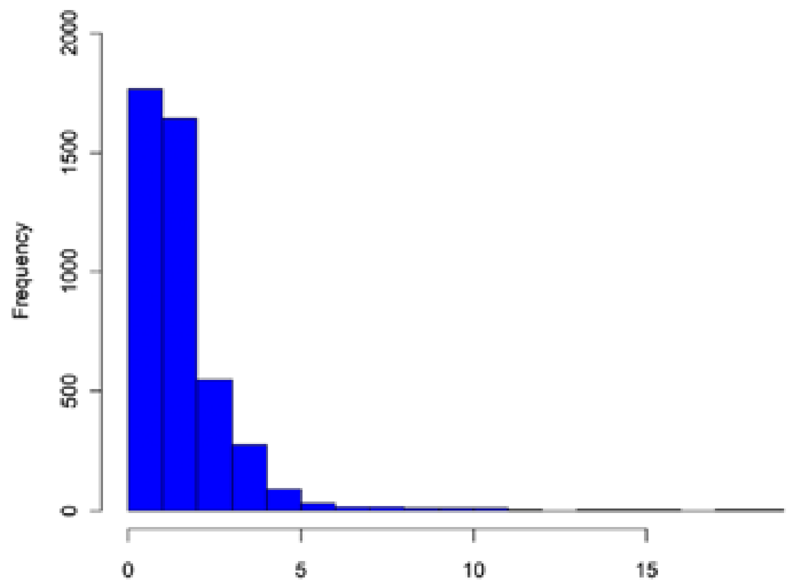

Figure 5. The number of people per vessel undertaking all activities observed during boat-based surveys.

Table 4. Environmental variables (derived from weather forecasts and observations) modelled using generalised linear models that may affect the likelihood of vessels operating on Moreton Bay on any day. 'Day type' is weekend day vs weekday, 'rain prior day' is the observed average rain over five locations (Bribie Island (40978), Redcliffe (40958), Brisbane Airport (40842), Steiglitz Wharf (540295), Gold Coast Seaway (40764)) the day prior to the survey, 'rain survey' is the observed average rain at those locations on the day of survey, 'wind forecast' is the upper limit of the forecast wind range provided by the Bureau of Meteorology (BOM), 'wind direction' as forecast by BOM, 'maximum temperature' as forecast by BOM. Df: degrees of freedom.

Variable	Df	Deviance	Residual Df	Residual deviation	F	Prob. (>F)
Marine national park	20	1578.3	316	2107.5	15.9691	<0.0001***
Day type	1	618.08	315	1489.5	125.0738	<0.0001***
Rain prior day	1	9.69	314	1479.8	1.9606	0.162
Rain survey	1	0.04	313	1479.7	0.0076	0.931
Wind forecast (upper limit)	1	70.83	312	1408.9	14.3329	0.0002***
Wind direction	5	27.91	307	1381.0	1.1294	0.345
Maximum temperature	1	0.08	306	1380.9	0.0161	0.899

As reported by Kenyon *et al.* (37), despite a thirty-fold increase in no-take area in the MBMP, there was minimal change in the spatial distribution of all on-water activities, including recreational fishing. Low spatial displacement was due to the strategic placement of MNP zones as an outcome of science-based planning and community consultation. This included prioritising conservation/no-take zones in areas of high biodiversity but with relatively low historical fishing effort (37, 39). While the main objective of no-take zones is to sustain ecosystem function and biodiversity, leisure activities such as 'weekends on the water' (lifestyle vessels), sailing and paddling, and scuba diving were activities that future studies may demonstrate benefit from less fishing activity in MNPs. Over 30% of on-water activity on Moreton Bay and close-in offshore waters is non-extractive. Therefore, given the low displacement of fishers, enhancement of the experience of all MBMP users under 16% coverage of no-take zoning is feasible.

While the numbers of vessels engaged in non-extractive activity in future MNPs were too few to be analysed, the numbers of vessels engaged in all activity types in MNPs increased after rezoning. Few vessels were fishing illegally after zoning (2.6%) (37). Thus, the majority of vessels observed in no-take zones were engaged in non-extractive use. As well, a significant proportion of fishers recorded in no-take zones were located on the boundary of the no-take zones (e.g. at Lamb Island (MNP27) and Swan Bay (MNP31)), perhaps the operators considered they were fishing just outside the zone's boundary (37). The presence of vessels in no-take MNPs suggests that their operators continue to enjoy an amenity that non-extractive activities provided within these areas.

The numbers of vessels encountered post rezoning increased by about 200%, an increase not fully explained by an increase in vessel ownership and possible vessel use in the Moreton Bay

Region during the 2000s (37). Post-rezoning, roughly double the numbers of vessels were encountered during each survey day in each season, a consistent pattern (37). Four per cent more weekend days were surveyed after the MBMP was rezoned and greater numbers of vessels were encountered on weekends (37), both factors enhancing vessel encounters post implementation of the new zoning plan. However, trends in overall vessel use of MBMP require future attention.

Non-extractive users are highly discriminatory in their 'enjoyment criteria' and appreciation of particular attributes of on-water locations (31). Locations such as St Helena Island and Prices Anchorage provide anchorages for daytrippers and weekenders. Scuba diving and free diving are increasing uses of the MBMP in the eastern Bay and on the reef structures off Moreton and Stradbroke islands, especially Flinders Reef and Flat Rock. It is conceivable that the future use of MNP zones by non-extractive users will be enhanced by their no-take status, and hence their improved habitat protection and fish abundance. Scuba diving is a good example where an expected increase in fish abundance and size following no-take zoning will enhance the user experience (15, 16, 26).

The typical on-water user of MBMP was one or two people in a small vessel (≤5m) fishing at one of their preferred locations. State-wide recreational fishing surveys by the Queensland Department of Agriculture and Fisheries also found small vessels (4–5m) to be the most common size owned (43). At locations outside the Bay, the typical users were two to four people in a 5–8-m vessel fishing at a preferred location that was more adventurous to access, but still on a daytrip basis. Most overnight stays on Moreton Bay are made at anchorages within the Bay in vessels within the 8–15-m size range which feature cooking facilities and sleeping accommodation. Thus, the largest vessels operated in the marine park do not travel the greatest distances. Historical anecdotes suggest that this was not always the case. Thirty to forty years ago, large vessels provided the safety and fuel capacity requirements for offshore operation. However, particularly in the last 20 years, innovation in vessel design and the capacity of outboard motor propulsion has much increased the operational capability of mid-size vessels. New design and configuration of 5–8-m vessels (in particular 5–6-m vessels) has brought vessels with high sea-going capacity within scope for users of coastal waters, including recreational fishers.

These vessels have stronger hulls, more freeboard, self-draining decks, much-improved electronics (location, depth sounder and communication equipment), greater fuel capacity (e.g. underfloor) and more reliable outboard motors with improved power-to-weight ratios (pers. obs., 43). These vessels have enabled many recreational fishers to access locations and ocean conditions that would have been unsafe in vessels of this size range in the past. Modern-design vessels have increased the 'fishing power' of recreational fishers; fishing power being a concept of an increased ability to catch per vessel that has been well documented in commercial fisheries (44, 45). For example, in Australia's Northern Prawn Fishery, fishing power (fleet efficiency) is estimated using a range of vessel characteristics - obvious parameters such as horsepower and net configuration, but also parameters such as electronic navigation aids, skipper experience and ease-of-inter- and intra-vessel communication (45, 46). Commercial fishing power or the ability to catch has generally increased over time; and likewise over the decades, improved recreational vessel design and configuration would create a similar increase in ability to catch both by access to new fishing locations and within historical fishing grounds.

Declining catch rates augmented by improved search technology and access to new fishing grounds was documented in south east Queensland as early as the late 1800s and early 1900s (47). From the late 1800s, an offshore recreational snapper fishery was exploited by steam-powered chartered displacement vessels leaving from Brisbane. By the early 1900s, about 10-12 steamboats took groups of fare-paying recreational fishers (~8-50 anglers) offshore from Moreton and Stradbroke Islands. By the 1900s, catch rates in the snapper fishery had declined at close-in reefs and steamboat captains were forced to expand their search range for un-fished grounds. Faster vessels and experienced captains had an advantage to maintain historical catch rates (47). The best technology of the day, these relatively large, crewed charter vessels, have little in common with the owner-operated smaller, fast planing hull vessels used by recreational anglers today. But innovation in vessel design and technology continues; allowing recreational fishers to safely access waters once navigable only using large, relatively slow vessels.

During the 1970s/1980s, a typical (~ 5 m) recreational fishing vessel was a fibreglass, outboard-powered planing hull that offered fishers greater access to coastal waters compared with the wooden displacement hulls of the 1950s. It was characterised by:

- Hull configuration with an open bilge that allowed the ingress of water (perhaps with a bilge pump),
- Fuel storage in ~20 l industry-standard containers loosely positioned in the stern of the vessel,
- Relatively low freeboard, stern partially low-cut to fit the outboard motor (perhaps with an ‘outboard well’),
- A forward, seated helm position that was not optimal in poor sea conditions,
- (Electronic) navigation/communication equipment limited to a marine compass and a radio; supplemented by distress signalling equipment.

However, since the initial development of the planing hull, major improvements to vessel configuration and equipment, and hence, access to coastal waters has continued. By the 2010s, a typical (~5 m) recreational fishing vessel was characterised by:

- Hull configuration incorporating a sealed self-draining deck and underfloor bilge pump, perhaps with underfloor flotation buoyancy,
- An underfloor fuel tank (≥100 l) built into the structure of the vessel,
- High freeboard with broad gunwales continuous around the stern, outboard motor stern-mounted on an external pod or hull extension,
- A midships (or slightly astern) standing helm position that facilitates optimal operation of the vessel in poor sea conditions,
- Electronic navigation/communication equipment featuring satellite-assisted location fixing; an electronic map-display featuring the vessel’s position; a depth sounder; a marine radio (possibly two) and mobile phone; an emergency position indicating radio beacon (EPIRB); as well as the marine compass and distress signalling equipment.

Recreational vessel configuration and use of electronic technology should be documented in the same manner as has occurred for some fleets of commercial vessels to estimate recreational ‘fishing power’. Improved access to fishing grounds by a large proportion of the public must be considered when evaluating the spatial distribution and extraction pressure of historical fishing effort in respect to stock sustainability (47). However, the effect of increased access would be moderated by output-controls on fishing take, such as bag and size limits.

In Moreton Bay in 2004–06, Leon and Warnken (48) surveyed vessels at anchor from the air to estimate pollutant loads entering the Bay. They photographed vessels in popular anchorages and later analysed the photographs by standardised hull shape and estimated size. A secondary output from their data provided an estimate of patterns of vessel characteristics and vessel-based use of Moreton Bay in relation to day of the week (available leisure time) and weather conditions. Like the current study, they found greater use of Moreton Bay on weekends and when weather conditions were favourable for small vessel operation.

The daily and seasonal patterns of use that we observed match the observations of Leon and Warnken (48). From 2008–2011, vessel use was greater on the weekends than weekdays. On weekdays, the majority of potential boaters were likely engaged in paid work. Matching our observations, the researchers also found a spike in use on days associated with long weekends or over Easter or Christmas holidays. Clearly, access to leisure time and extended leisure time during national holiday periods influences boating activity (similar to the ‘leisure time availability index’ in (48)). In contrast to Leon and Warnken (48), we found that the influence of weather was confined to wind strength.

Vessel operation and safety can be compromised in strong winds (>25 knots) and uncomfortable at medium to strong wind speeds (~15–25 knots). We found fewer vessels were observed on the Bay when the wind was strong (>15 knots) and seas were rougher. During Leon and Warnken’s (48) study, wind alone was not a significant variable predicting vessel use. But their ‘boating conditions forecast index’ (a combination of predicted rainfall, wind speed and BOM weather warnings) was significant and negatively correlated with vessel numbers on Moreton Bay. Overall, they found that the availability of leisure time to vessel operators in the Moreton Bay Region to take their vessel out on MBMP was the strongest factor affecting vessel use.

Leon and Warnken (48) observed vessels in similar categories to our ‘lifestyle vessels’ and yachts as their ‘large fast’ and ‘large slow’ vessels. They found these vessels were common at anchorages on the western sides of Moreton Island and North and South Stradbroke islands. We did not survey as many anchorages as they did, but those that we did survey had a similar array of vessel types. Interestingly, Leon and Warnken (48) observed a larger proportion of vessels > 6m in their surveys than we did, but that was likely because we surveyed vessels both in and beyond anchorages. Leon and Warnken (48) observed vessels in popular anchorages only, and large vessels with onboard accommodation for an overnight stay strongly align with this particular use. Their surveys were done in the early morning or evening, likely before or after vessel operators had completed their day activities and were intent on accessing a safe anchorage for the night. Trailer-able vessels without overnight accommodation would have returned to their launch point by late afternoon or be at fishing locations early morning. Our surveys were conducted over about eight hours of each survey day when vessels were active away from anchorages or launch points.

An interesting contrast in the size of vessels using similar MNP zones is between the Flinders Reef and Flat Rock MNPs; both reef habitats are close and north of a major sand island forming the eastern boundary of Moreton Bay (Moreton and North Stradbroke islands, respectively). While 5–8-m vessels comprise a major proportion of the vessel observations at both reef MNPs, few large vessels > 10m were encountered at Flat Rock, while they were common in the vicinity of Flinders Reef. This was because large cabin vessels trolling for game fish and overnight commercial dive vessels (weekend trips) operate in the waters north of Moreton Island. North of North Stradbroke Island, trolling for game fish was less common and the dive vessels that accessed Flat Rock were often rigid inflatable vessels or daytrip dive vessels that originate from Point Lookout or Manly Harbour.

Leon and Warnken (48) used a size cut-off of 6m for their two size categories of vessels. The > 6m size category served their aim of determining vessels that likely would have anti-fouled hulls and toilet compartments and thus contribute pollutants to the Bay. We used a 5m size cut-off to describe small vs larger vessels, as many modern-designed runabouts in the 5–6m range are designed and built to innovative standards that provide much-enhanced safety capacity and voyage range. These purpose-built 5–6m 'offshore' vessels were popular for diving or fishing activity outside Moreton Bay and were common in these offshore waters as a centre-console or walk-around cabin configuration. Vessels < 5m were much less common offshore; this vessel type was often older style vessels or dinghies which are less safe and less capable of the voyage to access offshore waters.

Together with the communication of benefits to non-extractive users of no-take zones, public attitudes seem to support and appreciate including a significant percentage by area of no-take areas in the design of a marine park (19, 28, 49–51). Support for MPAs is strong despite what appeared to be a consistent media bias in favour of presenting views opposing MPAs (52). Internationally, a large majority of the general population values biodiversity and cultural benefits and favour significant levels of protection of marine habitats via management that limits extraction or other uses (30, 49, 51). Nationally, the public favour significant levels of protection for iconic marine areas such as the Great Barrier Reef (17, 19); as demonstrated through multiple-user support for ~30% bio-representative no-take zoning. In large part, broad public support was gained via comprehensive planning, consultation and implementation of the new management plan (19). Importantly, including high-value habitats within no-take management zones (such as those that previously sustained high rates of extraction), may greatly enhance biodiversity objectives (53, 54), while also enhancing the experience of non-extractive users such as scuba divers (12, 16, 26). Moreover, increasing evidence suggests that extractive users, such as commercial fishers, may benefit from zoning MPAs as they supply fish stocks to adjacent habitats that can be fished (5). Yet these contentions remain challenged by the commercial fishing sector that spoke out against the rezoning of the MBMP (34), and the displacement of commercial fishing effort has been contentious whenever a zoning plan for MPAs in the Australian Exclusive Economic Zone has been proposed (52).

Increasingly, greater areas of coastal and marine seabed are being included in MPAs (53, 55). After considerable debate about no-take zone boundaries, a series of Commonwealth MPAs were enacted around the Australian coastline on 1 July 2018. The MPAs cover close-shore and offshore habitats, including sections of the continental shelf and pelagic waters, ranging from <5% to about 40% MPA protection over the 38 Integrated Marine and Coastal Regionalisation of Australia provinces (53). Since the original 2012 enactment on the federal marine park legislation, the boundaries of the no-take MPAs have been reviewed and rezoned to allow extractive activity over a greater extent of the Marine Park. One large MPA has been implemented in the Coral Sea, though it is a pelagic ecosystem that is being protected from extractive activity and not a series of coastal habitats like the MBMP. Although the extent of no-take zoning has been increased to 16% in the MBMP, it remains low relative to the GBRMP where 33% of the parks' area sits within no-take zones (53). However, the extent of no-take zoning is relatively high for a coastal, high-use large embayment so close to a major city. The enactment of the MBMP acts as a useful example for similar regions.

While extractive activity is the most common use of the MBMP, non-extractive use is also a major component. No-take zones enhance the on-water experience and the willingness of non-extractive users to pay (12, 16). In addition, the non-market value to the recreational fishing sector using Moreton Bay has likely increased by $1.3 million per year due to rezoning (8). Adding new artificial reefs and enhancing the then-existing artificial reefs (36) also improved the fishing experience for extractive users. On balance, the increase in no-take zones in the marine park from 0.5 to 16% may benefit the universal use of the MBMP and the local economy. Both extractive users (mostly fishers and aquarium collectors) and non-extractive users (such as scuba divers, whale watchers, yachties and the operators of leisure vessels) have access to locations of high-benefit to each group. However, some sectors such as commercial fishers have lost access to a natural resource, and total income across the commercial fishing sector has declined (34, 35).

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Appendices

Maps of Moreton Bay and catchment

E. Electronic Appendix* is accessible from https://moretonbayfoundation.org/books-and-research-papers.

Index

Moreton Bay *Quandamooka* & Catchment: *Past, present, and future* is an eBook available on https://moretonbayfoundation.org/books-and-research-papers. There it can be readily searched for authors, topics or any other information.

*The electronic appendix is associated with Saeck *et al*., Water quality in Moreton Bay and its major estuaries: Change over two decades (220-2018), Chapter 4.

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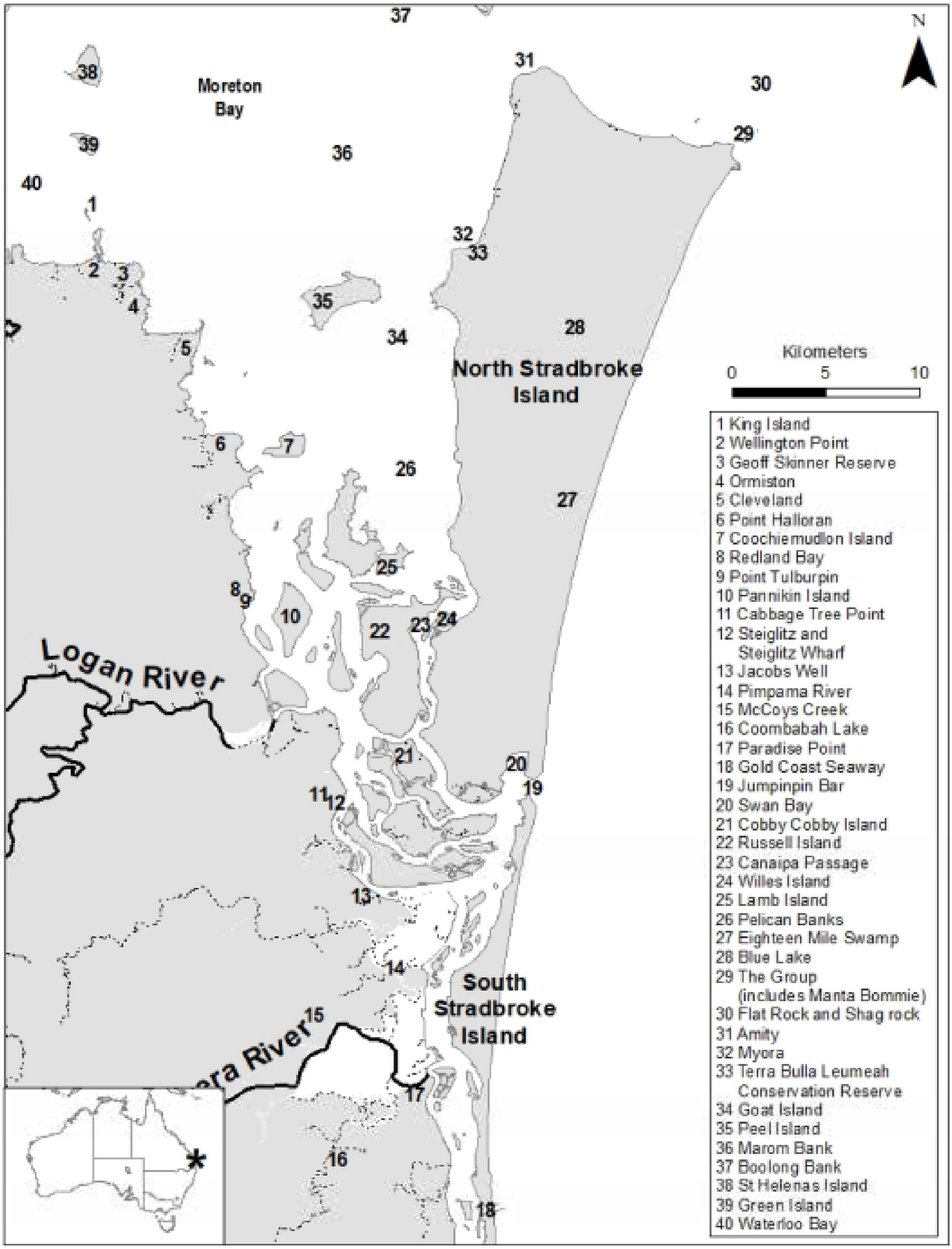
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10 Pannikin Island
11 Cabbage Tree Point
12 Steiglitz and Steiglitz Wharf
13 Jacobs Well
14 Pimpama River
15 McCoys Creek
16 Coombabah Lake
17 Paradise Point
18 Gold Coast Seaway
19 Jumpinpin Bar
20 Swan Bay
21 Cobby Cobby Island
22 Russell Island
23 Canaipa Passage
24 Willes Island
25 Lamb Island
26 Pelican Banks
27 Eighteen Mile Swamp
28 Blue Lake
29 The Group (includes Manta Bommie)
30 Flat Rock and Shag rock
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40 Waterloo Bay

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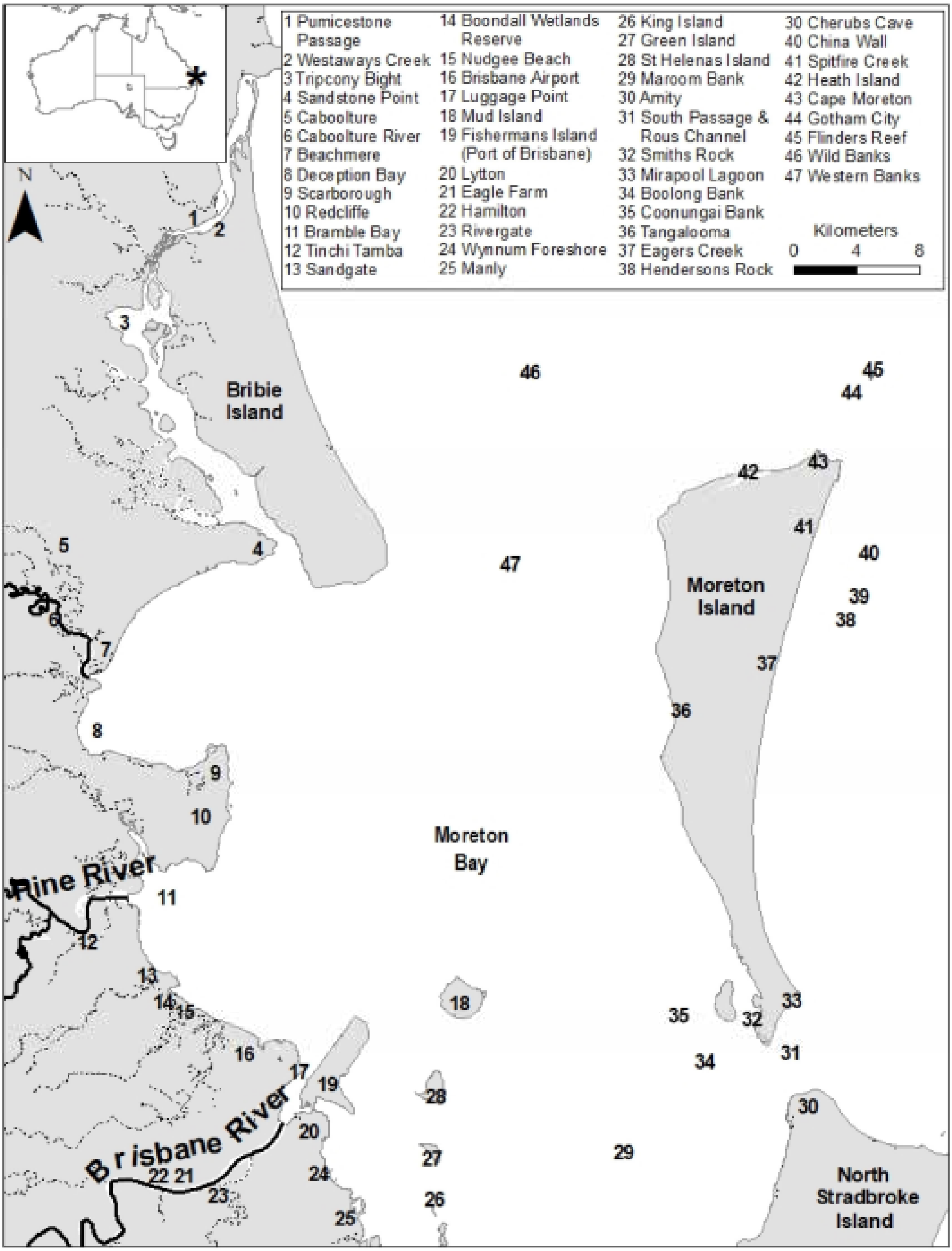
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12 Tinchi Tamba
13 Sandgate
14 Boondall Wetlands Reserve
15 Nudgee Beach
16 Brisbane Airport
17 Luggage Point
18 Mud Island
19 Fishermans Island (Port of Brisbane)
20 Lytton
21 Eagle Farm
22 Hamilton
23 Rivergate
24 Wynnum Foreshore
25 Manly
26 King Island
27 Green Island
28 St Helenas Island
29 Maroom Bank
30 Amity
31 South Passage & Rous Channel
32 Smiths Rock
33 Mirapool Lagoon
34 Boolong Bank
35 Coonungai Bank
36 Tangalooma
37 Eagers Creek
38 Hendersons Rock
30 Cherubs Cave
40 China Wall
41 Spitfire Creek
42 Heath Island
43 Cape Moreton
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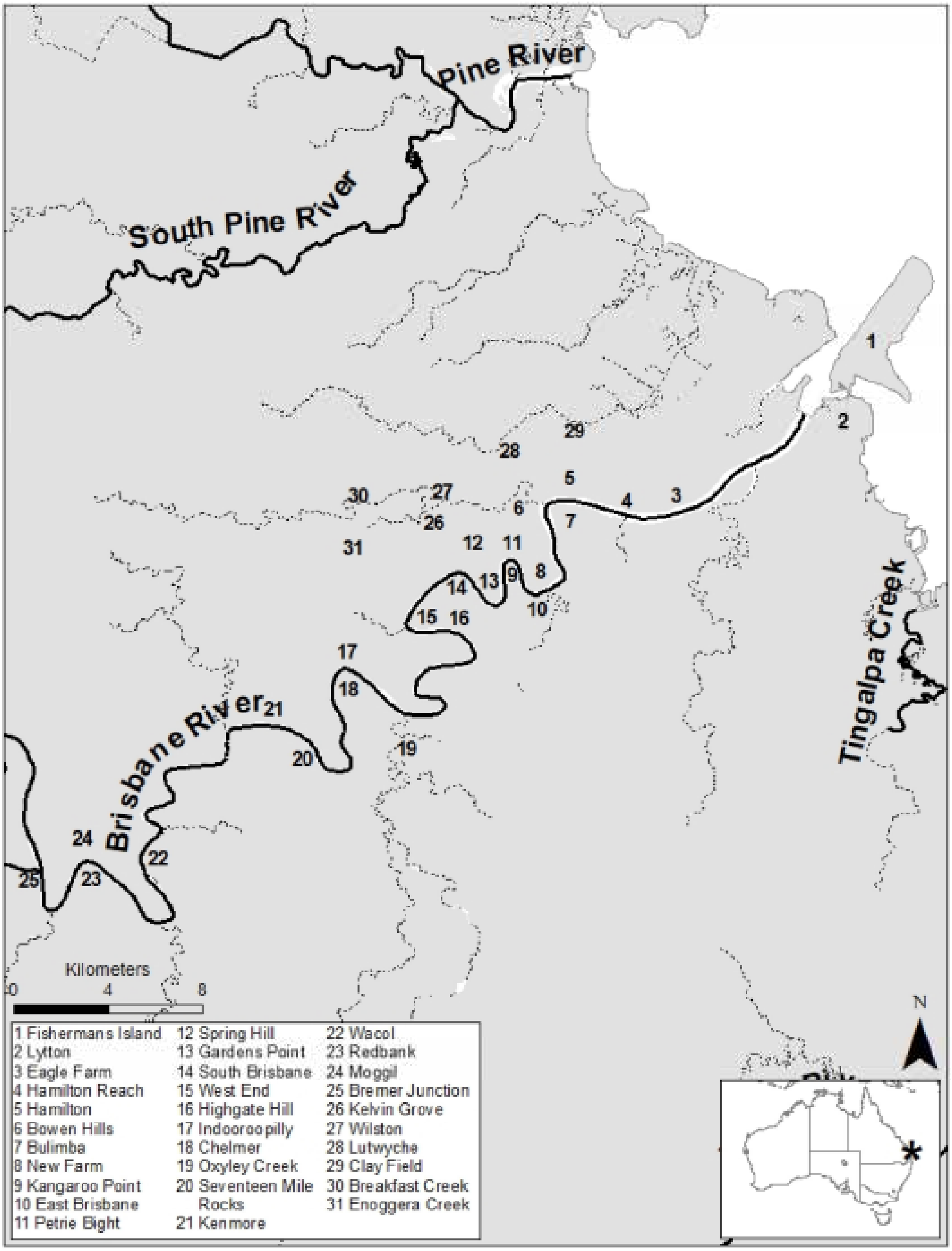
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6 Bowen Hills
7 Bulimba
8 New Farm
9 Kangaroo Point
10 East Brisbane
11 Petrie Bight
12 Spring Hill
13 Gardens Point
14 South Brisbane
15 West End
16 Highgate Hill
17 Indooroopilly
18 Chelmer
19 Oxyley Creek
20 Seventeen Mile Rocks
21 Kenmore
22 Wacol
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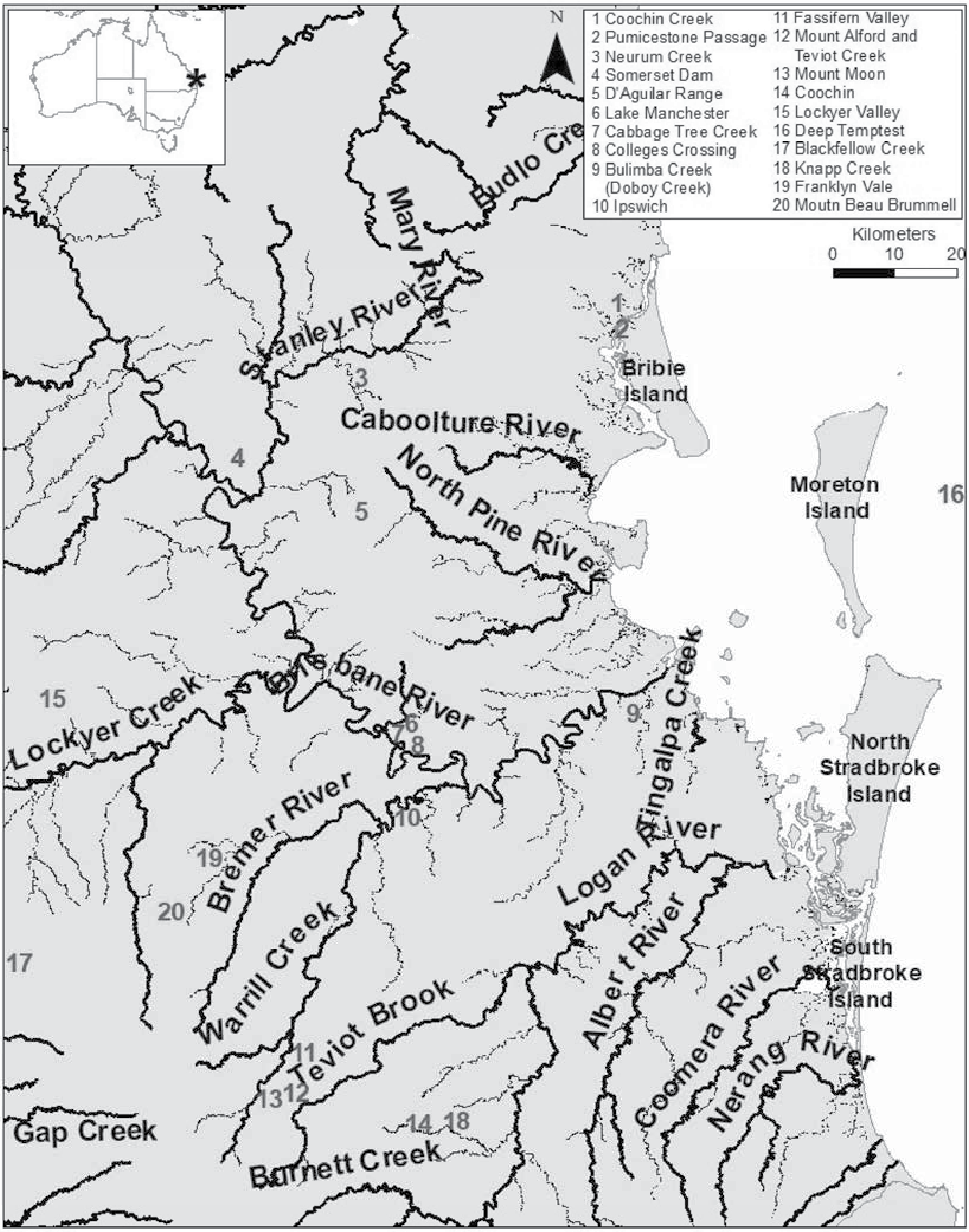
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6 Lake Manchester
7 Cabbage Tree Creek
8 Colleges Crossing
9 Bulimba Creek (Doboy Creek)
10 Ipswich
11 Fassifern Valley
12 Mount Alford and Teviot Creek
13 Mount Moon
14 Coochin
15 Lockyer Valley
16 Deep Temptest
17 Blackfellow Creek
18 Knapp Creek
19 Franklyn Vale
20 Moutn Beau Brummell
N
Kilometers
0 10 20
Mary River
Stanley River
Caboolture River
North Pine River
Bribie Island
Moreton Island
North Stradbroke Island
South Stradbroke Island
Lockyer Creek
Brisbane River
Tingalpa Creek
Bremer River
Logan River
Albert River
Warrill Creek
Teviot Brook
Coomera River
Nerang River
Gap Creek
Burnett Creek

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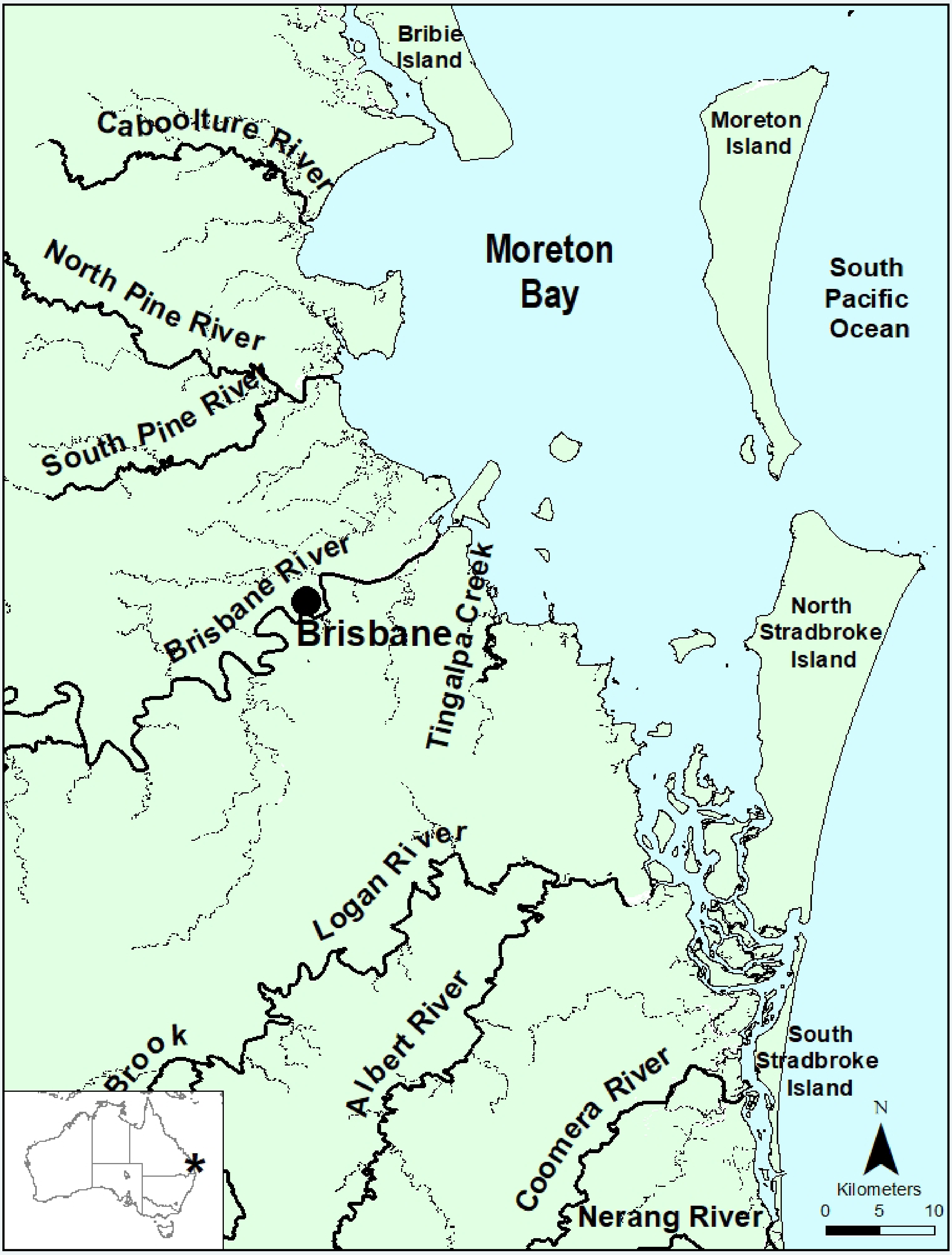
Bribie
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North Pine River
South Pine River
Brisbane River
Brisbane
Tingalpa Creek
North
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Island
Logan River
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The Moreton Bay Foundation, editors and authors acknowledge the Traditional Owners of Country in and around Moreton Bay, and their continuing connection to land, sea and community. We pay respect to them and their cultures, and to Elders past, present and emerging.

Twenty years on from the first Moreton Bay and Catchment book this peer-reviewed publication provides an authoritative update on the health of the waterways of South East Queensland. It details the history of the Bay and its catchment, present usage, climate change impacts, citizen science, community values, information on water quality, fauna and flora as well as the important roles of Traditional Owners in managing their Land and Sea Country. The connections forged through the 2016 Forum, the development of this book, and the recent establishment of The Moreton Bay Foundation, give cause for optimism for a brighter, more sustainable future for Moreton Bay *Quandamooka*.

Hopefully, this is the first of many publications by The Moreton Bay Foundation. We see this as a valuable resource for scientists, managers, policy makers, teachers, students, conservation and community groups, and other Moreton Bay users.

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