Marine Policy 152 (2023) 105595

Contents lists available at ScienceDirect

Marine Policy

journal homepage: www.elsevier.com/locate/marpol

Identifying social thresholds and measuring social achievement in social-ecological systems: A cross-regional comparison of fisheries in the United States

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A R T I C L E I N F O

Keywords:
Thresholds
Social regimes
Social indicators
Social-ecological systems
Fisheries

A B S T R A C T

In marine social-ecological systems (SESs), environmental and human-induced stressors can push ecosystems from a high-functioning state into a new, often undesirable state (i.e., regime shift) with limited delivery of ecological goods and services (e.g., high to low fisheries production). While ecological regime shifts are well studied, social regime shifts within SESs are underexplored. Socioeconomic indicators were used to identify thresholds and trends in fisheries and coastal employment for six marine SESs around the U.S. These study sites represent coastal regions delineated by the National Oceanic and Atmospheric Administration for which periodic monitoring and data collection occur. We first used Generalized Additive Modeling to identify periods of change, then linked them to potential regional and national drivers. Social outcomes were ranked using composite social and environmental indices for each region, constructed using Data Envelopment Analysis. Technological innovation and national regulatory changes (e.g., Magnuson Stevens Act) co-occurred with detected nationwide shifts in fisheries productivity, while engagement in specific fisheries determined local regional shifts. Our study demonstrates the effectiveness of the complementary threshold analysis and outcome ranking methods in identifying regimes and assessing performance. Together, they provide management information and insight into possibilities for preventing unfavorable shifts and to assess society's ability to adapt to those shifts.

1. Introduction

Human communities benefit from coastal ecosystem goods and services (EGS; e.g., fishing revenue, ocean recreation), endure risks from natural hazards, and alter ecological systems through stewardship and resource use [1–4]. To ensure sustained benefits from EGS, standardized methods are needed to evaluate resource-dependent human well-being (i.e., the collective achievement of various social objectives). Social indicators can measure such achievement and signal when thresholds are crossed into undesirable regimes. Ecological regime shifts are well-studied, while social regime shifts are underexplored, particularly in terms of quantitative assessments. Few studies analytically describe social regimes or directly address regime shifts in the context of ecosystem service provision [5]. Describing distinct social regimes,

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https://doi.org/10.1016/j.marpol.2023.105595
Received 18 October 2022; Received in revised form 28 February 2023; Accepted 24 March 2023
Available online 3 April 2023

along with their regulatory and environmental drivers, will help identify management actions that can encourage desirable regimes or avoid undesirable regimes. Methods that identify possible thresholds points in historical time series can help resource managers understand system dynamics and possible drivers of change. This understanding, coupled with assessment of which regimes are favorable, can help design management actions to sustain EGS delivery and prevent undesirable regime shifts.

Although periodic monitoring and assessment efforts that produce time series data have conventionally focused on ecological aspects of social-ecological systems (SESs), new approaches to monitoring social and economic system performance are emerging, such as ecosystem-based fisheries management (EBFM) [6]. EBFM is an integrative marine ecosystems conservation paradigm that has the goal of sustaining natural resources for human use [7]. NOAA Fisheries' integrated ecosystem assessment (IEA) [8] program supports EBFM by conducting research across all coastal SESs of the United States [9]. IEAs have historically focused on ecological objectives; our study aims to expand the social aspects of IEAs by quantitatively assessing social indicators (e.g., fisheries revenue, food provisioning) [10]. Thus, our research is guided by the following questions: (i) have social regime shifts (i.e., threshold crossings) occurred in marine SESs across the United States and are they consistent across regions, (ii) what types of regulatory actions or ecological changes precede or co-occur with identified trends and thresholds, and (iii) to what extent can existing socioeconomic datasets be used to assess these regime shifts? We use the expansive geographical scope of the national IEA program (Fig. 1) and its comprehensive datasets to address these questions, assessing human well-being through a fisheries lens and comparing regional outcomes.

1.1. Social indicators, thresholds, and outcomes

A suite of indicators can be used to quantify collective social state within a given SES [11]. Social indicators can be used to evaluate local conditions and help ensure accountability of management agencies by measuring progress towards social (including economic) goals. Additionally, incorporating social indicators into management evaluation allows decision-makers to adopt dynamic strategies as social conditions change. In SESs, resource users may have the capacity to induce undesirable shifts through overuse or desirable shifts through proper management and stewardship. Social indicators can signal social tipping points (i.e., threshold values that separate distinct social regimes) [11]. Social regimes can be defined by their achievement of social objectives. For example, in fisheries-based SESs, distinct social regimes may be characterized by high vs. low fishing catch, revenue, employment, food provisioning, recreation, etc. Such indicators can be monitored through standardized methods, allowing analyses and comparisons across different geographical regions. Alternative social regimes are separated by a threshold, which can be detected in time series data by various analytical methods [18].

A threshold is a region in a non-linear relationship where the value of a response variable changes rapidly as a result of a small change in a pressure variable [18]. A regime shift occurs when perturbations push a system past a threshold into a new state (i.e., regime) with different, often less desirable, essential functions and attributes (e.g., coral-macroalgal phase shifts) [19–21]. The ease with which thresholds can be identified and anticipated is dependent on the functional form of a driver-response relationship; thus, a flexible method that supports multiple functional forms would be useful [22]. While quantified ecological shifts are well-documented [12–15], studies on social regime shifts are often qualitative or do not cover a wide range of social objectives [16,17]. A multi-criteria ranking method can combine a suite of indicators to determine which outcomes represent higher achievement of various social objectives. For example, Weijerman et al. identified five important human well-being domains: Economic, Social Relations, Health, Culture & Spirituality, and Safety & Security [26]. Combining indicators from all domains gives a well-rounded representation of social achievement as a whole. In the study of SESs, there has been a lack of multi-criteria ranking methods to measure overall social system success via differential achievement of multiple objectives [27]. By assessing social thresholds and ranking social outcomes, the methodology used in this study can provide managers with valuable information to address and possibly prevent undesirable social shifts.

2. Methods

To explore social regime shifts in various systems, a cross-regional study was conducted involving all coastal regions across the United States, represented as six regions monitored by the Integrated Ecosystem Assessment (IEA) program: Alaska, California Current, Northeast (North Atlantic), Southeast (South Atlantic), Gulf of Mexico, and Hawai'i (Fig. 1). In the Hawaiian Islands, the IEA program only covers the west coast of Hawai'i Island, but the datasets assessed in our study cover all of the main Hawaiian Islands and include fishing and employment statistics relevant to fisheries across the entire island chain. This research synthesizes time series data from national monitoring programs to detect thresholds between distinct social regimes and assess changes in the achievement of social objectives over time. We explored different methods to identify thresholds and rank social outcomes that can be used in SES management for describing the causes and effects of social regime shifts across systems.

A methodological review across multiple disciplines was first conducted to identify analytical methods for threshold analysis and multi-criteria ranking of social outcomes. We further explored methods that: (1) had frequent references in the literature base and repeated successful applications, (2) were time and cost-efficient, and 3) could be flexibly applied across datasets. This exploration led to the selection of Generalized Additive Modeling (GAM) to identify thresholds and Data Envelopment Analysis (DEA) to rank multi-objective social outcomes. GAM is a flexible method for modeling non-linear relationships that can fit multiple forms of relationships and is robust to unequally spaced data [23]. Additionally, GAM can be used to identify trends and thresholds and is suitable for modeling pre-existing social data due to its flexibility. DEA is a data-driven method that can computationally determine objective weightings using historical system performance contained within the data themselves [28].

2.1. Indicators and data sources

To ensure the results will be comparable across regions, this study used publicly available annual datasets of socioeconomic indicators that supply consistent data types across all IEA regions (Table 1). Fisheries data were species disaggregated and cover both commercial (1950–2019) and recreational sectors (1981–2019).[1] Employment data cover individuals employed by businesses (2001–2019) as well as self-employed individuals (1997–2018). The environmental data were satellite chlorophyll-a data calculated from radiance measurements obtained from the SeaWiFS and MODIS-Aqua satellite sensors (https://oceancolor.gsfc.nasa.gov/). Chlorophyll-a is a significant indicator of environmental productivity in large marine ecosystems and thus a good predictor of fisheries yield [32,33]. Mean annual chlorophyll-a concentrations covered 1998–2017 and represent composites of 50-km^2 boxes within the specified area of each IEA region (Fig. 1). For analyses of individual indicators, all available data were used to inspect trends and thresholds over time. For direct comparisons and the construction of

[1] Commercial catches used in this study only cover vessels with U.S. ownership which only represented a proportion of total fishing effort and catches in the pre-1976 period, particularly in Alaska. Americanization of the Alaska groundfish fleet is the primary driver of increased fisheries catches in Alaska by U.S. owned vessels during the 1980 s, as reported in Fig. 2.

Fig. 1. Geographic representation of the six study regions, which reflect IEA regions. Areas are delineated to encompass marine and coastal areas relevant to the datasets assessed in this study, including fishing grounds.

composite indices, only data from the time period during which all datasets overlap were used.

2.2. Threshold analyses: generalized additive modeling (GAM)

2.2.1. GAM analysis

GAMs are non-parametric models that use smoothers to represent multiple, smaller functions within a non-linear relationship and do not require prior identification of the form (quadratic, polynomial, etc.) of the relationship [24]. To detect trends and thresholds that have been crossed over time, GAMs were fit with socioeconomic indicators from the national datasets (i.e. commercial catch and revenue, recreational catch and angler trips, and fishing and seafood industry employment) as response variables and time as the smoothed predictor. The package 'mgcv' (v1.8.40) [34] in R (v4.0.2) [35] was used to fit the GAM models with the formula:

$$Y = \alpha + S(X) + \varepsilon,$$

where Y is the social indicator, α is a constant, X is time, S() is the smoothing function, and ε is an error term which is calculated based on the Bayesian posterior covariance matrix. The restricted maximum likelihood (REML) criterion was used in smoothing parameter estimation because it is resistant to overfitting, has lower smoothing parameter variability, and is less prone to local minima, compared to other criteria [36]. Thin plate regression spline smoothers, which are a reduced rank version of thin plate splines and do not use 'knots', enabled bypassing knot placement issues [37]. A truncated eigen-decomposition is used to achieve rank reduction which reduces the number of basis expansions, allowing for direct fitting of GAMs. Models fully converged and model fit was checked with estimated degrees of freedom (edf) and residual plots.

2.2.2. Identifying periods of change with GAMs

To identify periods of change and significant thresholds in each model, first and second derivative functions were estimated using the package 'gratia' (v0.7.2) [38] in R. An increasing trend in a driver-response relationship occurs when the first derivative is positive, and a decreasing trend occurs when the first derivative is negative. Thresholds in these non-linear relationships occur when a smoother's trajectory changes significantly, indicated by the second derivative changing sign. Derivatives, the instantaneous rate of change (slope) of the fitted GAM, were calculated using finite differences for each of 10, 000 draws from the posterior distribution of the model [39]. Each draw represents a fitted spline that accounts for model uncertainty. Simultaneous (confidence) intervals (SI) were calculated for the derivative functions which entirely contain about 95 % of these posterior draws. A significant trend or threshold was identified when the first or second derivative function, respectively, crossed zero [23]. A derivative function's SI may cross zero at a region instead of a distinct point, and the most probable point for a threshold occurs where the SI is the furthest away from zero. By calculating the first and second derivatives of GAMs, this analysis can identify significant social trends over time, as well as thresholds between distinct regimes [23,25]. Pinpointing these periods of change and linking them to concurrent regulatory and ecological changes allows us to explore potential causal relationships by linking observations to concurrent regulatory and ecological changes.

2.2.3. Monte Carlo simulations of recreational data

The Marine Recreational Information Program (MRIP) underwent a change in survey design in 2018 for recreational fisheries in the Northeast, Southeast, Gulf, and Hawai'i (see: https://www.fisheries.noaa.gov/recreational-fishing-data/transitioning-new-recreational-fishing-survey-designs). To account for any error introduced by this change, Monte Carlo simulations were run using percent standard errors (PSE) provided with the MRIP dataset. Missing PSE values for Alaska and recent years in California Current were extrapolated using linear regressions between PSE and recreational catch as well as effort. Monte Carlo methods are commonly used to incorporate error in a given statistic by observing its behavior through repeated simulation models that sample data drawn from the true population [40]. For both recreational catch and effort data, 1000 GAM runs were simulated using random draws at each time point from a normal distribution generated with the observed value and error provided. Trends and thresholds were identified in each simulation by calculating first and second derivative functions. The summary GAM function used in the results represents the mean of 1000 simulations, and trends and thresholds at a given time point were considered significant only when they were present in the majority of simulations (> 65 %).

Table 1
Sources and descriptions of socioeconomic indicators used in GAM and DEA analyses.

Socioeconomic indicator group	Source	Indicator	Definition and units of measurement
Commercial Fishing	NOAA Fisheries; https://foss.nmfs.noaa.gov/apexfoss/f?p=215:200:6724777967495::NO:::	Commercial Catch	Millions of pounds landed
		Commercial Revenue	Millions of dollars in revenue from catch sold, deflated using US Bureau of Economic Analysis implicit price deflator (https://fred.stlouisfed.org/data/GDPDEF.txt)
		Catch Diversity	Shannon Diversity Index: calculated from the commercial catch data
		Revenue Diversity	Shannon Diversity Index: calculated from the commercial revenue data
Recreational Fishing	NOAA FIsheries and Partners, accessed through the Marine Recreational Information Program; https://www.fisheries.noaa.gov/data-tools/recreational-fisheries-statistics-queries)	Recreational Catch	Millions of pounds landed
		Recreational Effort	Millions of angler trips
Marine Resource-Related Employment	US Bureau of Labor Statistics; https://data.bls.gov/cgi-bin/dsrv?en	Employment	Total number of individuals employed by establishments in four marine resource-related sectors (Fishing, Seafood Markets, Seafood Packaging, Seafood Wholesale)
		Earnings	Total wages paid to employees of establishments in the four marine resource-related sectors
		Establishments	Number of establishments in the four marine resource-related sectors
	US Census Bureau, Nonemployer Statistics; https://www.census.gov/programs-surveys/nonemployer-statistics/data/datasets.html	Self-Employment	Number of self-employed individuals in three marine resource-related sectors (Fishing, Seafood Markets, Seafood Packaging) as well as a combined total
		Earnings (Self-Employed)	Millions of dollars in total receipts from self-employed individuals in the three sectors listed above

2.3. Multi-criteria outcome ranking

To fill the gap for multi-criteria ranking of social outcomes outlined in Section 1.1, we constructed a standardized index to represent integrated achievement of social objectives. DEA is a data-driven method derived from the Operations Research field that is used to estimate production frontiers and can be used to measure productive efficiency. Ranking social outcomes with multiple objectives requires weighting of objectives. However, even with expert elicitation, assigning weights to different objectives can be precarious due to implicit value judgements. DEA bypasses the issue of subjective weighting, allowing the construction of a composite index of social achievement and environmental achievement as outlined in Färe and Grosskopf [29–31].

In order to rank social outcomes based on the national datasets, we calculated an 'ecological input' index and a 'social output' index, then combined the two to arrive at the final 'social-ecological index.' The social output index compares the maximal outputs that can be produced in two time periods using a reference set of environmental conditions. The outputs to build the social index were commercial catch, commercial revenue, recreational landings, recreational trips per million of population, and total marine resource-related employment per million of population from both U.S. Census Bureau's Nonemployer Statistics (NES) and U.S. Bureau of Labor Statistics' employment data (BLS). The ecological input index compares the minimal environmental conditions needed between two time periods to produce a given level of output. The input for the ecological index was chlorophyll-a concentration. The final index value was calculated as the ratio of the first index to the second and effectively represents productivity. All observations were normalized to regional means, and benchmarked to a reference observation, which was Alaska in 2003. Change in index values over time represents relative change within a region, with values greater than one representing improvement and values less than one depicting regression.

Output- and input-oriented distance functions were used to calculate our indices [41]. Given a set of inputs, the social output index was calculated by measuring the possible radial expansion (i.e., distance) for a set of outputs to a theoretical efficient production frontier, which represents the optimal yield of outputs based on the given inputs (i.e., maximum efficiency). Similarly, the ecological input index was calculated by measuring the possible radial contraction to the frontier for a set of inputs, given a fixed set of outputs. In the input-oriented model, the efficient frontier represents the minimum inputs necessary to produce a given level of output. For the output distance function, values equal to one indicate that no output expansion is possible and the observation is considered efficient, while values less than one indicate that outputs can be expanded further. Similarly, for an input distance function, values of one indicate that no input contraction is possible, while values less than one mean inputs can be reduced further [42]. Mathematically, the indices are constructed as follows, and are based on Färe and Grosskopf [31]. The social output index is constructed as the ratio of output distance functions from periods k and l, utilizing a reference environmental vector z^0 and observed output y:

$$Q_y(y^k, z^0, y^l, z^0) = \frac{D_o(y^k, z^0)}{D_o(y^l, z^0)} \tag{1}$$

The ecological input index is defined as the ratio of input distance functions from periods k and l, using a reference level of output and observed environmental vector z:

$$Q_z(y^0, z^k, y^0, z^l) = \frac{D_I(y^0, z^k)}{D_I(y^0, z^l)} \tag{2}$$

The final social-ecological index is the ratio of the two indices shown above:

$$QE^{k,l}(y^k, z^k, y^l, z^l) = \frac{Q_y(y^k, z^0, y^l, z^0)}{Q_z(y^0, z^k, y^0, z^l)} \tag{3}$$

Our indices are constructed using Data Envelopment Analysis (DEA), a nonparametric method which uses linear programming techniques to calculate the distance functions. In our calculations, we set the value for y^l and z^l equal to the reference year. The DEA programs used to calculate these distance functions are shown in Appendix 1.

The social-ecological index represents productivity in the social-ecological system as social output per unit of ecological input. With constant inputs, a change in outputs would result in a proportional change in the productivity index. If the input and output indices increase or decrease by the same amount, the productivity index would remain constant. Using all three indices together can help identify changes in overall system performance and whether the cause was social or

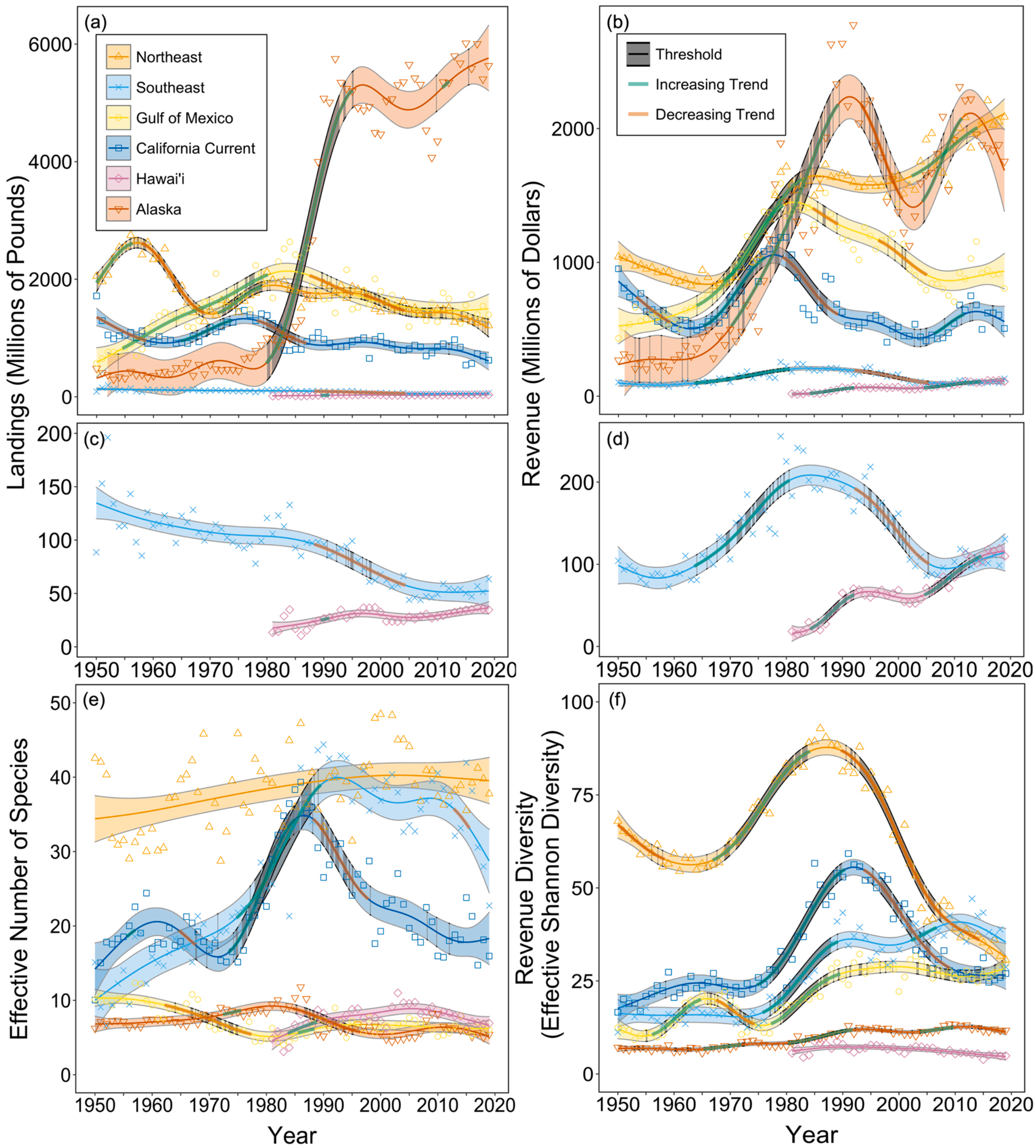

Fig. 2. Generalized additive model (GAM) functions (± 95 % CI) representing cross-regional comparisons of commercial fisheries (a) landings, (b) revenue, (c,d) close-ups of (a) and (b), (e) catch diversity, and (f) revenue diversity. Points represent raw data. Significant increases (green) and decreases (red) calculated from first derivative functions are highlighted in bold. Thresholds are shaded in gray with black outlines.

environmental. This study demonstrates the utility of these indices through a regional comparison using time series data collected from national programs, but this methodology can be flexibly adapted to different combinations of indicators to answer different research or management questions.

2.4. Integrated interpretation: GAM and DEA

Taken together, the approach outlined above allowed an integrated assessment of performance with respect to social objectives across social regimes. The GAM identified if and when regime shifts occurred historically in the provision of benefits derived from the marine system. The DEA analysis ranked system outcomes in terms of outputs and environmental conditions compared to a reference year. Following both analyses, we worked with NMFS collaborators from each region and reviewed regional literature to link social regime shifts to management or ecological changes unique to each region. Coauthors include representatives from each region who helped interpret the trends, thresholds, and system outcomes for each region and identify relevant management and ecological changes as well as key literature discussing those changes. This work represents the initial effort to apply the outlined analytical methods to a small suite of generic indicators and demonstrates how standardized indicators can aid in applying these analyses across different geographic regions.

3. Results and discussion

3.1. Thresholds and trends

3.1.1. Commercial fishing

The regimes identified by our analyses align with fishery management periods that have been qualitatively described in prior work (i.e., pre-Magnuson-Stevens, Americanization/expansion, contraction), and also include a recent period of fishery growth [43]. Results are presented and discussed by these management periods to highlight consistencies across multiple regions in trends and thresholds identified by our methodology. Trends and thresholds are presented graphically and model *p*-values and deviances are shown in Appendices 2 and 3, respectively. Catch and revenue from commercial fishing followed similar trends, with revenue undergoing larger fluctuations (Fig. 2a, b). Trends and thresholds were identified by calculating the first and second derivative functions, respectively; therefore, a significant trend represents a steep slope in the data, while a threshold represents a rapid change in slope. Thus, thresholds are always accompanied by significant trends, while trends are not always accompanied by thresholds. All regions demonstrated significant revenue increases in the 1970s. These increases were accompanied by thresholds, indicating a nationwide regime shift in commercial fishing. The regime shift observed in the data is likely explained by major societal changes. In the early era, from 1950 to 1975, fisheries rapidly expanded to feed demand from a rapidly growing global population, facilitated by improving technologies, such as better refrigeration, and more effective fishing gear and instruments to detect fish aggregations [44]. Double rig trawls facilitated shrimp fisheries in the Southeast and Gulf of Mexico, enlarged pelagic trawls extracted pollock in Alaska and redfish in the Northeast, and purse seines and gillnets efficiently harvested menhaden in the Atlantic and Gulf, as well as tuna and salmon in the Pacific. In the Gulf and California Current, increasing production coincided with lower diversity, suggesting specialization toward higher volumes of commercially important, high demand species (Fig. 2c–e).

As innovations led to enhanced fishing capacity and rapid harvesting of fish stocks, the need for sustainable fisheries management grew. The Magnuson-Stevens Fishery Conservation and Management Act (MSA) was implemented in 1976 and is now the primary law that governs modern fisheries [45]. In the following years, Alaska and Hawaiʻi exhibited a regime shift to higher fisheries production that hinged on a few target species. This expansion occurred after the MSA created exclusive economic zones (EEZs) that pushed foreign fleets 200 miles offshore, opening up domestic fishing opportunities for U.S. flagged vessels. This era is often referred to as the Americanization of many pelagic fisheries that were previously dominated by foreign fleets [43, 46]. In Hawaiʻi, data collection began after MSA implementation, and there was a revenue increase and threshold in the mid-80s to early-90s. Catch displayed the same trend, with a shorter region of significant increase. Government subsidies for new gear, fuel rebates, etc. also facilitated the Americanization of fisheries [43,47]. Increasing catch diversity accompanied the increasing revenue, suggesting that new opportunities allowed local fishers to diversify catch to more valuable species, particularly bigeye tuna and swordfish in the pelagic longline fishery [48,49]. Modern longline vessels that use a single monofilament mainline were introduced to Hawaiʻi in 1985 and greatly improved fishery efficiency [50]. In Alaska, the passage of the MSA allowed for the transition of a foreign-flagged fleet for groundfish to a new domestic fleet (primarily targeting walleye pollock and pacific cod), likely explaining the significant revenue increase that extended into the 1990s [51,52]. Catch diversity simultaneously decreased, which is consistent with specialization. The creation of EEZs augmented fishery harvests in Alaska and Hawaiʻi more so than other regions, likely due to proportionally larger coastlines and proximity to foreign nations that historically fished in their coastal waters [51,53].

After MSA implementation and the subsequent reauthorization in 1996, regions in the contiguous U.S. exhibited declines in fishery production, in part due to stricter fishery conservation, as well as declining stocks. In the California Current, Southeast, and Gulf of Mexico, regime shifts occurred that were characterized by diminished landings and revenue with increased catch diversity and revenue diversity. This juxtaposition between production and diversity likely demonstrates compensatory diversification to alternative stocks. In the California Current, the shift was largely driven by limited entry and licensing requirements in the salmon fishery [54]. In the Gulf and Southeast, the declines were partially driven by structural changes in the high volume menhaden fishery, which was explored in a separate analysis discussed at the end of Section 3.1.1 (Fig. 3) [55]. Additionally, many stocks declined in these regions due to overharvesting, as strict rebuilding plans were not implemented until the 1996 reauthorization of the MSA (i.e., Sustainable Fisheries Act) and harvests were not strictly limited by scientific catch recommendations until the 2006 reauthorization [56–58]. The Gulf and Southeast shifts were also driven by increased gear restrictions on the shrimp trawl fishery due to high incidences of bycatch [59,60]. The Gulf red snapper, a valuable commercial and recreational species, drove shrimp trawl fishery regulations, represented the first successful rebuilding plan, and the stock was declared not overfished in 2018 [61–63]. Although fishery restrictions and consolidation throughout different regions led to decreased fishery production, stock conditions eventually improved and revenues in these regions have either stabilized or increased in recent years. These outcomes suggest that specific rebuilding plans involving limited entry, gear restrictions, and catch limits have led to fishing practices that are better poised to sustain long-term fisheries profitability.

The mid-2000s marked another period of growth for commercial fisheries. In Alaska, pollock and salmon drove the fluctuations in catch and revenue and remain the most influential fisheries in the region. The preceding revenue decrease in the 1990s can be attributed to a decrease in salmon value despite consistent harvests, as well as a temporary pollock stock decrease [64,65]. In 1998, the American Fisheries Act precipitated efficient fishing practices that improved product quality, increasing revenues in Alaska without overharvesting [46]. In the California Current, the recent uptick in revenue was preceded by a revenue diversity decline, suggesting specialization to more valuable species. The uptick was due to increased revenues in the Dungeness crab fishery, and to a lesser extent, increased groundfish revenue. The West Coast Groundfish Trawl Buyback Program removed 93 vessels from the groundfish fleet, resulting in a smaller, more technically efficient fleet with better pricing power [66,67]. With reasonably good stock conditions and a strong export market, Pacific whiting and sablefish were important contributors to the revenue increase [68]. In the Northeast, revenue increased as landings and revenue diversity decreased, signaling a boom in the lucrative lobster and sea scallop fisheries that buffered decreases from a declining groundfish fishery [69–71]. Lastly, the revenue increase in the 2000s in Hawaiʻi can be attributed to increased harvest and value of bigeye and yellowfin tuna, likely driven by a favorable market for raw tuna [72]. Tourism in Hawaiʻi also spiked following the global recession from 2007 to 2009, likely contributing to increased demand for and value of fresh fish [73,74]. This trend plateaued in recent years, likely due to a phased reduction in bigeye tuna catch limits from 2015 to 2017 set by the Western and Central Pacific Fisheries Commission [75]. During these years, annual closures of the longline fishery occurred within the final months of each year once the catch limit was met [72].

In an analysis of commercial fishing with and without menhaden (Fig. 3), our results suggest that high volume species may mask important nuances in regional SES regimes. Menhaden comprise a high-volume reduction fishery where the majority of harvest is reduced to fish meal and oil during processing [76,77]. Catch diversity is significantly higher without menhaden, indicating that high volume common species can mask diversity in lower poundage species. Inclusion of menhaden has no effect on trends in revenue and revenue diversity, suggesting that menhaden are a low value species by weight and account for a consistent proportion of revenue. The consistency in revenue diversity also suggests that it is robust to the inclusion of high-volume common species and may be an indicator that better reflects social outcomes. In the 1980s, menhaden catch declined (Fig. 3a–c) as consolidation occurred in the reduction fishery and led to the closure of several menhaden reduction plants in both the Atlantic and the Gulf.

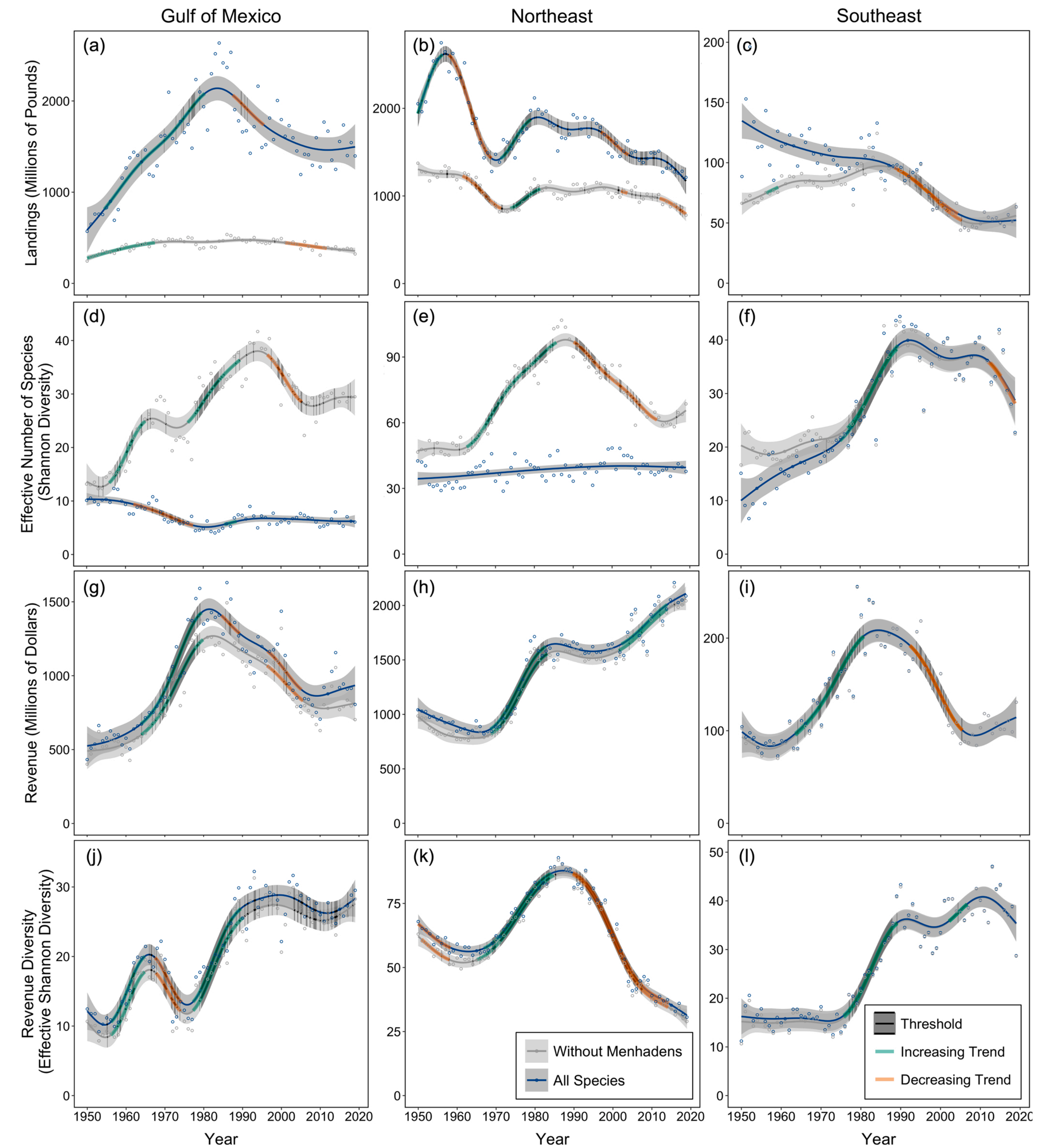

Fig. 3. GAM functions (± 95 % CI) comparing commercial fisheries (a–c) landings, (d–f) revenue, (g–i) catch diversity, and (j–l) revenue diversity in regions where menhaden are fished. Shading represents calculations with (darker) and without (lighter) menhaden. Significant increases (green) and decreases (red) calculated from first derivative functions are highlighted in bold. Thresholds are shaded in darker gray.

This was due to stricter fishing restrictions, social problems of factory operation in urban areas, and saturation of fish meal and fish oil products in the global market that diminished the value of menhaden harvests [55,76,78]. Without processing plants, fishers in the Southeast halted engagement in the menhaden fishery altogether (Fig. 3c, f). Comparing a suite of indicators enabled addressing the disproportionate effect of high-volume species on fishery statistics and teasing apart important drivers of change. Other regions likely demonstrate similar effects of high-volume species common to each region (e.g., coastal pelagic species in California Current, pollock in Alaska, tuna in Hawaiʻi).

3.1.2. *Recreational fishing*

Recreational fishing patterns largely decreased or remained consistent and frequently opposed commercial trends, suggesting competition or perhaps lateral movement between the two sectors (Fig. 4). In the 1980s, while commercial fisheries expanded, recreational fisheries experienced a decrease in catch despite consistent fishing effort. In the California Current, the decrease was driven by declining harvests of many groundfish species [79] and some pelagic species [80]. Spatial declines in rockfish have been linked to areas of high recreational effort [81]. Temporal declines in chub mackerel have been associated with climatic factors that affect their thermal environment and wintering ground condition [82]. In the Northeast, the decrease was driven by declining winter flounder populations, a commercially exploited species in the groundfish fishery [83]. Recreational fishing is the most prominent in the Southeast, where landings are comparable to the commercial sector and it is the dominant source of fish mortality [84]. The beginning of the time series demonstrated decreasing recreational catch with consistent effort. This may be attributed to declines in various pelagic species; for example, Atlantic croaker populations have declined due to a combination of environmental variability, fishing, and habitat loss [85]. Additionally, red porgy and black seabass in the Southeast, as well as red snapper, red grouper and amberjack in the Gulf underwent declines in the 1980s and were listed as overfished by 1990 [86].

In the Southeast, Northeast, and Gulf of Mexico, recreational efforts increased in the 1990s when commercial activities were in a lull, possibly indicating a tradeoff between the two sectors. This juxtaposition may demonstrate plasticity in fisher behavior in response to changes in resource availability or regulatory change. Fishers may have reallocated effort from commercial to recreational fishing, induced by increasingly stringent regulations in the commercial sector, affordable fishing technology (e.g., navigation systems), and increased information sharing among recreational anglers [84]. The interaction between commercial and recreational sectors suggests that ecosystem-based management efforts would be most effective if both sectors were managed in an integrated manner. For example, addressing fishery interactions and managing for stock sustainability as a whole may be more effective than simply setting separate catch allowances in sectors. Greater leniency in regulations in one sector over the other may also lead to overharvesting. Addressing recreational mortality has already facilitated the recovery of important species such as red snapper [62]. This is particularly important in the Southeast and Gulf of Mexico fisheries, where recreational fishing activities frequently dwarf their commercial counterparts [86].

3.1.3. Marine resource-related employment

Analyses of employment data demonstrated differences between commercial production and employment that may indicate an increase in harvest and processing efficiency. Despite stable harvests in recent years and an increase in commercial fishing revenue, significant decreases and thresholds were observed in fishing and seafood processing and packaging (hereafter, seafood processing) employment (Figs. 2, 5, 6). This juxtaposition suggests that fewer employees are required for the same output of fishery products and that value by weight is increasing. This value increase may be due to increased freshness of catch and/or a shift to harvesting more valuable species, perhaps supported by better refrigeration, shorter travel time, and improved gear. During this period, self-employment in seafood processing increased, suggesting that some fishers may be transitioning to self-processing and/or direct marketing of their catch. However, the number of self-employed individuals is negligible compared to total employment across larger businesses. Increased incidences and risk of hurricanes, as well as the Deepwater Horizon oil spill, have been shown to influence the seafood processing industry, and may have also contributed to consolidation in this sector

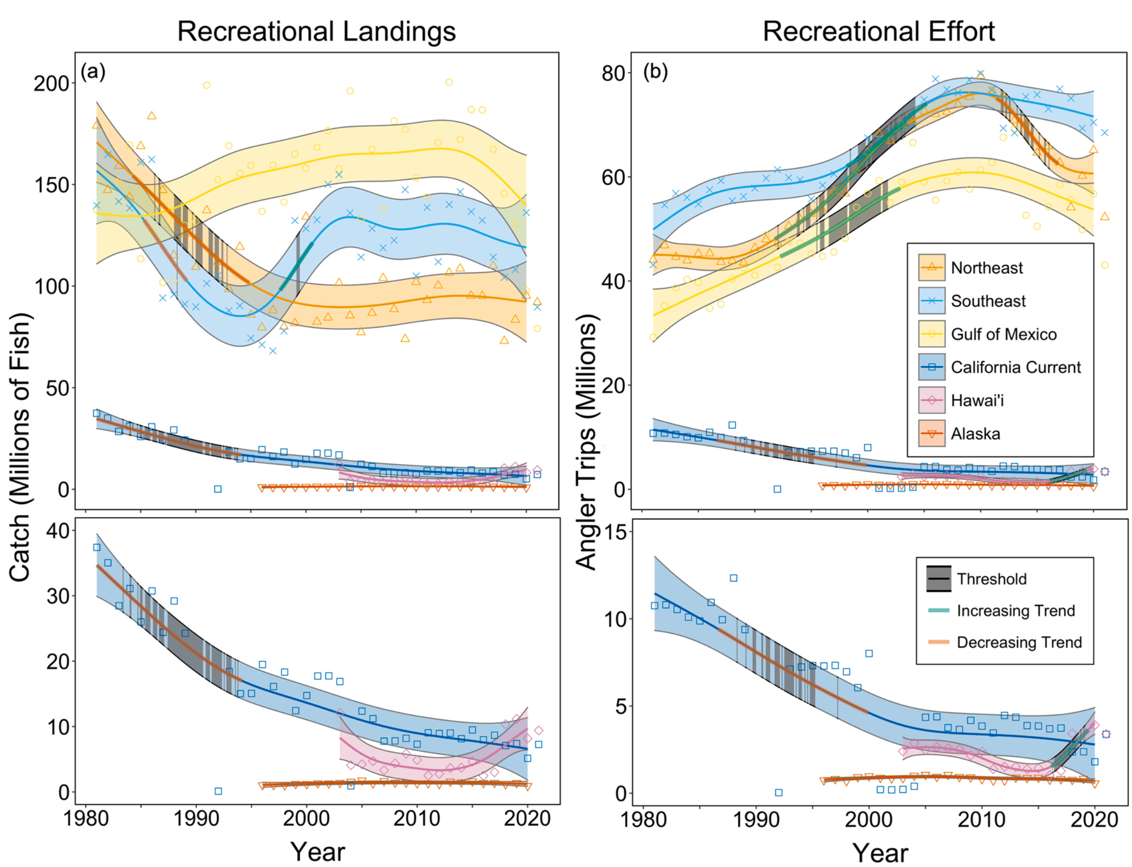

Fig. 4. Generalized additive model (GAM) functions (± 95 % CI) representing cross-regional comparisons of recreational fisheries (a) catch and (b) effort from 1981 to 2021. Bottom panels are close-ups of the California Current and Hawaiʻi regions, respectively. Points represent raw data. Significant increases (green) and decreases (red) calculated from first derivative functions are highlighted in bold. Thresholds are shaded in gray.

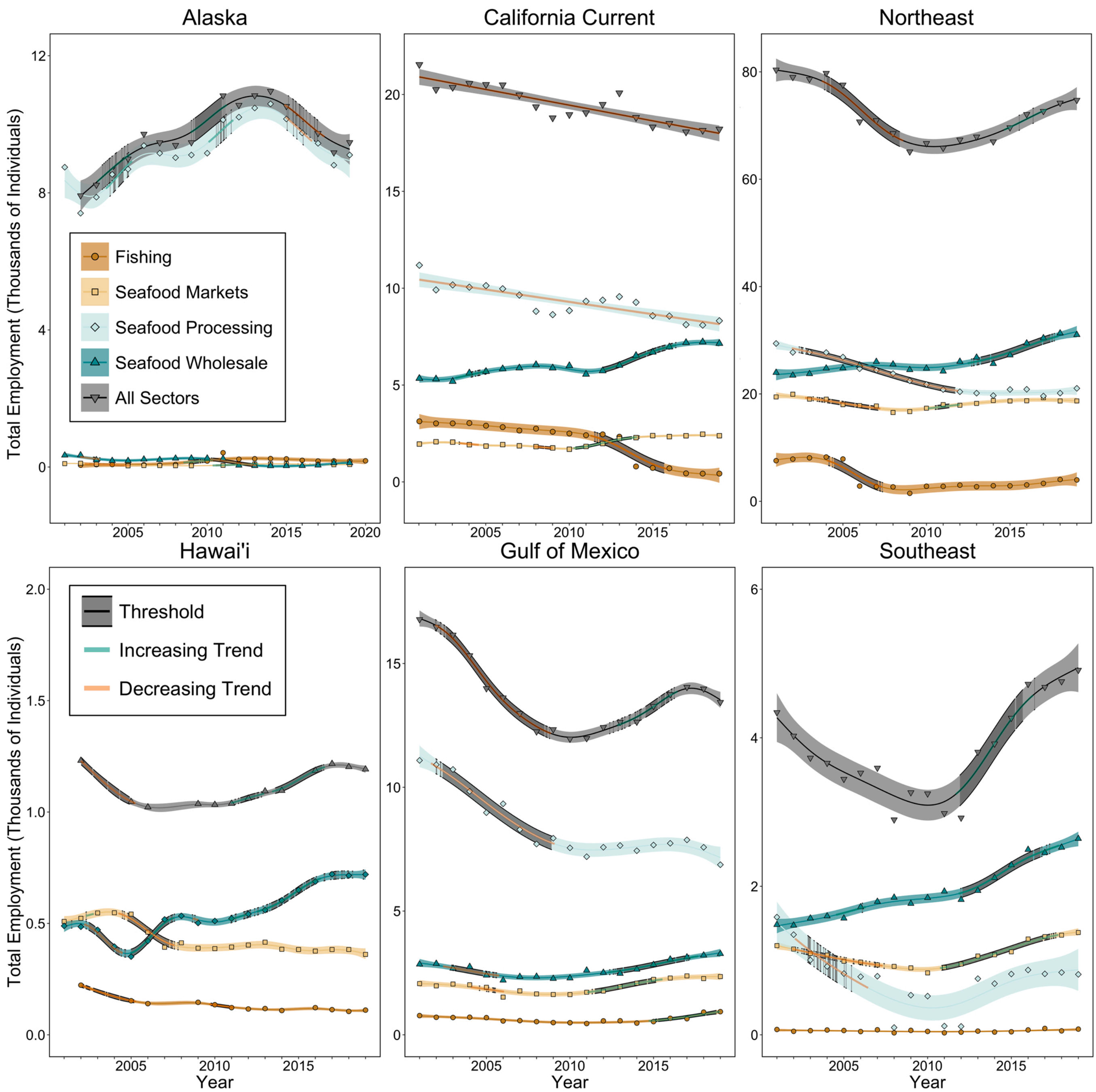

Fig. 5. GAM functions (± 95 % CI) representing total employment in marine resource-related industries across regions reported by the Bureau of Labor Statistics (BLS). Significant increases (green) and decreases (red) calculated from first derivative functions are highlighted in bold. Thresholds are shaded in gray.

[87]. Conversely, employment in seafood markets and seafood wholesale displayed increasing trends as well as thresholds across most regions after 2010 (Fig. 5) and may have driven increased commercial revenue in recent years via enhanced seafood distribution. This may also suggest a growing domestic market for fresh or live seafood, but interpretation is complicated by seafood exports that may account for a significant proportion of wholesale business [88,89].

Wages closely tracked employment for both BLS and NES, suggesting that both respond to similar system drivers (Figs. 7, 8). Individual wages were consistently higher for self-employed individuals, which may suggest higher profitability in self-employment. However, these are gross receipts and do not consider business expenses, which may be high for self-employed individuals. Establishment numbers and employment displayed similar trends over time, but had vastly different sector contributions (Figs. 5, 9). For every region except Alaska, seafood processing had the lowest number of establishments but substantial employment, suggesting that this sector consists of a few large businesses with many employees. In Alaska, the substantial number of seafood processing establishments decreased as employment increased, demonstrating consolidation. Seafood markets and wholesalers appear to have proportionate employment, suggesting moderately sized businesses.

Seafood processing and fishing were the two foremost sectors of marine employment. Seafood processing represented the majority of BLS employment (Fig. 5) and fishing dominated self-employment (Fig. 6). In Alaska, seafood processing represented the majority of total employment and a regime shift to higher seafood processing employment was detected. This increase aligned with increased

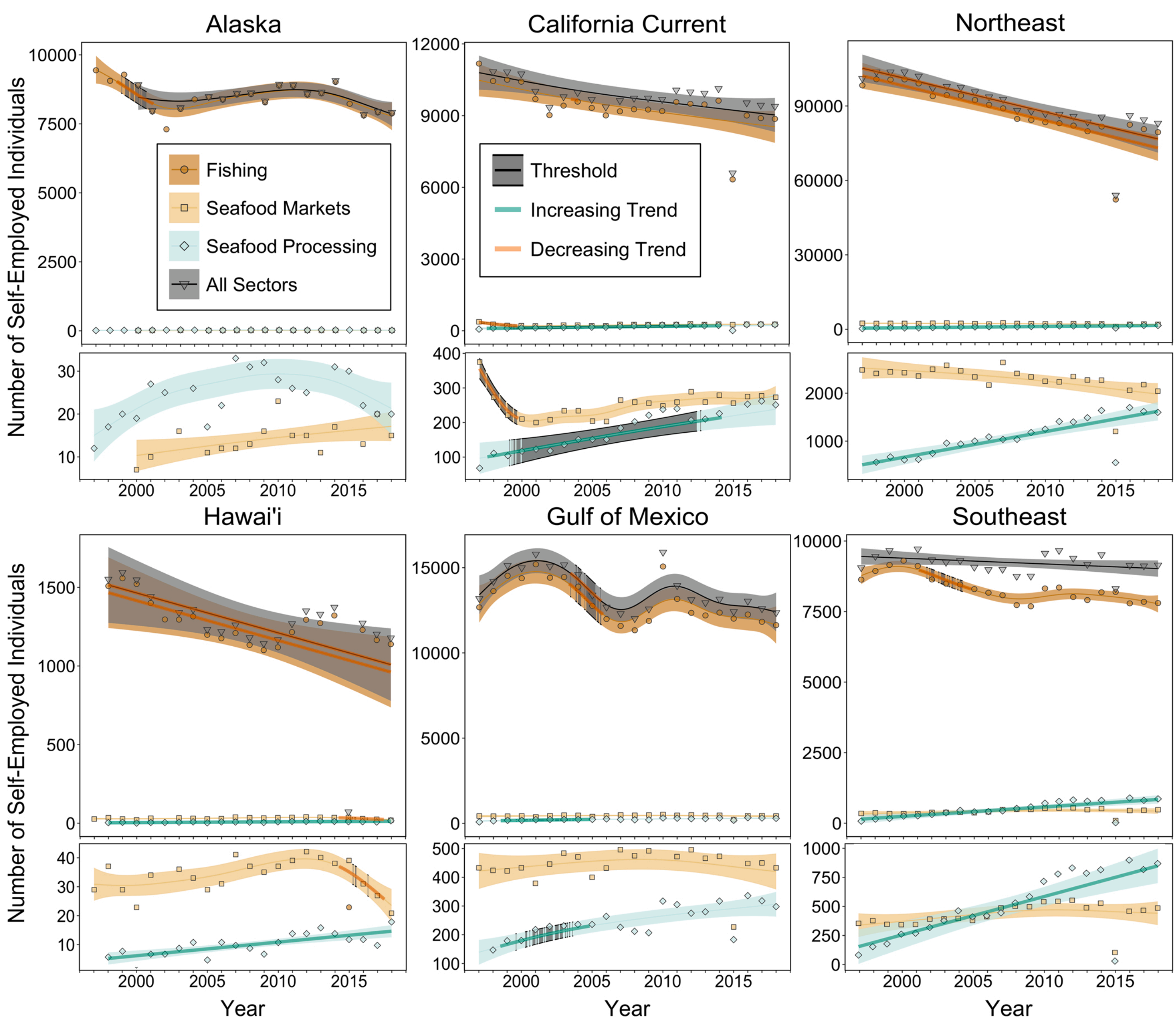

Fig. 6. GAM functions (± 95 % CI) representing self-employment in marine resource-related industries across regions reported by U.S. Census Bureau Nonemployer Statistics (NES). Bottom panels for each region display zoomed-in plots of seafood markets and seafood processing. Significant increases (green) and decreases (red) calculated from first derivative functions are highlighted in bold. Thresholds are shaded in gray.

commercial yield of pollock and cod, which tend to undergo complex processing methods, such as the production of the fish paste surimi [90,91]. The next highest seafood processing employment, relative to total employment, occurred in the Gulf of Mexico, where high-volume menhaden are processed into meal, oil, and condensed soluble proteins [76,77]. Fishing comprised the lowest proportion of BLS employment, but the highest proportion of NES employment. Fishers are generally considered to be self-employed and permit holders do not need to report employee numbers, so the vast majority of fishing employment is reported as self-employment [92]. This may also indicate a high proportion of owner-operators involved in the commercial fishing industry. Fishing and seafood processing demonstrated similar trends as processing is required for most harvested seafood. Therefore, at-sea processing vessels and shoreside plants provide processing services ranging from simple heading and gutting to reduction of fish oil [90,93].

Environmental shifts are likely to affect fish stocks and the resulting social impacts will vary across regions. Northern regions may be disproportionately affected by warming temperatures as many target species shift their ranges northward. Studies have already detected changes in the range and distribution of commercially important species such as pollock and cod in Alaska [94,95] and lobster and scallop in the Northeast [96]. Additionally, indirect effects of climate change have been shown to affect even species that range toward the south. As resource status changes, there will likely be redistribution of effort among different employment sectors, and larger establishments may have better capacity to adapt, but their employees may be more prone to downsizing. For example, changes in harvest of Gulf menhaden and Alaskan pollock may induce changes in seafood processing employment and drastically affect workforce composition in marine sectors [97,98]. As fisheries are faced with increasing instability in the harvest of important species, diversification of target species may provide value by buffering regional fisheries from future environmental changes, thus enhancing job security across sectors. These potential fluxes in employment can also be attenuated or amplified by management actions, such as the movement toward catch shares management [99–102].

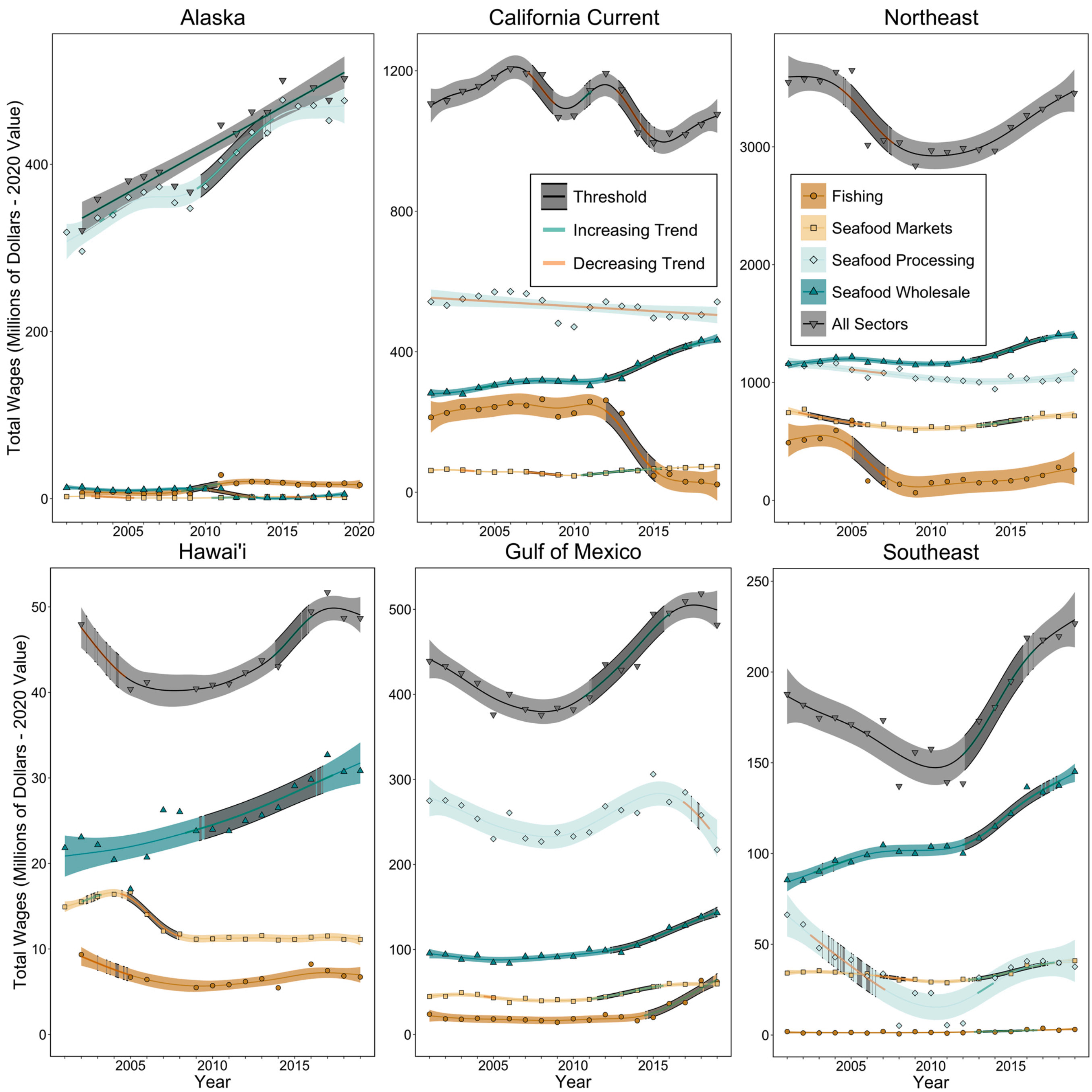

Fig. 7. GAM functions (± 95 % CI) representing total wages (deflated to 2020 dollars) in marine resource-related industries across regions reported by the Bureau of Labor Statistics (BLS). Significant increases (green) and decreases (red) calculated from first derivative functions are highlighted in bold. Thresholds are shaded in gray.

3.2. Multi-criteria outcome ranking

Peaks and dips of social indices in many of the regions followed peaks and dips in environmental indices, demonstrating some coupling of fisheries socioeconomics to environmental productivity that is frequently accompanied by lag time. However, social indices did not rigidly track environmental indices, indicating other drivers of change such as management actions. Regions displayed variable trends from 2001 to 2017, the years during which the different datasets overlapped (Fig. 10). In the Gulf of Mexico, Northeast, and Southeast, the social-ecological (productivity) index decreased over the assessed time period and was steepest initially. This trend was partially due to increasing environmental indices in these three regions, with a particularly steep increase at the beginning. As environmental productivity increases, fish biomass is expected to increase [32]. However, fishery regulations and other socioeconomic factors may limit harvest volume even as stock abundance increases. For example, the decline in the number of menhaden reduction plants as well as shrimp trawl fishery regulations may have limited overall fisheries production in these regions. In these three regions, social indices decreased then increased to varying degrees and were largely reflective of employment trends. In the Gulf, a steep drop preceded an equally steep rebound, due to similar trends in commercial revenue and employment. The Gulf social index declined again in recent years, reflecting declining recreational engagement and commercial revenue, neither of which were detected in the GAMs as significant on their own. In the Southeast,

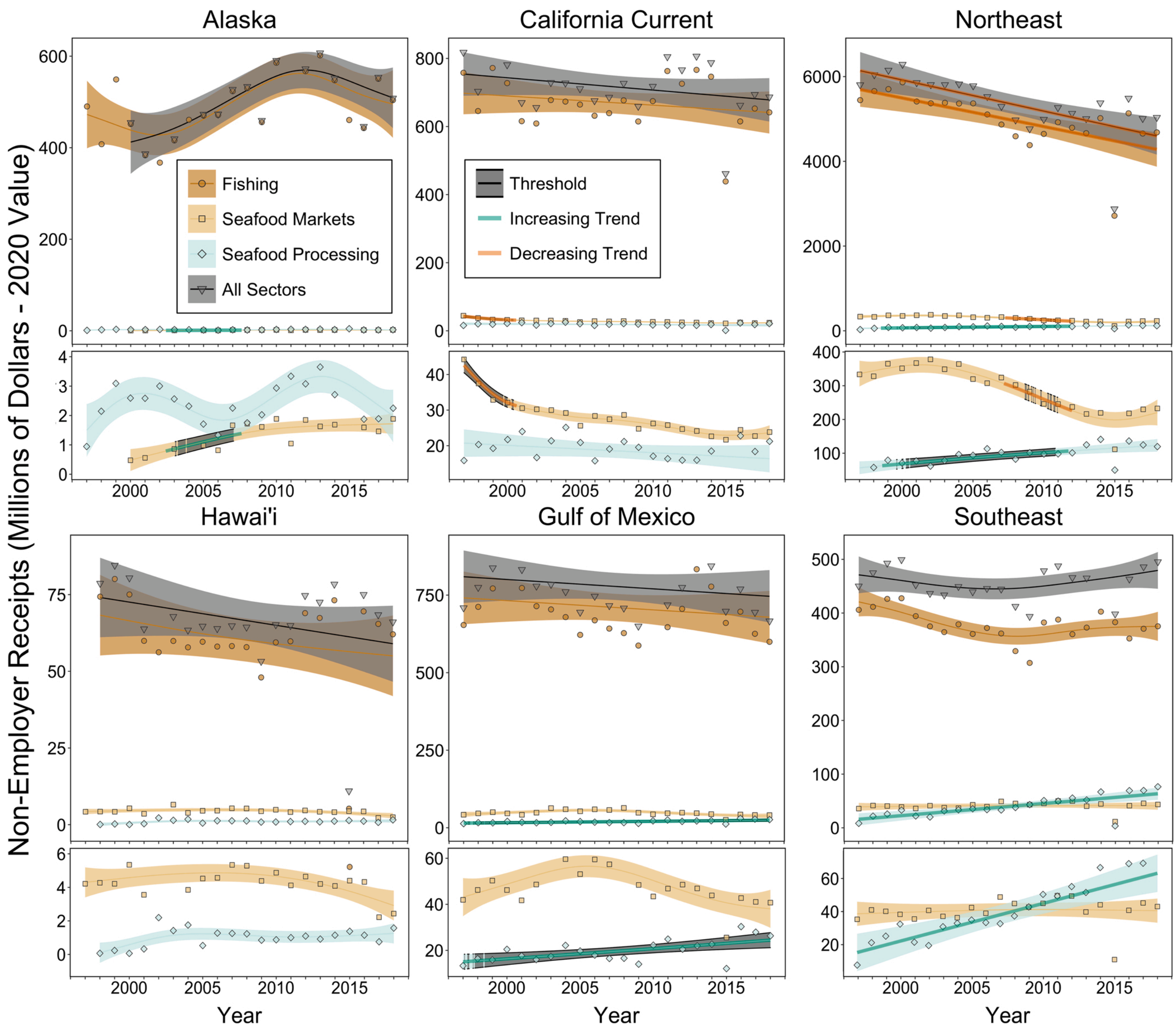

Fig. 8. GAM functions (± 95 % CI) representing total receipts (gross earnings deflated to 2020 dollars) for self-employed individuals in marine resource-related industries across regions reported by U.S. Census Bureau Nonemployer Statistics (NES). Bottom panels for each region display zoomed-in plots for seafood markets and seafood processing. Significant increases (green) and decreases (red) calculated from first derivative functions are highlighted in bold. Thresholds are shaded in gray.

decreasing commercial landings and revenue also contributed to a steep early decline in the social index, which leveled out after the mid-2000s. Of these three regions, the Northeast's social index was the most stable, likely buffered by recreational trips displaying opposing trends to employment.

In Hawaiʻi and Alaska, the social index did not closely track the environmental index. In Hawaiʻi, this may be because most fisheries engagement in these regions is focused on migrating pelagic species that may not reflect local environmental productivity. These regions were missing data points at the beginning of the time series and DEA results began later than the rest of the regions. In both regions, the productivity index briefly dipped in the middle of the time series, which was due to recreational activities in Hawaiʻi and commercial activities in Alaska. Alaska showed a slight downward trend throughout the time series due to an increasing environmental index coupled with a stable social index. For Hawaiʻi, the social index displayed a steep increase after the dip due to the compounding effects of many indicators increasing simultaneously, some of which are accompanied by significant trends and, less commonly, thresholds. Continued increases in harvested value and marine employment suggest that extractive resource users were able to adapt to reduced catch limits, possibly facilitated by increased tourism driving up fresh fish values [72,74]. Although recreational fishing indices in Hawaiʻi displayed a temporary decline, it was not significant enough to be detected in the GAM analysis of recreation effort or landings and did not present a threshold. In the California Current, the productivity index displayed a shallow decline, then remained relatively stable. The social index mostly reflected the environmental index, except for a dip in the middle of the time series (2007–2011). Despite a significant increase in commercial revenue, the social index reflected dips in employment and recreational activities. This demonstrates the importance of addressing tradeoffs in generating new management policies, as increased revenue only constitutes one of many management objectives. The recent downturn reflected commercial activities but did not represent significant trends in the GAMs, and future data collection is needed to determine whether trends emerge.

These results reflected tradeoffs among commercial fishing,

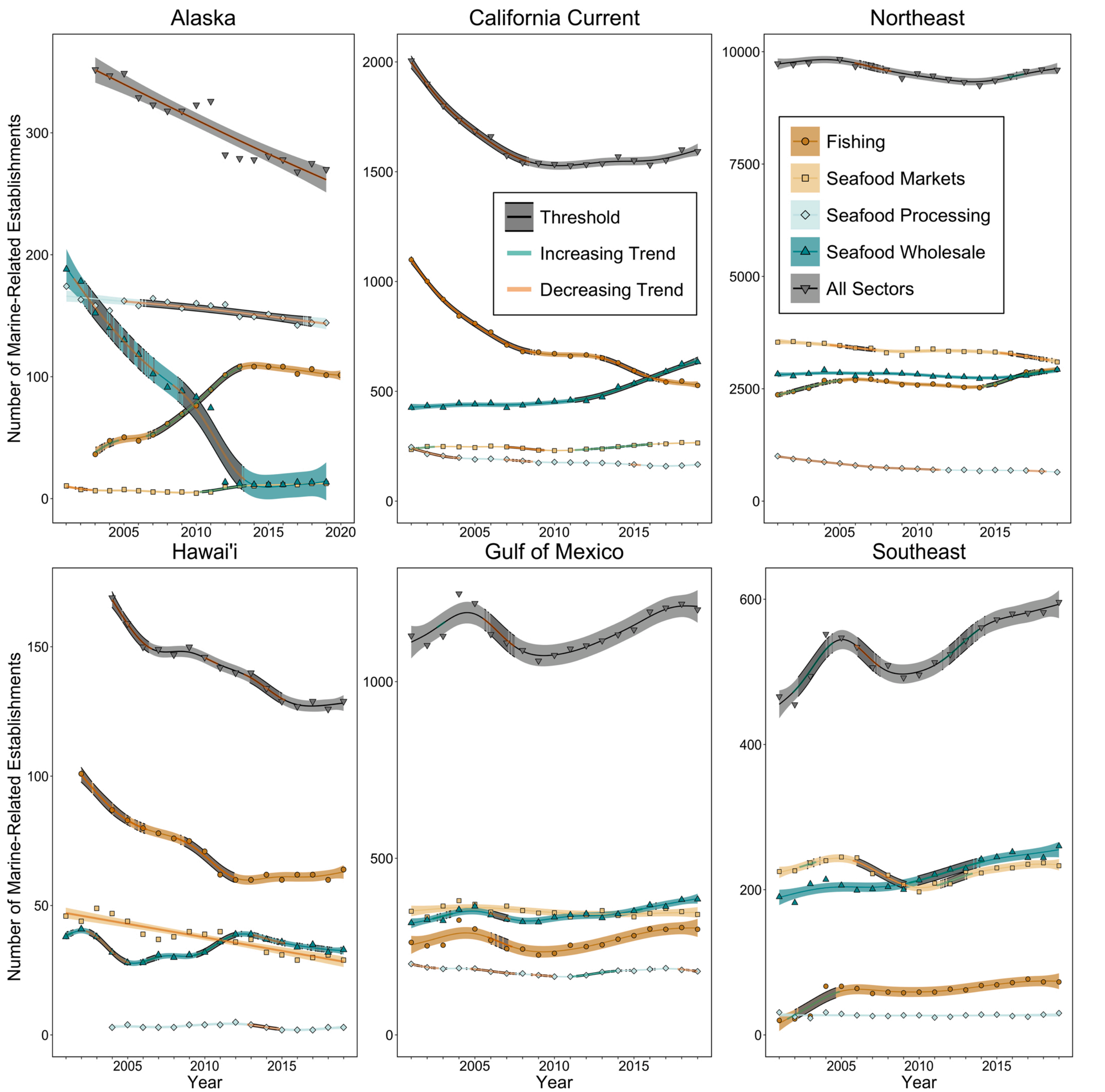

Fig. 9. GAM functions (± 95 % CI) representing the number of marine resource-related establishments across regions reported by the Bureau of Labor Statistics (BLS). Significant increases (green) and decreases (red) calculated from first derivative functions are highlighted in bold. Thresholds are shaded in gray.

recreational fishing, and employment distribution, indicating that behavioral plasticity allows human resource users to adapt to changing conditions by altering resource use methods. Such plasticity may demonstrate enhanced SES resilience and ability to cope with environmental and regulatory changes (i.e., adaptive capacity) and aligns with firsthand research conducted in many small fishing communities [103–105]. They also demonstrate that all regions fluctuate between regimes of higher and lower social achievement, and most are on the rise after a dip. Averaging each index over the assessed time period enabled comparison of central tendencies and temporal variation across regions. The indices did not differ significantly across the six regions, suggesting comparable fisheries performance across all regions (Fig. 11). Again, there is a decoupling of social and environmental indices in Hawai'i, as a comparatively low ecological input did not result in a low social output. This highlights the importance of the longline fishery, which is less dependent on local conditions. Using a small suite of standardized national indicators, our analysis demonstrates shared and unique social regime shifts across coastal social-ecological systems in the United States and identifies a tradeoff between recreational and commercial sectors. The transition towards ecosystem-based fisheries management may involve explicitly addressing this tradeoff and managing the two sectors in an integrated manner instead of as distinct entities.

4. Conclusions

This study used a standardized methodology across regions to build a

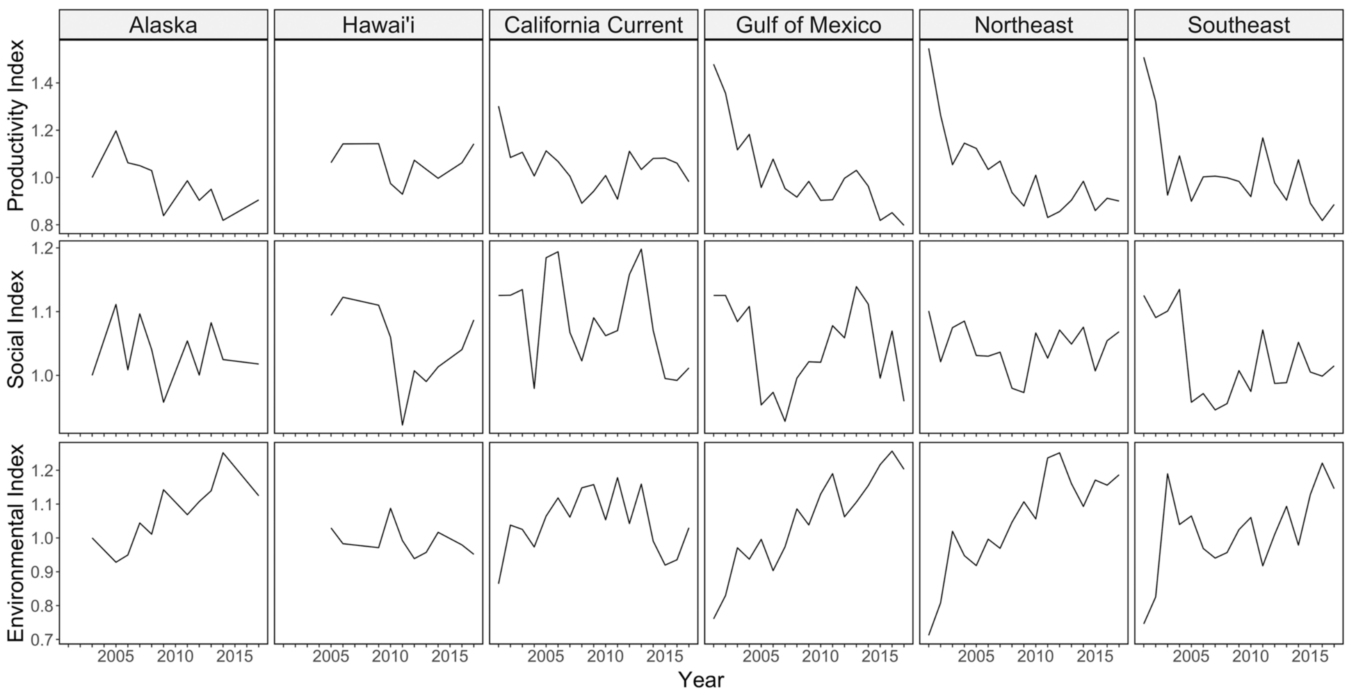

Fig. 10. Plots of social-ecological (productivity), social (output), and ecological (input) indices for each region from 2001 to 2017. The environmental index represents chlorophyll-a concentrations.

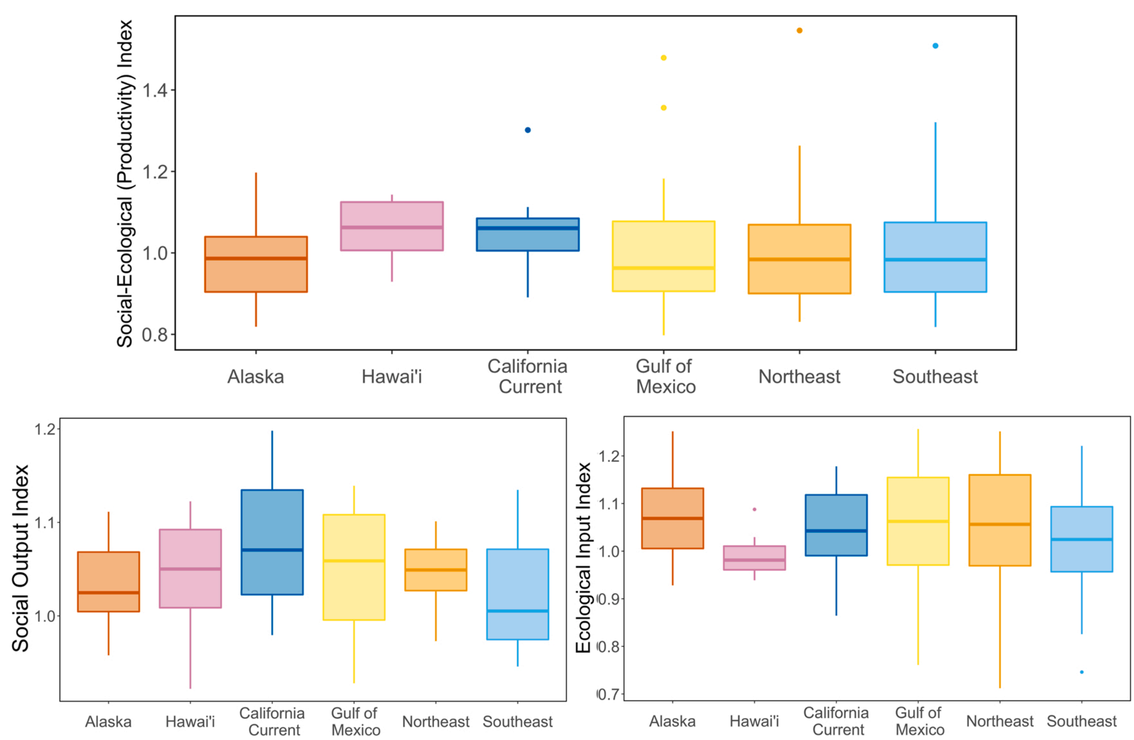

Fig. 11. Boxplots summarizing medians and variabilities of social-ecological (productivity), social (output), and ecological (input) from 2001 to 2017 in each region.

comprehensive profile of changes that occurred concurrently across distinct social-ecological systems (SESs) as well as those that were unique to individual regions. The analyses highlighted regulatory impacts on social and economic components of SESs. Across regions, thresholds occurred following global technological advancements and widespread structural changes in fisheries management. Region-specific thresholds co-occurred with fisheries-specific population declines and gear or entry restrictions (e.g., salmon fishery in California Current, shrimp fisheries in the Gulf and Southeast). These results suggest that widespread regulations may disproportionately impact regions; for example, Alaska and Hawai'i experienced proportionally higher increases in commercial harvests by U.S. flagged vessels than other regions after the creation of exclusive economic zones. Our results also highlight tradeoffs among opposing social objectives, such as commercial productivity and recreational engagement. Additionally, while prior studies have demonstrated that environmental factors such as chlorophyll-a concentration can limit fisheries yield [32], our study also highlights regulatory changes as a potentially important determinant of realized fisheries yield. Ultimately, environmental and social drivers interact to control benefits derived in SESs and our results demonstrate the necessity of assessing SESs as integrated systems.

This research serves as a proof of concept that the standardized methodology presented has the capability to identify social thresholds and, combined with qualitative and historical analyses, describe potential drivers of system changes. This analysis used readily available, consistent secondary datasets that allowed for national and multi-decadal comparisons. Although the shortest dataset limited the temporal extent of the composite indices, the methodology was able to illustrate trends occurring over almost two decades. Given the spatial overlap between our environmental indicator and fishing zones the divergence between the social and environmental indices in Hawaiʻi revealed a dependence on migratory stocks imported (i.e., tuna) into its marine ecosystems. This indicates that a limitation of the study is using an ecological indicator that does not affect migratory stocks. Future work that utilizes our analytical framework could incorporate additional environmental indicators such as dissolved oxygen, degree heating weeks, or upwelling events. The suite of socioeconomic indicators used is not exhaustive and provides an overview of social states in these coastal SESs using standardized, comparable indicators. This methodology was developed as a tool that can be adapted for various social-ecological systems with unique social objectives and data availability to identify local regime shifts, rank outcomes across regimes and regions, and be coupled with historical analysis to potentially explain drivers of change within different SESs.

CRediT authorship contribution statement

Lansing Perng: Conceptualization, Methodology, Software, Validation, Formal analysis, Data curation, Writing – original draft, Writing – review & editing, Visualization. **John Walden:** Methodology, Software, Validation, Formal analysis, Resources, Writing – review & editing, Visualization. **Kirsten Leong:** Conceptualization, Validation, Resources, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition. **Geret DePiper:** Conceptualization, Validation, Resources, Writing – review & editing, Visualization, Supervision, Project administration, Funding acquisition. **Cameron Speir:** Conceptualization, Validation, Writing – review & editing, Visualization, Funding acquisition. **Suzana Blake:** Conceptualization, Validation, Writing – review & editing, Visualization, Funding acquisition. **Karma Norman:** Conceptualization, Validation, Writing – review & editing, Visualization, Funding acquisition. **Stephen Kasperski:** Conceptualization, Validation, Writing – review & editing, Visualization, Funding acquisition. **Mariska Weijerman:** Conceptualization, Validation, Resources, Writing – review & editing, Visualization, Supervision, Funding acquisition. **Kirsten Oleson:** Conceptualization, Validation, Resources, Writing – review & editing, Visualization, Supervision.

Declarations of interest

None.

Data Availability

Data are publicly available and linked in Table 1. Code will be made available on request.

Acknowledgements

This research was supported by the National Oceanic and Atmospheric Administration's Integrated Ecosystem Assessment (NOAA IEA) Program contribution no. 2022_4. This research was also funded by the University of Hawaiʻi and NOAA's Cooperative Institute of Marine and Atmospheric Research Project # 6105142. The authors thank the Human Dimensions working group participants for their input in this IEA special project and are grateful for the expertise contributed by researchers from each of the study regions.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.marpol.2023.105595.

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