Cross-Chapter Paper 3: Deserts, Semi-Arid Areas and Desertification

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Executive Summary

Introduction

This Cross-Chapter Paper on "Deserts, semi-arid areas and desertification" provides an update and extension to Chapter 3 on "Desertification" in the IPCC Special Report on Climate Change and Land (SRCCL). It assesses new information and links it to the findings across the chapters of Working Group II's contribution as well as relevant chapters of Working Group I's contribution to the IPCC Sixth Assessment Report (AR6), with a more focused treatment of deserts than was within the scope of the SRCCL.

Where are we now: Observed impacts and adaptation responses

Deserts and semi-arid areas have already been affected by climate change and desertification, with some areas becoming more arid and other areas becoming greener. Mixed trends of decreases and increases in vegetation and biodiversity have been observed, depending on the time period, geographic region, detection methods used and vegetation type under consideration. Warming rates have been two times higher in tropical drylands compared to humid regions (*high confidence*). There is no evidence, however, of a global trend in dryland expansion based on analyses of vegetation patterns, precipitation and soil moisture (*medium confidence*). Deserts and semi-arid areas host unique biodiversity, rich cultural heritage and provide globally valuable ecosystem services. They are also highly vulnerable to climate change. The vitality of natural ecosystems in arid and semi-arid regions greatly depends on water availability, as they are highly sensitive to changes in precipitation and potential evapotranspiration. From 1920 to 2015, surface warming of 1.2ºC to 1.3ºC over global drylands exceeded the 0.8ºC to 1.0ºC warming over humid lands. From 1982 to 2015, the combination of unsustainable land use and anthropogenic climate change caused desertification of 6% of the global dryland area, while 41% showed significant greening and 53% of the area had no notable change. Observed trends in deserts and semi-arid areas have led to varying impacts on flora, fauna, soil, and water resources. Ecological changes in dryland ecosystems detected and attributed primarily to climate change include tree mortality and loss of mesic tree species at specific sites in the African Sahel from the 1940s to the 2000s; and in North Africa from 1970 to 2007; and losses of bird species in the Mojave Desert of North America from 1908 to 2016. In contrast, the growth in herbaceous vegetation production has increased in some dryland areas since the 1980s. Widespread woody encroachment has occurred in many savannahs in Africa, Australia and South America, due to a combination of land use change, changes in rainfall, fire suppression, and CO_2 fertilization. {CCP3.1.2, CCP3.2.1, CCP3.2.2}

The impacts of climate change have affected the ecosystem services that humans can harness from drylands, with important implications for livelihoods, human health and wellbeing, particularly in deserts and semi-arid areas with lower adaptive capacities (*high confidence*). Dryland populations are showing a steady increase, accompanied with rapid urbanisation, growing incomes and consumption. The pressures that these trends place on ecosystems often lead to their degradation and desertification, which can exacerbate poverty, water insecurity, hunger, poor health, and marginalisation. Ecosystem degradation and desertification threaten the abilities of both natural and human systems to adapt to climate change. What happens in the world's deserts and semi-arid areas has substantial implications for the rest of the world, e.g., through sand and dust storms, economic and social teleconnections (for example through health, trade, potential implications for conflicts and migration). These changes most acutely affect human populations that are directly dependent on natural resources, who also often have lower capacities to adapt to climate change, particularly given structural limitations of dryland areas where e.g., health care, sanitation, infrastructure and markets are often lacking (*high confidence*). {CCP3.1.1, CCP3.2.1, CCP3.2.2}

Where are we going? Risks and adaptation under warming pathways

Some drylands will expand by 2100, while others will shrink (*high confidence*). Climate change affects drylands through increased temperatures and more irregular rainfall, with important differences between bimodal and unimodal rainfall areas. Projections are nevertheless uncertain and not well supported by observed trends, while different methodological approaches and indices exhibit different strengths and weaknesses (*medium confidence*). A fundamental methodological challenge is how to attribute projected impacts to climate change when background climate variability in drylands is so high.

Some projections show aridity (as measured by the aridity index) to expand substantially on all continents except Antarctica. Expansion of arid regions is likely in southwest North America, the northern fringe of Africa, the far west Sahel, southern Africa and Australia. The main areas of semiarid expansion are likely to occur in the north side of the Mediterranean, southern Africa and North and South America. In contrast, India, northern China, eastern equatorial Africa and the southern Saharan regions are projected to have shrinking drylands. Under the Representative Concentration Pathway 8.5, aridity zones could expand by one-quarter of the 1990 area by 2100, increasing to over half the global terrestrial area. Lower greenhouse gas emissions, under Representative Concentration Pathway 4.5, could limit expansion to one-tenth of the 1990 area by 2100. Nevertheless, the utility of the aridity index in delineating dryland biomes is limited under an increasing CO_2 environment (*medium confidence*). The impacts of climate change, and dust and sand storm activity are projected to be substantial, however, there is large regional variability in terms of rainfall seasonality, land management practices, as well as differences in rates of change and the scales at which the projections are undertaken. The characteristics and speed of human responses and adaptations also affect future risks and impacts (*high confidence*). Increased variability of precipitation would generally contribute to increased vulnerability for people in drylands, intensifying the challenges that populations residing in deserts and semi-arid areas will face for their sustainable development (*medium confidence*). {CCP3.3.1, CCP3.3.2}

Contributions of adaptation measures to climate resilient development

Drivers of dryland dynamics such as desert expansion and greening are numerous, and differ across different types of drylands, yet a suite of successful adaptations can address human drivers of change, support resilience and build the adaptive capacity of dryland inhabitants (*medium confidence*). Deserts and semi-arid areas have a rich cultural heritage, indigenous knowledge, and local knowledge which enrich and influence sustainability and land use globally. Growing evidence and experience, including that grounded in indigenous knowledge and local knowledge, highlight the necessary features of an enabling environment for dryland adaptation. Key aspects include supportive policies, institutions and governance approaches that strengthen the adaptive capacities of dryland farmers, pastoralists and other resource users (*high confidence*). There is a persistent gap in terms of scaling-up already known good practices, combining nature based, land based, and ecosystem-based approaches that facilitate sustainable land management together with contextually appropriate governance solutions (e.g., those supporting land tenure security) (*medium confidence*). Land based adaptations can help manage dryland changes including dust and sand storms and desertification, while technological options linked to water management draw from both traditional practices and new innovations. Adequate financing and investment is required to harness multiple benefits for managing the impacts of climate change and desertification whilst accelerating progress towards sustainable development in desert and semi-arid areas. {CCP3.4}

CCP3.1 Introduction

CCP3.1.1 Concepts, Definitions and Scope

Deserts and semi-arid areas come under the overarching term ‘drylands’, which comprise hyper-arid, arid, semi-arid and dry sub-humid areas (Figure CCP3.1). Drylands cover about 45-47% of the global land area (Prăvălie, 2016; Koutroulis, 2019) and are home to about 3 billion people (van der Esch et al., 2017). Drylands host a unique and often rich biodiversity (Maestre et al., 2015) and collectively provide important ecosystem services to a largely rural population (Bidak et al., 2015; Lu et al., 2018). In addition, in the last few decades, 6% of the global “big cities” were established in arid areas and 2% in hyper-arid desert areas, slightly reducing the total area of desert natural ecosystems (Cherlet et al., 2018). As highlighted in the Intergovernmental Panel on Climate Change (IPCC) Special Report on Climate Change and Land (SRCCL), dryland populations have a rich cultural and historical heritage, but in many places in developing countries, they are experiencing poverty, hunger, poor health, economic and political marginalisation and, in some places, growing extent and severity of land degradation (Mbow et al., 2019; Mirzabaev et al., 2019). Such challenges threaten their abilities to adapt to climate change. Often these degradation processes are caused by land use and cover changes driven by rapid human population growth (Tappan, 2016; Tong et al., 2020). As rural human populations steadily increase in tropical drylands and some of the Mediterranean drylands, accompanied with rapid urbanisation, pressure is placed on natural dryland ecosystems, often contributing to degradation (Guengant Jean-Pierre, 2003; Tabutin and Schoumaker, 2004; Denis and Moriconi-Ebrard, 2009).

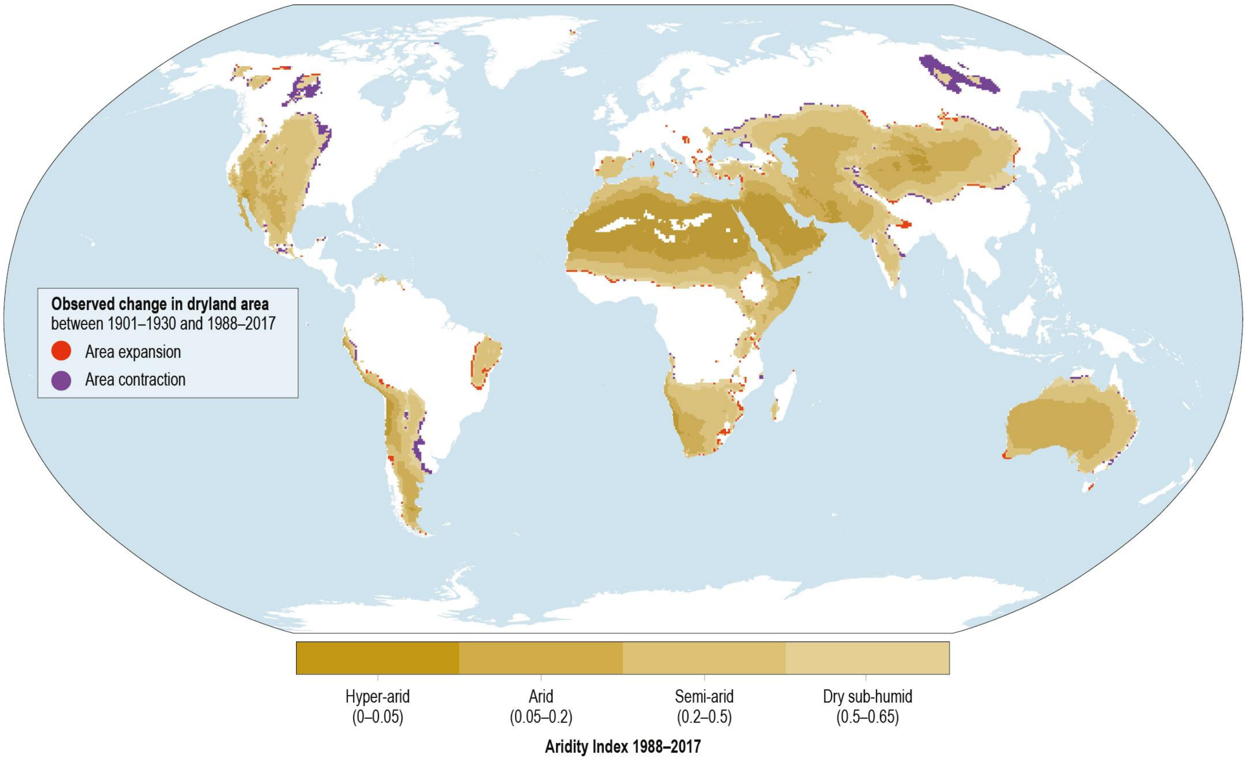

Figure CCP3.1: Aridity zones and observed changes in dryland areas. Aridity zones, according to the (United Nations Educational and Organization, 1979) and (UNEP, 1992) classification, defined by the aridity index (AI), the ratio of average annual precipitation to potential evapotranspiration: (i) dry sub-humid ($0.5 \leq AI < 0.65$), (ii) semi-arid ($0.2 \leq AI < 0.5$), (iii) arid ($0.05 \leq AI < 0.2$) and (iv) hyper-arid ($AI < 0.05$). Drylands include land with $AI < 0.65$ (UNEP, 1992) and potential evapotranspiration ≤ 400 mm y^{-1} (Spinoni et al., 2015). Deserts represent a major part of the hyper-arid and arid zones. The aridity zones are shown for climate in the period 1988-2017 and changes in dryland area (combined area of four aridity zones) are shown between the periods 1901-1930 and 1988-2017, based on climate time series at 50 km spatial resolution (Harris et al., 2020). It should be noted that the aridity index has various limitations in assessing dryland expansion (see SRCCL section 3.2.1) so different methods may highlight different areas of change.

Neither "desert" nor "desertification" are strictly defined terms; each is subject to various interpretations due to the diverse components, processes and states they may denote. While recognizing that "land degradation" is a contested and perceptual term reflecting the fact that different actors value landscapes (Blaikie and Brookfield, 1987; Behnke and Mortimore, 2016; Robbins, 2020), this Cross-Chapter Paper, for practical purposes, follows the definition provided by the SRCCL where land degradation is defined as "a negative trend in land condition, caused by direct or indirect human-induced processes including anthropogenic climate change, expressed as long-term reduction or loss of at least one of the following: biological productivity, ecological integrity or value to humans" (Olsson et al., 2019). Desertification is land degradation in arid, semi-arid, and dry sub-humid areas (UNCCD, 1994). Desertification is more common in desert lands located in arid and semi-arid climates than in the larger areas of hyper-arid climates, and occurs mostly in oases and irrigated cultivated desert lands in both arid and hyper-arid deserts (Ezcurra, 2006; Dilshat et al., 2015). Hyper-arid areas, except wetlands such as oases, wadis and riverbanks, are not included in the United Nations Convention to Combat Desertification (UNCCD) definition of desertification used in this Cross-Chapter Paper, yet many of the world's deserts are found in hyper-arid areas. For this reason, hyper-arid areas are included when discussing deserts but not when discussing desertification. The assessment of desertification also includes wetland areas which are facing significant challenges due to both desertification and climate change. Deserts are not the end point in a desertification process (Ezcurra, 2006), and there is robust evidence of desertification in deserts, mostly driven by human activities and climate variability, expressed as land productivity reductions to below natural levels (Moridnejad et al., 2015). A study of prehistory and contemporary history of desert land use provides evidence of persistent expressions of degradation in a hyper-arid Negev Desert area (Stavi et al. 2017), suggesting that dryland dynamics and desertification are not confined to arid, semi-arid and dry sub-humid areas but can affect all desert types.

Climate variability and change are important determinants of agricultural production, rangeland productivity and soil moisture regimes and soil nutrients in arid and semi-arid areas (De Vries and Djitèye, 1982; Rockström and De Rouw, 1997; de Ridder et al., 2004; Sivakumar, 2005; Akponikpe, 2008; Hiernaux et al., 2009; Mganga et al., 2015; Omoyo et al., 2015; Gaur and Squires, 2017; Zhang et al., 2018). Changes to these aspects linked to climate change can have negative impacts on human health, livelihoods and wellbeing, as well as the land-based options available to support climate change adaptation and mitigation (Reed and Stringer, 2016). At the same time, non-climate change factors are important. Dryland livelihoods that are heavily reliant on natural ecosystems face pressures caused by human factors such as high population growth rates, weak or bad governance, low levels of investment, unemployment and poverty, market distortions and misconceived perceptions of the value of drylands (Stringer et al., 2017; Bawden, 2018) on top of growing climate change challenges. These pressures intersect with broader societal challenges such as conflict and civil unrest (Okpara et al., 2015), which together, can contribute to human migration in some drylands. Nevertheless evidence linking conflict with climate change and desertification is weak (Benjaminsen et al., 2012).

While much of the literature focuses on the problems in dryland systems, these areas also offer opportunities for adapting to and mitigating climate change. They host valuable natural assets including abundant solar energy, opportunities for cultural and nature-based tourism, rich plant biodiversity in some areas (e.g., Namibia) extensive traditional knowledge and experience of adapting to dynamic dryland climates (Christie et al., 2014; Stringer et al., 2017), e.g., across West Asia and North Africa (Louhaichi and Tastad, 2010; Hussein, 2011). Improved understanding of challenges and opportunities in drylands can be achieved by transdisciplinary, multi-scale and inter-sectoral approaches encompassing links between physical, biological and socioeconomic, and institutional systems (Reynolds et al., 2007; Stringer et al., 2017).

This cross-chapter paper on "Deserts, semi-arid areas and desertification" provides an update and extension to the SRCCL, specifically its Chapter 3 on Desertification. It assesses new information and links it to findings from across the chapters of Working Group II (as well as relevant chapters of Working Group I) contribution to the Sixth Assessment cycle (AR6), with a more focused treatment of deserts than was within the scope of the SRCCL. The SRCCL highlighted that the increasing number and frequency of extreme climatic events projected under climate change increase the risks from desertification in arid, semi-arid and dry sub-humid areas. Climate change is strongly affecting many desert and semi-arid areas, together with desertification, lowering their agricultural productivity and eroding biodiversity, including unique desert fauna and flora, and in some locations, contributing to lower surface- and groundwater. The IPCC Special Report on Global Warming of 1.5 °C (IPCC, 2018) noted that, in general, deserts are expected to become drier and warmer at a faster rate than other terrestrial areas, and that little is known about the effects of higher aridity on future increases in dust storms. Overall, more unpredictability, fluctuations and irregularity of rainfall and extreme weather events are expected.

Beyond these IPCC special reports, the links between climate change and deserts, desertification and semi-arid areas have not been extensively considered in previous IPCC assessment cycles. The fifth assessment cycle AR5 noted that desertification contributes to the production of atmospheric dust, identifying desertification as one of several challenges needing consideration within climate change mitigation and adaptation governance and decision making (Boucher et al., 2013; Myhre et al., 2013). AR5 further stated that desertification can reduce crop yields and livelihood resilience, which has also been observed by others (Boucher et al., 2013; Myhre et al., 2013; Field et al., 2014; Fleurbaey et al., 2014; Klein et al., 2014). Indeed, the interactions between climate change and desertification in drylands create challenges for both ecosystems and humans, affecting ecosystem services, biodiversity, food security, human health and wellbeing (Reed and Stringer, 2016). While desertification of desert ecosystems reduces the flow of desert provisioning and regulating ecosystem services, flows of cultural services, significant to desert dwellers and others living off deserts, have not yet been documented to be affected, although cultivation and urbanization, alongside climate change, may put them at risk (Safriel et al., 2005; Ezcurra, 2006).

This Cross-Chapter-Paper focuses on both environmental and human aspects of deserts and semi-arid areas, finding that climate change impacts will intensify the challenges that populations residing in these ecosystems face in terms of their sustainable development. However, viable options exist for adapting to climate change, reducing desertification and moving towards sustainable development and the Sustainable Development Goals (SDGs) in these systems, particularly through the combined use of modern science, traditional knowledge, and local knowledge, as well as livelihood and land management strategies that support land-based adaptation and nature based solutions to climate change.

CCP3.1.2 Dryland Dynamics and Key Areas of Emphasis

From 1920 to 2015, surface warming of 1.2ºC to 1.3ºC over global drylands exceeded the 0.8ºC to 1.0ºC warming over humid lands (Huang et al., 2017) These increasing temperatures due to climate change have increased aridity (Dai and Zhao, 2017; Huang et al., 2017), expanding the area of drylands, as measured by the aridity index, by ~4% from 1948 to 2004 (Ji et al., 2015; Spinoni et al., 2015; Huang et al., 2016) (Figure CCP 3.1). Within drylands, the semi-arid zone ($0.2 \leq AI < 0.5$) was estimated to have expanded at the greatest rate (~7%) (Huang et al., 2016). Observations from the Sahel demonstrated that temperature seasonality changes differ from rainfall seasonality changes (Guichard et al., 2015). Studies from the Middle East focusing on 20 countries showed highest and lowest aridity trends in their sampled countries to be in north Sudan (96%) and eastern Arabia (61%) over the period 1948-2018 (Sahour et al., 2020). In some drylands with winter-rain pulses, climate change is leading to wetter conditions (e.g., Gobi Desert in China). Models project higher total rainfall in the Sahel, but with fewer rainfall events, later onset and increased unpredictability (Biasutti, 2013). In the Sahel, there has been an increase in surface water and groundwater recharge since the 1980s. This is referred to as "the Sahel paradox" (Favreau et al., 2009; Gardelle et al., 2010; Descroix et al., 2013; Gal et al., 2017; Wendling et al., 2019). Along with total rainfall amounts, changes in rainfall patterns also have major impacts on desert and semi-arid areas. Carbon-fertilization is facilitating vegetation/lichen growth (e.g., in Central Asia) (Lioubimtseva, 2007), while aridity trend relationships with vegetation growth in drylands is complicated by irrigation practices and precipitation increases in some areas (He et al., 2019).

From 1982 to 2015, the combination of unsustainable land use and anthropogenic climate change caused desertification of 6% of the global dryland area, while 41% showed significant greening and 53% of the area had no notable change (Burrell et al., 2020). In contrast, (Yuan et al., 2019) conclude that for the period 1999-2015, trends of vegetation production reversed globally and in drylands, showing extensive declines. Analyses of vegetation, soil, and physical characteristics of over 50 000 sample points in drylands around the world indicate that aridification causes ecological degradation at three successive thresholds: vegetation decline at aridity index = 0.56, soil disruption at aridity index = 0.3, and loss of plant cover at aridity index = 0.2 (Berdugo et al., 2020) However, as shown in the SRCCL Chapter 3 on Desertification, the aridity index, already an imperfect proxy for drylands, will be of limited use under a changing CO_2 environment due to higher water use efficiency by some plants. Although some dryland areas will expand due to climate change

(Figure CCP 3.1), there is no evidence of a global trend in dryland expansion based on vegetation patterns, precipitation and soil moisture (*medium confidence*). The eastern Nama-Karoo (southern Africa) has experienced increased herbaceous vegetation production. Vegetation production showed declines in Burkina Faso (Zida et al., 2020). The Sahara Desert was suggested to have expanded 10% from 1902 to 2013 (Thomas and Nigam, 2018), although herbaceous vegetation production has increased in general in the Sahel, demonstrating a trend of "re-greening" since the dry 1980s (Eklundh and Olsson, 2003; Anyamba and Tucker, 2005; Herrmann et al., 2005; Hutchinson et al., 2005; Olsson et al., 2005; Fensholt et al., 2006; Dardel et al., 2014; Hiernaux et al., 2016; Stith et al., 2016; Benjaminsen and Hiernaux, 2019; Hiernaux and Assouma, 2020). Re-greening can mean a variety of things, so it is important to account for encroachment of unpalatable plant species to rangeland areas (e.g., in East Africa and southern Africa's Kalahari), the loss of open ecosystems through woody plant invasion, and intensive use of chemical fertilizers in croplands (e.g., in Asia) through ground-truthing of remotely sensed trends. What may appear as "greening" may be masking underlying land degradation processes and losses of ecosystem services, livelihood and adaptation options (e.g., (Reed et al., 2015; Le et al., 2016; Chen et al., 2019). Ultimately, the vulnerability of an area to shrub encroachment depends on a combination of the land use and the functional traits of plants that shape how they respond to all drivers, human and climatic (Bond, 2008; Stevens et al., 2017; Thomas et al., 2018).

Despite global greening trends, dust and sandstorms have been highlighted as a particular concern for desert areas under conditions of climate change and desertification (Middleton, 2017). Although there is *high confidence* that desertification contributes to dust and sand storm activity, currently, there is limited knowledge on the role of climate change in dust and sand storms (Mirzabaev et al., 2019), even though those effects can be substantial. In West Africa, the frequency and intensity of dust storms increased during droughts of the 1970s-1980s then decreased afterwards with increased rainfall (Kergoat et al., 2017). Only about 20% of deserts are covered by sand, but desert dust and sandstorms provide an important feedback mechanism to climate (Pu and Ginoux, 2017), with the literature showing that some areas have very high numbers of dust days (Figure CCP 3.2) (Ginoux et al., 2012). Deserts and other natural dryland surfaces produced 75% to 90% of dust in the air globally in the early 21st century, with the remaining fraction coming from agricultural and other land dominated by human land use (Ginoux et al., 2012; Stanelle et al., 2014).

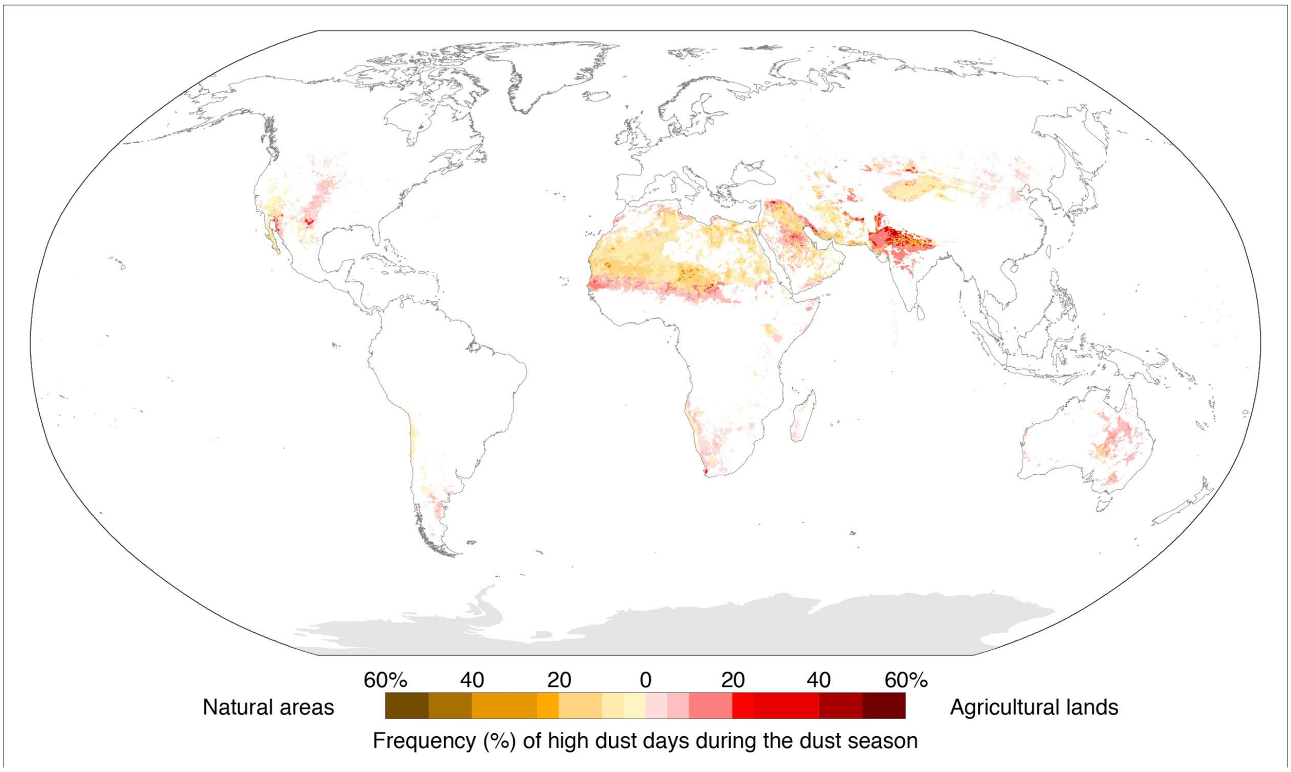

Figure CCP3.2: Frequency of high dust days (dust optical depth >0.2) during the dust season, based on 2003-2009 remote sensing, the most recent data analysed, and divided into areas primarily in agriculture and areas dominated by natural land cover (Ginoux et al., 2012). Dust seasons: Africa (North), January-December; Africa (South), September-

February; America (North), March-May; America (South), December-February), Asia, March-May; Australia, September-February.

CCP3.2 Observed Impacts of Climate Change Across Sectors and Regions

CCP3.2.1 Observed Impacts on Natural Systems in Desert and Semi-arid Areas

Dryland ecosystems have shown mixed trends of decreases and increases in vegetation and biodiversity, depending on the time period, geographic region, and vegetation type assessed. Increases in shrub and tree cover in arid areas have been recorded in the North American drylands (Caracciolo et al., 2016; Archer et al., 2017; Chambers et al., 2019), Namib desert (Rohde et al., 2019), the Karoo (Ward et al., 2014; Masubelele et al., 2015b), north and central Mexico (Pérez-Sánchez et al., 2011; Báez et al., 2013; Castillón et al., 2015; Sosa et al., 2019), in large parts of the West African Sahel with some local exceptions (Brandt et al., 2016), and in Central Asia (Jia et al., 2015; Li et al., 2015; Deng et al., 2016; Wang et al., 2016; Jiao et al., 2016). Increasing woodiness in the Namib is consistent with an increase in rainfall extremes and westward expansion of convective rainfall (Haensler et al., 2010; Rohde et al., 2019) whilst woody increase in other drylands is often a product of interactions between land use and climate change (Archer et al., 2017). Particularly in arid areas, rising concentrations of CO_2 improve water use efficiency, which can benefit shrubs (Polley et al., 1997; Morgan et al., 2004; Donohue et al., 2013) and is a cause of woody encroachment in these regions, alongside changes in land use (Hoffman et al., 2018), while greening can relate to both rainfall increases, improved local land management (Reij et al., 2005), and improved irrigation (He et al., 2019).

Because of a rainfall increase in the Sahel since the 1980s, the remote sensing-derived normalized difference vegetation index (NDVI) (Tucker, 1979) found an increase in herbaceous cover (Eklundh and Olsson, 2003; Olsson et al., 2005; Fensholt et al., 2006; Dardel et al., 2014). NDVI remote sensing, calibrated by field measurements, also found increases of woody foliage biomass across the Sahel from 1992 to 2012 (Brandt et al., 2019) and increases in woody cover from 1992 to 2011 (Brandt et al., 2016; Brandt et al., 2017). NDVI is not without its challenges, however. See SRCCL section 3.2.1.1 for an evaluation of NDVI and remote sensing approaches. Furthermore, farmers in many parts of the Sahel engage in natural tree regeneration, so these activities played a role in increasing tree cover, particularly next to villages (Gonzalez, 2001; Reij et al., 2005; Gonzalez et al., 2012; Reij and Garrity, 2016; Brandt et al., 2018) (*high confidence*). One particular limitation of NDVI is that the AVHRR sensor of the main NDVI time series only came into service in 1981 (Tucker et al., 1983). Drought in the Sahel in the periods 1968-1973 and 1982-1984 resulted in low herbaceous cover at the start of the NDVI time series in 1982, explaining much of the subsequent increase in herbaceous cover (Anyamba and Tucker, 2005; Ahmed et al., 2017; Kusserow, 2017). To illustrate, Dardel et al. (2014) and Brandt et al. (2019) found increased NDVI across the West African Sahel for the period 1981-2011, while Yuan et al. (2019) and Zida et al. (2020a) found that NDVI time series increased in the first part of the period, from 1982 to 1998, then decreased from 1999 to 2015, when an increase in aridity constrained net primary productivity.

Contrasting with the above findings, field measurements have also detected tree mortality and loss of mesic tree species at some sites across the Sahel (Gonzalez et al., 2012; Kusserow, 2017; Brandt et al., 2018; Ibrahim et al., 2018; Trichon et al., 2018; Zwarts et al., 2018; Bernardino et al., 2020; Zida et al., 2020) and a reduction of mesic species in favour of drought-tolerant species (Hänke et al., 2016; Kusserow, 2017; Ibrahim et al., 2018; Trichon et al., 2018; Zida et al., 2020b) (*high confidence*). This follows earlier research finding extensive tree mortality across the drier parts of the Sahel resulting from the droughts of the 1970s and 80s (Benjaminsen, 1996; Gonzalez, 2001; Wezel and Lykke, 2006; Maranz, 2009; Vincke et al., 2010; Gonzalez et al., 2012). Climate research associates the Sahelian droughts of the 1970s and 80s with increases in sea surface temperature (Folland et al., 1986; Giannini et al., 2003; Biasutti and Giannini, 2006; Zhang et al., 2007; Suárez-Moreno et al., 2018b) due to anthropogenic climate change (IPCC, 2013; IPCC, 2019) and anthropogenic aerosols (Ackerley et al., 2011) (*high confidence*). The impact of drought in the southern Sahel and sub-humid regions has been exacerbated by land clearance for farming, further decreasing woody population density and cover in some places (Mahamane et al., 2007; Rischkowsky et al., 2008), but also with large temporal and spatial variations (Brandt et al. 2016).

Other site-specific impacts include tree mortality in south-western Morocco (Le Polain de Waroux and Lambin, 2012), mortality of *Austrocedrus* and *Nothofagus* forests in the dry Patagonia forest-steppe (Rodríguez-Catón et al., 2019), and a tree range contraction of *Aloidendron dichotmum* of South (Foden et al., 2007b). In Morocco, tree mortality was most highly correlated to an increase in aridity, measured by the Palmer Drought Severity Index (PDSI), which showed a statistically significant increase since 1900 due to anthropogenic climate change (Dai et al., 2004; Esper et al., 2007; Dai, 2011). Since the IPCC's Fifth Assessment Report, a loss of bird biodiversity in the Mojave Desert in the United States has also been detected and attributed to increased aridity caused by the increasing temperatures of anthropogenic climate change (Iknayan and Beissinger, 2018; Riddell et al., 2019). Experimental studies indicate that under warming scenarios some succulent plants experience reduced physiological performance, loss of seed banks, lower germination rates and, in some instances, increased mortality (Musil et al., 2005; Aragón-Gastélum et al., 2014; Shryock et al., 2014; Martorell et al., 2015; Carrillo-Angeles et al., 2016; Aragón-Gastélum et al., 2017; Aragón-Gastélum et al., 2018; Koźmińska et al., 2019).

In the Mojave and Sonoran deserts of the south-western United States, a drought since 2000, mainly due to anthropogenic climate change (Williams et al., 2020), together with land use change, invasive plant species, and an increase in wildfire (Syphard et al., 2017), has led to reductions in individual desert plant species (DeFalco et al., 2010; Conver et al., 2017) and perennial vegetation cover (Munson et al., 2016). An increase in invasive exotic grasses has amplified wildfires in these desert ecosystems in which fire had been rare, while burning reduces native vegetation cover in favour of invasive exotic grasses (Brooks and Matchett, 2006; Abatzoglou and Kolden, 2011; Hegeman et al., 2014; Horn and St. Clair, 2017).

At numerous sites in Africa, Australia, and South America, woody encroachment into savannahs has occurred due to a combination of land use change, changes in rainfall, fire suppression and CO_2 fertilization (Stevens et al., 2017) (*high confidence*). Widespread encroachment has occurred in African savannahs (O'Connor et al., 2014; Stevens et al., 2016; Skowno et al., 2017; Venter et al., 2018; Zhang et al., 2019). The encroachment has been attributed to increased rainfall (Venter et al., 2018; Zhang et al., 2019), warming (Venter et al., 2018) and CO_2 fertilisation (Kgope et al., 2010; Bond and Midgley, 2012; Buitenwerf et al., 2012; Stevens et al., 2016; Quirk et al., 2019) but it is probable that these impacts also interacted with land use (Archer et al., 2017; Venter et al., 2018) including grazing intensity by settled pastoralists (e.g., in Kenya and Botswana). In some cases, it has been balanced locally either by changes in the run-off system (Trichon et al., 2018) or by human clearing or cutting practices for fuel wood, as in western Niger, northern Nigeria, and at the periphery of major towns (Montagné et al., 2016). Lower rates of savannah encroachment are occurring in Australian savannahs (Stevens et al., 2017). Extremely high rates of both woody encroachment and forest expansion into savannahs are occurring in South America (Stevens et al., 2017; Rosan et al., 2019) with the causes being most strongly attributed to land-use abandonment and fire suppression (Durigan and Ratter, 2016; Eloy et al., 2019; Rosan et al., 2019). Land use may also interact with changing CO_2 which enhances tree growth in these regions (Quirk et al., 2019). Detection and attribution of this and other ecological changes in drylands remains a research gap.

Changes in aridity (Rudgers et al., 2018) have caused the expansion of dominant grasses into desert shrublands in the Chihuahuan desert (Collins and Xia, 2015; Rudgers et al., 2018) (*low confidence*). Arid grassland has expanded (between 10-100km) into the eastern Karoo, South Africa, due to shift in rainfall seasonality (du Toit et al., 2015; Masubelele et al., 2015a; Masubelele et al., 2015b) (*high confidence*). Observations from 100-year-old grazing trials demonstrate that the increase in grassiness is a product of shift in rainfall seasonality and an increase in rainfall (Du Toit and O'Connor, 2014; du Toit et al., 2015; Masubelele et al., 2015a; Masubelele et al., 2015b; du Toit et al., 2018).

Zhang et al. (2020) noted that the degree of desertification had decreased in north-eastern and north-western regions of China during 1975 to 1990, mainly owing to shifting climatic trends. Similar trends of land degradation and desertification as an impact of changing climatic trends have been reported by Savage et al. (2009) for Afghanistan, by Mahmoudi et al. (2011) for Iran, by Barbosa et al. (2015) for Argentina, while Kamali et al. (2017) reported the frequency of droughts to increase in future, owing to changing climate in the semi-arid Karkheh River Basin of Iran. Climate change was also flagged as being responsible for land degradation in Jaggar watershed area, in Rajasthan, India (Javed et al., 2012).

Changes in vegetation and exposure of soil to wind and water erosion can have important impacts on soil dust emissions. Soil dust emissions are highly sensitive to changing climate conditions but also to changing land use and management practices (*high confidence*). Distinguishing between the effects of these two sets of drivers is not however straightforward, even in well-documented locations (Middleton, 2019). Assessing anthropogenic dust loads remains highly uncertain at all scales (Webb and Pierre, 2018). In dryland regions, sand and dust storms are common (Ahmed et al., 2016). Currently, there is *limited evidence and low agreement* about the impacts of climate change on sand and dust storms (SDS), with available studies pointing to either substantial increases (+300%) or decreases (-60%) (Boucher et al., 2013). At present, climate models cannot adequately model the impact of climate change on dust and sand storm activity (Mirzabaev et al., 2019). However, there is *high confidence* that land degradation, loss of vegetative cover, and drying of water bodies in semi-arid and arid areas will contribute to dust and sand activity (Mirzabaev et al., 2019). This will impact ecosystems and human systems, affecting health, water, food, livelihoods, and socio-economic structures and cultural practices.

Recent changes in dust emissions and their attributions vary geographically. Warming in Iran over the period 1951–2013 has been associated with an increase in the frequency of dust events (Alizadeh-Choobari and Najafi, 2018) and a trend (2000–2014) towards increased fine atmospheric mineral dust concentrations in the US southwest has been linked to increasing aridity (Hand et al., 2017). Conversely, increases in rainfall, soil moisture, and vegetation linked to changes in circulation strength of the Indian summer monsoon since 2002 have led to a substantial reduction of dust in the Thar Desert and surrounding region showing agreement with findings from the Sahel and the West African Monsoon (Kergoat et al., 2017). A decreasing trend in the number and intensity of sand and dust storms in spring (2007-2016) in East Asia has also responded to higher precipitation and soil moisture, related to a decrease in the intensity of the polar vortex, favouring better vegetation cover during the period studied (An et al. 2018). Dust effects can range over long distances. For example, dust from the Gobi Desert traverses the Pacific Ocean and increases dust aerosols in western North America (Liu et al., 2019b). Global climate change, transboundary movement of aeolian material by atmospheric flows from Central Asia, dynamics of the Caspian Sea regime, processes of erosion, salinization of soils, as well as the loss of land as a result of the placement of industrial facilities have contributed to the expansion of land prone to desertification in Russia. Currently, desertification has been observed to some extent in 27 sub-regions of the Russian Federation on the territory of more than 100 million hectares (Edelgeriev, 2019). Eastern and south-eastern regions of Kalmykia, in Russia, serve as dust storm sources, while dust and sand masses from the areas of the Black Land sometimes move far beyond to parts of Rostov, Astrakhan, Volgograd, and Stavropol regions. Agricultural land in these areas can become covered with a layer of dust and sand up to 10 centimetres or more thick, with important negative impacts on yields (Edelgeriev, 2019).

Water bodies have also been affected by dust and sand storms, while climate change and desertification have been linked to water loss and a negative effect on water (Bayram and Öztürk, 2014; Schwilch et al., 2014; Mohamed et al., 2016), through decreases in water quantity for irrigation and contamination of surface water bodies (Middleton, 2017). Increased runoff in areas in the Sahel with shallow soils increased water flows to lakes and the recharge of water tables (Favreau et al., 2009; Gardelle et al., 2010; Descroix et al., 2013; Amogu et al., 2015; Kaptué et al., 2015; Gal et al., 2017). Water scarcity was among the first impacts of climate change recognized in North African countries such as Morocco which have extensive dryland areas. The decrease in water availability in Morocco was substantial in terms of both surface water supply (Rochdane et al., 2012; Choukri et al., 2020) and groundwater (Bahir et al., 2020), threatening agricultural production, the backbone of the country's economy.

Table CCP3.A.1 in Appendix CCP3.A provides examples of observed ecological changes in drylands and highlights the role of anthropogenic climate change and non-climatic factors in causing these changes.

CCP3.2.1.1 Teleconnections

Vegetation-atmosphere feedbacks connect drylands and the rest of the world, affecting the severity of climate change in drylands and globally. Deforestation in one region can reduce evapotranspiration inputs to the atmosphere, leading to drier conditions elsewhere, often in drylands (Avissar and Werth, 2005; Devaraju et al., 2015; Wang et al., 2016; Swann et al., 2018). In areas of increased herbaceous cover, slight cooling due to increased evapotranspiration and latent heat flux can occur (Yu et al., 2017). In the West African

Sahel, climate research has, however, demonstrated that rainfall is driven more by changes in sea surface temperature of the global oceans, rather than the albedo effect (Folland et al., 1986; Stith et al., 2016). Hence, periodic drying in the Sahel in the 20th century, including the anomalously wet decades of the 1950s and 1960s, were suggested to have been initiated by warmer sea surface temperatures due to anthropogenic climate change (Giannini et al., 2003; Shanahan et al., 2009; Giannini, 2016; Stith et al., 2016; Suárez-Moreno et al., 2018a; Villamayor et al., 2018). Reduced vegetation cover in Guinean forests and Sudanian woodlands may, however, have amplified periodic drying via reduced evapotranspiration (Zeng et al., 1999; Liu et al., 2019a).

CCP3.2.2 Observed Impacts of Climate Change on Human Systems in Desert and Semi-arid Areas

The SRCCL found that interaction of climate change and desertification, including alongside other drivers of degradation, reduces dryland ecosystem services, including losses of biodiversity, water, food, and impacts human health and well-being *(high confidence*) (Mirzabaev et al., 2019) resulting in the disruption of the economic structures and cultural practices of affected communities (Elhadary, 2014; Middleton, 2017). Desertification and sand and dust storms (SDSs) can cause substantial socioeconomic damage in drylands (UNEP, 2016). SDS result in both short- and long-term economic impacts. Short-term costs include impacts on health, food production systems, infrastructural damage (e.g., to buildings, energy generating plants, and communications), interruption of transport and related economic productivity, air and road traffic accidents, and costs of clearing sand and dust from affected deposition areas) (Mirzabaev et al., 2019). Longer-term costs include loss of ecosystem services, biodiversity and habitat, chronic health problems, soil erosion and reduced soil quality (particularly through nutrient losses), soil pollution through deposition of pollutants, and disruption of global climate regulation (UNEP, 2016; Middleton, 2018; Allahbakhshi et al., 2019). Dust deposition nevertheless can offer some environmental and economic benefits, bringing e.g., important nutrients that improve and sustain soil fertility (Marticorena et al., 2017). Preventing and reducing SDS entails upfront investment costs but full cost-benefit analyses of different measures compared to the costs of inaction are scarce and would also need to consider the likely frequency and magnitude of SDS events (Tozer and Leys, 2013).

CCP3.2.2.1 Human Health

The potential impacts of climate change, recurrent droughts and desertification on human health in drylands include: higher risks from water scarcity (linked to deteriorating water quality and water-borne diseases), food insecurity and malnutrition; respiratory, cardiovascular and infectious diseases caused by dust and sand storms (Mirzabaev et al., 2019), potential displacement and migration and mental health consequences (Chapter 7). SDS can have negative impacts on human health through various pathways causing respiratory, cardiovascular diseases and facilitating infections (Díaz et al., 2017; Goudarzi et al., 2017; Allahbakhshi et al., 2019; Münzel et al., 2019) (*high confidence*). Inhalation of fine dust particles (PM 10 and PM 2.5) can cause or aggravate diseases such as chronic obstructive pulmonary disease, asthma, bronchitis, emphysema and lung fibrosis (Gross et al., 2018). Chronic exposure to fine dust is associated with premature death due to cardio-respiratory diseases (Münzel et al., 2019). More than 400,000 cardiopulmonary deaths and 3.47 million of years of life lost were estimated in 2005 globally (Giannadaki et al., 2014). Fine dust carries a range of pollutants, spores, bacteria, virus and fungi, and can cause or facilitate infections such as influenza A virus, pulmonary coccidioidomycosis, bacterial pneumonia, and meningococcal meningitis (Achakulwisut et al., 2018). In the Sahel, there is a strong correlation between dust loads from the Sahara and meningitis, with 350 million people at risk across 21 Sahel countries (Jusot et al., 2017). SDS can cause mortality and injuries related to transport accidents (Goudie, 2014). Recent studies in China suggest that prenatal exposure to SDS can affect children's cognitive function (Li et al., 2018). The exact nature of the pollutants that are entrained and ingested or inhaled closely links back to the land management strategies in the source areas.

Droughts are the climate shocks that have produced the greatest adverse impact on human populations out of any natural hazard during the 20th century (Mishra and Singh, 2010). Although droughts just represented 11% events, their impacts amounted to 80% of affected people (270 million) (CRED, 2019). Drought exposure has been associated with a higher risk of undernutrition, not only during the drought, but also several years after the event (Kumar, 2016). These impacts can be lifelong for children affected by undernutrition during their first 1,000 days of life (IFPRI, 2016.) leading to stunted growth, which is associated with impaired cognitive ability and reduced school and work performance in the future

(UNICEF/WHO/WBG, 2019). The corresponding costs of children stunting in terms of lost economic growth can be of the order of 10% of GDP per year in Africa (Wagstaff, 2016). Drought has been linked to excess mortality through inducing undernutrition, micronutrient deficiencies, food- and water-borne diseases; aggravating chronic diseases; declining crop and livestock production; and triggering drought-induced migration (Delbiso et al., 2017). In Ethiopia in 2015–2016, following the devastating impact of El Niño weather events, Ethiopia experienced one of the worst droughts in the last five decades. Consequently, more than 10 million people (over 10% of the total population) were in need of urgent food assistance.

CCP3.2.2.2 Agro-ecological food systems, livelihoods and food security

Climate change, rising temperatures, variation in rainfall patterns and frequent extreme weather events have made the agricultural systems vulnerable in some dryland regions (Zhu et al., 2013; Amin et al., 2018), especially in developing countries (Haider and Adnan, 2014; Ahmed et al., 2016; ur Rahman et al., 2018). At the same time, climate changes have created environmental and economic opportunities in some other agro-ecological systems (Bonnet, 2013). Higher frequency and intensity of dust storms also impact agro-ecological food systems and landscapes, reduce crop and livestock productivity, affecting food security and human wellbeing. SDS can adversely impact agro-ecological landscapes and food systems by directly damaging crops and other vegetation by sandblasting (resulting in loss of plant tissue and reduced photosynthetic activity), and burial of seedlings under sand and dust deposits, delaying plant development and increasing end of season drought risks (Stefanski and Sivakumar, 2009).

Recurrent droughts in recent decades, coupled with wind erosion, endangered vast areas in Argentina, and led to land abandonment and agricultural fields being covered by sand and invasive plants (Abraham et al., 2016). Soil productivity losses are encountered as fertile top soils are removed (Sivakumar, 2005; Bayram and Öztürk, 2014; Omoyo et al., 2015; Al-Hemoud et al., 2017; Middleton and Kang, 2017), while contamination can occur by deposition of saline or toxic dusts on soils, for example, in the former Aral Sea area (Issanova et al., 2015). Temperature increases have contributed to reduced yields of wheat in arid, semi-arid and dry sub-humid zones of Pakistan (Sultana et al., 2009). For example, agricultural production in the drylands of South Punjab is experiencing irreversible impacts since the grain formulation phase has become swifter with a warmer climate, leading to improper grain formulation and reduced yields (Rasul et al., 2011) while Aslam et al. (2018) regard the impacts of climate change to be particularly threatening to the livestock sectors, water resources and food security and the economy beyond agriculture in South Punjab. In the livestock sector, observed impacts include reduction of plant cover in rangelands, reduced livestock and crop yields, loss of biodiversity and increased land degradation and soil nutrient loss (Mganga et al., 2015; Ahmed et al., 2016; Mohamed et al., 2016; Eldridge and Beecham, 2018), as well as injury and livestock death due to SDS. This is particularly worrisome for traditional pastoralists who have few safety nets and limited adaptive capacities. Together, these observed impacts can result in increased costs of food production and threaten sustainability more generally (Middleton, 2017) (also see Box CCP3.1 on Pastoralism and Climate change below).

[START BOX CCP3.1 HERE]

Box CCP3.1: Pastoralism and Climate Change

Pastoralism is a livestock keeping system based on the herding of animals. Migrations often take place over long distances to track variable and unpredictable plant growth that tends to be patchy in time and space (Homewood, 2018). This means that pastoralism should be distinguished from stall-feeding and ranching – two other common livestock keeping systems, but which do not involve herding (Hiernaux and Assouma, 2020). Pastoralism has a considerably lower carbon budget than other livestock-keeping systems. Research on pastoralism in the Sahel concluded that this system may in fact have a neutral carbon balance (Assouma et al., 2019). Grazing livestock do, however, contribute directly to greenhouse gas emissions by methane enteric emissions and indirectly through faeces-driven CO_2, CH_4 and N_2O emissions during mineralisation (Assouma et al., 2017).

Pastoralists migrate with their animals in some of the most remote and marginal environments on the globe such as the dry tropics, the Arctic and high mountain areas. Globally, mobile pastoralists number about 200 million households and use about 25% of the Earth's landmass (Dong, 2016).

Many pastoralists operate in environments that can be characterised as non-equilibrial, which means that these environments are unstable, fluctuating and generally uncertain, and driven more by climatic variation than livestock numbers and grazing pressure (Behnke et al., 1993). Typical examples of such non-equilibrial systems are grazing areas in the dry tropics (Sandford, 1983; Ellis and D.M, 1988; Turner, 1993; Sullivan and Rohde, 2002; Benjaminsen et al., 2006; Hiernaux et al., 2016), but also, rangelands in the Arctic may exhibit non-equilibrial properties (Behnke, 2000; Tyler et al., 2008; Benjaminsen et al., 2015; Marin et al., 2020).

Through time and over many generations, pastoralists have accumulated practical experience and knowledge about how to cope with uncertainty, mainly through a mobile and flexible approach, which means that they may be better suited than other land users to adapt to a changing climate (Davies and Nori, 2008; Krätli and Schareika, 2010; Jones and Gutzler, 2016). But pastoralists are also at risk from climate change, since their livelihoods are based on the use of renewable resources in these variable and uncertain environments, which are exposed to rising temperatures and increasing rainfall variability.

While pastoralists possess great adaptive capacity as a result of their indigenous knowledge and local knowledge, this capacity has been under pressure during the last few decades through continued loss of livestock corridors (essential to mobility) and pastures in general due to competing land-uses such as farming, mining, crop expansion and the establishment or extension of protected areas (Thébaud and Batterbury, 2001; Brockington, 2002; Benjaminsen and Ba, 2008; Upton, 2014; Johnsen, 2016; Tappan, 2016; Homewood, 2018; Weldemichel and Lein, 2019; Bergius et al., 2020). Many of these competing land uses erect fences and exclude other uses, depending on the property rights the often privilege sedentary farming populations. The remoteness of many pastoral communities also restricts the availability of social safety nets and the ease with which disaster aid can reach vulnerable populations during times of crisis.

Modern states have typically tried to settle pastoralists and confine their movements within clearly defined boundaries, justifying such actions through claims that pastoral land-use is neither ecologically sustainable nor economically productive. Based on such negative and often flawed views, stall-feeding and ranching are often presented by policy-makers as successful models of livestock keeping in contrast to the pastoral way of life(Steinfeld et al., 2006; Chatty, 2007). Sedentarization and villagization projects have been common results of how policy-makers tend to see pastoral systems. However, these practices can lead to higher overall emissions from the sector.

Current pressures and processes of pastoral change are not uniform, but spatially variable and complex, and in general tend to result in further economic and political marginalization of pastoralists, with adverse effects on livelihoods and landscapes. With climate change, which is projected to lead to higher temperatures and more frequent fluctuations in precipitation, maintaining flexibility and resilience in pastoral land use is essential. However, current processes of marginalization make pastoralists more vulnerable and constrain them from fully employing their adaptive capacities (Davies and Nori, 2008). The skills and capacities held by pastoralists may, however, also provide lessons for society at large in its struggle to adapt to climate change and deal with increased uncertainty (Davies and Nori, 2008; Scoones, 2009).

[END BOX CCP3.1 HERE]

CCP3.2.2.3 Gender differentiated impacts

Desertification, climate change, and environmental degradation impacts, vulnerability, and capacity to adapt have gendered differences. These differences are determined by socially structured gender-specific roles and responsibilities, access and control over natural resources and technology, decision making, and capacity to cope and adapt to long-term changes (Mirzabaev et al., 2019). Assessments of the gender dimension of desertification and climate change impacts and responses are very scarce, since they are highly context specific. For example, in many lower income countries, rural women often produce most of the food consumed at the household and are responsible for preparing the food, collecting fuelwood and fetching water from increasingly remote areas due to desertification and water scarcity (Mekonnen et al., 2017). Droughts and water scarcity particularly affect women and girls in drylands because they need to spend more time and energy collecting water and fuelwood, have less time for education or engaging in income generating activities, and they may be more exposed to physical and sexual violence (Sommer et al., 2014). Women are also commonly excluded from family and community decision making on actions to address desertification and climate change, yet their engagement in climate adaptation is critical. International policy efforts are currently seeking to better recognise and address this challenge (Okpara et al., 2019).

CCP3.2.2.4 Climate change, migration and conflict

Dryland populations are generally mobile due to a highly fluctuating resource base. To track environmental variation, pastoralists migrate every year, often over several hundred kilometres. Many rural dwellers in drylands also move to urban areas for seasonal work when there is less need for farm labour. In Africa, there is also a long tradition of legal as well as illegal labour migration to Europe (Tiemoko, 2004). Lack of livelihood opportunities and food insecurity are the main reasons given for migration by the migrants themselves. For instance, in a survey in Libya in 2016, 80% of migrants interviewed said they had left home because of economic hardship (Tiemoko, 2004; Hochleithner and Exner, 2018).

Hence, causes of migration as well as of conflict need to be seen in a wider historical, agrarian, political, economic and environmental context, and should be understood within a multi-scalar perspective integrating various levels of analysis from the local to the global (Glick Schiller, 2015). Isolating environmental or climate factors is, however, complicated. Quantitative studies tend to conclude that climate change has so far not significantly impacted on migration levels (Owain and Maslin, 2018), although with some disagreement (Missirian and Schlenker, 2017). In a rare study of the climate change-migration-conflict interface, Abel et al. (2019) found limited empirical evidence supporting a link between climatic shocks, conflict and asylum seeking for the period 2006–2015 from 157 countries. The authors found evidence of such a link for the period 2010–2012 relating to some countries affected by the Arab Spring, and they conclude that the impact of climate on conflict and migration is limited to specific time periods and contexts.

The same lack of general causality is largely concluded on the specific link between climate change and conflict (Buhaug et al., 2014; Buhaug et al., 2015; von Uexkull et al., 2016; Koubi, 2019), but also here with a minority among quantitative studies arguing for a stronger causal association (Hsiang et al., 2013). In a recent expert elicitation study, Mach et al. (2019) found considerable agreement among experts that climate variability and change have influenced the risk of organized armed conflict within countries. But the experts also agreed that other factors, such as state capacity and level of socioeconomic development, have played a much larger role.

Qualitative case studies tend to frame conflict and migration within a larger political economic and historical context. A number of studies find that land dispossession is a key driver of both migration and conflict resulting from large-scale resource extraction or land encroachment often associated with processes of elite capture and marginalization (Benjaminsen and Ba, 2009; Benjaminsen et al., 2009; Cross, 2013; Glick Schiller, 2015; Nyantakyi-Frimpong and Bezner Kerr, 2017; Obeng-Odoom, 2017; Benjaminsen and Ba, 2019; Bergius et al., 2020).

By undermining livelihoods, exacerbating poverty, and setting rural population groups adrift, dispossession may lead to increased migration to urban areas or out of the country. In addition, it may lead to other types of reactions including violent resistance (Oliver-Smith, 2010; Cavanagh and Benjaminsen, 2015; Hall et al., 2015). Such resistance may originate in feelings of marginalization and disempowerment resulting from the loss of access to land or livelihood options, combined with opposition to government corruption, mismanagement, and policies that do not serve the interests of small-scale producers (Benjaminsen and Ba, 2019).

We have already seen increased resistance and migration following a rural crisis in the West African Sahel, especially since 2012. The main drivers of the current crisis in, for instance, Mali, include decades of bureaucratic mismanagement and widespread corruption, the spill-over of jihadist groups from Algeria after the civil war there in the 1990s, and the North American Treaty Organisation (NATO) bombing of Libya in

2011. Climate change has played a marginal role as a cause of conflicts in the Sahel (Benjaminsen et al., 2012; Benjaminsen and Ba, 2019). Within fragile systems, climate change has, however, the potential to exacerbate the situation in the future with regards to migration and conflict (Owain and Maslin, 2018).

CCP3.3 Future Projections

CCP3.3.1 Projected Changes and Risks in Natural Systems

CCP3.3.1.1 Temperature

Warming rates have been twice as high in drylands compared to humid regions, because the sparse vegetation cover and lower soil moisture of dryland ecosystems amplify temperature and aridity increases (Huang et al., 2016). This enhanced warming is expected to continue in the future (Huang et al., 2016; Huang et al., 2017). Surface warming over drylands is projected to reach ~6.5°C (~3.5°C) under the high RCP8.5 (low-moderate RCP4.5) emissions scenario by the end of this century. While exploring the spatial variations between the aeolian desertification response in selected climate change scenarios, Wang et al. (2017) reported that temperature rise could trigger aeolian desertification in West Asia, Central China and Mongolia.

CCP3.3.1.2 Rainfall, evaporation and drought

Dryland areas are highly sensitive to changes in precipitation and potential evapotranspiration (PET). Potential evapotranspiration is projected to increase in all regions globally, under all representative concentration pathways (RCPs) (Mirzabaev et al., 2019). Drought conditions (frequency, severity and duration) are expected to substantially worsen in many regions of the world, driven by a higher saturation threshold and more intense and frequent dry spells under rising temperatures (Liu et al., 2019a; Liu et al., 2019b). In a 1.5°C warmer world, historical 50-year droughts (based on the Standardised Precipitation-Evapotranspiration Index (SPEI)) could double across 58% of global landmasses, an area that increases to 67% under 2°C of warming (Gu et al., 2020). Multi-year drought events of magnitudes exceeding historical baselines will increase by 2050 in Australia, Brazil, Spain, Portugal, and the USA (Jenkins and Warren, 2015). The magnitude of drought stress in different regions differs depending on the metric used. Projections based on the Palmer Drought Severity Index (PDSI) suggest drought stress will increase by more than 70% globally, while a substantially lower estimate of 37% is found when precipitation minus evapotranspiration (P-E) is used (Swann et al., 2016). However, the two metrics agree on increasing drought stress in regions with more robust decreases in precipitation, such as southern North America, north-eastern South America and southern Europe (Swann et al., 2016).

CCP3.3.1.3 Aridity

Studies based on the aridity index (the ratio of potential evaporation to precipitation), almost always project conditions of increasing aridity under climate change, leading to projections of widespread expansion of drylands (Huang et al., 2016). Projections indicate potentially severe aridification in the Amazon, Australia, Chile, the Mediterranean region, southwest China, northern, southern and west Africa, south-western United States, and South America (Feng and Fu, 2013; Greve and Seneviratne, 2015; Jones and Gutzler, 2016; Park et al., 2018) (*medium confidence*). However, limitations in the use of the aridity index for projecting future conditions have been identified and are described in detail in Chapter 3 of the Special Report on Climate Change and Land (Mirzabaev et al., 2019). The key concern is that the AI does not incorporate potential changes to plant transpiration under increasing CO_2 concentration and therefore overestimates drought conditions and aridity. SRCCL concluded that while aridity will increase in some places (*high confidence*), there is insufficient evidence to suggest a global change in dryland aridity (*medium confidence*). Nevertheless, a comparison of several metrics of aridity showed robust aridity increases are projected for several hotspots such as the Mediterranean region and South Africa (Greve et al., 2019). Under RCP8.5, aridity zones could expand by one-quarter of the 1990 area by 2100, increasing to over half of the global terrestrial area (Huang et al., 2016; Lickley and Solomon, 2018). Lower greenhouse gas emissions, under RCP4.5, could limit the expansion to one-tenth of the 1990 area by 2100 (Huang et al., 2016). Aridity could expand substantially on all continents except Antarctica (Huang et al., 2016), with expansion first manifesting in the Mediterranean region, southern Africa, southern South America, and western Australia (Lickley and Solomon, 2018). In the Northern Hemisphere, aridity zones could expand as much as 11 degrees of latitude poleward (Rajaud and Noblet-Ducoudré, 2017). By 2100, the population of dryland areas could increase by 700 million people and, under RCP8.5, three billion people might live in areas with a 25% or greater increase in aridity (Lickley and Solomon, 2018). There are many studies pointing at an increasing dryland area based on the aridity index, but there is low agreement on the actual amount and area of change (Feng and Fu, 2013; Scheff and Frierson, 2015; Huang et al., 2017). The inconsistency between studies is largely due to the substantial internal climate variability in regional precipitation. For example, changes in annual precipitation have been shown to range from -30% to 25% over drylands. Consistent changes in precipitation are only found at high latitudes, while total potential evapotranspiration is projected to increase over most land areas. This leads to more consistent, widespread drying in the tropics, subtropics and mid-latitudes in most models (Feng and Fu, 2013; Cook et al., 2014; Scheff and Frierson, 2015; Zhao and Dai, 2015).

CCP3.3.1.4 Dryland extent

The area of drylands (bases on aridity index) globally is projected to expand by ~10% by 2100 compared to 1961-1990 under a high emission scenario (WGI AR6 Chapter 12). However, there are significant regional differences in the drivers of dryland expansion and subsequent estimates of change in dryland extent. Observed and projected warming and drying trends are most severe in transitional climate regions between dry and wet climates, which are often highly populated agricultural regions with fragile ecosystems (Cheng and Huang, 2016). In contrast, P-E predicts decreasing drought stress across temperate Asia and central Africa (Swann et al., 2016). Expansion of arid regions is likely in southwest North America, the northern fringe of Africa, the far west Sahel, southern Africa and Australia. The main areas of semiarid expansion are likely to occur in the north side of the Mediterranean, southern Africa and North and South America. In contrast, India, northern China, eastern equatorial Africa and the southern Saharan regions are projected to have shrinking drylands (Biasutti and Giannini, 2006; Biasutti, 2013; Feng et al., 2014; Rowell et al., 2016). It has been suggested that future projections may underestimate dryland expansion, since the Coupled Model Intercomparison Project (CMIP) 5 models underestimate historical warming (Huang et al., 2016) and overestimate precipitation over drylands, particularly in the semiarid and dry sub-humid regions (Ji et al., 2015). However, estimates vary depending on the metric used (Swann et al., 2016; Berg et al., 2017). Studies based on off-line aridity and drought metrics (calculated from model output of precipitation, evapotranspiration or temperature) project strong surface drying trends (Cook et al., 2014; Scheff and Frierson, 2015; Zhao and Dai, 2015), while projections based on total soil water availability from CMIP5 models show weaker and less extensive drying (Berg et al., 2017). In contrast, projections in southern Africa may overestimate future drying, with systematic rainfall biases being found in the present-day climatology in models that simulate extreme future drying (Munday and Washington, 2019). Improvements in projections of future changes in aridity will require better understanding of land hydrology and the feedbacks between projected soil moisture decrease on land surface temperature, relative humidity and precipitation (Huang et al., 2016).

Higher dust emissions are consistent with climate change projections indicating an expansion in the global area of drylands (Feng and Fu, 2013; Huang et al., 2016) and an increased risk of drought (Cook et al., 2014; Xu et al., 2019), but future trends in dust event frequency and intensity as a result of human-induced climate change are uncertain and will not be the same everywhere (Jia, 2019). The combined effects of climate change and anthropogenic activities are projected to increase sand encroachment and extreme dust storms (Omar Asem and Roy, 2010; Sharratt et al., 2015; Pu and Ginoux, 2017) as a result of increased aridity, accelerating soil erosion (Sharratt et al., 2015) and loss of biomass (Sharratt et al., 2015; Middleton and Kang, 2017). Shifts in dust storm occurrences to earlier in spring are also projected (Hand et al., 2016). Dustiness is projected to increase in the southern US Great Plains in the late 21st century under the (RCP8.5) climate change scenario but decrease over the northern Great Plains (Pu and Ginoux, 2017). A declining trend in dust emission and transport from the Sahara Desert under the Representative Concentration Pathways(RCP) 8.5 scenario was detected by (Evan et al., 2016) but the results of regional climate model experiments conducted by (Ji et al., 2018) under the same scenario indicated that overall dust loadings would increase by the end of the 21st century over West Africa. New dust sources may also emerge with changing climate conditions, as (Bhattachan et al., 2012) propose for the Kalahari Desert in southern Africa, due to vegetation loss and dune remobilization.

Self-reinforcing feedback loops may occur in the dust aerosol-cloud-precipitation interactions over drylands. As precipitation declines, more dust storms occur which reduces cloud cover and relative humidity (via the semi-direct effect), further contributing to decreasing precipitation (Huang et al., 2014). The relative contribution of albedo and evapotranspiration to regional trends in surface temperature (Charney, 1975). remains unresolved, and may be determined by different mechanisms in different systems, depending on site-specific conditions such as snow coverage, vegetation and soil moisture (Yu et al., 2017). For example, the vegetation-albedo feedback mechanism may dominate in the arctic tundra (Blok et al., 2011; te Beest et al., 2016), while the vegetation-evaporation feedback may drive change in other regions. Actions that increase forest cover across Africa could thus moderate projected future temperature increases (Wu et al., 2016; Diba et al., 2018). Soil drying exacerbates atmospheric aridity, which causes more soil drying in a self-reinforcing land–atmosphere feedback that could intensify under RCP8.5 (Zhou et al., 2019).

There is *low confidence* on future atmospheric dust loads at the global and regional scale. Models of future dust emissions are limited by the low accuracy of models of present anthropogenic dust emissions, which range from 10% and 60% of the total atmospheric dust load (Webb and Pierre, 2018). A global compilation of data from sedimentary archives (e.g., ice cores), remote sensing, airborne sediment sampling and meteorological station data estimated that anthropogenic dust emissions have at least doubled over the past 250 years (Hooper and Marx, 2018). While future emissions of natural dust sources are projected to decrease (Mahowald et al., 2006) or remain stable (Ashkenazy et al., 2012), when sources of human emissions are included, projections of future atmospheric dust loads suggest that emissions may increase (Stanelle et al., 2014). The cause of observed changes in atmospheric dust loads is uncertain, with climate variability, land cover change and changes in erodible sediment supply and surface wind speeds all considered possible mechanisms (Ridley et al., 2014; Webb and Pierre, 2018).

Changes to the composition, structure and functioning of natural communities in deserts and dryland ecosystems are key risks, resulting from water stress, drought intensity and continued habitat degradation, greater frequency of wildfire, biodiversity loss and the spread of invasive species (Hurlbert et al., 2019). Not all these stresses occur at the same time in a particular environment, with some areas more exposed to e.g., wildfire than others, especially in areas with high amounts of dry herbaceous biomass. Many desert species have morphological, physiological and/or behavioural adaptations to cope with climatic extremes, including rapid regeneration following droughts as found in the 1970s and 1980s Sahel droughts (Boudet, 1977; Hiernaux and Le Houérou, 2006), alongside long histories of adaptation to climate change (Brooks et al., 2005; Ballouche and Rasse, 2007), while many live near their physiological limits (Vale and Brito, 2015). Substantial ecological effects may occur when extreme events such as heatwaves or droughts are superimposed on the warming trend, pushing species beyond their physiological and mortality thresholds (Hoover et al., 2015). Africa has experienced more frequent and intense climate extremes (including droughts and heavy rainfalls) in the period 2000-2019 as a result of climate change (CRED, 2019), a trend that is likely to continue as climate change impacts intensify (Hoegh-Guldberg et al., 2018).

Continued climate change increases the risk of continued range retractions of Karoo succulents in South Africa (Young et al., 2016), dry argan woodlands in Morocco (Alba-Sánchez et al., 2015), and other plant species exposed to higher aridity. Projected increases in heat could increase mortality of trees and shrubs in Sonoran Desert ecosystems in the United States (Munson et al., 2012; Munson et al., 2016), reduce sagebrush shrubland in arid ecosystems of the western United States (Renwick et al., 2018), and contribute to the replacement of perennial grasses with xeric shrubs in the south-western United States (Bestelmeyer et al., 2018). CO_2 fertilization and warmer conditions could increase invasive grasses and wildfire in desert ecosystems of Australia and the south-western United States where wildfire has historically been absent or infrequent (Abatzoglou and Kolden, 2011; Horn and St. Clair, 2017; Klinger and Brooks, 2017; Syphard et al., 2017). Trends of woody encroachment may continue in some North American drylands or at least not reverse (Caracciolo et al., 2016). Impacts of woody encroachment on drylands may show a slight increase in carbon, but a decline in water and huge negative impacts on biodiversity, with a tendency for open ecosystem species to be most affected (Archer et al., 2017). Expansion of C4 grasses into these arid shrublands has the potential to transform them rapidly, especially through the acceleration of the fire cycle (Bradley et al., 2016). However, the impact of increased aridity may be offset by changing water use efficiency by plants under high CO_2 concentrations, limiting the expansion of dryland ecosystems (Swann et al., 2016; Mirzabaev et al., 2019).

CCP3.3.2 Projected Impacts on Human Systems

The projected impacts of climate change and desertification on human systems in dryland areas were extensively assessed in the SRCCL (Mirzabaev et al., 2019), hence this section largely focuses on the new information available during the preparation period of this Cross-Chapter-Paper. Across many dryland areas, human-induced causes of desertification, sand and dust storms, climate change and unsustainable land use, are projected to become more pronounced over the next several decades with global consequences. Future climate changes with increasing frequency, intensity and scales of droughts and heat waves, are projected to further exacerbate the vulnerability and risk to humans and ecosystems from desertification (Hurlbert et al., 2019).

Sand and dust storms exert a wide range of impacts on human society both within deserts and semi-deserts but also outside dryland environments because of long-range dust transport (Middleton, 2017). For instance, a series of three dust storms in north-western India in early May 2018 resulted in >150 people losing their lives in the very strong winds and associated lightning strikes(Sarkar et al., 2019). Many of the deaths occurred when trees fell onto buildings or as walls and roofs collapsed. Thousands of electricity poles were also blown over causing widespread power cuts. Notable impacts on society occur in diverse sectors, including agriculture (Borrelli et al., 2014), human health, solar power generation (Costa et al. 2016, 2018), and water availability (Painter et al. 2018). An increased incidence of dust storms is associated with an increase in the incidence of respiratory diseases (Schweitzer et al., 2018), cardio-vascular diseases (Achakulwisut et al., 2018), Rift Valley Fever (Tong et al., 2017; Gorris et al., 2018), and mortality of people from dust-associated health problems (Crooks et al., 2016; Achakulwisut et al., 2018; Schweitzer et al., 2018).

There is a notable lack of published research on the economic impacts of sand and dust storms, and studies that have been conducted lack consistency in data collection methods and analysis (Middleton, 2019). An assessment of costs for a single severe dust storm in the Australian state of New South Wales in 2009 was approximately AU$299 million, most of which was incurred by households for cleaning and associated activities (Tozer and Leys, 2013). The cost of sand, and to a lesser extent dust, to the oil and gas industry in Kuwait was conservatively estimated by Al-Hemoud et al. (2019) to be US$1.2 million annually. Projections are rarely modelled in the literature. Estimated economic damages of increased dust-related health impacts and mortality under RPC8.5 could total $47 billion/year additional to the 1986-2005 value of $13 billion/year in southwest USA (Allahbakhshi et al., 2019).

The projected impacts of climate change on the risk of food insecurity is a particular concern for the dryland areas in the developing world (Chapter 16; Mirzabaev et al., 2019), potentially leading to the breakdown of food production systems, including crops, livestock, and fisheries, as well as disruptions in food supply chains and distribution(Myers et al., 2017). Dryland areas in developing countries are particularly vulnerable to this risk due to higher share of populations with lower income, lower physical access to nutritious food, social discrimination or other factors. For example, countries such as Somalia, Yemen and Sudan faced recent and resurging challenges from an increase in desert locusts, the effects of which in 2020 extended from East Africa through the Arabian Peninsula as far as India and Pakistan. Meynard et al. (2020) note that under climate change, some areas suffering from previous outbreaks may see changes in formation of swarms of *Schistocerca gregaria*. Salih et al. (2020) recognise that attributing the 2020 swarms as a single event to climate change remains challenging, but nevertheless highlight that projected temperature and rainfall increases in deserts and strong tropical cycles can cause the conducive conditions to develop for the development, aggregation, outbreak and survival of locusts, underscoring the importance of this in terms of its impacts on food security under projected climate change. Mandumbu et al. (2017) highlight how crop parasites such as *Striga spp.* may benefit from projected climate changes in southern Africa, with high temperatures and rainfall activating dormant seeds, and high winds aiding their dispersal. Combined with increasing risks of erosion and soil fertility losses (*Striga* is able to tolerate a low nitrogen environment), this can have important impacts on yields of key dryland crops such as maize and millet. Moreover, higher frequency, intensity and scales of dust storms due to climate change-desertification interactions, can impact agro-ecological landscapes and food systems, reduce crop and livestock productivity, adversely affecting food security and human wellbeing (Mirzabaev et al., 2019), though it is not clear if dust storm increases are projected for all drylands, given observed decreases since the mid-1990s in the Sahel (Kergoat et al., 2017).

How humans respond to these changes is important too and can exacerbate desertification processes under climate change conditions, even in deserts. While areas close to cross-desert rivers, dryland groundwater reserves and desert sites irrigated by the transport of water from other areas can dramatically increase local desert soil productivity, the large human populations supported through such increased cultivation potential, can encourage unsustainable land use practices. In turn, this can result in desert desertification, expressed as soil erosion and salinisation. For example, in India, about 7.0 M ha arable land area is currently salt-affected (Sharma et al., 2015; Sharma and Singh, 2015). It is projected that unsustainable use of marginal quality waters in irrigation and neglect of drainage, combined with climate change impacts, would accelerate land salinization, rendering another 9.0 M ha area salty and less productive by 2050 (ICAR-CSSRI, 2015). This has important cost implications given that annually, 16.84 million tonnes of farm production valued at INR 230.19 billion is already lost in India due to salinity and associated problems (Sharma et al., 2015). The literature further shows evidence of desertification of oases and irrigated lands of northern China's deserts, the Indian subcontinent's deserts, as well as the Mesopotamian Arabian Desert (Ezcurra 2006; Dilshat et al 2015). More broadly, SRCCL also concluded that the area at risk of salinisation is projected to increase in the future (Mirzabaev et al., 2019).

CCP3.4 Adaptations and Responses

Adaptation to climate change impacts in human systems varies depending on types of responses, who is responding, the extent of adaptation response and the potential of these responses to reduce risk/vulnerability (Chapter 16). Different groups require different kinds of supports and levers to enable them to follow adaptive pathways (Stringer et al., 2020) with spatial patterns of adaptive capacity explained by capital assets in some dryland areas (Mazhar et al., submitted). Adaptation can be transformational or incremental. Transformational adaptation alters the fundamental characteristics of the system while responding to climate change. Large scale water desalination projects in extremely water scarce areas could support transformational adaptation. Other transformational responses involve relocating the population away from those areas where incremental adaptation is no longer viable, for example, due to reaching thermal limits of habitability (Andrews et al., 2018). Incremental adaptation preserves existing systems and practices but improves their resilience to climate change by smaller modifications (e.g., through use of improved crop varieties or changing the timing of agricultural activities). What constitutes incremental adaptation in one location may represent transformation in another.

Adaptation to climate change, desertification, drought management and sustainable development activities largely overlap in dryland areas, pointing at synergies between them (Reichhuber et al., 2019). For example, support to communal and flexible land tenure could bring about benefits across multiple dimensions. Currently, more than 100 countries around the world, particularly in drylands, are taking steps to achieve their land degradation neutrality (LDN) targets. The LDN concept, and its hierarchical response mechanisms of avoiding, reducing and reversing land degradation, can provide an overarching framework for implementing adaptation at the national level (Orr et al., 2017; Cowie et al., 2018; Mirzabaev et al., 2019). However, the LDN approach has also received criticism that it insufficiently considers socio-economic and human wellbeing aspects in the assessment of progress towards its targets given the indicators agreed at the international level (Dallimer and Stringer, 2018). Adaptations present synergies and trade-offs along various dimensions of sustainable development such as poverty reduction, enhancing food security and human health or providing improved access to clean energy (see Section 8.6). Distributional effects of adaptation options also may vary between different socio-economic groups within countries or locally among communities, pushing social justice concerns to the forefront (see Section 8.4). Measures that seek to promote particular adaptations need to take into account such consequences, yet this is only just beginning to be addressed within the literature (Dallimer and Stringer, 2018).

Natural systems are also able to adapt, be adapted and become more resilient to desertification. For example, the root network architecture of the hyper-arid Negev Desert acacia trees has enabled them to withstand intensive cultivation and climate-change driven desertification (Winter et al., 2015) while vegetation-induced sand mounds ("coppice dunes") in the Arabian Desert have reduced desertification through reducing wind erosion and enriching sand desert land with water and nutrients (Quets et al., 2017). Research further shows that vegetation cover of psammophyte shrub species (in the "desert oasis transitional area") surrounding the Dunhuang Oasis (northwest China) reduces oasis land degradation risk through reducing sand grain size and velocity of wind speed arriving from the surrounding aeolian desert (Zhang et al., 2017); while land use planning in the Negev Desert of Israel taking a 'sharing' approach between cultivation and urbanization has helped to minimise the external degrading effects of adjacent desert land ecosystems (Portnov and Safriel, 2004). How natural dryland systems are managed following e.g., fire is important too. (van den Elsen et al., 2020) found that establishing vegetation and mulch cover after a fire in Mediterranean ecosystem reduced soil erosion, helping to maintain soil fertility and nutrients. However, they also note the importance of the livelihood system, as different management objectives require different adaptations. Adaptations that increase resilience to wildfire (e.g., vegetation clearance, firebreaks) can reduce resilience to drought, while practices that reduce degradation caused by land use (e.g., pine afforestation) can increase vulnerability to wildfire. Combinations of different land management practices and governance approaches tackling a range of different stresses appear to best support sustainability over the long term.

Table CCP3.A.2 in Appendix CCP3.A provides examples of illustrative adaptation options responding to major challenges of climate change and desertification in deserts and semi-arid areas. Some adaptations present no-regrets options while others tackle desertification and/ or climate changes to different extents.

Community collective action can facilitate the implementation of adaptation responses and can help to tackle challenges associated with upscaling of successful land based adaptations (Thomas et al., 2018). However, a lack of coordination between stakeholders and across sectors can become barriers to effective adaptation outcomes (Amiraslani et al., 2018), showing the importance of the multi-stakeholder engagement approach itself (De Vente et al., 2016). Multi-stakeholder engagement is recognized as an essential part of desertification control, as well as vital in tackling climate change (Reed and Stringer, 2016), with participation taking place to different extents in different parts of the world according to the prevailing governance system. For example, in China, the Grain for Green programme (e.g., is an example of a large-scale ecological restoration programme securing local engagement through payments for ecosystem services.

A combination of short-, medium- and long-term approaches have been identified to protect human systems from the impacts of desertification and climate change. In the short- to medium-term, monitoring, prediction and early warning can e.g., help reduce negative impacts of SDS on human systems by mobilising emergency responses. Preparedness and emergency response procedures would benefit from covering diverse sectors, such as public health surveillance, hospital services, air and ground transportation services, and public awareness, suggesting the need for a coherent, multi-sector governance approach. Longer-term actions include prioritizing sustainable land management measures (UNEP, 2016; Middleton and Kang, 2017), based on both indigenous and local knowledge (ILK) and modern science, along with the investment of financial and human capital in supporting these measures. Devolved adaptation finance in dryland areas of e.g., Kenya (Nyangena and Roba, 2017) and Mali (Hesse, 2016) have indicated some promising insights, highlighting the importance of climate information services and local government support for community prioritisation of adaptation activities. Such actions can enable substantial benefits for poor and marginalised men and women. Among international institutional measures, a global coalition to combat SDS was launched at the United Nations Convention to Combat Desertification Conference of Parties (UNCCD COP14) held in 2019, which could help to better mobilize a global response to SDS. Similarly, there have been calls for increased investment in regional institutions such as the Desert Locust Control Organisation for Eastern Africa to support efforts to both pre-empt and tackle locust plagues (Salih et al., 2020), requiring trans-boundary cooperation.

Regarding responses to droughts, (Mirzabaev et al., 2019) recognized three often overlapping policy approaches including reactive crisis management, proactive drought planning, and lastly proactive drought risk mitigation (policies aimed at reducing the future impacts of droughts). There is *high agreement and robust evidence* that shifting emphasis to proactive drought risk mitigation, including solutions for wind erosion and dust management, instead of exclusive focus on disaster management, reduces vulnerability and improves adaptive capacity (Sivakumar, 2005; Grobicki et al., 2015; Wieriks and Vlaanderen, 2015; Aguilar-Barajas et al., 2016; Runhaar et al., 2016; Wilhite and Pulwarty, 2018; Wilhite, 2019). Building capacity by improving the knowledge base and access to information about drought and its indicators, encourages vulnerable economic sectors and populations to adopt self-reliant measures that promote integrated drought risk management, and the sustainable use of natural resources (Sivakumar, 2005; Wieriks and Vlaanderen, 2015; Aguilar-Barajas et al., 2016; Middleton and Kang, 2017; Wilhite, 2019) *(high confidence*). Engaging agricultural producers as active participants in drought planning and technology adoption using extension services, financial grants and services geared to the local area, is helpful for building drought resilience (Webb and Pierre, 2018). Drought risk mitigation measures that can be taken in anticipation of future droughts include, *inter alia*: i) Policies, public advocacy, and social media campaigns that improve water use efficiency, especially in agriculture and industry, which can bring about behaviour change and reduce water consumption (Yusa et al., 2015; Tsakiris, 2017; Booysen et al., 2019), ii) water transfers and trade, which can reduce drought costs and provide timely adaptations to droughts (Harou et al., 2010; Hurlbert, 2018), iii) Restoration, reclamation, and landscape heterogeneity strategies, to promote ecosystem resilience to wind erosion and provide dust abatement (Duniway et al., 2019), iv) Prevention of soil erosion and provision of dust abatement, accomplished by changing grazing techniques, post fire restoration, minimum tillage, sustainable land management, integrated landscape management, planting trees and other vegetation as long term wind breaks (Middleton and Kang, 2017); and v) The creation of drought tolerant food crops through participatory plant breeding (Grobicki et al., 2015) and investment in research and development of drought resistant varieties of crops (Basu et al., 2017; Mottaleb et al., 2017; Dar et al., 2020). The net economic benefits of ex ante resilient plant development far outweigh the research investment (Basu et al., 2017; Mottaleb et al., 2017; Dar et al., 2020).

Many drought risk management measures can be linked to drought early warning systems. A robust early warning system that provides information and improves knowledge surrounding drought allows for early recovery (Wilhite, 2019). Forecasting and predicting drought seasons can provide entry points for drought adaptation including: using drought tolerant variety crops and adjusting planting periods (Frischen et al., 2020); abatement of dust and aeolian processes, wind erosion through land use changes such as changing grazing processes, closing roads, and avoiding dust creating activities (Duniway et al., 2019); integrating access to insurance, work-for insurance, financial services, savings programs, and cash transfers that can increase the effectiveness of drought response and result in significant cost savings (Berhane et al., 2014; Bazza et al., 2018 ; Guimarães Nobre et al., 2019). conclude, however, that preventative drought management models have been adopted in limited settings; but it has been well recognized that it is preferable to increase drought preparedness before it happens, provide incentives for adaptation instead of insurance, provide insurance instead of relief, but provide relief instead of regulation (Sivakumar, 2005). The absence of proactive drought risk mitigation and resulting crisis management increases vulnerability, increases government reliance, reduces self-reliance and increases cost (Grobicki et al., 2015; Wilhite, 2019). Assessing drought and its impacts before it happens allows for an assessment of the appropriate division of public and private responsibilities for climate adaptation in terms of comprehensiveness, transparency, legitimacy, and effectiveness (Runhaar et al., 2016).

Frequently Asked Questions

FAQ CCP3.1: How has climate change already affected drylands and why are they so vulnerable?

Human-caused climate change has so far had mixed effects across the drylands, leading to fewer trees and less biodiversity in some areas and increased grass and tree cover in others. In those dryland areas with increasing aridity, millions of people face difficulties for maintaining their livelihoods because of increased water scarcity.

Drylands are the hottest and most arid areas on Earth. Human-caused climate change has been intensifying this heat and aridity, increasing temperatures more across global drylands than in humid areas. As a result, the area of the world with arid climates has expanded. In addition, the increased aridity has caused e.g., tree death and loss of tree species in the African Sahel and the loss of bird species in the Mojave Desert of North America. Globally, climate change caused increased rainfall across extensive areas. Increased rainfall, combined with the plant-fertilizing effect of more carbon dioxide in the atmosphere, has increased grass and tree foliage production and contributed to increased shrub cover in many dryland areas, particularly southern Africa. Because water is scarce in drylands and aridity limits the productivity of agriculture, millions of people living in drylands have faced severe difficulties in maintaining their livelihoods. This challenge is exacerbated by non-climate change factors, such as low levels of infrastructure, remoteness, and limited livelihood options that are less dependent on scarce natural resources. High temperatures in drylands increase the vulnerability of people to potential heat-related illnesses and deaths from heat under continued climate change.

FAQ CCP3.2: How will climate change impact the world's drylands and their people?

Climate change is projected to lead to higher temperatures and more irregular rainfall across the drylands, reducing crop yields, increasing land degradation and increasing water scarcity. These projections have profound implications for both dryland environments and their human inhabitants.

There is considerable uncertainty about the changes that may occur in drylands in the future and how people and ecosystems will be affected. Projections based on the aridity index suggest aridity could expand substantially on all continents except Antarctica, further reducing the availability of water and productivity of agriculture. However, in contrast, most climate models project increased rainfall in tropical drylands, but also more variability. High natural climatic variability in drylands makes predictions uncertain. Understanding future impacts is further complicated by many interacting factors such as land use change and urbanisation that affect the condition of drylands. Future trends in dust and sandstorm activity are also uncertain and will not be the same everywhere, but there will likely be increases in some regions (e.g., United States) in the long-term. The impacts of climate change in deserts and semi-arid areas have substantial implications globally: for agriculture, biodiversity, health, trade and poverty, as well as potentially, conflicts and migration. Increasing temperatures and more irregular rainfall are expected to affect soil and water resources and contribute to tree mortality and loss of biodiversity. In other places, woody encroachment onto savannas may increase, in response to the combination of land use change, changes in rainfall, fire suppression, and CO_2 fertilization. Crop yields are projected to decline in some areas, with adverse impacts on food security. The likelihood of conflicts and migration is greatest in regions with lower adaptive capacity associated with socioeconomic development and where marginalized groups are dispossessed of access to their land.

FAQ CCP3.3: What can be done to support sustainable development in desert and semi-arid areas, given projected climate changes?

Water is a key limiting factor in drylands. Many efforts to support sustainable development aim to improve water availability, access and quality, ranging from large engineering solutions that move or desalinise water; to herders' migrations with their animals to locations that have water; to land management and water harvesting practices that conserve water and support land cover. These solutions draw on both *traditional knowledge and innovative science and can help to address multiple sustainable development goals.*

Different desert and semi-arid areas can benefit from different incremental and transformational solutions to move toward sustainable development under climate change. In some dryland areas facing critical water shortages, transformational adaptations may be needed - for example introduction of large-scale water desalination when they have access to sea water. In dryland agricultural areas across the world, incremental adaptations include use of improved crop varieties or changing grazing patterns and herd mobility. What counts as a transformational change in some places may be incremental in others. Often solutions can target multiple development goals. For example, water harvesting can make water available during drought, buffering water scarcity impacts, while also supporting food production, agricultural livelihoods and human health. Land based approaches, e.g., restoration of wetlands or forests, are important for ensuring ecological integrity, soil protection and preventing livelihoods from being undermined as a result of growing extreme weather events. It is important that policies, investments and interventions that aim to support sustainable development take into account which groups are likely to be most affected by climate change. Those people directly dependent on natural resources for their survival are generally most vulnerable but least able to adapt. The capacity to translate local and indigenous knowledge and experience into actions can require external support. Governments and other stakeholders can help by investing in early warning systems, providing climate information, alongside developing alternative livelihood options that are less exposed and sensitive to climate change. Involving all relevant stakeholders has been shown to be important. For example, in China the Grain for Green programme secured local engagement by paying people to manage the environment more sustainably. At a global level important groups have emerged to cooperate and offer solutions around issues such as sand and dust storms. Efforts are needed across all scales from local to global to support sustainable development in desert and semi-arid areas, given projected climate changes.

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Appendix CCP3.A: Supplementary Material

Table CCP3.A.1: Observed ecological changes in drylands.

Region	Observed change	Climate change factors	Attribution to anthropogenic climate change	Non-climate change factors	Confidence in observed change	References
Hyper arid						
Asian hyper arid regions (Gobi)	Loss of shallow rooted desert plants	Increase in extreme warm temperatures			*Medium*	Li et al. (2015)
North America - Mojave Desert	Loss of mesic bird species	Decreased rainfall	Yes. Analyses of causal factors find decreased rainfall more important than non-climate factors.	Livestock, human-ignited fires	*Medium*	Iknayan and Beissinger (2018); Riddell et al. (2019)
	Decline of desert tortoise (*Gopherus agassizii*) population 90% from 1993 to 2012 at one site in the Mojave	Decreased rainfall				Lovich et al. (2014)
	Reduced perennial vegetation cover, including trees and cacti, in the Mojave and Sonoran deserts of the southwestern United States	Increased temperature, decreased rainfall, wildfire		Land use change, invasive plant species	*High*	Defalco et al. (2010); Munson et al. (2016); Conver et al. (2017)
Arid						
African Sahel	Woody cover increase in parts of the Sahel	Changes in rainfall and increased CO_2		Restoration planting	*High*	Dardel et al. (2014); Brandt et al. (2015); Venter et al. (2018); Zhang et al. (2018); Brandt et al. (2019); Bernardino et al. (2020)
	Increase in grass production across Sahel	Increases in rainfall and increased CO_2			*Medium*	Brandt et al. (2019)
	Decline of mesic tree species at field sites across the Sahel	Decreased rainfall, increased temperature	Yes. multivariate statistical analyses find climate factors more important than non-climate factors.		*High*	Gonzalez (2001); Wezel and Lykke (2006); Maranz (2009); (Gonzalez et al., 2012); Hänke et al. (2016); Kusserow (2017); Ibrahim et al. (2018); Zida et al. (2020b)

Region	**Observed change**	**Climate change factors**	**Attribution to anthropogenic climate change**	**Non-climate change factors**	**Confidence in observed change**	**References**
	Increased tree mortality at field sites across the Sahel	Decreased rainfall, increased temperature	Yes. multivariate statistical analyses find climate factors more important than non-climate factors.	Agricultural expansion, modified runoff on shallow soils	*High*	Gonzalez (2001); Wezel and Lykke (2006); Maranz (2009); Vincke et al. (2010); Gonzalez et al. (2012); Hänke et al. (2016); Kusserow (2017); Brandt et al. (2018); Ibrahim et al. (2018); Trichon et al. (2018); Zwarts et al. (2018); Wendling et al. (2019); Bernardino et al. (2020); Zida et al. (2020a)
	Latitudinal biome shift of the Sahel and Sudan	Decreased rainfall, increased temperature	Yes. multivariate statistical analyses find climate factors more important than non-climate factors.		*High*	Gonzalez (2001); Hiernaux et al. (2009); Maranz (2009); Gonzalez et al. (2012)
Namib desert	Increase in woody plant cover and a shift of mesic species into more arid regions	Increase in amount of fog from westward expansion of convective rainfall and increase in number of extreme rainfall events. Elevated CO2 and warming effects on the Bengula upwelling system			*Medium*	Morgan et al. (2004); Haensler et al. (2010); Donohue et al. (2013); Rohde et al. (2019)
Southern Africa - Nama-Karoo		Shifting rainfall seasonality (debate if its cyclical or directional); elevated CO2			*Medium*	Du Toit and O'Connor (2014); du Toit et al. (2015); Masubelele et al. (2015a); Masubelele et al. (2015b)
	Eastern Karoo has experienced a significant increase in the end of the growing season length	Shift in rainfall seasonality and increase in MAP			*Low*	Davis-Reddy (2018)
	Woody encroachment has been observed throughout the Nama-Karoo in valley bottoms, ephemeral stream banks and the slopes of Karoo hills.	Rising concentration of CO_2		Changing land use and herbivore management	*Medium*	Polley et al. (1997); Morgan et al. (2004); Donohue et al. (2013); Ward et al. (2014); Masubelele et al. (2015a); Hoffman et al. (2018)

Region	**Observed change**	**Climate change factors**	**Attribution to anthropogenic climate change**	**Non-climate change factors**	**Confidence in observed change**	**References**
Southern Africa - Succulent Karoo	*Succulent Karoo*: Range shift in tree aloe *Aloidendron dichotomum* with mortality in the warmer and drier range and increase in recruitment in the cooler southern range, populations have positive growth rates, possibly due to anthropogenic warming, although this finding has been challenged	Warming and drying			*Medium*	Foden et al. (2007a); Jack et al. (2016)
Northern Africa - Morocco	Increased vulnerability of oasis's, and reduced ecosystem service provision	High temperature and reduced precipitation causing soil and water salinization, drying up of surface water. Hot winds and sandstorms.		Agricultural growth, high population growth and unregulated and indiscriminate land development	*Medium*	Karmaoui et al. (2014); Salem et al. (2019)
	Reduced surface water availability	Increased temperature and reduced precipitation		High demand (population growth) and landuse change	*Medium*	Rochdane et al. (2012); Choukri et al. (2020)
	Reduction of resilience of *Abies pinasapo- Cedrus atlantica* forests to subsequent droughts	Successive droughts			*Medium*	Navarro-Cerrillo et al. (2020)
North American drylands	Dominant grass species of the Chihuahuan desert are expanding into arid grasslands.	Increase in aridity and increased inter-annual variation in climate trends			*Medium*	Collins and Xia (2015); Rudgers et al. (2018)
	Widespread woody plant encroachment. *Prosopis sp* encroachment in arid desert regions (Chihuahuan and Sonoran Desert) at a rate of ~3% per decade.	Increasing temperature, elevated CO_2 and changing rainfall		Fire suppression and altered grazing/browsing regimes,	*High*	Caracciolo et al. (2016); Archer et al. (2017)
	Plant desert community shift changes the albedo through the reduction in dark biocrusts	Warming and drought			*Medium*	Rutherford et al. (2000)

Region	**Observed change**	**Climate change factors**	**Attribution to anthropogenic climate change**	**Non-climate change factors**	**Confidence in observed change**	**References**
South Chihuahuan Desert - North and central Mexico	Shrub encroachment of grassland (*Berberis trifoliolata, Ephedra aspera, Larrea tridentata*) changes on dominant species in shrub areas loss of less resistant shrubby species (*Leucophyllum laevigatum, Lindleya mespiloides, Setchellanthus caeruleu*). Shrub encroachment of mesic and temperate areas	decreased rainfall + increase in temperature increase CO_2		Urban growth, mechanized agriculture, and changes in land use	*High*	Pérez-Sánchez et al. (2011); Báez et al. (2013); Castillón et al. (2015); Sosa et al. (2019)
	Shifts on soil microbial community to more abundant in fungi (Ascomycota and Pleosporales)	decreased rainfall and increase in temperature		changes in land use	*Low*	Vargas-Gastélum et al. (2015)
	Limited ecological connectivity of shrubby populations	decreased rainfall + increase in temperature			*Medium*	Sosa et al. (2019)
	Loss of Cacti species (*Echinocactus platyacanthus, Pediocactus bradyi, Coryphantha werdermannii, Astrophytum*) due to decline in physiological performance, loss of seed banks and lower germination rates	decreased rainfall + increase in temperature		Cattle grazing, looting	*High*	Aragón-Gastélum et al. (2014); Shryock et al. (2014); Martorell et al. (2015); Carrillo-Angeles et al. (2016); Aragón-Gastélum et al. (2018)
Arid and semiarid territories in Argentina	Decreases in vegetation indexes	Decreased rainfall		human-induced land degradation	*Low*	(Barbosa et al., 2015)
Argentina Chaco Region	Dryland salinity	changes in rainfall		Land use change Overexploitation of water resources	*Medium*	Amdan et al. (2013); Marchesini et al. (2017)
South America Arid Diagonal	Marked reduction in streamflow from the Andes mountain "water towers" due to the persistent reduction in precipitation."	Decrease in precipitation in the upper Andes. The unprecedented 10-year extreme dry period has been called the "Mega-drought			*High*	Bianchi et al. (2017); Rivera and Penalba (2018); Masiokas et al. (2019); Rodríguez-Morales et al. (2019)

Region	**Observed change**	**Climate change factors**	**Attribution to anthropogenic climate change**	**Non-climate change factors**	**Confidence in observed change**	**References**
South American Andes	Extensive glacier retreat across the Andes	Increasing sub-continental temperature and regional reduction in snow precipitation			*High*	Dussaillant et al. (2019); Falaschi et al. (2019); Masiokas et al. (2019)
Patagonian Andes	Widespread tree mortality of *Austrocedrus* and *Nothofagus* forests in the dry ecotone forest-steppe across Patagoina	Increase in extreme drought events			*High*	Rodríguez-Catón et al. (2019)
	Increase in elevation of the upper-forest Nothofagus treeline across Patagonia	Increase in temperature and duration of the growing season at high elevation in the Patagonian Andes			*High*	Srur et al. (2016); Srur et al. (2018)
Central Asian arid lands	Shrub encroachment into arid grasslands within the past 10 years	Temperature of central Asian arid regions experienced a sharp increase since 1997 and has been in a state of high variability since then			*Medium*	Li et al. (2015)
Loess Plateau, China	Widespread vegetation greening in the Loess Plateau region; soil moisture declining widely, and deficit in forests and orchards. The runoff of the Yellow River is declining	Significant warming, slight increase in precipitation.		The land use and cover change, ecological restoration, mainly induced by Grain for Green Project	*High*	Jia et al. (2015); Wang et al. (2015); Deng et al. (2016); Jiao et al. (2016)
The Three-River Source Region of the Tibetan Plateau, China	The runoff increases, the total water storage and groundwater increasing. NPP increase	The precipitation increasing and evapotranspiration (ET) slight decreasing		Grassland protection	*High*	Chen (2014); (Xu et al., 2019)
Semi-arid						
Australian arid lands	Widespread greening	Elevated CO2			*Medium*	Donohue et al. (2013)

Region	**Observed change**	**Climate change factors**	**Attribution to anthropogenic climate change**	**Non-climate change factors**	**Confidence in observed change**	**References**
African savanna	Doubling of tree cover from 1940 – 2010 in South Africa changing land use), and 20% increase in spread of woody areas into previously open areas in the last 20 years	Warming, elevated CO_2, altered rainfall regimes		Removal of mega-herbivores, fire suppression, changed herbivore regime	*High*	Skowno et al. (2017); Stevens et al. (2017); Venter et al. (2018); García Criado et al. (2020)
African savanna	Widespread increase in tree cover across Africa with only 3 countries across continent experiencing a net decline in tree cover	Warming, changing rainfall, mention of CO2		Fire suppression	*High*	Venter et al. (2018)
African savanna	Biodiversity responses to changes in vegetation structure (woody encroachment) causing declines in functional groups that are open area specialists. Records in birds, rodents, termites, mammals, insects.	Woody encroachment			*Medium*	Blaum et al. (2007); Blaum et al. (2009); Sirami et al. (2009); Parr et al. (2012); Sirami and Monadjem (2012); Gray and Bond (2013); Péron and Altwegg (2015); Smit and Prins (2015)
African semi-arid regions (savanna)	Reduced tourism experience due to woody encroachment	Woody encroachment			*Low*	Gray and Bond (2013)
North American drylands – sagebrush steppes	Sagebrush steppes are being invaded by non-native grasses	Increase in temperature and favourable climates			*High*	Bradley et al. (2016); Hufft and Zelikova (2016)
	Shrub encroachment,(*Prosopis glandulosa, Juniper ashei* and *Juniper pinchotti*) is occurring in the semi-arid grasslands of the southern great plains at a rate of ~8% per decade	Increasing temperature, elevated CO2 and changing rainfall		Fire suppression and altered grazing/browsing regimes	*High*	Caracciolo et al. (2016); Archer et al. (2017)
	Woody encroachment in sagebrush steppes (cold deserts) (*Juniper occidentalis*) at a rate of 2% per decade	a) Warming and associated decline in snowpack b) Less precipitation falling as snow and an			*High*	Chambers et al. (2014); Mote et al. (2018)

Region	**Observed change**	**Climate change factors**	**Attribution to anthropogenic climate change**	**Non-climate change factors**	**Confidence in observed change**	**References**
		increase in the rain fraction in winter.				
Central Mexico	Desertification (as decreases in vegetation indexes).	decreased rainfall + increase in temperature		Land use change and intensification	*Medium*	and Becerril-Pina et al. (2015); Noyola-Medrano and Martínez-Sías (2017)
Chinese drylands	Widespread greening trend of vegetation in China over the last three decades; regional difference	Warming, CO2 increase. 1 Rising atmospheric CO2 concentration and nitrogen deposition are identified as the most likely causes of the greening trend in China, explaining 85% and 41% of the average growing-season LAI trend. 2 Negative impacts of climate change in north China and Inner Mongolia and the positive impact in the Qinghai-Xizang plateau		Ecological protection	*Medium*	Piao et al. (2015)
Dry sub-humid						
African mesic savannas	Forest expansion into mesic savannas	Increases rainfall, elevated CO_2		Fire suppression	*Medium*	Baccini et al. (2017); Aleman et al. (2018)
South American cerrado	8% rate of woody cover increase	Elevated Co2		Fire exclusion	*High*	Stevens et al. (2017); Rosan et al. (2019)
South American cerrado	Expansion of forest into cerrado	Elevated CO2		Fire exclusion	*High*	Passos et al. (2018); Rosan et al. (2019)
Australian savannas	2% rate of woody cover increase and greening of drylands				*High*	Donohue et al. (2013); Stevens et al. (2017); Bernardino et al. (2020)

Table CCP3.A.2: Synthesis of adaptation measures and responses to risks in deserts and semi-arid areas.

Challenge	**Adaptation Measures and Responses**	**References**
Soil erosion	Rainwater harvesting and soil conservation, grass reseeding, agroforestry. Use of different breeds of grazing animals, altered livestock rotation systems, crop desertification, use of new crop varieties, development of management strategies that reduce the risk of wildfire.	Eldridge and Beecham (2018)
Overgrazing	Modification of production and management systems that involve diversification of livestock animals and crops, integration of livestock systems with forestry and crop production, and changing the timing and locations of farm operations. Improved breeds and feeding strategies and adoption of improved breeds for households without cows (both economic & environmental gain).	Kattumuri et al. (2015) (Shikuku et al., 2017)
Deforestation	Carbon sequestration through decreasing deforestation rates, reversing of deforestation by replanting, targeting for higher-yielding crops with better climate change adapted varieties, and improvement of land and water management Agroforestry role in addressing various on-farm adaptation needs besides fulfilling many roles in AFOLU-related mitigation pathways (assets and income from carbon, wood energy, improved soil fertility and enhancement of local climate conditions; it provides ecosystem services and reduces human impacts on natural forests). Implementation of co-benefits strategies including provision of incentives across multiple scales and time frames, fostering multidimensional communication networks and promoting long-term integrated impact assessment. Achievement of triple-wins in SSA through provision of development benefits by making payments for forest services to smallholder farmers, mitigation benefits by increasing carbon storage, and adaptation benefits by creating opportunities for livelihood diversification.	Kattumuri et al. (2017) (Mbow et al., 2014) Spencer et al., 2017 Suckall et al. (2014)
Woody encroachment	Biomass harvesting and selective clearing; utilising intense fires to manage encroachment, combined browsing and fire management. Rewilding in open ecosystems and reintroduction of mega-herbivores (e.g., in parts of Africa) to counter negative impact of woody encroachment.	Davies and Nori (2008); Stafford et al. (2017); Cromsigt et al. (2018); Ding and Eldridge (2019)
Droughts	Pro-active drought risk mitigation vs reactive crisis management approaches. Promoting collective action in livestock management, optimizing livestock policies and feed subsidies. interventions in livestock markets during drought onset. Expanding sustainable irrigation and shifting to drought-resistant crops and crop varieties. Environmentally sustainable sea water desalination. Promoting behavioural changes for more efficient residential water use. Moving away from water-intensive agricultural practices in arid areas. Harvesting rainwater by local communities; empowering women and engagement in local climate adaptation planning community based early warning systems	Morton and Barton (2002); Abebe et al. (2008); Alary et al. (2014); Catley et al. (2014); Mohamed et al. (2016)
Grassland and savanna restoration	Prescribed fire and tree cutting, invasive plant removal, grazing management, reintroduction of grasses and forbs, restoration of soil disturbance.	(For review see Buisson et al 2020)

Rangeland degradation (decreasing fodder quality or yield , invasion by fodder poor value species/refusals)	Promote herd local and regional mobility during the growing season to avoid intense grazing pressure on growing annual herbaceous vegetation of rangelands near settlements, water points, market. Moderate grazing facilitates grass tillering and herbaceous flora diversity. Ecological restoration of grazing ecosystems by sowing a mixture of zone-typical dominant species and life forms of plants on severely degraded land. Ecological restoration of arid ecosystems by sowing a mixture of zone-typical dominant species and life forms of fodder plants with partial (ribbon) treatment of pasture lands. Ecological restoration of secondary salted irrigated soils using halophytes.	De Vries and Djitèye (1982); (Hiernaux et al., 1994); Hiernaux (1998); Hiernaux and Le Houérou (2006); Rasmussen et al. (2018)
Poor livestock productivity (reproduction/dairy/meat) in relation with poor seasonal nutrition	Promote seasonal-regional herd mobility to optimise the use of complementary fodder resources (rangelands, browses, crop residues). Implies institutionalized communal access, community agreements and infrastructures (water points, livestock path, grazing reserves, access to education, health care, markets for transhumant population). Cross state boundary mobility implies international agreements such as promoted by N'djamena meeting (declaration 2013)	Schlecht et al. 2001; Turner (1993); Schlecht et al. (2004); (Fernández-Rivera et al., 2005); Bonnet and Herault (2011); Bonnet (2013); Hiernaux et al. (2016)
	Promote strategic supplementation of reproductive and young animals by the end of dry and early wet season. Secondary effect on excretion quantity/ quality to manure croplands.	Many trials in research stations and in farm: example Sangaré et al. (2002a); Sangaré et al. (2002b); (Osbahr et al., 2011); Sanogo (2011)
Decrease trend in cropland soil fertility	Rotational corralling of livestock in field during the dry season (and on cleared fallow the following year in the wet season) to ensure maximum retrieval of organic matter and nutrients from faeces and urine deposited. Application or mineral N and P fertilisers as placed (per poquet) microdoses (50-80 kg/ha) to intensify staple crop production. Impact on soil fertility, rain use efficiency, vegetation cover, organic matter production and recycling. Legume association with cereals (millet-cowpea; Sorghum-groundnut). Adapting cultivars and cropping techniques (calendar, fertilisation)	Pieri (1989); Breman et al. (2001); Gandah et al. (2003); Manlay et al. (2004); (Abdoulaye and Sanders, 2005); Reij et al. (2005); Akponikpe (2008); Bagayoko et al. (2011); Bationo et al. (2011); Sendzimir et al. (2011); Hiernaux and Diawara (2014); (Turner and Hiernaux, 2015); Weston et al. (2015); Reij and Garrity (2016)
Salinisation	Indigenous and scientific adaptive practices to cope with salinity. Farmers in waterlogged saline areas harness sub-surface drainage, salt tolerant crop varieties, land-shaping techniques and agroforestry to adapt to salinity and waterlogging risks. Locally adapted crops and landraces, and the traditional tree- and animal-based means to sustain livelihoods in face of salinisation.	Sengupta (2002); Buechler and Mekala (2005); Singh (2009); Wassmann et al. (2009); Singh (2010); Jnandabhiram and Sailen Prasad (2012); Manga et al. (2015); Sharma et al. (2015); Gupta and Dagar (2016); Nikam et al. (2016); Bundela et al. (2017); Sharma et al. (2017); Singh et al. (2017b); Acharyya and Mishra (2018); Mandal

		et al. (2018); ICAR-CSSRI (2019); Singh (2019a.); Dutta et al. (2020); Kumar and Sharma (2020); Patel et al. (2020); Singh et al. (2020b); Sharma (2016)
Sand and dust storms	Use of live windbreaks or shelterbelts, protection of the loose soil particles through the use of crop residues or plastic sheets or chemical adhesives, increasing the cohesion of soil particles by mechanical tillage operations or soil mulching.	Ahmed et al. (2016); Al-Hemoud et al. (2017)
	Use of perennial plant species that have the ability to trap sediments (sand and fallen dust) and form sandy mound around it, such as *Haloxylon salicornicum*, *Cyperus conglomerates*, *Lycium shawii*, and *Nitraria retusa.* In Sahel: promote herbaceous (not woody plants) to trap sand annuals such as Colocynthis vulgaris, Chrozophora senegalensis, Farsetia ramosissima, perennials such as Cyperus conglomeratus, Leptadenia hastate.	Sivakumar (2005); Hiernaux et al. (2009); Hiernaux et al. (2016); Pierre et al. (2018)
	In Sahel: leaving at least part of the crop residues (stalks) laid down on the soil during the dry season (100kg dry matter per hectare has already significant effect on wind erosion, many trials on Millet in Niger). Trampling by grazing livestock improves the partial burying of the residues.	Lamers et al. (1995); Michels et al. (1998); Bielders et al. (2002); Bielders et al. (2004)
	Improve monitoring, prediction and early warning. Monitoring, prediction and early warning to mobilize emergency responses for human systems & prioritize long-term sustainable land management measures. Establishment of a Global Dust-Health Early Warning System (building on the SDS-WAS initiative). Multi-sectoral preparedness and response including public health, hospital services, air and ground transportation and communication services	UNEP (2016)