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" updates and extends 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 2's contribution as well as relevant chapters of Working Group 1's contribution to the IPCC Sixth Assessment Report (AR6), with an added focus on deserts which were outside 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, with some areas experiencing increases in aridity. Mixed trends of decreases and increases in vegetation productivity have been observed, depending on the time period, geographic region, detection methods used and vegetation type under consideration (*high confidence*[1]). These changes have had varying and location-specific impacts on biodiversity, and have altered ecosystem carbon balance, water availability and the provision of ecosystem services (*high confidence*). There is no evidence, however, of a global trend in dryland expansion based on analyses of vegetation patterns, precipitation and soil moisture, with overall, more greening than drying in drylands since the 1980s (*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 {3.1.2; 3.2.1}, as well as to land management practices. Multiple lines of evidence from 1920-2015 indicate that surface warming of 1.2ºC-1.3ºC over global drylands (Section 1.1.1) exceeded the 0.8ºC-1.0ºC warming over humid lands. From 1982 to 2015, unsustainable land use and climate change combined caused desertification of 6% of the global dryland area, while 41% showed significant increases in vegetation productivity (greening) and 53% of the area had no notable change, although greening rates are slowing or declining in some locations. Greening may cause biodiversity loss and ecosystem service degradation in relation to livelihood systems {3.2.2}. Observed trends in deserts and semi-arid areas have led to varying impacts on flora, fauna, soil, nutrient cycling, the carbon cycle and water resources. Ecological changes in dryland ecosystems detected and attributed primarily to climate change include tree mortality and losses of mesic tree species at specific sites in the African Sahel particularly during the droughts of the 1970s and 80s, and in North Africa from 1970 to 2007 (CCP4.3.2); and losses of bird species in the Mojave Desert of North America from 1908 to 2016 (CCP4.3.2). In contrast, growth in herbaceous vegetation production has increased in some drylands since the 1980s. Widespread woody encroachment has occurred in many shrublands and savannas in Africa, Australia, North America and South America, due to a combination of land use change, changes in rainfall, fire suppression, and CO_2 fertilization {3.2.1, 3.2.2} which, together with unsustainable management, alters biodiversity and reduces ecosystem services such as water availability and grazing potential.

The impacts of climate change have affected the ecosystem services that humans can harness from drylands, with largely negative implications for livelihoods, human health and wellbeing, particularly in deserts and semi-arid areas with lower adaptive capacities (*high confidence*). Ecosystem degradation (Section 16.5.2.3.1) and desertification threaten the abilities of both natural and human systems to adapt to climate change (*high confidence*) {3.1.1}. Changes in desert and semi-arid ecosystem services most acutely affect people who are directly dependent on naatural resources for their livelihoods and survival. These groups also often have lower capacities to adapt, particularly given structural limitations of some drylands where healthcare, sanitation, infrastructure and efficient markets are lacking, reinforcing existing inequalities (*high confidence*) {3.2.1, 3.2.2}. In rural drylands in tropical and Mediterranean areas, human populations are steadily expanding with mixed implications for ecosystem services under climate change, while rapid

[1] In this Report, the following summary terms are used to describe the available evidence: limited, medium, or robust; and for the degree of agreement: low, medium, or high. A level of confidence is expressed using five qualifiers: very low, low, medium, high, and very high, and typeset in italics, e.g., *medium confidence*. For a given evidence and agreement statement, different confidence levels can be assigned, but increasing levels of evidence and degrees of agreement are correlated with increasing confidence.

urbanisation in new and existing dryland megacities put additional pressure on water ecosystem services (*high confidence*). Impacts resulting from consumption of dryland ecosystem services elsewhere, alongside other teleconnections associated with health, trade, conflict and migration, mean that dryland adaptive capacities have far reaching implications for other locations, while other locations affect dryland adaptation options {3.1.1; 3.4}.

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 areas with different rainfall distributions linked to the dominant climate systems in each location (Chapter 9). 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 probable in southwest North America, the northern fringe of Africa, southern Africa and Australia. The main areas of semi-arid expansion are *likely*[2] to occur on the north side of the Mediterranean, southern Africa and North and South America. India, parts of northern China, eastern equatorial Africa and the southern Saharan regions are projected to have shrinking drylands. Under RCP 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 RCP 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*) and how well the index fits observed trends has been questioned in recent research. The impacts of climate change on sand and dust 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 temperature and rainfall variability will significantly change the inter-annual variability in the global carbon cycle which is strongly influenced by the world's drylands and the ways they are managed (*medium confidence*). Increased variability of precipitation would generally contribute to increased vulnerability for people in drylands, intensifying the challenges that people living in deserts and semi-arid areas will face for their sustainable development (*medium confidence*) {3.3.1, 3.3.2}.

Contributions of adaptation measures to climate resilient development

Drivers of desert expansion and greening are numerous, are attributed to environmental and human processes and differ across dryland types, yet a suite of adaptations can help to address human drivers of change, support resilience and build the adaptive capacity of dryland people (*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 research evidence and experience highlight the necessary features of an enabling environment for dryland adaptation (Section 8.5.2). Key enablers include supportive policies, institutions and governance approaches that strengthen the adaptive capacities of dryland farmers, pastoralists and other dryland resource users (*high confidence*), addressing drivers (proximate and underlying) as well as symptoms of desertification. For instance, the skills and capacities held by the mobile and adaptive approach of pastoralists may provide lessons for society at large in adapting to climate change and dealing with increased uncertainty. Such a policy would stand in contrast to previous attempts at settling pastoralists. 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, with contextually appropriate and responsible governance systems (e.g., including those supporting communal land tenure arrangements and Indigenous knowledge) (*medium*

[2] In this Report, the following terms have been used to indicate the assessed likelihood of an outcome or a result: Virtually certain 99–100% probability, Very likely 90–100%, Likely 66–100%, About as likely as not 33–66%, Unlikely 0–33%, Very unlikely 0–10%, and Exceptionally unlikely 0–1%. Additional terms (Extremely likely: 95–100%, More likely than not >50–100%, and Extremely unlikely 0–5%) may also be used when appropriate. Assessed likelihood is typeset in italics, e.g., *very likely*). This Report also uses the term '*likely* range' to indicate that the assessed likelihood of an outcome lies within the 17-83% probability range

confidence). Land based adaptations can help manage dryland changes including sand and dust storms and desertification (*high confidence*), 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 deserts and semi-arid areas {3.4}.

CCP3.1 Introduction

CCP3.1.1 Concepts, Definitions and Scope

Deserts and semi-arid areas are in '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 residing primarily in semi-arid and dry sub-humid areas (van der Esch et al., 2017). Drylands host unique, rich biodiversity (Maestre et al., 2015) and provide important ecosystem services (Bidak et al., 2015; Lu et al., 2018), while dryland people have a rich cultural and historical heritage. Rural human populations are growing in some Mediterranean and tropical drylands, while many are rapidly urbanizing (Guengant Jean-Pierre, 2003; Tabutin and Schoumaker, 2004; Denis and Moriconi-Ebrard, 2009), with varying impacts on ecosystem services and adaptive capacities. In recent decades, 6% of global megacities have been established in arid areas and 2% in hyper-arid desert areas (Cherlet et al., 2018), with many of these areas suffering from severe water security challenges (Stringer et al., 2021). Dryland inhabitants in many developing countries are also experiencing poverty (Section 16.1.4.3), hunger, poor health, land degradation, and economic and political marginalisation (Mbow et al., 2019; Mirzabaev et al., 2019), which sometimes limits their access to common pool resources. These challenges, together with a weak enabling environment, threaten opportunities to adapt to climate change.

The terms "desert" and "desertification" are subject to various interpretations due to the diverse components, processes and states they denote. Recognizing "land degradation" as a contested and perceptual term (Blaikie and Brookfield, 1987; Behnke and Mortimore, 2016; Robbins, 2020), this cross-chapter paper, defines land degradation as "a negative trend in land condition, caused by direct or indirect human-induced processes including 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). Following the above definitions, desertification is more common in arid and semi-arid climates than in hyper-arid climates. When desertification does occur in arid and hyper-arid ecosystems it is often in oases and irrigated cultivated lands (Ezcurra, 2006; Dilshat et al., 2015). Hyper-arid areas, except wetlands such as oases, wadis and riverbanks, are excluded in the United Nations Convention to Combat Desertification (UNCCD) definition of desertification used here, yet many of the world's deserts are in hyper-arid areas. Hyper-arid areas are therefore included when discussing deserts but not when discussing desertification. 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 loss of biological productivity, ecological integrity or value to humans to below their natural levels (Moridnejad et al., 2015).

Interactions between climate change and desertification in drylands create challenges for both ecosystem and human resilience, affecting ecosystem services, biodiversity, food security, human health and wellbeing (Reed and Stringer, 2016). Dryland livelihoods that heavily rely on natural ecosystems face pressures including high population growth rates, weak or poor governance, low investment, unemployment and poverty, market distortions and underestimates of the value of drylands (Stringer et al., 2017; Bawden, 2018). These pressures intersect with broader societal challenges such as conflict and civil unrest (Okpara et al., 2015; Almer et al., 2017), which together, can contribute to human displacement (Section 16.2.3.8) in some drylands (Warner, 2010; Abel et al., 2019). Nevertheless, evidence linking conflict with climate change and desertification is weak (Benjaminsen et al., 2012) and data are insufficient to draw robust conclusions.

Drylands yield important opportunities for adapting to and mitigating climate change. They offer abundant solar energy which could support mitigation efforts, opportunities for cultural and nature-based tourism, rich plant biodiversity in some areas (e.g. Namibia), and extensive Indigenous knowledge and experience of adapting to dynamic 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).

Chapter 3 of the IPCC Special Report on Climate Change and Land (SRCCL) focused on desertification, but links between climate change and deserts, desertification and semi-arid areas have not been extensively considered in recent IPCC assessment cycles. AR5 noted that desertification contributes to atmospheric dust production, identifying desertification as needing consideration within climate change mitigation and adaptation governance and decision-making (Boucher et al., 2013; Myhre et al., 2013). This cross-chapter paper focuses on environmental and human aspects, finding that climate change impacts will intensify the challenges faced by dryland populations in advancing sustainable development. However, viable options exist for adapting to climate change, reducing desertification and supporting progress towards the Sustainable Development Goals (SDGs), particularly by combining modern science, Indigenous knowledge, and local knowledge, as well as livelihood and land management strategies that enable land-based adaptation, mitigation and nature-based solutions (Section 16.3.2.3).

CCP3.1.2 Key Measurement Challenges and Observed Dryland Dynamics

Maps of dryland extent commonly employ a climate-based approach measured using the aridity index (AI), or consider the extent of dryland vegetation. The two approaches sometimes do not demarcate the same geographical areas as being drylands, particularly when projecting future changes (Stringer et al., 2021). Dryland dynamics therefore need to be viewed specifically in relation to the definitions and measurements being used. From 1982 to 2015, unsustainable land use and climate change combined caused desertification of 6% of the global dryland area, while 41% showed significant greening (i.e. increased vegetation productivity), and 53% of the area had no notable change (Figure CCP3.1; Burrell et al., 2020);). In contrast Yuan et al. (2019) conclude that during 1999-2015, trends of vegetation production reversed globally and in drylands, showing extensive declines. Thus, while overall greening has occurred, this trend now appears to be declining. 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). Drylands nevertheless show different dynamics depending on the index used and the variables assessed.

Based on the AI, some drylands are projected to expand and others to contract due to climate change. However, there is no evidence of a global trend in dryland expansion based on vegetation patterns, precipitation and soil moisture, based on the satellite record from the 1980s to the present (*medium confidence*). The AI will also be of limited use under a changing CO_2 environment due to higher water use efficiency by some plants (Mirzabaev et al., 2019), and it overvalues the role of potential evapotranspiration (PET) relative to rainfall. It also does not account for CO_2 impacts on evapotranspiration, and seasonality in rainfall and evapotranspiration. Higher annual PET because of increased temperatures will have little impact if temperature and actual evapotranspiration are not rising during the period of vegetation growth (Stringer et al., 2021).

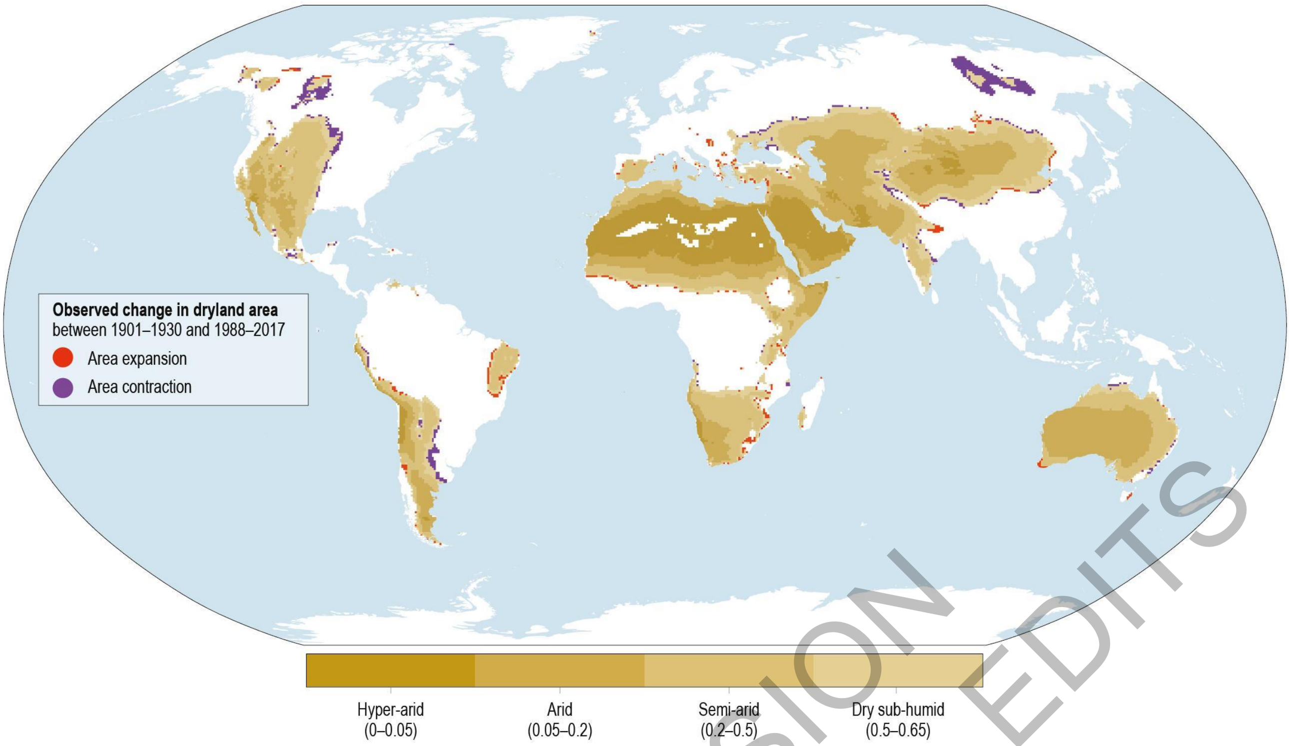

Figure CCP3.1: Aridity zone extent and observed changes in dryland areas as defined by the Aridity Index. Aridity zones, according to UNESCO (1979) and UNEP (1992) classifications, defined by the aridity index (AI), consider the ratio of average annual precipitation to potential evapotranspiration: (i) 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 $AI < 0.65$, humid lands are those with $AI > 0.6$. Drylands include land with $AI < 0.65$, humid lands are those with $AI > 0.65$ (UNEP, 1992). 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). The AI has various limitations in assessing dryland expansion and different indices highlight different areas and different changes. This is known as the aridity paradox (Greve et al., 2019). See SRCCL Section 3.2.1 (Mirzabaev et al., 2019) for an in-depth analysis of limitations, and Stringer et al. (2021) for a summary of different measures and indices used in the literature.

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

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

CCP3.2.1.1 Temperature and Rainfall

Significant warming has occurred across drylands globally (WGI, 2021). Surface warming (from 1920-2015) of 1.2ºC-1.3ºC in global drylands has exceeded the 0.8ºC-1.0ºC warming over humid lands (Huang et al., 2017). As measured by the AI, this has expanded the area of drylands by ~4% from 1948-2004 (Ji et al., 2015; Spinoni et al., 2015; Huang et al., 2016). However, as mentioned in Figure CCP3.1, the AI has various limitations in assessing drylands expansion. Increases in potential evapotranspiration have exceeded increases in precipitation in the last half of the period 1901-2017 (Pan et al., 2021). Observations from the Sahel demonstrated that temperature seasonality changes differ from rainfall seasonality changes (Guichard et al., 2015), and there has been an increase in surface water and groundwater recharge in the Sahel since the 1980s, referred to as "the Sahel paradox" (Favreau et al., 2009; Gardelle et al., 2010; Descroix et al., 2013; Wendling et al., 2019). Research from the USA suggests that historical soil moisture levels can contribute to such variability (Heisler-White et al., 2009). Studies from the Middle East show rising temperatures and declining rainfall trends (ESCWA, 2017), with most decreasing aridity trends in north Sudan and most increasing aridity trends in eastern Arabia over the period 1948-2018 (Sahour et al., 2020).

CCP3.2.1.2 Ecosystem Processes

Semi-arid ecosystems have a disproportionately large role in the global carbon cycle, driving trends and inter-annual variability of the global carbon sink (Alstrom et al., 2015). These systems are highly sensitive to annual precipitation and temperature variations (*high confidence*) (Alstrom et al., 2015, Poulter et al., 2014). The positive trend in semi-arid regions is consistent with widespread woody encroachment and increased vegetation greenness (Andela et al., 2013; Piao et al., 2019; Piao et al., 2020) driven by CO_2 fertilisation and rainfall increases (Sitch et al., 2015; Piao et al., 2020), although some trends are complicated by irrigation practices (He et al., 2019). Increases in temperature and drought diminish this trend through reduced vegetation productivity and increased vegetation mortality (Brandt et al., 2016; Ma et al., 2016; Fernández-Martínez et al., 2019; Maurer et al., 2020) with indications that this trend is declining or reversing in some locations (Yuan et al., 2019; Wang et al., 2020).

Changed climates have increased water constraints of vegetation growth most notably in the Mediterranean (CCP1.2.3.2, CCP4.2.1) and west and central Asia (Jiao et al., 2021). Climate change and elevated CO_2 have both increased and decreased vegetation sensitivity to rainfall throughout drylands, with the degree of variation shaped by region, land-use and vegetation traits (Haverd et al., 2017; Abel et al., 2021). Mineral nitrogen production in drylands may become increasingly decoupled from consumption by plants over prolonged dry periods, and more extreme hydrological events can drive multiple changes to nutrient cycling (Manzoni et al., 2019). Soil biocrusts (composed of lichens, bryophytes and soil microorganisms) which contribute to dryland ecosystem function including carbon uptake and soil stabilisation (Reed et al., 2019), are sensitive to warming and altered rainfall in a shift in biocrust communities of mosses and lichens in favour of early successional cyanobacteria-dominated biocrusts (Escolar et al., 2012; Reed et al., 2012), which can increase surface albedo (Rutherford et al., 2017).

CCP3.2.1.3 Vegetation Changes

CCP3.2.1.4 Woody Cover Increase

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 (see Table CCP3.1 for examples of observed environmental changes and impacts in drylands and the role of climate change and non-climatic factors in causing these changes).

Increases in shrub cover in arid deserts and shrublands have been recorded in the North American drylands (Caracciolo et al., 2016; Archer et al., 2017; Chambers et al., 2019), the 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), 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; Jiao et al., 2016; Wang 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). Increasing rainfall and rising CO_2 concentrations (which improves water use efficiency) benefits some shrubs (Polley et al., 1997; Morgan et al., 2004; Donohue et al., 2013). Together with changes in land use (Hoffman et al., 2018), improved land management (Reij et al., 2005) and improved irrigation (He et al., 2019) this contributes to woody cover increases. Extensive woody encroachment has been recorded in savannas (measured between 1920-2015, over the past century) in Africa (2.4% woody cover increase/decade), Australia (1% increase/decade), and South America (8% increase/decade) (O'Connor et al., 2014; Stevens et al., 2016; Skowno et al., 2017; Venter et al., 2018; Zhang et al., 2019). Following drought in the Sahel (1968-1973 and 1982-1984), a rainfall increase since the mid-1990s has been linked to increases of woody cover between 1992-2011/2012 (Brandt et al., 2016; Brandt et al., 2017; Brandt et al., 2019). See SRCCL section 3.2.1.1 for an evaluation of NDVI and remote sensing approaches used in these studies. Tree regeneration by farmers has also increased woody cover, particularly next to villages (*high confidence*) (Reij et al., 2005; Reij and Garrity, 2016; Brandt et al., 2018). Otherwise, savanna encroachment has been attributed to combinations of 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) interacting with changing land use (Archer et al., 2017; Venter et al., 2018) where herbivory and fire regimes are altered (O'Connor et al., 2014; Archer et al., 2017;see also discussion on fire and herbivory in Section 2.4.3.1.2). In some cases, woody increase has been balanced locally by changes in runoff (Trichon et al., 2018), or by land clearing and fuel wood harvesting, as seen in western Niger, northern Nigeria, and at the periphery of major towns (Montagné et al., 2016).

CCP3.2.1.5 Tree Death and Woody Cover Decline

Field measurements have also detected tree mortality and loss of mesic tree species at some Sahel sites during drought periods (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 (*high confidence*) (Hänke et al., 2016; Kusserow, 2017; Ibrahim et al., 2018; Trichon et al., 2018; Dendoncker et al., 2020; Zida et al., 2020b), with attribution to climate change (Gonzalez et al., 2012). Furthermore, vegetation productivity per unit of rainfall showed a net decline of 4% in the period 2000-2015 across drylands globally, with the greatest net declines in Africa (16%) and Asia (33%) (Abel et al., 2021), but with location-specific increases in vegetation-rainfall sensitivity, e.g. in southern and eastern Africa and parts of the Sahel. Furthermore, NDVI declines were reported across the Sahel from 1999 to 2015 (Yuan et al., 2019; Zida et al., 2020a). However, field site monitoring showed a strong regeneration of the decimated woody populations except on shallow soil where the runoff system had evolved towards a web of gullies (Hiernaux et al., 2009a; Trichon et al., 2018; Wendling et al., 2019) .

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* in Southern Africa (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 climate change (Dai et al., 2004; Esper et al., 2007; Dai, 2011).

In deserts of the south-western United States, a drought since 2000, mainly due to climate change (Williams et al., 2020), together with land use change, invasive plant species, and wildfire (Syphard et al., 2017), has led to reductions in native desert plant species (Defalco et al., 2010; Conver et al., 2017) and perennial vegetation cover (Munson et al., 2016a; Munson et al., 2016b). An increase in invasive exotic grasses has increased wildfires in these desert ecosystems in which fire had been rare (Brooks and Matchett, 2006; Abatzoglou and Kolden, 2011; Hegeman et al., 2014; Horn and St. Clair, 2017). In the Mojave Desert in the United States, a loss of bird biodiversity has also been detected and attributed to increased aridity caused by climate change (Iknayan and Beissinger, 2018; Riddell et al., 2019).

CCP3.2.1.6 Change in Herbaceous Cover

Changes in aridity (Rudgers et al., 2018) have caused some expansion of dominant grasses (often invasive) into desert shrublands. The spread of invasive *Bromus tectorum* may be enhanced by altered precipitation and freeze-thaw cycles (*low confidence*) (Collins and Xia, 2015; Rudgers et al., 2018). Arid grassland has expanded (between 10-100 km) into the eastern Karoo, South Africa (*high confidence*) (du Toit et al., 2015; Masubelele et al., 2015a; Masubelele et al., 2015b). 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). These changes are causing an increase in fire frequency in these seldom burnt areas (du Toit et al., 2015). 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 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).

Trends of land degradation (Section 16.4.1.2) and desertification (as demonstrated by loss of cover or reduced vegetation productivity) as an impact of changing climatic trends have been reported in Burkina Faso (Zida et al., 2020), the north-western regions of China during 1975-1990 (Zhang et al., 2020) in Afghanistan (Savage et al., 2009), Iran (Mahmoudi et al., 2011; Kamali et al., 2017), Argentina (Barbosa et al., 2015) and India (Javed et al., 2012). Encroachment, re-greening and an increase of unpalatable plant species into rangeland areas (e.g. in East Africa and southern Africa's Kalahari) all contribute to dryland degradation through the loss of open ecosystems and their services (Reed et al., 2015; Le et al., 2016; Chen et al., 2019b).

Table CCP3.1: Observed ecological changes in drylands.
[INSERT TABLE CCP3.1 HERE]

CCP3.2.1.7 Sand and Dust Storms

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 drivers is not straightforward, even in well-documented locations (Middleton, 2019). There is *limited evidence and low agreement* about the impacts of climate change on sand and dust storms (SDS), with studies pointing to either substantial increases (+300%) or decreases (-60%) (Boucher et al., 2013). Current climate models cannot adequately model the impact of climate change on SDS 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 sand and dust activity (Mirzabaev et al., 2019).

Sand and dust storms remain a major concern for desert areas under conditions of climate change and desertification (Middleton, 2017). Only about 20% of deserts are covered by sand, but desert sand and dust storms provide an important feedback mechanism to climate (Pu and Ginoux, 2017), with literature showing that some areas have very frequent dust days (Figure CCP3.2; Ginoux et al., 2012). In some locations such as the USA, desert dust can be deposited downwind on snowpacks, hastening snowmelt and altering river hydrology (Painter et al., 2010). Deserts and other natural dryland surfaces produced 75-90% of atmospheric dust globally in the early 21st century, with the remainder from agricultural and other land dominated by human land use (Ginoux et al., 2012; Stanelle et al., 2014).

Recent changes in dust emissions and their attributions vary geographically. Warming in Iran over the period 1951–2013 has been associated with an increased 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 SDS 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 higher vegetation cover during the period studied (An et al., 2018). Global climate change, transboundary movement of aeolian material by atmospheric flows from Central Asia, dynamics of the Caspian Sea regime, erosion, salinization, as well as the loss of land as a result of the placement of industrial facilities have expanded the land area prone to desertification in Russia. Desertification has been observed to some extent in 27 sub-regions of the Russian Federation on territory of more than 100 million hectares (Kust et al., 2011; also recently confirmed by National Report, 2019). Eastern and south-eastern regions of Kalmykia, Russia, serve as dust 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 dust and sand 10 cm or more thick, with negative impacts on yields (Tsymbarovich et al., 2020). High dust day frequency is occurring also in the High Latitude Dust (HLD) source areas not reported in Figure CCP3.2 such as in Iceland, Patagonia, Canada, Alaska, and based on *in situ* measurements in Antarctica (Dagsson-Waldhauserová et al., 2014; Bullard et al., 2016; Dagsson-Waldhauserova and Meinander, 2019; Bachelder et al., 2020). Active HLD dust sources cover at least 500,000 km^2 and produce at least 5% of global dust budget (Bullard et al., 2016). HLD has negative impacts on the cryosphere via albedo changes and snow/ice melting (Boy, 2019; Dagsson-Waldhauserova and Meinander, 2019).

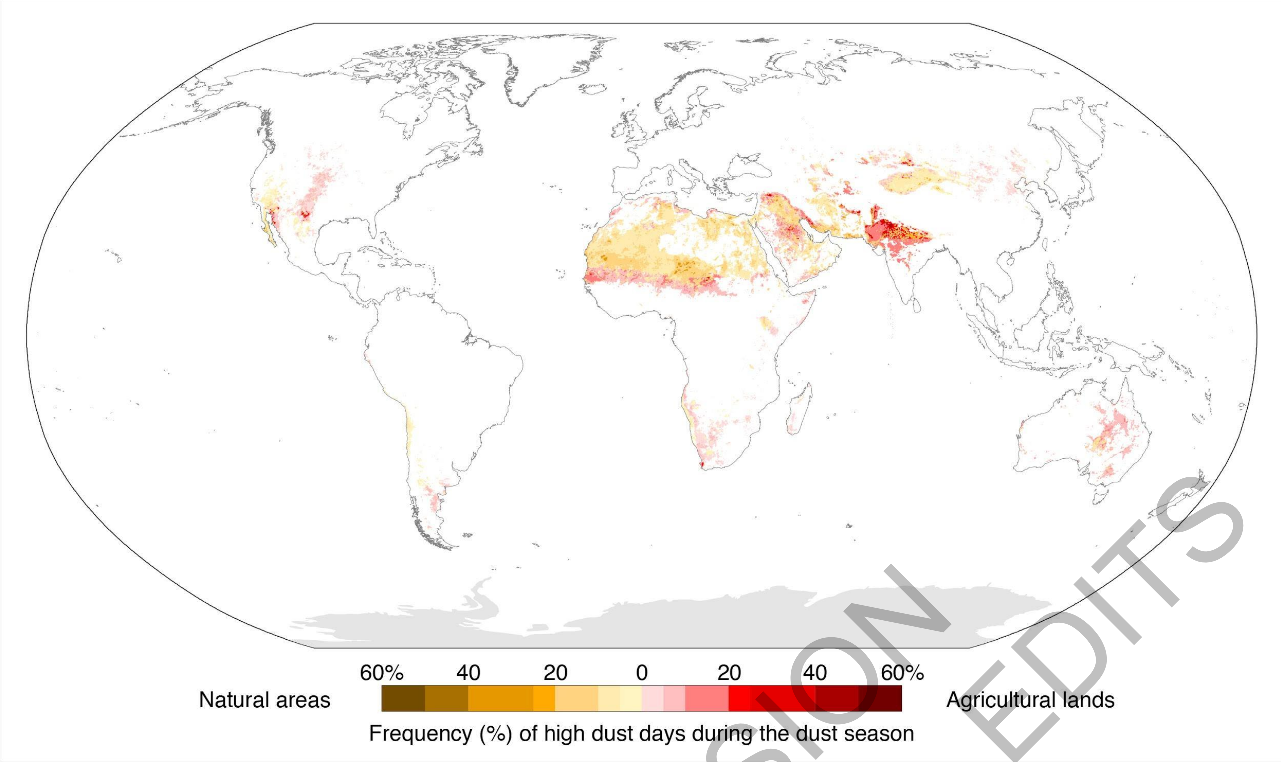

Figure CCP3.2: Frequency of high dust days (dust optical depth >0.2) during the dust season, based on 2003-2009 remote sensing, the most recent data analysed, and divided into areas primarily in agriculture and areas dominated by natural land cover (Ginoux et al., 2012). Dust seasons: Africa (North),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

CCP3.2.1.8 Water Scarcity

Climate change and desertification have been linked to water loss (Bayram and Öztürk, 2014; Schwilch et al., 2014; Mohamed et al., 2016), 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; Kaptué et al., 2015; Gal et al., 2017). Water scarcity (Section 16.5.2.3.7) was among the first impacts of climate change recognized in North African countries such as Morocco which have extensive dryland areas, with countries such as Turkey, Libya, USA and China carrying out large-scale water transfer projects (Sternberg, 2016; Stringer et al., 2021). 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.

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

Climate change and desertification, alongside other drivers of degradation, reduce dryland ecosystem services, leading to losses of biodiversity, water, food, and impacts on human health (CCP4.2.3, WG2) and well-being *(high confidence*) (Mirzabaev et al., 2019) resulting in disruption to the economic structures and cultural practices of affected communities (Elhadary, 2014; Middleton, 2017).

CCP3.2.2.1 Sand and Dust Storms

Desertification and SDS can cause substantial socioeconomic damage in drylands (UNEP, 1992; Opp et al., 2021) over both the short and long term. Short-term impacts occur on health, food production systems, infrastructure (damaging buildings, energy systems, and communications), transport and related economic productivity, air and road traffic, and costs are incurred in clearing sand and dust from deposition areas (Mirzabaev et al., 2019). In the Arab region increasing frequency of SDS events is projected to further exacerbate water scarcity and drought (ESCWA, 2017). Longer-term costs include loss of ecosystem services, biodiversity and habitat, chronic health problems, soil erosion and reduced soil quality (particularly through nutrient losses and deposition of pollutants), and disruption of global climate regulation (Middleton, 2018; Allahbakhshi et al., 2019). Dust deposition nevertheless can offer environmental and economic benefits, bringing 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 need to consider the likely frequency and magnitude of SDS events (Tozer and Leys, 2013).

CCP3.2.2.2 Human Health

Potential impacts of climate change, recurrent droughts and desertification on human health in drylands include: higher risks from water scarcity (linked to deteriorating surface and ground water quality and water-borne diseases; Stringer et al., 2021), food insecurity and malnutrition (Section 16.2.3.3) in the absence of sufficient imports; respiratory, cardiovascular and infectious diseases caused by SDS (Mirzabaev et al., 2019), potential displacement and migration and mental health consequences (Chapter 7; Stringer et al., 2021) and heat stress (Dunne et al., 2013; Zhao et al., 2015; Russo et al., 2016). SDS negatively impact human health through various pathways, causing respiratory, cardiovascular diseases and facilitating infections (*high confidence*) (Díaz et al., 2017; Goudarzi et al., 2017; Allahbakhshi et al., 2019; Münzel et al., 2019). SDS can cause mortality and injuries related to transport accidents (Goudie, 2014). Research from China suggests that prenatal exposure to SDS can affect children's cognitive function (Li et al., 2018). The pollutants that are entrained and ingested or inhaled closely link to the land management strategies in source areas.

Droughts (TS.2.6 L, AR6, WGI) are among the natural hazards with the highest adverse impacts on human populations (Mishra and Singh, 2010). Although droughts just represented 4% of hazard events, their impacts amounted to 31% of affected people (29 million) (Louvain, 2019). Drought exposure relates to a higher risk of undernutrition (Section 16.5.2.3.6), among vulnerable populations (Kumar, 2016), particularly children (IFPRI, 2016) for whom the impacts can lead to lifelong consequences through stunted growth, impaired cognitive ability and reduced future educational and work performance (UNICEF/WHO/WBG, 2019). The corresponding costs of children stunting in terms of lost economic growth can be of the order of 7% of per capita income in developing countries (Galasso and Wagstaff, 2018).

CCP3.2.2.3 Agro-ecological Food Systems, Livelihoods and Food Security

Rising temperatures, variation in rainfall patterns and frequent extreme weather events associated with climate change have adversely affected agro-ecological food systems and pastoral systems in some drylands (Section 16.3.2.6Zhu et al., 2013; Amin et al., 2018), especially in developing countries (Haider and Adnan, 2014; Ahmed et al., 2016; ur Rahman et al., 2018) where desertification is a key challenge to agricultural livelihoods. Recurrent droughts in recent decades, coupled with wind erosion (particularly of fine sediment which gives soil its water holding capacity and nutrients), affected vast areas in Argentina, leading to land abandonment and agricultural fields being covered by sand and invasive plants (Abraham et al., 2016). Temperature increases have contributed to reduced wheat yields in arid, semi-arid and dry sub-humid zones of Pakistan (Sultana et al., 2019). Agricultural production in the drylands of South Punjab is experiencing irreversible impacts since the grain formation phase has become swifter with a warmer climate, leading to improper growth and reduced yields (Rasul et al., 2011).

Aslam et al. (2018) regard climate change impacts to be particularly threatening to the livestock sector, water and food security and the economy beyond agriculture in South Punjab, particularly as yields decrease. In the livestock sector across global drylands (TS.4.3.2.10, AR 6, WGI), 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 (Van de Steeg, 2012; 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 find themselves with fewer safety nets and limited adaptive capacities than in the past, particularly where mobility, access and tenure rights are becoming restricted (Section 16.3.2.6; Box CCP3.1) and where use of technologies such as mobile phones can result in mixed effects, as found in Morocco (Vidal-González and Nahhass, 2018). Observed SDS impacts can increase food production costs and threaten sustainability more generally (Middleton, 2017).

Woody-plant encroachment and greening may be masking underlying land degradation processes and losses of ecosystem services, livelihood and adaptation options in pastoral livelihood systems (Reed et al., 2015; Chen et al., 2019a). Woody encroachment alters ecosystem services, particularly in rangelands, resulting in reduction of grass cover, hindering livestock production (Anadón et al. 2014), reducing water availability (Honda and Durigan 2016, Stringer et al., 2021) but increasing availability of wood (Mograbi et al., 2019).

[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 space and variable in time (Homewood, 2018). Pastoralism has a considerably lower carbon budget than other livestock-keeping systems, with research on pastoralism in the Sahel concluding that this system may be carbon neutral (Assouma et al., 2019), despite contributing directly to greenhouse gas emissions via methane enteric emissions and indirectly through faeces-driven CO_2, CH_4 and N_2O emissions during mineralisation (Assouma et al., 2017). Efforts to sedentarize and villagize pastoralists can lead to land degradation and higher overall emissions from the sector (Section 16.3.2.6).

Pastoralists migrate with their animals in some of the most remote and marginal environments on the planet. Globally, mobile pastoralists number about 200 million households and use about 25% of the Earth's landmass (Dong, 2016). Many pastoralists operate in non-equilibrial environments that are unstable, fluctuating and generally uncertain, and driven more by climatic variation than livestock numbers and grazing pressure (Behnke et al., 1993). Examples of such systems are grazing areas in the dry tropics (Sandford, 1983; Turner, 1993; Sullivan and Rohde, 2002; Benjaminsen et al., 2006; Hiernaux et al., 2016), and rangelands in the Arctic (Behnke, 2000; Tyler et al., 2008; Benjaminsen et al., 2015; Marin et al., 2020).

Over many generations, pastoralists have accumulated practical experience and knowledge to cope with uncertainty and value variability (Krätli and Schareika, 2010), mainly through a mobile and flexible approach. While pastoralists are also at risk of climate change impacts, they may be better able to adapt to a changing climate than other land users (Davies and Nori, 2008; Krätli and Schareika, 2010; Jones and Gutzler, 2016).

While pastoralists possess substantial adaptive capacity as a result of their Indigenous knowledge, this 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, 2009; 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, while property rights often privilege sedentary farming.

Modern states have typically tried to settle pastoralists and confine their movements within clearly defined boundaries, claiming 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 policymakers as successful models of livestock keeping in contrast to the pastoral way of life (Steinfeld et al., 2006; Chatty, 2007).

Current pressures and processes of pastoral change are spatially variable and complex, and 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, in addition to increased insecurity in some drylands (e.g. the Sahel), 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, offer lessons for society at large in its struggle to adapt to climate change and deal with increased uncertainty (Davies and Nori, 2008; Scoones, 2009; Nori and Scoones, 2019).

[END BOX CCP3.1 HERE]

CCP3.2.2.4 Gender Differentiated Impacts

Impacts of desertification, climate change, and environmental degradation, as well as vulnerability and capacity to adapt, are gendered. Differences are determined by socially structured gender-specific roles and responsibilities, ownership of, access to and control over natural resources and technology, decision making, and capacity to cope and adapt to long-term changes (Mirzabaev et al., 2019; Cross-Chapter Box GENDER in Chapter 18). Assessments of the gender dimension of desertification and climate change impacts and responses are scarce, and highly context specific. For example, in many lower income countries, rural women produce most of the household food, and are responsible for food preparation and collecting fuelwood and water from increasingly distant sources (Mekonnen et al., 2017; Droy, 2020). Drought 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 income generating activities, and may be more exposed to violence (Sommer et al., 2014) and less able to migrate as an adaptation option. 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).

CCP3.2.2.5 Climate Change, Migration and Conflict

Dryland populations pursuing traditional land-based livelihood options are generally mobile due to a highly fluctuating resource base (Box CCP3.1). Many rural dwellers in drylands also move to urban areas for seasonal work which can have positive impacts in terms of remittances. While reasons for migration vary and can be positive or negative, oppression and human rights abuses, lack of livelihood opportunities and food insecurity tend to be among the main push factors, while emerging opportunities at the rural-urban nexus present lucrative pull factors (Cross-Chapter Box MIGRATE in Chapter 7). In a survey in Libya in 2016, 80% of migrants interviewed said they had left home because of economic hardship (Hochleithner and Exner, 2018), which in drylands under water scarcity linked to climate change, would be exacerbated.

Causes of migration and violent conflict need to be seen in a wider historical, agrarian, political, economic and environmental context, in a multi-scalar perspective integrating levels of analysis from the local to the global (Glick Schiller, 2015). Quantitative studies tend to conclude that climate change has so far not significantly impacted migration including in drylands (Owain and Maslin, 2018), although with some disagreement (Lima et al., 2016; Missirian and Schlenker, 2017). In a 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 concluded 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 a minority of quantitative studies argue for a stronger causal association (Hsiang et al., 2013). 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 they also agreed that other factors, such as state capacity and level of socioeconomic development, played a much larger role. These factors also play a role in determining adaptation possibilities and in shaping the enabling environment (Section 8.5.2).

Qualitative case studies tend to frame conflict and migration within a larger political, economic and historical context. A number of studies from African drylands 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; Bergius et al., 2020). By undermining livelihoods, exacerbating poverty, and setting rural population groups adrift, land dispossession in the Sahel may lead to increased migration to urban areas, to rural sites of non-farm employment (e.g. mines) (Chevrillon-Guibert et al., 2019) 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) as already seen in the Sahel in terms of the emergence of jihadist armed groups (Benjaminsen and Ba, 2019). Major drivers of the current crisis in 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 current civil war in Libya. Climate change has played a marginal role as a driver of conflicts in the Sahel (Benjaminsen et al., 2012; Benjaminsen and Hiernaux, 2019) but has 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

Globally, warming rates have been twice as high in drylands compared to humid lands, 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. 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, relative to the historical period (1961-1990) (Huang et al., 2016; Huang et al., 2017). 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. The number of extremely hot days with temperatures above 40°C is projected to increase considerably across the Arab region by the end of the 21st century (ESCWA, 2017).

CCP3.3.1.2 Rainfall, Evaporation and Drought

Drylands are highly sensitive to changes in precipitation and evapotranspiration. Potential evapotranspiration (PET) is projected to increase in all regions globally, under all RCPs, as a result of increasing temperatures and surface water vapour deficit (Mirzabaev et al., 2019). Simulations based on coupled land surface, energy and water and vegetation models in the Central Sahel showed a strong response of the water budget. Under +2°C and +4°C warming scenarios, decreased evapotranspiration, runoff and drainage were found for all scenarios except those with the highest precipitation (Léauthaud et al., 2015).

Globally, soil moisture declined over the 20th century (Gu et al., 2019), a trend that is projected to continue under all emissions scenarios (WGI AR6). Projected drier soils can further amplify aridity through feedbacks with land surface temperature, relative humidity and precipitation (Berg et al., 2016).

Drought conditions (frequency, severity and duration) are expected to substantially worsen in global drylands, 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 world, historical 50-year droughts (based on the Standardised Precipitation-Evapotranspiration Index (SPEI)) could occur twice as frequently across 58% of global landmasses relative to the 1976–2005 period, an area that increases to 67% under 2°C warming (Gu et al., 2020). Multi-year drought events of magnitudes exceeding historical baselines will increase by 2050 in countries with drylands including 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 (Section 14.4.3.1), north-eastern South America (Section 12.3.1.1) and southern Europe (Section 13.1.3; Swann et al., 2016).

CCP3.3.1.3 Aridity

Studies based on the AI (the ratio of annual potential evapotranspiration to precipitation), almost always project conditions of increasing aridity under climate change, and associated widespread expansion of drylands (Huang et al., 2016). The limitations of the AI are widely reported (Mirzabaev et al., 2019), with alternative indices that consider different variables including the Ecohydrological Index, PDSI, Standardised Precipitation Index and SPEI (Stringer et al., 2021). AI projections indicate potentially severe aridification in the Amazon, Australia, Chile, the Mediterranean region, northern, southern and west Africa, south-western United States, and South America (*medium confidence*) (Feng and Fu, 2013; Greve and Seneviratne, 2015; Jones and Gutzler, 2016; Park et al., 2018). However, the AI does not incorporate potential changes to plant transpiration under increasing CO_2 concentration and therefore overestimates drought conditions and aridity. Additionally, it does not reflect seasonality in rainfall and evapotranspiration, which is important in regions where temperature and actual evapotranspiration are not increasing during the wet season when vegetation growth is occurring. Mirzabaev et al. (2019) 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 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 poleward as much as 11 degrees of latitude (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). Many studies point to an increasing dryland area based on the AI, 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. 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 PET is projected to increase over most land areas (Feng and Fu, 2013). 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

Global dryland area (based on the AI) is projected to expand by ~10% by 2100 compared to 1961-1990 under a high emission scenario (Chapter 12, WGI). However, there are significant regional differences in the drivers of dryland expansion and subsequent estimates of change in dryland extent. Subtropical drylands are projected to expand as the climate in these regions shifts from temperate to subtropical and aridity increases in currently sub-humid subtropical regions, resulting in the loss of temperature-controlled seasonal cycles (Schlaepfer et al., 2017). Observed and projected warming and drying trends are most severe in transitional climate regions between dry and wet climates, with some exceptions (Nkrumah et al., 2019), 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 anticipated in southwest North America, the northern fringe of Africa, southern Africa and Australia. The main areas of semi-arid expansion are expected to occur in the north side of the Mediterranean, southern Africa and North and South America. In contrast, India, eastern equatorial Africa and other areas of the southern Saharan regions are projected to have shrinking drylands (Biasutti and Giannini, 2006; Biasutti, 2013; Rowell et al., 2016). 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 semi-arid and dry sub-humid regions (Ji et al., 2015). However, estimates vary depending on the metric used (Swann et al., 2016; Berg et al., 2017b). 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., 2017a). 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 require better understanding of seasonality, 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 increased drought risk (Cook et al., 2014; Xu et al., 2019), but future trends in dust event frequency and intensity as a result of climate change are uncertain and will vary geographically (Jia, 2019). 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 (Section 4.4.8; Sharratt et al., 2015) and loss of biomass (Sharratt et al., 2015; Middleton and Kang, 2017). Shifts in dust storm timings are also projected in some regions (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 under RCP8.5 was detected by Evan et al. (2016) but 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 emerge with changing climate conditions, as Bhattachan et al. (2012) indicate for the Kalahari Desert in southern Africa, due to vegetation loss and dune remobilization. There is overall *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 (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 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 (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, theoretically, moderate projected future temperature increases (Wu et al., 2016; Diba et al., 2018), but with potentially negative effects on biodiversity (Chapter 2). 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).

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. Grassland composition may shift as C3 plants are replaced by C4 species, which have higher optimal temperatures and higher water use efficiency (although seasonality of precipitation also plays a role) (Knapp et al., 2020). Many desert species have morphological, physiological and/or behavioural adaptations to cope with climatic extremes, including rapid regeneration following droughts (Boudet, 1977; Hiernaux and Le Houérou, 2006), leaf dropping during the dry season to reduce water loss (Santos et al., 2014), alongside long histories of adaptation to climate change (Brooks et al., 2005; Ballouche and Rasse, 2007), while many animals 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; Harris et al., 2018).

Climate change increases risks of continued range retractions of Karoo succulents in South Africa (Young et al., 2016), dry argan woodlands in Morocco (Alba-Sánchez et al., 2015), epiphytic cacti in Brazil (Cavalcante and Duarte, 2019; Cavalcante et al., 2020) and other plant species exposed to higher aridity. Projected increases in heat and aridity could increase mortality of trees and shrubs in Sonoran Desert ecosystems in the United States (Munson et al., 2012; Munson et al., 2016b), reduce sagebrush 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, combined with changes in timing and availability of moisture, 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 and African drylands or at least not reverse (Higgins and Scheiter, 2012; 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 grasses into these arid shrublands has the potential to transform them rapidly, especially through the acceleration of the fire cycle (Bradley et al., 2016). While 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), increased plant growth in response to elevated CO_2, which results in increased water consumption, may counteract this. Increased water use efficiency is therefore not expected to counterbalance increased evaporative demand (Chapter 8). There is *medium confidence* that succulent species will be particularly vulnerable to increased heat and aridity due to reduced physiological performance, loss of seed banks, lower germination rates and increased mortality (Table CCP3.1; 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; Koźmińska et al., 2019).

CCP3.3.2 Projected Impacts on Human Systems

Across many drylands, human-induced causes of desertification, SDS, 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 heatwaves, are projected to further exacerbate the vulnerability and risk to humans from desertification (Hurlbert et al., 2019).

Sand and dust storms exert a wide range of impacts on people, within deserts and semi-deserts but also outside dryland environments because of long-range dust transport (Middleton, 2017). Research on the economic impacts of SDS is lacking, while studies that have been conducted lack consistency in data collection methods and analysis (Middleton, 2019). Although projections are rarely modelled, estimated economic damages of increased dust-related health impacts and mortality under RCP8.5 could total $47 billion/year additional to the 1986-2005 value of $13 billion/year in southwest USA (Allahbakhshi et al., 2019).

Projected impacts of climate change on the risk of food insecurity are a particular concern for the developing world drylands (Chapter 16, WGI; Mirzabaev et al., 2019), potentially leading to breakdown of food production systems, including crops, livestock, and fisheries, as well as disruptions in food supply chains and distribution (Myers et al., 2017; Lewis and Mallela, 2018). Developing country drylands are particularly vulnerable due to a higher share of populations with lower income, lower physical access to nutritious food, social discrimination as well as other environmental factors that link to climate change. 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 and Iran 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 highlight that projected temperature and rainfall increases in deserts and strong tropical cycles can create conditions conducive to the development, aggregation, outbreak and survival of locusts. Mandumbu et al. (2017) highlight how crop parasites such as *Striga spp.* in southern Africa may benefit from higher temperatures and rainfall activating dormant seeds, while high winds aid their dispersal. Combined with increasing risks of erosion and soil fertility losses (*Striga* is able to tolerate drought and a low nitrogen environment), this can have important impacts on the yields of key dryland crops such as maize and pearl millet.

Human responses can exacerbate desertification processes under climate change conditions, even in deserts. Exploitation of mineral resources (e.g. lithium mining in Chile's Atacama Desert) can cause human population changes as people flock to the area for work (Liu et al., 2019), increasing vulnerability due to e.g. soil erosion and salinisation, as well as increasing pressure on potable water for human consumption (Stringer et al., 2021) and exhausting aquifers. Salinisation is projected to increase in the drylands due to climate change impacts in future (Mirzabaev et al., 2019). For example, in India, about 7 million 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, will accelerate land salinization in India, rendering another 9 million 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 and Singh, 2015). The literature further shows evidence of desertification of oases and irrigated lands in parts of northern China's drylands (Wang et al., 2020), the Indian subcontinent's deserts, as well as the Mesopotamian Arabian Desert (Ezcurra, 2006; Dilshat et al., 2015).

CCP3.4 Adaptations and Responses

Adaptations to climate change impacts in human systems vary depending on exposure to risks, types of risks and responses, underlying social vulnerabilities and adaptive capacities, including access to resources, the extent of adaptation responses and the potential of these responses to reduce risk/vulnerability (Chapter 16 ; Singh and Chudasama 2021). Adaptations tend to be applied locally, tackling symptoms of the problem and proximate drivers (e.g. of desertification), rather than distant or external drivers (Morris et al., 2016; Adenle and Ifejika Speranza, 2021). Different groups require different kinds of supports and levers to enable them to follow adaptive pathways (Stringer et al., 2020; Møller et al., 2017) and face different barriers and limits to adaptation (Chapter 18, WG2). What constitutes an incremental adaptation in one location may be transformational in another. Spatial patterns of dryland resilience and adaptive capacity can be partly explained by access to livelihood capitals (Mazhar et al., 2021) and are shaped by prevailing structures and power dynamics. Supportive policies, institutions and good governance approaches can strengthen the adaptive capacities of dryland farmers, pastoralists and other resource users (*high confidence*) (Stringer et al., 2017). Table CCP3.2 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.

Table CCP3.2: Synthesis of adaptation measures and responses to risks in deserts and semi-arid areas. Appropriateness of measures is context dependent and some adaptations will be incremental or even maladaptive in some dryland contexts while being transformational in other locations.
[INSERT TABLE CCP3.2 HERE]

Adaptations to climate change, desertification, drought management (Section 17.2.2.2) and sustainable development activities largely overlap in drylands, pointing to synergies between them (Reichhuber et al., 2019). For example, support for communal and flexible land tenure could bring about benefits across multiple dimensions, while attention to water as a limiting factor in drylands can link to multiple SDGs (Stringer et al., 2021) as well as adaptations in natural systems, where improved forecasting and anticipatory science and management can be appropriate (Bradford et al., 2018). Currently, more than 125 countries around the world, particularly in drylands, are setting land degradation neutrality (LDN) targets. LDN and its hierarchical response mechanisms of avoiding, reducing and reversing land degradation, can provide an overarching resilience-based framework for adaptation at the national level (Mirzabaev et al., 2019; Orr et al., 2017b; Cowie et al., 2018) and support biodiversity conservation (Akhtar-Schuster et al., 2017). However, achieving LDN will require a transparent decision and prioritisation process (Dallimer and Stringer, 2018), anchored in a socio-ecological systems approach (Okpara et al., 2018), with investment in all dimensions of an enabling environment, including inclusive policies and regulations, sustainable institutions, accessible finance and effective science-policy communications and interactions (Verburg et al., 2019; Allen et al., 2020). LDN calls for integrated land use planning to ensure land uses are optimized at a landscape scale to help balance competition for limited land resources and harness multiple benefits (Cowie et al., 2018, Verburg et al., 2019), recognising that 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, land water, and finance (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 fore (Section 8.4). Measures promoting particular adaptations need to take into account such consequences as well as the potential for some adaptations to become maladaptive at scale.

Natural systems are also able to adapt to climate change, 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). Vegetation cover of psammophyte shrub species (in the "desert oasis transitional area") surrounding the Dunhuang Oasis (northwest China) reduces oasis land degradation risk by reducing sand grain size and velocity of winds from the aeolian desert (Zhang et al., 2007); while land use planning in Israel's Negev Desert 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). Scholars are nevertheless questioning the wider suitability of tree planting in drylands, given concerns for water availability and other ecosystem services (Veldman et al., 2015; Bond et al., 2019; Veldman et al., 2019). How natural dryland systems are managed following disturbances such as wildfire is important too. van den Elsen et al. (2020) found that establishing vegetation and mulch cover after a fire in a Mediterranean dryland ecosystem reduced soil erosion, helping maintain soil fertility and nutrients. However, different management objectives require different adaptations. For example, adaptation measures that reduce land degradation through reforestation could increase vulnerability to fire if they exclude ecologically sound fire management or are based on plant species that are fire prone. Combinations of different land management practices and governance approaches tackling a range of different stresses appear to best support sustainability and adaptation over the long term (van den Elsen et al., 2020).

Collective action can facilitate the implementation of adaptation responses and help 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 be problematic (Amiraslani et al., 2018), showing the importance of multi-stakeholder engagement (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 drylands according to the prevailing governance system. In China, the Grain for Green programme is an example of a large-scale ecological restoration programme securing local engagement through payments for ecosystem services (Kong et al., 2021), while transdisciplinary stakeholder engagement involving researchers and central and local governments in the Heihe River Basin in China's arid and semi-arid northwest, using an interdisciplinary 'web' approach, enabled basin restoration. Multi-stakeholder efforts saw improvement in the condition of Juyan Lake and the surrounding catchment, increasing both the lake surface area and groundwater in downstream locations (Liu et al., 2019).

In the short- to medium-term, monitoring, prediction and early warning can support adaptation and e.g. help reduce negative impacts of SDS by mobilising emergency responses. Daily dust forecasts enable preparation to minimise risks from sand/dust storms to both human and natural systems (e.g. the WMO Sand and Dust Storm Warning Advisory and Assessment System: https://sds-was.aemet.es/forecast-products/dust-forecasts). Preparedness and emergency response procedures benefit from covering diverse sectors, such as public health surveillance, hospital services, air and ground transportation services, water and sanitation, food production systems and public awareness, suggesting the need for a coherent, multi-sector governance approach. Longer-term actions include prioritizing sustainable land management (Middleton and Kang, 2017), based on Indigenous knowledge and local knowledge, and modern science (Verner, 2012), 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) has yielded 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) 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 both pre-empt and tackle locust plagues (Salih et al., 2020), requiring trans-boundary cooperation.

There is *high agreement* and *robust evidence* that shifting emphasis to proactive risk mitigation, including solutions for drought, flooding erosion and dust management, instead of exclusive focus on disaster management, reduces vulnerability and improves adaptive capacity (Section 16.4.3.2 and 16.5.2.3.4; 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). It also underscores the LDN response hierarchy avoid > reduce > reverse (Orr et al., 2017a). Nevertheless, *ex ante* drought and flood risk mitigation has been adopted in limited dryland settings, despite that it is preferable to increase preparedness before it happens, provide incentives for adaptation instead of insurance, provide insurance instead of relief, and provide relief instead of regulation (Sivakumar, 2005). Yet, providing disaster relief is often more publicly visible and politically expedient, despite its social, economic and environmental challenges. The absence of proactive risk mitigation and resulting crisis management increases vulnerability, increases reliance on government support, reduces self-reliance and increases costs (Grobicki et al., 2015; Wilhite, 2019), as well as hindering progress towards the SDGs. In the case of drought and flooding, major obstacles for the transition from reactive management to proactive drought risk mitigation include path dependencies and lack of knowledge about relative costs and benefits of reactive versus proactive approaches. This lack of information can deter large-scale and long-term investments into proactive approaches (Mirzabaev, 2016).

A range of risk mitigation and adaptation measures can be taken, to address drought, desertification and other climate change-related challenges in deserts and semi-arid areas, some of which can be both proactive and reactive. These include *inter alia*:

i) Policies, public advocacy, and social media campaigns that improve water use efficiency, especially in agriculture and industry, which can foster behavioural changes and reduce water consumption (Yusa et al., 2015; Tsakiris, 2017; Booysen et al., 2019),
ii) Integrating access to insurance, financial services, savings programs, and cash transfers into policies to increase the effectiveness of e.g. drought responses. Such efforts can result in significant cost savings (Berhane et al., 2014; Bazza et al., 2018 ; Guimarães Nobre et al., 2019),
iii) Development of robust early warning systems that provide information and improve knowledge surrounding drought and SDS to enable early recovery (Wilhite, 2019), considering also vulnerability and impact assessments (i.e. who is at greatest risk),
iv) Water management and storage, including using methods that draw on Indigenous knowledge (Stringer et al., 2021), water transfers, and trade, all of which can reduce costs and provide timely adaptations to drought, supporting agricultural productivity and rural livelihoods (Harou et al., 2010; Hurlbert, 2018),
v) Restoration, reclamation, and landscape heterogeneity strategies, promoting ecosystem resilience to wind erosion and dust abatement (Duniway et al., 2019) as well as restoring important ecosystem services at a catchment scale,
vi) Prevention of soil erosion, provision of dust abatement and enhanced biodiversity by changing grazing techniques (e.g. rotational grazing), facilitating herd mobility, protecting rangeland areas from fragmentation, promoting common tenure and access rights on grazing land, enabling rapid post fire restoration efforts, minimum tillage, sustainable land management, integrated landscape management, planting and caring for non-irrigated indigenous trees and other vegetation (Middleton and Kang, 2017); and
vii) Creation of drought tolerant food crops through participatory plant breeding (Grobicki et al., 2015) and investment in research and development of drought resistant varieties (Basu et al., 2017; Mottaleb et al., 2017; Dar et al., 2020), alongside adjusted planting and harvesting periods (Frischen et al., 2020). Similar to other adaptations, 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 of these measures can also support climate change mitigation efforts in drylands. Uptake of adaptation measures is often grounded in clear communications and information provision to support behavioural changes, taking into account local risk aversion and risk perceptions (Zeweld et al., 2018; Jellason et al., 2019). Building capacity by improving the knowledge base and access to information as well as to financial and other resources, encourages vulnerable economic sectors and people to adopt more self-reliant measures that promote more integrated and sustainable use of natural resources *(high confidence*) (Sivakumar, 2005; Wieriks and Vlaanderen, 2015; Aguilar-Barajas et al., 2016; Middleton and Kang, 2017; Wilhite, 2019). Engaging natural resource users as active participants in planning and technology adoption using extension services, financial grants and services geared to the local area, can build resilience and drive changes in practices (Webb and Pierre, 2018), while approaches such as Integrated Water Resources Management (IWRM) can support adaptation and drought risk management, including in dryland urban megacities (Stringer et al., 2021) and in deserts and semi-arid areas where precipitation trends remain stable yet other pressures on water are growing (Reichhuber et al., 2019).

[START FAQ CCP3.1 HERE]

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 in maintaining their livelihoods particularly where there is water scarcity.

Drylands include the hottest and most arid areas on Earth. Human-caused climate change has been intensifying this heat and aridity in some places, increasing temperatures more across global drylands than in humid areas. In areas which are hotter and drier, tree death has occurred and in some locations bird species have been lost. Climate change has reduced rainfall in some dryland areas and increased rainfall in other areas. Increased rainfall, combined with the plant-fertilizing effect of more carbon dioxide in the atmosphere, can increase grass and shrub production in dryland areas. 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.

[END FAQ CCP3.1 HERE]

[START FAQ CCP3.2 HERE]

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

Climate change is projected to lead to higher temperatures across global drylands. Many drylands also risk more irregular rainfall leading to increased irregularity in crop yields, and increased water insecurity where less rainfall is projected, which may have profound implications for both dryland ecosystems and their human inhabitants.

There is, however, considerable uncertainty about the changes that may occur in drylands in the future and how people and ecosystems will be affected. In some drylands, higher temperatures and declining rainfall have increased aridity. However, this is not a global trend as many drylands are experiencing increases in vegetation cover and rainfall. Both the amount of rainfall and its seasonality have changed in many dryland areas, associated with natural variability and warming.

Most climate models project increased rainfall in tropical drylands, but 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 sand and dust storm activity are also uncertain and will not be the same everywhere, but there will likely be increases in some regions (e.g. the United States) in the long-term. The impacts of climate change in deserts and semi-arid areas may have substantial implications globally: for agriculture, biodiversity, health, trade and poverty, as well as potentially, for conflicts and migration. Increasing temperatures and more irregular rainfall are expected to affect soil and water and contribute to tree death 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 potential for conflicts and migration is primarily associated with socioeconomic development, while links to climate change remain uncertain and lack evidence.

[END FAQ CCP3.2 HERE]

[START FAQ CCP3.3 HERE]

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

Water is a major 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 Indigenous knowledge, local 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, large-scale water desalination when they have access to sea water, despite high energy use and negative environmental impacts of waste brine. In dryland agricultural areas across the world, incremental adaptations include water conservation measures, use of improved crop varieties or increasing 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 grassland, shrubland, and savanna ecosystems, 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, realigning policies and incentives for sustainable management, investing in supporting infrastructures, alongside developing alternative livelihood options that are less exposed and sensitive to climate change. Involving all relevant stakeholders is 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, and integrated drought management. Efforts are needed across all scales from local to global to support sustainable development in desert and semi-arid areas, given projected climate changes.

Large Tables

Table CCP3.1: Observed ecological changes in drylands.

Region	Observed change	Climate change factors	Attribution to 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. (2016b); Conver et al. (2017)
Arid						
African Sahel	Woody cover increase in parts of the Sahel	Increase in rainfall since the mid-1990s (compared to 1968-1993)and increased CO_2		Restoration planting Agroforestry	*High*	

	Increase in grass production across Sahel	Increases in rainfall since the mid-1990s (compared to 1968-1993) and increased CO_2			*Medium*	Hiernaux et al. (2009a); Hiernaux et al. (2009b); Dardel et al. (2014); Venter et al. (2018); Zhang et al. (2018); Brandt et al. (2019); Bernardino et al. (2020)
	Decline of mesic tree species at field sites across the Sahel	Decreased rainfall from 1901 to 2002 increased temperature	Yes. multivariate statistical analyses find climate factors more important than non-climate factors.	Land clearing for cropland expansion, Increase pressure on wood resources (rural demography, urbanization)	*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)
	Increased tree mortality at field sites across the Sahel	Decreased rainfall from 1901 to 2002, increased temperature	Yes. multivariate statistical analyses find climate factors more important than non-climate factors.	Agricultural expansion, modified runoff on shallow soils	*High*	Helldén (1984); Gonzalez, (2001); Wezel and Lykke (2006); Maranz (2009); Vincke et al. (2010); Hänke et al. (2016); 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	Decreased rainfall, increased temperature	Yes. multivariate statistical analyses find climate factors more important than non-climate factors.		*High*	Boudet (1977); Tucker and Nicholson (1999); Gonzalez, (2001); Hiernaux and Le Houérou (2006); Hiernaux et al. (2009a); Maranz (2009); Gonzalez et al. (2012)
Namib desert	Increase in woody plant cover and a shift of mesic	Increase in amount of fog from westward			*Medium*	Morgan et al. (2004); Haensler et al. (2010); Donohue et al. (2013); Rohde et al. (2019)

	species into more arid regions	expansion of convective rainfall and increase in number of extreme rainfall events. Elevated CO2 and warming effects on the Bengula upwelling system				
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)
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 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		Agricultural growth, high population growth	*Medium*	Karmaoui et al. (2014)

		causing soil and water salinization, drying up of surface water. Hot winds and sandstorms.		and unregulated and indiscriminate land development		
	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	Drought adapted species are increasing in Chihuahuan deserts	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)
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 and increase CO_2		Urban growth, mechanized agriculture, and changes in land use	*High*	Pérez-Sánchez et al. (2011); 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 semi-arid 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)
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 Patagonia	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*	Xu et al. (2019)
Semi-arid						
Australian arid lands	Widespread greening	Elevated CO2			*Medium*	Donohue et al. (2013)
African savanna	Doubling of tree cover from 1940 – 2010 in South Africa changing land use), and 20% increase in spread of woody	Warming, elevated CO_2, altered rainfall regimes		Removal of mega-herbivores, fire suppression,	*High*	Skowno et al. (2017); Stevens et al. (2017); Venter et al. (2018); García Criado et al. 2020)

	areas into previously open areas in the last 20 years			changed herbivore regime		
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 CO_2		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 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); Chambers (2018)
	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 increase in the rain fraction in winter.			*High*	Chambers et al. (2014); Mote et al. (2018)

Central Mexico	Desertification (as decreases in vegetation indexes).	decreased rainfall + increase in temperature		Land use change and intensification	*Medium*	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, CO_2 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 CCP3.2: Synthesis of adaptation measures and responses to risks in deserts and semi-arid areas. Appropriateness of measures is context dependent and some adaptations will be incremental or even maladaptive in some dryland contexts while being transformational in other locations.

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, 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)
Clearing of natural vegetation	Carbon sequestration through decreasing vegetation clearing rates, reversal through revegetation, 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), Suckall et al. (2014)
Invasive species and woody encroachment	Cliamte change is projected to facilitate the spread of invasive species. Invaive species can have profound impacts on dryland ecosystems functioning leading to the loss of biodiversity. 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. Chemical removal of undesirable encroached woody species	Mirzabaev et al. (2019); 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	Morton and Barton (2002); Abebe et al. (2008); Alary et al. (2014); Catley et al. (2014); Mohamed et al. (2016)

	based early warning systems, IRWM, water governance benchmarking, and exploration of palaeo channels as freshwater sources using remote sensing	
Grassland and savanna degradation	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. (2019)
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. Clearance of invasives. 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 and Le Houérou (2006); Reed et al. (2015)
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)	Turner (1993); Schlecht et al. (2004); Fernández-Rivera et al. (2005); Bonnet and Herault (2011); 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 on farm: for 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); Hiernaux et al. (2009b); Sendzimir et al. (2011); Turner and Hiernaux (2015); Weston et al. (2015; Reij and Garrity (2016)
Salinisation and groundwater depletion	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	Sengupta (2002); Buechler and Mekala (2005); Wassmann et al. (2009); Singh (2010); Jnandabhiram and Sailen Prasad

	in face of salinisation. Climate change is projected to increase the salinization of groundwaters. Current unsustainable use of groundwaters is already leading to their depletion in some dryland areas.	(2012); Manga et al. (2015); Sharma and Singh (2015); Gupta and Dagar (2016); Nikam et al. (2016); Bundela et al. (2017); Sharma and Singh (2017); Patel et al. (2020); Singh et al. (2020b); Sharma, (2016); Mirzabaev et al. (2019)
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. 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. 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. 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	Ahmed et al. (2016); Al-Hemoud et al. (2017); Sivakumar (2005); Hiernaux et al. (2009a); Hiernaux et al. (2016); Pierre et al. (2018); Lamers et al. (1995); Michels et al. (1998); Bielders et al. (2004),UNEP (2016); UNEP (1992)

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