

# CCP3

## Deserts, Semiarid Areas and Desertification

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## Executive Summary

### Introduction

This cross-chapter paper on 'Deserts, semiarid areas and desertification' updates and extends Chapter 3 on 'Desertification' in the IPCC Special Report on Climate Change and Land (SRCL) (Mirzabaev et al., 2019). It assesses new information and links it to the findings across the chapters of Working Group II's contribution as well as relevant chapters of Working Group I's contribution to the IPCC Sixth Assessment Report (AR6), with an added focus on deserts which were outside the scope of the SRCL.

### Where are we now: Observed impacts and adaptation responses

Deserts and semiarid 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*<sup>1</sup>). 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 semiarid 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 semiarid regions greatly depends on water availability, as they are highly sensitive to changes in precipitation and potential evapotranspiration, as well as to land management practices. Multiple lines of evidence from 1920–2015 indicate that surface warming of 1.2°C–1.3°C over global drylands (Section 1.1.1) exceeded the 0.8°C–1.0°C 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. Observed trends in deserts and semiarid 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 1980s, and in North Africa from 1970 to 2007; and losses of bird species in the Mojave Desert of North America from 1908 to 2016. In contrast, 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<sub>2</sub> fertilization which, together with unsustainable management, alters biodiversity and reduces ecosystem services, such as water availability and grazing potential {3.2.1, 3.2.2}.

**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 well-being, particularly in deserts and semiarid areas with lower adaptive capacities (*high confidence*).** Ecosystem degradation (Section 16.5.2.3.2) and desertification threaten the abilities of both natural and human systems to adapt to climate change (*high confidence*). Changes in desert and semiarid ecosystem services most acutely affect people who are directly dependent on natural 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*). In rural drylands in tropical and Mediterranean areas, human populations are steadily expanding with mixed implications for ecosystem services under climate change, while rapid urbanisation in new and existing dryland megacities puts 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, 3.2.1, 3.2.2, 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. 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, AI) 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 semiarid expansion are *likely*<sup>2</sup> to occur on the north side of the Mediterranean, southern Africa and North and South America. India,

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.

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

parts of northern China, eastern equatorial Africa and the southern Saharan regions are projected to have shrinking drylands. Under Representative Concentration Pathway (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 RCP4.5, could limit expansion to one-tenth of the 1990 area by 2100. Nevertheless, the utility of the AI in delineating dryland biomes is limited under an increasing CO<sub>2</sub> 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 and 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 interannual 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 semiarid areas will face for their sustainable development (*medium confidence*). {3.3.1, 3.3.2}

harness multiple benefits for managing the impacts of climate change and desertification while accelerating progress towards sustainable development in deserts and semiarid areas. {3.4}

#### *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 semiarid areas have a rich cultural heritage, and Indigenous knowledge and local knowledge (IKLK) 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 IKLK; *medium 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

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lies within the 17–83% probability range.

## CCP3.1 Introduction

### CCP3.1.1 Concepts, Definitions and Scope

Deserts and semiarid areas are in 'drylands', which comprise hyper-arid, arid, semiarid and dry sub-humid areas (Figure CCP3.1). Drylands cover about 45–47% of the global land area (Prävālie, 2016; Koutroulis, 2019) and are home to about 3 billion people residing primarily in semiarid 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 urbanising (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. Recognising 'land degradation' as a contested and perceptual term (Blaikie and Brookfield, 1987; Behnke and Mortimore, 2016; Robbins, 2020), this cross-chapter paper (CCP), 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, semiarid and dry sub-humid areas (UNCCD, 1994). Following the above definitions, desertification is more common in arid and semiarid 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). 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 well-being (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 16.2.3.10) 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); for example, 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, socioeconomic and institutional systems (Reynolds et al., 2007; Stringer et al., 2017).

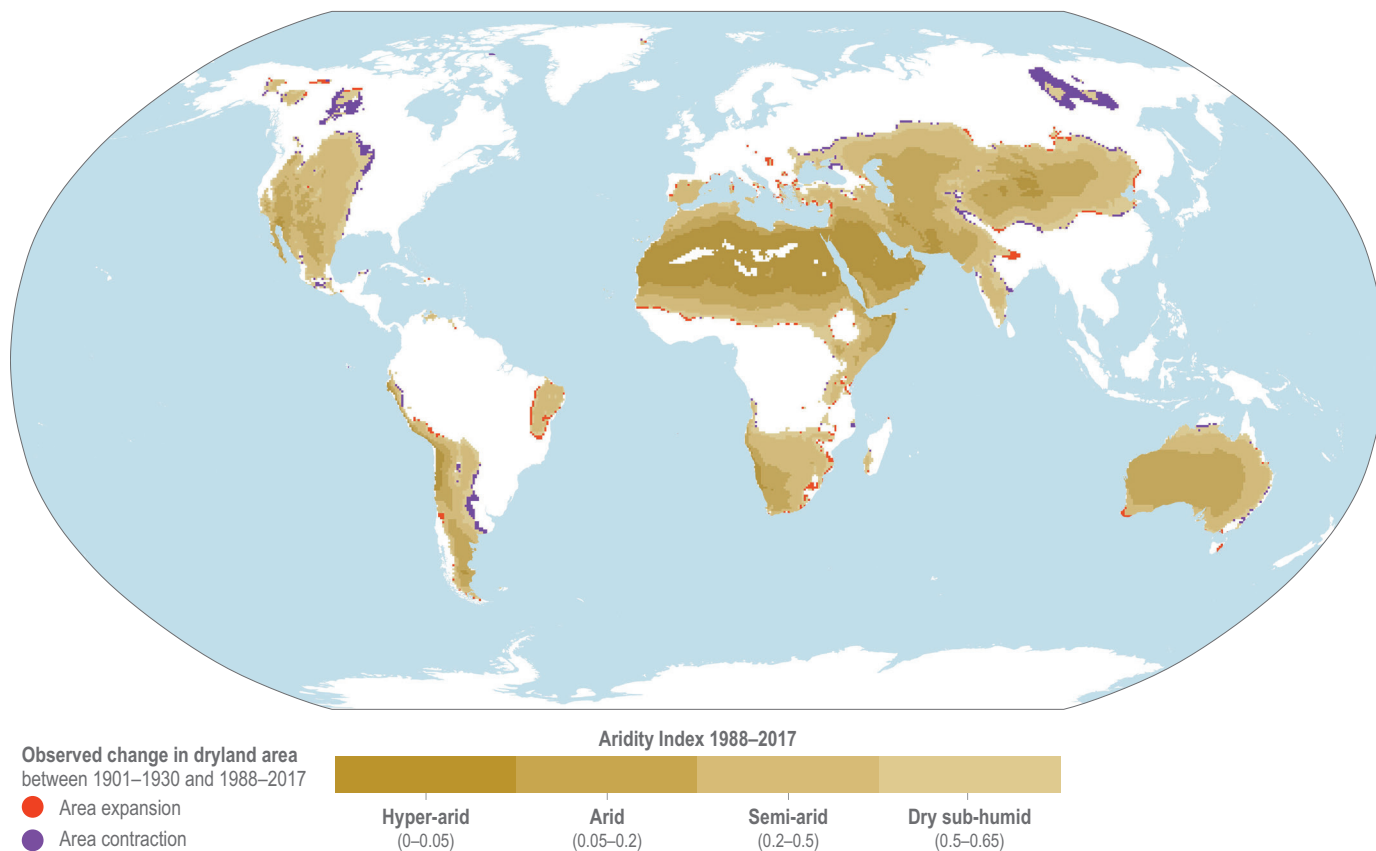
Chapter 3 of the IPCC Special Report on Climate Change and Land (SRCL) focused on desertification (Mirzabaev et al., 2019), but links between climate change and deserts, desertification and semiarid areas have not been extensively considered in recent IPCC assessment cycles. Working Group II Assessment Report 5 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, IKLK, and 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



## Aridity zone extent and observed changes in dryland areas as defined by the Aridity Index



**Figure CCP3.1 | Aridity zone extent and observed changes in dryland areas as defined by the Aridity Index (AI).** Aridity zones, according to UNESCO (1979) and UNEP (1992) classifications, defined by the 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  $AI > 0.65$  (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.

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  $AI = 0.56$ , soil disruption at  $AI = 0.3$  and loss of plant cover at  $AI = 0.2$  (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).

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

#### CCP3.2.1 Observed Impacts on Natural Systems in Arid and Semiarid Areas

##### CCP3.2.1.1 Temperature and Rainfall

Significant warming has occurred across drylands globally (IPCC, 2021). Surface warming (1920–2015) of  $1.2^\circ C$ – $1.3^\circ C$  in global drylands has exceeded the  $0.8^\circ C$ – $1.0^\circ C$  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

Semiarid ecosystems have a disproportionately large role in the global carbon cycle, driving trends and interannual 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 semiarid 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<sub>2</sub> fertilization 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 (Sections CCP1.2.3.2; CCP4.2.1) and West and Central Asia (Jiao et al., 2021). Climate change and elevated CO<sub>2</sub> 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; Castellón et al., 2015; Sosa et al., 2019), large parts of the West African Sahel with some local exceptions (Brandt et al., 2016) and 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<sub>2</sub> 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 per decade), Australia (1% increase per decade), and South America (8% increase per 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 the normalized difference vegetation index (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<sub>2</sub> fertilization (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). 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

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
<i>Hyper-arid</i>						
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	Iknyan and Beissinger (2018); Riddell et al. (2019)
	Decline of desert tortoise ( <i>Gopherus agassizii</i> ) population by 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 USA	Increased temperature, decreased rainfall, wildfire			Land use change, invasive plant species	high
<i>Arid</i>						
African Sahel	Woody cover increase in parts of the Sahel	Increase in rainfall since the mid-1990s (compared to 1968–1993) and increased CO <sub>2</sub>		Restoration planting, agroforestry	high	
	Increase in grass production across the Sahel	Increases in rainfall since the mid-1990s (compared to 1968–1993) and increased CO <sub>2</sub>			medium	Hiernaux et al. (2009a; 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, increased pressure on wood resources (rural demography, urbanisation)	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)

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Region	Observed change	Climate change factors	Attribution to climate change	Non-climate change factors	Confidence in observed change	References
Namib desert	Increase in woody plant cover and a shift of mesic species into more arid regions	Increase in amount of fog from westward expansion of convective rainfall and increase in number of extreme rainfall events; elevated CO <sub>2</sub> and warming effects on the Benguela upwelling system			medium	Morgan et al. (2004); Haensler et al. (2010); Donohue et al. (2013); Rohde et al. (2019)
Southern Africa— Nama-Karoo		Shifting rainfall seasonality (debate over whether it is cyclical or directional); elevated CO <sub>2</sub>			medium	Du Toit and O'Connor (2014); Du Toit et al. (2015); Masubelele et al. (2015a; 2015b)
	Eastern Karoo has experienced a significant increase in the end of the growing season length	Shift in rainfall seasonality and increase in Mean Annual Precipitation			low	Davis-Reddy (2018)
	Woody encroachment observed throughout the Nama-Karoo in valley bottoms, ephemeral stream banks and the slopes of Karoo hills	Rising concentration of CO <sub>2</sub>		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	Range shift in tree aloe <i>Aloidendron dichotomum</i> 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 oases and reduced ecosystem service provision	High temperature and reduced precipitation causing soil and water salinisation, drying up of surface water; hot winds and sandstorms		Agricultural growth, high population growth and unregulated and indiscriminate land development	medium	Karmaoui et al. (2014)
	Reduced surface water availability	Increased temperature and reduced precipitation		High demand (population growth) and land use change	medium	Rochdane et al. (2012); Choukri et al. (2020)
	Reduction of resilience of <i>Abies pinsapo</i> – <i>Cedrus atlantica</i> 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 interannual variation in climate trends			medium	Collins and Xia (2015); Rudgers et al. (2018)
	Widespread woody plant encroachment; <i>Prosopis</i> sp. encroachment in arid desert regions (Chihuahuan and Sonoran Desert) at a rate of ~3% per decade	Increasing temperature, elevated CO <sub>2</sub> and changing rainfall		Fire suppression and altered grazing/ browsing regimes	high	Caracciolo et al. (2016); Archer et al. (2017)
	Plant desert community shift changes the albedo through the reduction in dark biocrusts	Warming and drought			medium	Rutherford et al. (2000)

Region	Observed change	Climate change factors	Attribution to climate change	Non-climate change factors	Confidence in observed change	References
South Chihuahuan Desert— North and Central Mexico	Shrub encroachment of grassland ( <i>Berberis trifoliolata</i> , <i>Ephedra aspera</i> , <i>Larrea tridentata</i> ) changes dominant species in shrub areas; loss of less resistant shrubby species ( <i>Leucophyllum laevigatum</i> , <i>Lindleya mespiloides</i> , <i>Setchellanthus caeruleu</i> ); shrub encroachment of mesic and temperate areas	Decreased rainfall, increase in temperature and increase CO <sub>2</sub>		Urban growth, mechanised agriculture and changes in land use	high	Pérez-Sánchez et al. (2011); Castillón et al. (2015); Sosa et al. (2019)
	Shifts in soil microbial community to being 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 and increase in temperature			medium	Sosa et al. (2019)
	Loss of cacti species ( <i>Echinocactus platyacanthus</i> , <i>Pediocactus bradyi</i> , <i>Coryphantha werdermannii</i> , <i>Astrophytum</i> ) due to decline in physiological performance, loss of seed banks and lower germination rates	Decreased rainfall and increase in temperature		Cattle grazing, looting	high	Aragón-Gastélum et al. (2014); Shryock et al. (2014); Martorell et al. (2015); Carrillo-Angeles et al. (2016); Aragón-Gastélum et al. (2018)
Arid and semiarid territories in Argentina	Decreases in vegetation indexes	Decreased rainfall		Human-induced land degradation	low	Barbosa et al. (2015)
Argentina Chaco Region	Dryland salinity	Changes in rainfall		Land use change, overexploitation of water resources	medium	Amdan et al. (2013); Marchesini et al. (2017)
South America Arid Diagonal	Marked reduction in streamflow from the Andes mountain 'water towers' due to the persistent reduction in precipitation	Decrease in precipitation in the upper Andes; the unprecedented 10-year extreme dry period has been called the 'Mega-drought'			high	Bianchi et al. (2017); Rivera and Penalba (2018); Masiokas et al. (2019); Rodríguez-Morales et al. (2019)
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 <i>Austrocedrus</i> and <i>Nothofagus</i> 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 <i>Nothofagus</i> treeline across Patagonia	Increase in temperature and duration of the growing season at high elevation in the Patagonian Andes			high	Srur et al. (2016; 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 in 1997 and has been in a state of high variability since then			medium	Li et al. (2015)

Region	Observed change	Climate change factors	Attribution to climate change	Non-climate change factors	Confidence in observed change	References
Loess Plateau, China	Widespread vegetation greening in the Loess Plateau region; soil moisture declining widely, and deficit in forests and orchards; Yellow River runoff declining	Significant warming, slight increase in precipitation		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	Runoff increases, total water storage and groundwater increasing, Net Primary Productivity increase	Precipitation increasing and evapotranspiration slightly decreasing		Grassland protection	high	Xu et al. (2019)
<i>Semi-arid</i>						
Australian arid lands	Widespread greening	Elevated CO <sub>2</sub>			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 areas into previously open areas in the last 20 years	Warming, elevated CO <sub>2</sub> , altered rainfall regimes		Removal of mega-herbivores, fire suppression, changed herbivore regime	high	Skowno et al. (2017); Stevens et al. (2017); Venter et al. (2018); García Criado et al. (2020)
African savanna	Widespread increase in tree cover across Africa with only three countries across the continent experiencing a net decline in tree cover	Warming, changing rainfall, mention of CO <sub>2</sub>		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 for 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, ( <i>Prosopis glandulosa</i> , <i>Juniper ashei</i> and <i>Juniper pinchotti</i> ) occurring in the semi-arid grasslands of the southern Great Plains at a rate of ~8% per decade	Increasing temperature, elevated CO <sub>2</sub> 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) ( <i>Juniper occidentalis</i> ) at a rate of 2% per decade	Warming and associated decline in snowpack, 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 and increase in temperature		Land use change and intensification	medium	Becerril-Pina et al. (2015); Noyola-Medrano and Martínez-Sías (2017)

Region	Observed change	Climate change factors	Attribution to climate change	Non-climate change factors	Confidence in observed change	References
Chinese drylands	Widespread greening trend of vegetation in China over the last three decades; regional differences	Warming, CO <sub>2</sub> increase Rising atmospheric CO <sub>2</sub> 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 Leaf Area Index trend Negative impacts of climate change in north China and Inner Mongolia and positive impacts in the Qinghai-Xizang plateau		Ecological protection	medium	Piao et al. (2015)
<i>Dry subhumid</i>						
African mesic savannas	Forest expansion into mesic savannas	Increased rainfall, elevated CO <sub>2</sub>		Fire suppression	medium	Baccini et al. (2017); Aleman et al. (2018)
South American cerrado	8% rate of woody cover increase	Elevated CO <sub>2</sub>		Fire exclusion	high	Stevens et al. (2017); Rosan et al. (2019)
South American cerrado	Expansion of forest into cerrado	Elevated CO <sub>2</sub>		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)

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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, for example, 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 southwestern 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 southwestern USA, 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; Conner et al., 2017) and perennial vegetation cover (Munson et al., 2016a; 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 USA, 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; 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; 2018; Masubelele et al., 2015a; 2015b). These changes are causing an increase in fire frequency in these seldom burnt areas (du Toit et al., 2015). The Sahara 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 northwestern 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).

### CCP3.2.1.7 Sand and Dust Storms

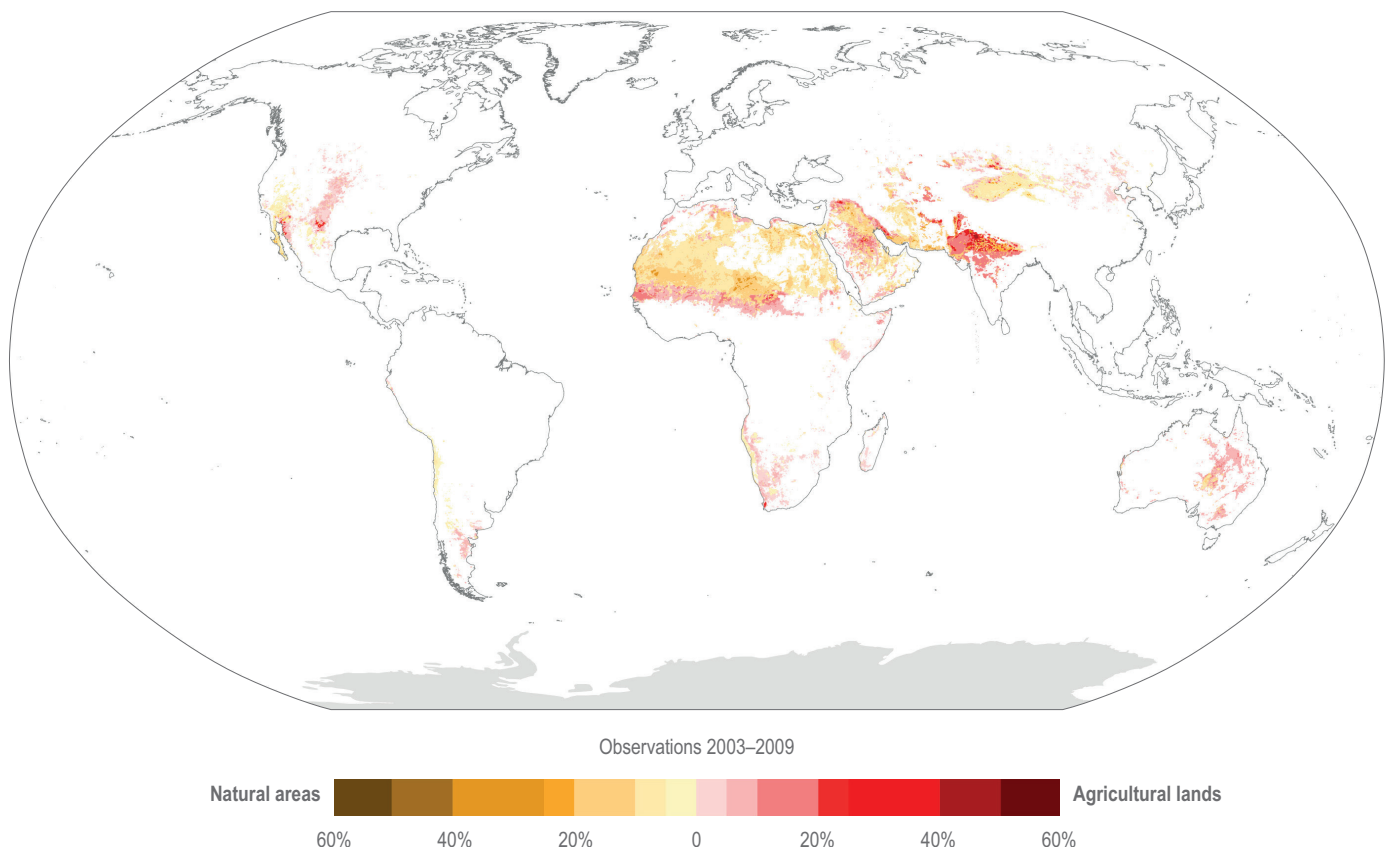
Soil dust emissions are highly sensitive to changing climate conditions but also to changing land use and management practices (*high confidence*). Distinguishing between the effects of these drivers is not straightforward, even in well-documented locations (Middleton, 2019). There is *limited evidence* 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 semiarid and arid areas will contribute to sand and dust activity (Mirzabaev et al., 2019).

SDS 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 SDS 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

### Frequency of high dust days during the dust season



**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 under 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.



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, salinisation and 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 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 also occurring 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 sources cover at least 500,000 km<sup>2</sup> 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).

#### 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 recognised 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 (Section CCP4.2.3) 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 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 benefit–cost 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

The 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 16.2.3.4) 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 are among the natural hazards with the highest adverse impacts on human populations (Mishra and Singh, 2010; Arias et al., 2021). Although droughts represented just 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 (Zhu et al., 2013; Amin et al., 2018), especially in developing countries (Haider and Adnan, 2014; Ahmed et al., 2016; ur Rahman et al., 2018) 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, semiarid 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 as 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 (WGI TS.4.3.2.10), 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, Arias et al., 2021), 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 more limited adaptive capacities than in the past, particularly where mobility, access and tenure rights are becoming restricted (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).

### 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 CCP 3.1). 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 organised 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).

### 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. Research on pastoralism in the Sahel concluded 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<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O emissions during mineralisation (Assouma et al., 2017). Efforts to sedentarise and settle pastoralists in villages can lead to land degradation and higher overall emissions from the sector.

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-equilibrium environments that are unstable, fluctuating and generally uncertain, and are 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 marginalisation 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 marginalisation, 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).

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 marginalisation (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 as in 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  $\sim 6.5^{\circ}\text{C}$  ( $\sim 3.5^{\circ}\text{C}$ ) under the high Representative Concentration Pathway (RCP) 8.5 (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  $40^{\circ}\text{C}$  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  $+2^{\circ}\text{C}$  and  $+4^{\circ}\text{C}$  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). 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; 2019b). In a  $+1.5^{\circ}\text{C}$  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  $2^{\circ}\text{C}$  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 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, northeastern 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 western Africa, southwestern USA 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  $\text{CO}_2$  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 aridity increases 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  $11^{\circ}$  latitude (Rajaud and Noblet-Ducoudré, 2017). By 2100, the population of dryland areas could increase by 700 million people and, under RCP8.5, 3 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 (Feng and Fu, 2013). 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 semiarid 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 5 (CMIP5) models underestimate historical warming (Huang et al., 2016) and overestimate precipitation over drylands, particularly in the semiarid and dry sub-humid regions (Ji et al., 2015). However, estimates vary depending on the metric used (Swann et al., 2016; Berg et al., 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 remobilisation. 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% to 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, for example, 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 USA (Munson et al., 2012; 2016b), reduce sagebrush in arid ecosystems of the western USA (Renwick et al., 2018), and contribute to the replacement of perennial grasses with xeric shrubs in the southwestern USA (Bestelmeyer et al., 2018). CO<sub>2</sub> 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 southwestern USA, 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<sub>2</sub> concentrations, limiting the expansion of dryland ecosystems (Swann et al., 2016; Mirzabaev et al., 2019), increased plant growth in response to elevated CO<sub>2</sub>, 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; 2017; Shryock et al., 2014; Martorell et al., 2015; Carrillo-Angeles et al., 2016; 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).

SDS 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 USD 47 billion/year additional to the 1986–2005 value of USD 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; Mirzabaev et al., 2019), potentially leading to the breakdown of food production systems, including crops, livestock and fisheries, as well as disruptions in food supply chains and distribution (Myers et al., 2017; 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 and 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, for example, 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 hectares of arable land area is currently affected by salt (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 salinisation in India, rendering another 9 million hectares 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 (Møller et al., 2017; Stringer et al., 2020) and face different barriers and limits to adaptation (Chapter 18). 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 semiarid areas. Some adaptations present no-regrets options while others tackle desertification and/ or climate changes to different extents.

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 optimised 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 socioeconomic 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 urbanisation 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; 2019; Bond 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 recognised 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). Transdisciplinary stakeholder engagement involving researchers and central and local governments in the Heihe River Basin in China's arid and semiarid 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).

**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 and 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 agriculture, forestry and other land use-related mitigation pathways (assets and income from carbon, wood energy, improved soil fertility and enhancement of local climate conditions; 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 sub-Saharan Africa 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	Climate change is projected to facilitate the spread of invasive species that can have profound impacts on dryland ecosystem 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); Crooms et al. (2018); Ding and Eldridge (2019)
Droughts	Proactive drought risk mitigation compared with reactive crisis management approaches Promoting collective action in livestock management, optimising 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 seawater desalination Promoting behavioural changes for more efficient residential water use; moving away from water-intensive agricultural practices in arid areas; harvesting rainwater by local communities; empowering women and engagement in local climate adaptation planning, community-based early warning systems, Integrated Water Resources Management, water governance benchmarking, and exploration of palaeo channels as freshwater sources using remote sensing	Morton and Barton (2002); Abebe et al. (2008); Alary et al. (2014); Catley et al. (2014); Mohamed et al. (2016)
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 local and regional herd mobility during the growing season to avoid intense grazing pressure on growing annual herbaceous vegetation of rangelands near settlements, water points, markets 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 Djitéye (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 institutionalised 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) 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	Turner (1993); Schlecht et al. (2004); Fernández-Rivera et al. (2005); Bonnet and Herault (2011); Hiernaux et al. (2016) Many trials in research stations and on farm: for example Sangaré et al. (2002a; 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 of mineral N and P fertilizers as placed (per pocket) 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, fertilization).	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); Battono et al. (2011); Hiernaux et al. (2009b); Sendzimir et al. (2011); Turner and Hiernaux (2015); Weston et al. (2015); Reij and Garrity (2016)

Challenge	Adaptation measures and responses	References
Salinisation and groundwater depletion	<p>Indigenous and scientific adaptive practices to cope with salinity</p> <p>Farmers in waterlogged saline areas harness subsurface drainage, salt tolerant crop varieties, land-shaping techniques and agroforestry to adapt to salinity and waterlogging risks</p> <p>Locally adapted crops and landraces and the traditional tree- and animal-based means to sustain livelihoods in face of salinisation</p>	<p>Sengupta (2002); Buechler and Mekala (2005); Wassmann et al. (2009); Singh (2010); Jnandabhiram and Sainen Prasad (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)</p>
Sand and dust storms	<p>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</p> <p>Use of perennial plant species that can trap sediments (sand and fallen dust) and form sandy mounds, such as <i>Haloxylon salicornicum</i>, <i>Cyperus conglomerates</i>, <i>Lycium shawii</i> and <i>Nitraria retusa</i></p> <p>In the Sahel, promote herbaceous (not woody plants) to trap sand: annuals such as <i>Colocynthis vulgaris</i>, <i>Chrozophora senegalensis</i>, <i>Farsetia ramosissima</i>; perennials such as <i>Cyperus conglomeratus</i>, <i>Leptadenia hastate</i></p> <p>In the Sahel, leaving at least part of the crop residues (stalks) on the soil during the dry season (100 kg dry matter per hectare has already had significant effect on wind erosion, many trials on millet in Niger); trampling by grazing livestock improves the partial burying of the residues</p> <p>Improve monitoring, prediction and early warning to mobilise emergency responses for human systems and prioritise long-term sustainable land management measures; establish a Global Dust–Health Early Warning System (building on the Sand and Dust Storm Warning Advisory and Assessment System (SDS-WAS) initiative); multi-sectoral preparedness and response including public health, hospital services, air and ground transportation and communication services</p>	<p>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)</p>

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In the short- to medium-term, monitoring, prediction and early warning can support adaptation and, for example, help reduce negative impacts of SDS by mobilising emergency responses. Daily dust forecasts enable preparation to minimise risks from SDS to both human and natural systems (e.g., the World Meteorological Organization 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 prioritising sustainable land management (Middleton and Kang, 2017), based on IKLK 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, for example, 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 mobilise 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 transboundary 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; 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 it being 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 semiarid areas, some of which can be both proactive and reactive. These include *inter alia*:

- Implementing 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; Booyesen et al., 2019).
- Integrating access to insurance, financial services, savings programmes and cash transfers into policies to increase the effectiveness of, for example, drought responses. Such efforts can result in significant cost savings (Berhane et al., 2014; Bazza et al., 2018; Guimarães Nobre et al., 2019).



- Developing robust early warning systems that provide information and improve knowledge surrounding drought and SDS to enable early recovery (Wilhite, 2019), also considering vulnerability and impact assessments (i.e., who is at greatest risk).
- Managing and storing water, 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).
- Implementing 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.
- Preventing soil erosion, providing of dust abatement and enhancing 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).
- Creating 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 can support adaptation and drought risk management, including in dryland urban megacities (Stringer et al., 2021) and in deserts and semiarid areas where precipitation trends remain stable yet other pressures on water are growing (Reichhuber et al., 2019).

#### Frequently Asked Questions

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

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

#### Frequently Asked Questions

##### 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.*



## FAQ 5.1 (continued)

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 USA) in the long term. The impacts of climate change in deserts and semiarid 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<sub>2</sub> 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.

## Frequently Asked Questions

### FAQ CCP3.3 | What can be done to support sustainable development in desert and semiarid 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 desalinate 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 IKLK and innovative science, and can help to address multiple Sustainable Development Goals.*

Different desert and semiarid 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 IKLK 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 semiarid areas, given projected climate changes.

## References

- Abatzoglou, J.T. and C.A. Kolden, 2011: Climate Change in Western US Deserts: Potential for Increased Wildfire and Invasive Annual Grasses. *Rangel. Ecol. Manag.*, **64**(5), 471–478, doi:10.2111/REM-D-09-00151.1.
- Abdoulaye, T. and J.H. Sanders, 2005: Stages and determinants of fertilizer use in semi-arid African agriculture: the Niger experience. *Agricultural Economics*, **32**(2), 167–179, doi:10.1111/j.0169-5150.2005.00011.x.
- Abebe, D., et al., 2008: Impact of a commercial destocking relief intervention in Moyale district, southern Ethiopia. *Disasters*, **32**, 167–189, doi:10.1111/j.1467-7717.2007.01034.x.
- Abel, C., et al., 2021: The human–environment nexus and vegetation–rainfall sensitivity in tropical drylands. *Nat. Sustain.*, **4**(1), 25–32, doi:10.1038/s41893-020-00597-z.
- Abel, G.J., M. Brottrager, J. Crespo Cuarema and R. Muttarak, 2019: Climate, conflict and forced migration. *Glob. Environ. Chang.*, **54**, 239–249, doi:10.1016/j.gloenvcha.2018.12.003.
- Abraham, E.M., J. Guevara, R.J. Candia and N.D. Soria, 2016: Dust storms, drought and desertification in the Southwest of Buenos Aires Province. *Argentina*, **48**, 221–241. pp.
- Aguilar-Barajas, I., et al., 2016: Drought policy in Mexico: a long, slow march toward an integrated and preventive management model. *Water Policy*, **18**(S2), 107–121, doi:10.2166/wp.2016.116.
- Ahmed, M., N. Al-Dousari and A. Al-Dousari, 2016: The role of dominant perennial native plant species in controlling the mobile sand encroachment and fallen dust problem in Kuwait. *Arab. J. Geosci.*, **9**(2), 134, doi:10.1007/s12517-015-2216-6.
- Akhtar-Schuster, M., et al., 2017: Unpacking the concept of land degradation neutrality and addressing its operation through the Rio Conventions. *J. Environ. Manag.*, **195**, 4–15, doi:10.1016/j.jenvman.2016.09.044.
- Akponikpe, P.B.I., 2008: *Millet response to water and soil fertility management in the Sahelian Niger: Experiments and modelling*. Université catholique de Louvain, Louvain-la-Neuve, Belgium. 168 pp.
- Al-Hemoud, A., et al., 2017: Socioeconomic effect of dust storms in Kuwait. *Arab. J. Geosci.*, **10**(1), 18, doi:10.1007/s12517-016-2816-9.
- Alary, V., et al., 2014: Livelihood strategies and the role of livestock in the processes of adaptation to drought in the Coastal Zone of Western Desert (Egypt). *Agric. Syst.*, **128**, 44–54, doi:10.1016/j.agsy.2014.03.008.
- Alba-Sánchez, F., J.A. López-Sáez, D. Nieto-Lugilde and J.-C. Svenning, 2015: Long-term climate forcings to assess vulnerability in North Africa dry argan woodlands. *Appl. Veg. Sci.*, **18**(2), 283–296, doi:10.1111/avsc.12133.
- Aleman, J.C., M.A. Jarzyna and A.C. Staver, 2018: Forest extent and deforestation in tropical Africa since 1900. *Nat. Ecol. Evol.*, **2**(1), 26–33, doi:10.1038/s41559-017-0406-1.
- Alizadeh-Chooabari, O. and M.S. Najafi, 2018: Extreme weather events in Iran under a changing climate. *Clim. Dyn.*, **50**(1), 249–260, doi:10.1007/s00382-017-3602-4.
- Allahbakhshi, K., D. Khorasani-Zavareh, R. Khani Jazani and Z. Ghomian, 2019: Preparedness components of health systems in the Eastern Mediterranean Region for effective responses to dust and sand storms: a systematic review. *F1000Res*, **8**, 146–146, doi:10.12688/f1000research.17543.1.
- Almer, C., J. Laurent-Lucchetti and M. Oechslin, 2017: Water scarcity and rioting: Disaggregated evidence from Sub-Saharan Africa. *J. Environ. Econ. Manage.*, **86**, 193–209, doi:10.1016/j.jeem.2017.06.002.
- Amdan, M.L., et al., 2013: Onset of deep drainage and salt mobilization following forest clearing and cultivation in the Chaco plains (Argentina). *Water Resour. Res.*, **49**(10), 6601–6612, doi:10.1002/wrcr.20516.
- Amin, A., et al., 2018: Regional climate assessment of precipitation and temperature in Southern Punjab (Pakistan) using SimCLIM climate model for different temporal scales. *Theor. Appl. Climatol.*, **131**(1), 121–131, doi:10.1007/s00704-016-1960-1.
- Amiraslani, F., A. Caiserman, F. Amiraslani and A. Caiserman, 2018: Multi-Stakeholder and Multi-Level Interventions to Tackle Climate Change and Land Degradation: The Case of Iran. *Sustainability*, **10**(6), 2000–2000, doi:10.3390/su10062000.
- An, L., et al., 2018: Temporal and spatial variations in sand and dust storm events in East Asia from 2007 to 2016: Relationships with surface conditions and climate change. *Sci. Total. Environ.*, **633**, 452–462, doi:10.1016/j.scitotenv.2018.03.068.
- Andela, N., et al., 2013: Global changes in dryland vegetation dynamics (1988–2008) assessed by satellite remote sensing: comparing a new passive microwave vegetation density record with reflective greenness data. *Biogeosciences*, **10**(10), 6657–6676.
- Anyamba, A. and C.J. Tucker, 2005: Analysis of Sahelian vegetation dynamics using NOAA-AVHRR NDVI data from 1981–2003. *J. Arid Environ.*, **63**(3), 596–614, doi:10.1016/J.JARIDENV.2005.03.007.
- Aragón-Gastélum, J.L., et al., 2017: Seedling survival of three endemic and threatened Mexican cacti under induced climate change. *Plant. Spec. Biol.*, **32**(1), 92–99, doi:10.1111/1442-1984.12120.
- Aragón-Gastélum, J.L., et al., 2018: Potential impact of global warming on seed bank, dormancy and germination of three succulent species from the Chihuahuan Desert. *Seed Sci. Res.*, **28**(4), 312–318.
- Aragón-Gastélum, J.L., et al., 2014: Induced climate change impairs photosynthetic performance in *Echinocactus platyacanthus*, an especially protected Mexican cactus species. *Flora Morphol. Distrib. Funct. Ecol. Plants*, **209**(9), 499–503.
- Archer, S.R., et al., 2017: Woody Plant Encroachment: Causes and Consequences. In: *Rangeland Systems: Processes, Management and Challenges* [Briske, D.D.(ed.)]. Springer, Cham, pp. 25–84. ISBN 978-3319467092.
- Ashkenazy, Y., H. Yizhaq and H. Tsoar, 2012: Sand dune mobility under climate change in the Kalahari and Australian deserts. *Clim. Change*, **112**(3–4), 901–923, doi:10.1007/s10584-011-0264-9.
- Aslam, A.Q., et al., 2018: Integrated climate change risk assessment and evaluation of adaptation perspective in southern Punjab, Pakistan. *Sci. Total. Environ.*, **628–629**, 1422–1436, doi:10.1016/j.scitotenv.2018.02.129.
- Assouma, M.H., et al., 2019: Contrasted seasonal balances in a Sahelian pastoral ecosystem result in a neutral annual carbon balance. *J. Arid Environ.*, **162**, 62–73, doi:10.1016/j.jaridenv.2018.11.013.
- Assouma, M.H., et al., 2017: Livestock induces strong spatial heterogeneity of soil CO<sub>2</sub>, N<sub>2</sub>O and CH<sub>4</sub> emissions within a semi-arid silvo-pastoral landscape in West Africa. *J. Arid Land*, **9**(2), 210–221, doi:10.1007/s40333-017-0001-y.
- Baccini, A., et al., 2017: Tropical forests are a net carbon source based on aboveground measurements of gain and loss. *Science*, **358**(6360), 230–234, doi:10.1126/science.aam5962.
- Bachelder, J., et al., 2020: Chemical and microphysical properties of wind-blown dust near an actively retreating glacier in Yukon, Canada. *Aerosol Sci. Technol.*, **54**(1), 2–20, doi:10.1080/02786826.2019.1676394.
- Báez, S., et al., 2013: Effects of experimental rainfall manipulations on Chihuahuan Desert grassland and shrubland plant communities. *Oecologia*, **172**(4), 1117–1127, doi:10.1007/s00442-012-2552-0.
- Bagayoko, M., et al., 2011: Microdose and N and P fertilizer application rates for pearl millet in West Africa. *Afr. J. Agric. Res.*, **6**, 1141–1150.
- Bahir, M., S. Ouhamdouch, D. Ouazar and N. El Moçayd, 2020: Climate change effect on groundwater characteristics within semi-arid zones from western Morocco. *Groundw. Sustain. Dev.*, **11**, 100380, doi:10.1016/j.gsd.2020.100380.
- Ballouche, A. and M. Rasse, 2007: L'homme, artisan des paysages de savane. *Pour Sci.*, (358), 56–61.

- Barbosa, H.A., L. Kumar and L.R.M. Silva, 2015: Recent trends in vegetation dynamics in the South America and their relationship to rainfall. *Nat. Hazards*, **77**(2), 883–899, doi:10.1007/s11069-015-1635-8.
- Basu, S., J. Jongerden and G. Ruivenkamp, 2017: Development of the drought tolerant variety Sahbhagi Dhan: exploring the concepts commons and community building. *Int. J. Commons*, **11**(1), 144, doi:10.18352/ijc.673.
- Bationo, J., et al., 2011: Comparative Analysis of the Current and Potential Role of Legumes in Integrated Soil Fertility Management in West and Central Africa. In: *Fighting Poverty in Sub-Saharan Africa: The Multiple Roles of Legumes in Integrated Soil Fertility Management* [Bationo, A., et al.(ed.)]. Springer, Dordrecht, Netherlands, pp. 117–150. ISBN 978-9400715356.
- Bawden, R., 2018: Global Change and Its Consequences for the World's Arid Lands. In: *Climate Variability Impacts on Land Use and Livelihoods in Drylands* [Gaur, M.K. and V.R. Squires(eds.)]. Springer, Cham, pp. 59–71. ISBN 978-3319566818.
- Bayram, H. and A.B. Öztürk, 2014: Global Climate Change, Desertification, and Its Consequences in Turkey and the Middle East. In: *Global Climate Change and Public Health* [Pinkerton, K.E. and W.N. Rom(eds.)]. Springer, New York, NY, pp. 293–305. ISBN 978-1461484172.
- Bazza, M., M. Kay and C. Knutson, 2018: *Drought Characteristics and Management in North Africa and the Near East*.
- Food and Agriculture Organisation of the United Nations (FAO), Drought characteristics and management in North Africa and the Near East, <http://www.fao.org/3/CA0034EN/ca0034en.pdf>. Accessed 2020 . (266 pp).
- Becerril-Pina, R., et al., 2015: Assessing desertification risk in the semi-arid highlands of central Mexico. *J. Arid Environ.*, **120**, 4–13.
- Behnke, R., 2000: Equilibrium and non-equilibrium models of livestock population dynamics in pastoral Africa: Their relevance to Arctic grazing systems. *Rangifer*, **20**, doi:10.7557/2.20.2-3.1509.
- Behnke, R.H. and M. Mortimore, 2016: *The End of Desertification? : Disputing Environmental Change in the Drylands*, 1st edn., Springer, Berlin, Heidelberg. 1 online resource (VIII, 560 pages 117 illustrations, 541 illustrations in color pp).
- Benjaminsen, T.A., K. Alinon, H. Buhaug and J.T. Buseeth, 2012: Does climate change drive land-use conflicts in the Sahel? *J. Peace. Res.*, **49**(1), 97–111, doi:10.1177/0022343311427343.
- Benjaminsen, T.A. and B. Ba, 2009: Farmer–herder conflicts, pastoral marginalisation and corruption: a case study from the inland Niger delta of Mali. *Geogr. J.*, **175**(1), 71–81.
- Benjaminsen, T.A. and B. Ba, 2019: Why do pastoralists in Mali join jihadist groups? A political ecological explanation. *J. Peasant. Stud.*, **46**(1), 1–20, doi:10.1080/03066150.2018.1474457.
- Benjaminsen, T.A. and P. Hiernaux, 2019: From Desiccation to Global Climate Change: A History of the Desertification Narrative in the West African Sahel, 1900–2018. *Glob. Environ.*, **12**(1), 206–236, doi:10.3197/ge.2019.120109.
- Benjaminsen, T.A., F.P. Maganga and J.M. Abdallah, 2009: The Kilosa Killings: Political Ecology of a Farmer–Herder Conflict in Tanzania. *Dev. Change*, **40**(3), 423–445, doi:10.1111/j.1467-7660.2009.01558.x.
- Benjaminsen, T.A., H. Reinert, E. Sjaastad and M.N. Sara, 2015: Misreading the Arctic landscape: A political ecology of reindeer, carrying capacities, and overstocking in Finnmark, Norway. *Norsk Geogr. Tidsskr.*, **69**(4), 219–229, doi:10.1080/00291951.2015.1031274.
- Benjaminsen, T.A., et al., 2006: Land Reform, Range Ecology, and Carrying Capacities in Namaqualand, South Africa. *Ann. Assoc. Am. Geogr.*, **96**(3), 524–540, doi:10.1111/j.1467-8306.2006.00704.x.
- Berdugo, M., et al., 2020: Global ecosystem thresholds driven by aridity. *Science*, **367**(6479), 787–790, doi:10.1126/science.aay5958.
- Berg, A., et al., 2016: Land–atmosphere feedbacks amplify aridity increase over land under global warming. *Nat. Clim. Change*, **6**(9), 869–874.
- Berg, A., J. Sheffield and P.C. Milly, 2017a: Divergent surface and total soil moisture projections under global warming. *Geophys. Res. Lett.*, **44**(1), 236–244.
- Berg, A., J. Sheffield and P.C.D. Milly, 2017b: Divergent surface and total soil moisture projections under global warming. *Geophys. Res. Lett.*, **44**(1), 236–244, doi:10.1002/2016GL071921.
- Berghuis, M., T.A. Benjaminsen, F. Maganga and H. Buhaug, 2020: Green economy, degradation narratives, and land-use conflicts in Tanzania. *World Dev.*, **129**, 104850, doi:10.1016/j.worlddev.2019.104850.
- Berhane, G., et al., 2014: Can Social Protection Work in Africa? The Impact of Ethiopia's Productive Safety Net Programme. *Econ. Dev. Cult. Change.*, **63**(1), 1–26, doi:10.1086/677753.
- Bernardino, P.N., et al., 2020: Uncovering Dryland Woody Dynamics Using Optical, Microwave, and Field Data—Prolonged Above-Average Rainfall Paradoxically Contributes to Woody Plant Die-Off in the Western Sahel. *Remote Sens.*, **12**(14), 2332.
- Bestelmeyer, B.T., et al., 2018: The Grassland–Shrubland Regime Shift in the Southwestern United States: Misconceptions and Their Implications for Management. *BioScience*, **68**(9), 678–690, doi:10.1093/biosci/biy065.
- Bhattachan, A., et al., 2012: The Southern Kalahari: a potential new dust source in the Southern Hemisphere? *Environ. Res. Lett.*, **7**(2), 24001.
- Bianchi, L.O., et al., 2017: A regional water balance indicator inferred from satellite images of an Andean endorheic basin in central-western Argentina. *Hydrol. Sci. J.*, **62**(4), 533–545.
- Biasutti, M., 2013: Forced Sahel rainfall trends in the CMIP5 archive. *J. Geophys. Res. Atmos.*, **118**(4), 1613–1623, doi:10.1002/jgrd.50206.
- Biasutti, M. and A. Giannini, 2006: Robust Sahel drying in response to late 20th century forcings. *Geophys. Res. Lett.*, **33**(11), doi:10.1029/2006GL026067.
- Bidak, L.M., S.A. Kamal, M.W.A. Halmy and S.Z. Heneidy, 2015: Goods and services provided by native plants in desert ecosystems: Examples from the northwestern coastal desert of Egypt. *Glob. Ecol. Conserv.*, **3**, 433–447.
- Bielders, C., J.-L. Rajot and K. Michels, 2004: L'érosion éolienne dans le Sahel nigérien : influence des pratiques culturelles actuelles et méthodes de lutte. *Sci. Chang. Planetair.*, **15**(1), 19–32.
- Blaikie, P.M. and H.C. Brookfield, 1987: Land degradation and society. In: 1st edn. Methuen, London, New York. ISBN 978-0416401509 (296 pp).
- Blaum, N., E. Rossmanith, A. Popp and F. Jeltsch, 2007: Shrub encroachment affects mammalian carnivore abundance and species richness in semiarid rangelands. *Acta Oecol.*, **31**(1), 86–92, doi:10.1016/j.actao.2006.10.004.
- Blaum, N., et al., 2009: Changes in arthropod diversity along a land use driven gradient of shrub cover in savanna rangelands: identification of suitable indicators. *Biodivers. Conserv.*, **18**(5), 1187–1199.
- Blok, D., et al., 2011: The response of Arctic vegetation to the summer climate: relation between shrub cover, NDVI, surface albedo and temperature. *Environ. Res. Lett.*, **6**(3), 35502, doi:10.1088/1748-9326/6/3/035502.
- Bond, W.J. and G.F. Midgley, 2012: Carbon dioxide and the uneasy interactions of trees and savannah grasses. *Philos. Trans. Royal Soc. London. Ser. B Biol. Sci.*, **367**(1588), 601–612, doi:10.1098/rstb.2011.0182.
- Bond, W.J., N. Stevens, G.F. Midgley and C.E.R. Lehmann, 2019: The Trouble with Trees: Afforestation Plans for Africa. *Trends Ecol. Evol.*, **34**(11), 963–965, doi:10.1016/j.tree.2019.08.003.
- Bonnet, B. and D. Herault, 2011: Gouvernance du foncier pastorale et changement climatique au Sahel. *Rev. Quest. Fonc.*, **2**, 157–187.
- Booyens, M.J., M. Visser and R. Burger, 2019: Temporal case study of household behavioural response to Cape Town's "Day Zero" using smart meter data. *Water Res.*, **149**, 414–420, doi:10.1016/j.watres.2018.11.035.
- Boucher, O., D. Randall, P. Artaxo, C. Bretherton, G. Feingold, P. Forster, V.-M. Kerminen, Y. Kondo, H. Liao, U. Lohmann, P. Rasch, S.K. Satheesh, S. Sherwood, B. Stevens and X.Y. Zhang, 2013: Clouds and Aerosols. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 571–658. ISBN 978-1107057991.



- Boudet, G., 1977: Désertification ou remontée biologique au Sahel. *Cahiers Orstom Ser. Biol.*, **12**(4), 293–300.
- Boy, M., 2019: *Interactions between the atmosphere, cryosphere, and ecosystems at northern high latitudes*. Vol. 19, 2015.
- Bradford, J.B., et al., 2018: Anticipatory natural resource science and management for a changing future. *Front. Ecol. Environ.*, **16**(5), 295–303, doi:10.1002/fee.1806.
- Bradley, B.A., C.A. Curtis and J.C. Chambers, 2016: Bromus Response to Climate and Projected Changes with Climate Change. In: *Exotic Brome-Grasses in Arid and Semiarid Ecosystems of the Western US: Causes, Consequences, and Management Implications* [Germino, M.J., J.C. Chambers and C.S. Brown(eds.)]. Springer International Publishing, Cham, pp. 257–274. ISBN 978-3319249308.
- Brandt, M., et al., 2016: Assessing woody vegetation trends in Sahelian drylands using MODIS based seasonal metrics. *Remote. Sens. Environ.*, **183**, 215–225, doi:10.1016/j.rse.2016.05.027.
- Brandt, M., et al., 2019: Changes in rainfall distribution promote woody foliage production in the Sahel. *Commun. Biol.*, **2**(1), doi:10.1038/s42003-019-0383-9.
- Brandt, M., et al., 2018: Reduction of tree cover in West African woodlands and promotion in semi-arid farmlands. *Nat. Geosci.*, **11**(5), 328–333, doi:10.1038/s41561-018-0092-x.
- Brandt, M., et al., 2017: Human population growth offsets climate-driven increase in woody vegetation in sub-Saharan Africa. *Nat. Ecol. Evol.*, **1**(4), 81, doi:10.1038/s41559-017-0081.
- Breman, H., J.J.R. Groot and H. v. Keulen, 2001: Resource limitations in Sahelian agriculture. *Glob. Environ. Change. Hum. Policy Dimens.*, **11**(1), 59–68.
- Brockington, D., 2002: *Fortress Conservation. The Preservation of the Mkomazi Game Reserve Tanzania*. James Currey, Oxford, UK, ISBN 978-0852554173.
- Brooks, M.L. and J.R. Matchett, 2006: Spatial and temporal patterns of wildfires in the Mojave Desert, 1980–2004. *J. Arid Environ.*, **67**, 148–164, doi:10.1016/j.jaridenv.2006.09.027.
- Brooks, N., et al., 2005: The climate-environment-society nexus in the Sahara from prehistoric times to the present day. *J. North Afr. Stud.*, **10**(3–4), 253–292.
- Buechler, S. and G.D. Mekala, 2005: Local responses to water resource degradation in India: Groundwater farmer innovations and the reversal of knowledge flows. *J. Environ. Dev.*, **14**(4), 410–438.
- Buhaug, H., T. Benjaminsen, E. Sjaastad and O. Theisen, 2015: Climate variability, food production shocks, and violent conflict in Sub-Saharan Africa. *Environ. Res. Lett.*, **10**, 125015, doi:10.1088/1748-9326/10/12/125015.
- Buhaug, H., et al., 2014: One effect to rule them all? A comment on climate and conflict. *Clim. Change*, **127**(3–4), 391–397, doi:10.1007/s10584-014-1266-1.
- Buisson, E., et al., 2019: Resilience and restoration of tropical and subtropical grasslands, savannas, and grassy woodlands. *Biol. Rev.*, **94**(2), 590–609, doi:10.1111/brv.12470.
- Buitenwerf, R., W.J. Bond, N. Stevens and W.S.W. Trollope, 2012: Increased tree densities in South African savannas: >50 years of data suggests CO<sub>2</sub> as a driver. *Glob. Change Biol.*, **18**(2), 675–684, doi:10.1111/j.1365-2486.2011.02561.x.
- Bullard, J.E., et al., 2016: High-latitude dust in the Earth system. *Rev. Geophys.*, **54**(2), 447–485, doi:10.1002/2016RG000518.
- Bundela, D.S., A.L. Pathan and R. Raju, 2017: *Performance evaluation of sub-surface drainage systems in Haryana and to implement interventions for improving operational performance and impact*. I. CAR-CSSRI Annual Report (2017-18). ICAR-Central Soil Salinity Research Institute (CSSRI), Karnal, Haryana, India, <https://cssri.res.in/wp-content/uploads/2018/07/Annual-Report-2017-18.pdf>, available on 06.03.2022. (36–38 pp).
- Burrell, A.L., J.P. Evans and M.G. De Kauwe, 2020: Anthropogenic climate change has driven over 5 million km<sup>2</sup> of drylands towards desertification. *Nat. Commun.*, **11**(1), doi:10.1038/s41467-020-17710-7.
- Caracciolo, D., E. Istanbuloglu, L.V. Noto and S.L. Collins, 2016: Mechanisms of shrub encroachment into Northern Chihuahuan Desert grasslands and impacts of climate change investigated using a cellular automata model. *Adv. Water. Resour.*, **91**, 46–62, doi:10.1016/j.advwatres.2016.03.002.
- Carrillo-Angeles, I.G., et al., 2016: Niche breadth and the implications of climate change in the conservation of the genus *Astrophytum* (Cactaceae). *J. Arid Environ.*, **124**, 310–317.
- Castillón, E.E., et al., 2015: Classification and ordination of main plant communities along an altitudinal gradient in the arid and temperate climates of northeastern Mexico. *Sci. Nat.*, **102**(9–10), 59, doi:10.1007/s00114-015-1306-3.
- Catley, A., B. Admassu, G. Bekele and D. Abebe, 2014: Livestock mortality in pastoralist herds in Ethiopia and implications for drought response. *Disasters*, **38**(3), 500–516, doi:10.1111/disa.12060.
- Cavalcante, A., A. Duarte and J. Ometto, 2020: Modeling the potential distribution of *Epiphyllum phyllanthus* (L.) Haw. under future climate scenarios in the Caatinga biome. *An. Acad. Bras. Cienc.*, **92**, doi:10.1590/0001-3765202020180836.
- Cavalcante, A. and A.S. Duarte, 2019: Modeling the Distribution of Three Cactus Species of the Caatinga Biome in Future Climate Scenarios. *Int. J. Ecol. Environ. Sci.*, **45**, 191–203.
- Cavanagh, C.J. and T.A. Benjaminsen, 2015: Guerrilla agriculture? A biopolitical guide to illicit cultivation within an IUCN Category II protected area. *J. Peasant. Stud.*, **42**(3–4), 725–745, doi:10.1080/03066150.2014.993623.
- Chambers, D.P., 2018: Using kinetic energy measurements from altimetry to detect shifts in the positions of fronts in the Southern Ocean. *Ocean. Sci.*, **14**(1), 105–116, doi:10.5194/os-14-105-2018.
- Chambers, J.C., et al., 2014: Resilience to Stress and Disturbance, and Resistance to Bromus tectorum L. Invasion in Cold Desert Shrublands of Western North America. *Ecosystems*, **17**(2), 360–375, doi:10.1007/s10021-013-9725-5.
- Chambers, J.C., et al., 2019: Operationalizing Resilience and Resistance Concepts to Address Invasive Grass-Fire Cycles. *Front. Ecol. Evol.*, **7**(185), doi:10.3389/fevo.2019.00185.
- Charney, J.G., 1975: *Dynamics of deserts and drought in the Sahel\**. **101**, 193–202 pp. <https://rmetsonline.wiley.com/doi/pdf/10.1002/qj.49710142802>, available on 06.03.2022.
- Chatty, D., 2007: Mobile Peoples: Pastoralists and Herders at the Beginning of the 21st Century. *Rev. Anthropol.*, **36**(1), 5–26, doi:10.1080/00938150601177538.
- Chen, C., et al., 2019a: China and India lead in greening of the world through land-use management. *Nat. Sustain.*, **2**(2), 122–129, doi:10.1038/s41893-019-0220-7.
- Chen, H., T. Li and Q. Wang, 2019b: Ten years of algal biofuel and bioproducts: gains and pains. *Planta*, **249**(1), 195–219, doi:10.1007/s00425-018-3066-8.
- Cheng, S. and J. Huang, 2016: Enhanced soil moisture drying in transitional regions under a warming climate. *J. Geophys. Res. Atmos.*, **121**(6), 2542–2555, doi:10.1002/2015jd024559.
- Cherlet, M., et al., 2018: *World atlas of desertification rethinking land degradation and sustainable land management*. ISBN 978-9279753503.
- Chevillon-Guibert, R., L. Gagnol and G. Magrin, 2019: Les ruées vers l’or au Sahara et au nord du Sahel. Ferment de crise ou stabilisateur? *Herodote*, **(1)**, 193–215.
- Choukri, F., et al., 2020: Distinct and combined impacts of climate and land use scenarios on water availability and sediment loads for a water supply reservoir in northern Morocco. *Int. Soil Water Conserv. Res.*, doi:10.1016/j.iswcr.2020.03.003.
- Christie, I.T., E.H. Fernandes, H.R. Messerli and L.D. Twining-Ward, 2014: *Tourism in Africa : harnessing tourism for growth and improved livelihoods. Africa development forum*. World Bank Group, Washington, DC.
- Collins, S. and Y. Xia, 2015: Long-Term Dynamics and Hotspots of Change in a Desert Grassland Plant Community. *The American Naturalist*, **185**, E30–E43.
- Conver, J.L., T. Foley, D.E. Winkler and D.E. Swann, 2017: Demographic changes over >70 yr in a population of saguaro cacti (*Carnegiea gigantea*) in the northern Sonoran Desert. *J. Arid Environ.*, **139**, 41–48, doi:10.1016/j.jaridenv.2016.12.008.

- Cook, B.I., J.E. Smerdon, R. Seager and S. Coats, 2014: Global warming and 21st century drying. *Clim. Dyn.*, **43**(9-10), 2607–2627, doi:10.1007/s00382-014-2075-y.
- Cowie, A.L., et al., 2018: Land in balance: The scientific conceptual framework for Land Degradation Neutrality. *Environ. Sci. Policy*, **79**, 25–35, doi:10.1016/j.envsci.2017.10.011.
- Cromsigt, J., et al., 2018: Trophic rewilding as a climate change mitigation strategy? *Philos. Trans. Royal Soc. B Biol. Sci.*, **373**, 20170440, doi:10.1098/rstb.2017.0440.
- Cross, H., 2013: Labour and underdevelopment? Migration, dispossession and accumulation in West Africa and Europe. *Rev. Afr. Polit. Econ.*, **40**(136), 202–218, doi:10.1080/03056244.2013.794727.
- Dagsson-Waldhauserová, P., Ó. Arnalds and H. Olafsson, 2014: Long-term variability of dust events in Iceland (1949–2011). *Atmos. Chem. Phys.*, **14**, 13411–13422.
- Dagsson-Waldhauserova, P. and O. Meinander, 2019: Editorial: Atmosphere—Cryosphere Interaction in the Arctic, at High Latitudes and Mountains With Focus on Transport, Deposition, and Effects of Dust, Black Carbon, and Other Aerosols. *Front. Earth Sci.*, **7**(337), doi:10.3389/feart.2019.00337.
- Dai, A., 2011: Drought Under Global Warming: A Review. *Wiley Interdiscip. Rev. Clim. Chang.*, **2**, 45–65, doi:10.1002/wcc.81.
- Dai, A., K. Trenberth and T.T. Qian, 2004: A Global Dataset of Palmer Drought Severity Index for 1870–2002: Relationship with Soil Moisture and Effects of Surface Warming. *J. Hydrometeorol.*, **5**, 1117–1130, doi:10.1175/JHM-386.1.
- Dar, M.H., et al., 2020: Drought Tolerant Rice for Ensuring Food Security in Eastern India. *Sustainability*, **12**(6), 2214.
- Dardel, C., et al., 2014: Re-greening Sahel: 30 years of remote sensing data and field observations (Mali, Niger). *Remote. Sens. Environ.*, **140**, 350–364, doi:10.1016/j.rse.2013.09.011.
- Davies, J. and M. Nori, 2008: *Managing and mitigating climate change through pastoralism*.
- Davis-Reddy, C., 2018: *Assessing vegetation dynamics in response to climate variability and change across sub-Saharan Africa*. Stellenbosch University, Stellenbosch, South Africa.
- De Vente, J., et al., 2016: How does the context and design of participatory decision making processes affect their outcomes? Evidence from sustainable land management in global drylands. *Ecol. Soc.*, **21**(2), doi:10.5751/es-08053-210224.
- De Vries, F.P. and M. Djitéyè, 1982: *La productivité des pâturages sahéliens: une étude des sols, des végétations et de l'exploitation de cette ressource naturelle*. Pudoc, ISBN 978-9022008065. Wageningen, NL.
- Defalco, L.A., T.C. Esque, S.J. Scoles-Sciulla and J. Rodgers, 2010: Desert wildfire and severe drought diminish survivorship of the long-lived Joshua tree (*Yucca brevifolia*; Agavaceae). *Am. J. Bot.*, **97**(2), 243–250, doi:10.3732/ajb.0900032.
- Dendoncker, M., et al., 2020: 50 years of woody vegetation changes in the Ferlo (Senegal) assessed by high-resolution imagery and field surveys. *Reg. Environ. Change*, **20**(4), 137, doi:10.1007/s10113-020-01724-4.
- Deng, Q., et al., 2016: Assessing the impacts of tillage and fertilization management on nitrous oxide emissions in a cornfield using the DNDC model. *J. Geophys. Res. Biogeosci.*, **121**(2), 337–349.
- Denis, E. and F. Moriconi-Ebrard, 2009: La croissance urbaine en Afrique de l'Ouest. *Chron. Ceped*, (57), 1–5.
- Descroix, L., et al., 2013: *Impact of Drought and Land – Use Changes on Surface – Water Quality and Quantity: The Sahelian Paradox*. InTech, London, UK.
- Díaz, J., et al., 2017: Saharan dust intrusions in Spain: Health impacts and associated synoptic conditions. *Environ. Res.*, **156**, 455–467, doi:10.1016/j.envres.2017.03.047.
- Diba, I., M. Camara, A. Sarr and A. Diedhiou, 2018: Potential Impacts of Land Cover Change on the Interannual Variability of Rainfall and Surface Temperature over West Africa. *Atmosphere*, **9**(376), 1–32, doi:10.3390/atmos9100376.
- Dilshat, A., et al., 2015: Study on the expansion of cultivated land and its human driving forces in typical arid area oasis: a case study of Charchan Oasis in Xinjiang. *Area Res. Dev.*, **34**, 132–136.
- Ding, J. and D.J. Eldridge, 2019: Contrasting global effects of woody plant removal on ecosystem structure, function and composition. *Perspect. Plant Ecol. Evol. Syst.*, **39**, 125460, doi:10.1016/j.ppees.2019.125460.
- Dong, S., 2016: *Overview: Pastoralism in the World*, 1–37. ISBN 978-3319307305.
- Donohue, R.J., M.L. Roderick, T.R. McVicar and G.D. Farquhar, 2013: Impact of CO<sub>2</sub> fertilization on maximum foliage cover across the globe's warm, arid environments. *Geophys. Res. Lett.*, **40**(12), 3031–3035, doi:10.1002/grl.50563.
- Droy, et al., 2020: *Gender issues in dryland areas. Women as key stakeholders in combating desertification*. Les dossiers thématiques du CSFD. N°13. CSFD/Agropolis Intern. Montpellier, France, 52.
- du Toit, J.C.O., T.G. O'Connor and L. Van den Berg, 2015: Photographic evidence of fire-induced shifts from dwarf-shrub- to grass-dominated vegetation in Nama-Karoo. *S. Afr. J. Bot.*, **101**, 148–152, doi:10.1016/j.sajb.2015.06.002.
- Du Toit, J.C.O. and T.G. O'Connor, 2014: Changes in rainfall pattern in the eastern Karoo, South Africa, over the past 123 years. *Water SA*, **40**(3), 453–453, doi:10.4314/wsa.v40i3.8.
- du Toit, J.C.O., T. Ramaswiela, M.J. Pauw and T.G. O'Connor, 2018: Interactions of grazing and rainfall on vegetation at Grootfontein in the eastern Karoo. *Afr. J. Range Forage Sci.*, **35**(3-4), 267–276, doi:10.2989/10220119.2018.1508072.
- Duniway, M.C., et al., 2019: Wind erosion and dust from US drylands: a review of causes, consequences, and solutions in a changing world. *Ecosphere*, **10**(3), e2650, doi:10.1002/ecs2.2650.
- Dunne, J.P., R.J. Stouffer and J.G. John, 2013: Reductions in labour capacity from heat stress under climate warming. *Nat. Clim. Change*, **3**(6), 563–566, doi:10.1038/nclimate1827.
- Dussaillant, I., et al., 2019: South American Andes elevation changes from 2000 to 2018, links to GeoTIFFs. *Pangaea*, doi:10.1594/PANGAEA.903618. Supplement to: Dussaillant, I et al. (2019): Two decades of glacier mass loss along the Andes. *Nature Geoscience*, **12**(10), 802–808, <https://doi.org/10.1038/s41561-019-0432-5>.
- Eklundh, L. and L. Olsson, 2003: Vegetation index trends for the African Sahel 1982–1999. *Geophys. Res. Lett.*, **30**(8), doi:10.1029/2002gl016772.
- Eldridge, D.J. and G. Beecham, 2018: The Impact of Climate Variability on Land Use and Livelihoods in Australia's Rangelands. In: *Climate Variability Impacts on Land Use and Livelihoods in Drylands* [Gaur, M.K. and V.R. Squires(eds.)]. Springer, Cham, pp. 293–315. ISBN 978-3319566818.
- Elhadary, Y.A.E., 2014: Examining drivers and indicators of the recent changes among pastoral communities of butana locality, gedarif State, Sudan. *Am. J. Sociol. Res.*, **4**(3), 88–101, doi:10.5923/j.sociology.20140403.04.
- Escolar, C., I. Martínez, M. A. Bowker and F.T. Maestre, 2012: Warming reduces the growth and diversity of biological soil crusts in a semi-arid environment: implications for ecosystem structure and functioning. *Philos. Trans. Royal Soc. B Biol. Sci.*, **367**(1606), 3087–3099.
- ESCWA, U. N. E. a. S. C. f. W. A., 2017: *Arab Climate Change Assessment Report – Main Report (Beirut)* E/ESCWA/SDPD/2017/RICCAR/Report.
- Esper, J., et al., 2007: Long-term drought severity variations in Morocco. *Geophys. Res. Lett.*, **34**, doi:10.1029/2007GL030844.
- Ezcurra, E., 2006: *Global deserts outlook*. UNEP/Earthprint., ISBN 978-9280727227. Nairobi, Kenya.
- Falascchi, D., et al., 2019: Brief communication: Collapse of 4&thinsp;Mm<sup>3</sup> of ice from a cirque glacier in the Central Andes of Argentina. *Cryosphere*, **13**(3), 997–1004, doi:10.5194/tc-13-997-2019.
- Favreau, G., et al., 2009: Land clearing, climate variability, and water resources increase in semiarid southwest Niger: A review. *Water Resources Research*, **45**, doi:10.1029/2007wr006785.



- Feng, S. and Q. Fu, 2013: Expansion of global drylands under a warming climate. *Atmos. Chem. Phys.*, **13**(19), 10081–10094, doi:10.5194/acp-13-10081-2013.
- Fensholt, R., I. Sandholt, S. Stisen and C. Tucker, 2006: Analysing NDVI for the African continent using the geostationary meteosat second generation SEVIRI sensor. *Remote. Sens. Environ.*, **101**(2), 212–229, doi:10.1016/j.rse.2005.11.013.
- Fernández-Martínez, M., et al., 2019: Global trends in carbon sinks and their relationships with CO<sub>2</sub> and temperature. *Nat. Clim. Change*, **9**(1), 73–79, doi:10.1038/s41558-018-0367-7.
- Fernández-Rivera, S., et al., 2005: *Nutritional constraints to grazing ruminants in the millet-cowpea-livestock farming system of the Sahel*. International Livestock Research Institute (ILRI), Nairobi, Kenya, <https://cgispace.cgiar.org/handle/10568/50886>. Accessed 2020. (157–182 pp).
- Foden, W., et al., 2007a: A changing climate is eroding the geographical range of the Namib Desert tree *Aloe* through population declines and dispersal lags: Namib Desert trees feel the heat of climate change. *Divers. Distrib.*, **13**, 645–653, doi:10.1111/j.1472-4642.2007.00391.x.
- Foden, W., et al., 2007b: A changing climate is eroding the geographical range of the Namib Desert tree *Aloe* through population declines and dispersal lags. *Divers. Distrib.*, **13**(5), 645–653, doi:10.1111/j.1472-4642.2007.00391.x.
- Frischen, J., et al., 2020: Drought Risk to Agricultural Systems in Zimbabwe: A Spatial Analysis of Hazard, Exposure, and Vulnerability. *Sustainability*, **12**(3), 752.
- Gal, L., et al., 2017: The paradoxical evolution of runoff in the pastoral Sahel: analysis of the hydrological changes over the Agoufou watershed (Mali) using the KINEROS-2 model. *Hydrol. Earth Syst. Sci.*, **21**(9), 4591–4613, doi:10.5194/hess-21-4591-2017.
- Gandah, M., et al., 2003: Strategies to optimize allocation of limited nutrients to sandy soils of the Sahel: a case study from Niger, west Africa. *Agric. Ecosyst. Environ.*, **94**(3), 311–319, doi:10.1016/S0167-8809(02)00035-X.
- García Criado, M., et al., 2020: Woody plant encroachment intensifies under climate change across tundra and savanna biomes. *Glob. Ecol. Biogeogr.*, **29**(5), 925–943, doi:10.1111/geb.13072.
- Gardelle, J., P. Hiernaux, L. Kergoat and M. Grippa, 2010: Less rain, more water in ponds: a remote sensing study of the dynamics of surface waters from 1950 to present in pastoral Sahel (Gourma region, Mali). *Hydrol. Earth Syst. Sci.*, **14**(2), 309–324, doi:10.5194/hess-14-309-2010.
- Genoux, P., et al., 2012: Global-scale attribution of anthropogenic and natural dust sources and their emission rates based on MODIS Deep Blue aerosol products. *Rev. Geophys.*, **50**(3), doi:10.1029/2012RG000388.
- Glick Schiller, N., 2015: Explanatory frameworks in transnational migration studies: the missing multi-scalar global perspective. *Ethn. Racial Stud.*, **38**, doi:10.1080/01419870.2015.1058503.
- Gonzalez, P., 2001: Desertification and shift of forest species in the West African Sahel. *Clim. Res.*, **17**, 217–228, doi:10.3354/cr017217.
- Gonzalez, P., C.J. Tucker and H. Sy, 2012: Tree Density and Species Decline in the African Sahel Attributable to Climate. *J. Arid Environ.*, **78**, doi:10.1016/j.jaridenv.2011.11.001.
- Goudarzi, G., et al., 2017: Health risk assessment of exposure to the Middle-Eastern Dust storms in the Iranian megacity of Kermanshah. *Public Health*, **148**, 109–116, doi:10.1016/j.puhe.2017.03.009.
- Goudie, A.S., 2014: Desert dust and human health disorders. *Environ Int*, **63**, 101–113, doi:10.1016/j.envint.2013.10.011.
- Gray, E.F. and W.J. Bond, 2013: Will woody plant encroachment impact the visitor experience and economy of conservation areas? *Koedoe*, **55**(1), doi:10.4102/koedoe.v55i1.1106.
- Greve, P., M. Roderick, A. Ukkola and Y. Wada, 2019: The aridity Index under global warming. *Environ. Res. Lett.*, **14**(12), 124006, doi:10.1088/1748-9326/ab5046.
- Greve, P. and S.I. Seneviratne, 2015: Assessment of future changes in water availability and aridity. *Geophys. Res. Lett.*, **42**(13), 5493–5499, doi:10.1002/2015gl064127.
- Grobicki, A., F. MacLeod and F. Pischke, 2015: Integrated policies and practices for flood and drought risk management. *Water Policy*, **17**(S1), 180–194, doi:10.2166/wp.2015.009.
- Gu, H., et al., 2019: Hypoxia aggravates the effects of ocean acidification on the physiological energetics of the blue mussel *Mytilus edulis*. *Mar. Pollut. Bull.*, **149**, 110538, doi:10.1016/j.marpolbul.2019.110538.
- Gu, L., et al., 2020: Projected increases in magnitude and socioeconomic exposure of global droughts in 1.5 and 2° C warmer climates. *Hydrol. Earth Syst. Sci.*, **24**(1), 451–472.
- Guengant Jean-Pierre, B.M., A. Quesnel, F. Gendreau and M. Lututala (eds.), 2003: *Dynamique des populations, disponibilités en terres et adaptation des régimes fonciers : le cas du Niger*. ITA; FAO; CICRED, Rome; Paris. 144 p pp. Available at: <https://www.documentation.ird.fr/hor/fdi:010032613>.
- Guimarães Nobre, G., et al., 2019: Financing agricultural drought risk through ex-ante cash transfers. *Sci. Total. Environ.*, **653**, 523–535, doi:10.1016/j.scitotenv.2018.10.406.
- Gupta, S. and J. Dagar, 2016: Agroforestry for ecological restoration of salt-affected lands. In: *Innovative Saline Agriculture*. Springer, Berlin Heidelberg, pp. 161–182.
- Haensler, A., S. Hagemann and D. Jacob, 2010: Will the southern African west coast fog be affected by climate change? *Erdkunde*, **65**(3), doi:10.3112/erdkunde.2011.03.04.
- Haider, S. and S. Adnan, 2014: Classification and assessment of aridity over Pakistan provinces (1960–2009). *Int. J. Environ.*, **3**(4), 24–35.
- Hall, R., et al., 2015: Resistance, acquiescence or incorporation? An introduction to land grabbing and political reactions 'from below'. *J. Peasant Stud.*, **42**(3–4), 467–488, doi:10.1080/03066150.2015.1036746.
- Hand, J.L., T. Gill and B. Schichtel, 2017: Spatial and seasonal variability in fine mineral dust and coarse aerosol mass at remote sites across the United States. *J. Geophys. Res. Atmos.*, **122**(5), 3080–3097.
- Hänke, H., L. Börjeson, K. Hylander and E. Enfors-Kautsky, 2016: Drought tolerant species dominate as rainfall and tree cover returns in the West African Sahel. *Land Use Policy*, **59**, 111–120, doi:10.1016/j.landusepol.2016.08.023.
- Harou, J.J., et al., 2010: Economic consequences of optimized water management for a prolonged, severe drought in California. *Water Resour. Res.*, **46**(5), doi:10.1029/2008wr007681.
- Harris, D.L., et al., 2018: Coral reef structural complexity provides important coastal protection from waves under rising sea levels. *Sci. Adv.*, **4**(2), eaao4350, doi:10.1126/sciadv.aao4350.
- Harris, I., T.J. Osborn, P. Jones and D. Lister, 2020: Version 4 of the CRU TS monthly high-resolution gridded multivariate climate dataset. *Sci. Data*, **7**(1), doi:10.1038/s41597-020-0453-3.
- Haverd, V., A. Ahlström, B. Smith and J.G. Canadell, 2017: Carbon cycle responses of semi-arid ecosystems to positive asymmetry in rainfall. *Glob. Change Biol.*, **23**(2), 793–800.
- He, B., S. Wang, L. Guo and X. Wu, 2019: Aridity change and its correlation with greening over drylands. *Agric. For. Meteorol.*, **278**, 107663, doi:10.1016/j.agrformet.2019.107663.
- Hegeman, E.E., B.G. Dickson and L.J. Zachmann, 2014: Probabilistic models of fire occurrence across National Park Service units within the Mojave Desert Network, USA. *Landsc. Ecol.*, **29**(9), 1587–1600, doi:10.1007/s10980-014-0078-z.
- Heisler-White, J.L., et al., 2009: Contingent productivity responses to more extreme rainfall regimes across a grassland biome. *Glob. Change Biol.*, **15**(12), 2894–2904, doi:10.1111/j.1365-2486.2009.01961.x.
- Hellén, U., 1984: Drought impact monitoring. A remote sensing study of desertification in Kordofan, Sudan. *Rapp. Och Notiser Lunds Univ. Naturgeogr. Inst.*
- Herrmann, S.M., A. Anyamba and C.J. Tucker, 2005: Recent trends in vegetation dynamics in the African Sahel and their relationship to climate. *Glob. Environ. Chang.*, **15**(4), 394–404, doi:10.1016/j.gloenvcha.2005.08.004.
- Hesse, C., 2016: *Decentralising climate finance to reach the most vulnerable*. IIED, London. <https://pubs.iied.org/pdfs/G04103.pdf>.

- Hiernaux, P. and M.H. Assouma, 2020: Adapting pastoral breeding to global changes in West and Central tropical Africa: Review of ecological views. *Rev. Elev. Med. Vet. Pays Trop.*, **73**(3).
- Hiernaux, P., C. Dardel, L. Kergoat and E. Mougin, 2016: Desertification, Adaptation and Resilience in the Sahel: Lessons from Long Term Monitoring of Agro-ecosystems. In: *The End of Desertification? : Disputing Environmental Change in the Drylands* [Behnke, R. and M. Mortimore(eds.)]. Springer, Berlin, Heidelberg, pp. 147–178. ISBN 978-3642160141.
- Hiernaux, P., et al., 2009a: Woody plant population dynamics in response to climate changes from 1984 to 2006 in Sahel (Gourma, Mali). *J. Hydrol. Reg. Stud.*, **375**(1), 103–113, doi:10.1016/j.jhydrol.2009.01.043.
- Hiernaux, P. and H.N. Le Houérou, 2006: Les parcours du Sahel. *Sci. Chang. Planetair. Secheresse*, **17**(1), 51–71.
- Hiernaux, P., et al., 2009b: Sahelian rangeland response to changes in rainfall over two decades in the Gourma region, Mali. *J. Hydrol. Reg. Stud.*, **375**(1-2), 114–127.
- Hiernaux, P.H.Y., M.I. Cissé, L. Diarra and P.N. De Leeuw, 1994: Fluctuations saisonnières de la feuillaison des arbres et des buissons sahéliens. Conséquences pour la quantification des ressources fourragères. *Agropastoralisme*, **47**(1), p. 117–125. doi: 10.19182/remvt.9123.
- Higgins, S.I. and S. Scheiter, 2012: Atmospheric CO<sub>2</sub> forces abrupt vegetation shifts locally, but not globally. *Nature*, **488**(7410), 209–212, doi:10.1038/nature11238.
- Hochleithner, S. and A. Exner, 2018: *Outmigration, development, and global environmental change: A review and discussion of case studies from the West African Sahel*. Working Paper No. 15. Swedish International Centre for Local Democracy. Visby, Sweden
- Hoffman, T.M., A. Skowno, W. Bell and S. Mashele, 2018: Long-term changes in land use, land cover and vegetation in the Karoo drylands of South Africa: implications for degradation monitoring. *Afr. J. Range Forage Sci.*, **35**(3-4), 209–221, doi:10.2989/10220119.2018.1516237.
- Homewood, K., 2018: Pastoralism. In: *The International Encyclopedia of Anthropology*, pp. 1–10. doi:10.1002/9781118924396.wbiea1559.
- Hooper, J. and S. Marx, 2018: A global doubling of dust emissions during the Anthropocene? *Glob. Planet. Change.*, **169**, 70–91, doi:10.1016/j.gloplacha.2018.07.003.
- Hoover, D.L., M.C. Duniway and J. Belnap, 2015: Pulse-drought atop press-drought: unexpected plant responses and implications for dryland ecosystems. *Oecologia*, **179**(4), 1211–1221, doi:10.1007/s00442-015-3414-3.
- Horn, K.J. and S.B. St. Clair, 2017: Wildfire and exotic grass invasion alter plant productivity in response to climate variability in the Mojave Desert. *Landsc. Ecol.*, **32**(3), 635–646, doi:10.1007/s10980-016-0466-7.
- Hsiang, S.M., M. Burke and E. Miguel, 2013: Quantifying the influence of climate on human conflict. *Science*, **341**(6151), doi: 10.1126/science.1235367
- Huang, J., et al., 2016: Global semi-arid climate change over last 60 years. *Clim. Dyn.*, **46**(3), 1131–1150, doi:10.1007/s00382-015-2636-8.
- Huang, J., et al., 2017: Drylands face potential threat under 2°C global warming target. *Nat. Clim. Change*, **7**(6), 417–422, doi:10.1038/nclimate3275.
- Hufft, R.A. and T.J. Zelikova, 2016: Ecological Genetics, Local Adaptation, and Phenotypic Plasticity in Bromus tectorum in the Context of a Changing Climate. In: *Exotic Brome-Grasses in Arid and Semiarid Ecosystems of the Western US: Causes, Consequences, and Management Implications* [Germino, M.J., J.C. Chambers and C.S. Brown(eds.)]. Springer, Cham, pp. 133–154. ISBN 978-3319249308.
- Hurlbert, M., J. Krishnaswamy, E. Davin, F.X. Johnson, C.F. Mena, J. Morton, S. Myeong, D. Viner, K. Warner, A. Wreford, S. Zakieldeen, Z. Zommers, 2019: Risk Management and Decision making in Relation to Sustainable Development. In: *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems* [P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D.C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, J. Malley, (eds.)]. In press.
- Hurlbert, M.A., 2018: *Adaptive Governance of Disaster: Drought and Flood in Rural Areas*. Springer, Berlin Heidelberg, ISBN 978-3319578002.
- Hussein, I.A.E., 2011: Desertification process in Egypt. In: *Coping with Global Environmental Change, Disasters and Security: Threats, Challenges, Vulnerabilities and Risks* [Brauch, H.G., et al.(ed.)]. Springer, Berlin, Germany, pp. 863–874.
- Hutchinson, C., S. Herrmann, T. Maukonen and J. Weber, 2005: Introduction: The “Greening” of the Sahel. *J. Arid Environ.*, **63**, 535–537, doi:10.1016/j.jaridenv.2005.03.002.
- Ibrahim, Y.Z., H. Balzter and J. Kaduk, 2018: Land degradation continues despite greening in the Nigeria-Niger border region. *Glob. Ecol. Conserv.*, **16**, e0505, doi:10.1016/j.gecco.2018.e00505.
- ICAR-CSSRI, 2015: *ICAR-CSSRI Vision 2050*. ICAR-Central Soil Salinity Research, Karnal, Haryana, India, [https://cssri.res.in/download/vision\\_2050\\_cssri\\_karnal/?wpdmdl=3031](https://cssri.res.in/download/vision_2050_cssri_karnal/?wpdmdl=3031), available on 06.03.2022.
- IFPRI, 2016: *Global Nutrition Report 2016: From Promise to Impact: Ending Malnutrition by 2030*. International Food Policy Research Institute, Washington, D.C., <https://www.ifpri.org/publication/global-nutrition-report-2016-promise-impact-ending-malnutrition-2030>. Accessed 2020.
- Iknayan, K.J. and S.R. Beissinger, 2018: Collapse of a desert bird community over the past century driven by climate change. *Proc. Natl. Acad. Sci.*, **115**(34), 8597, doi:10.1073/pnas.1805123115.
- IPCC, 2021: *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, 745–757. doi:10.1111/ddi.12438. In Press.
- Jack, S. L., M. T. Hoffman, R. F. Rohde and I. Durbach, 2016: Climate change sentinel or false prophet? The case of Aloe dichotoma. *Divers. Distribut.*, **22**(7), 745–757, doi:10.1111/ddi.12438.
- Javed, A., S. Jamal and M.Y. Khandey, 2012: *Climate change induced land degradation and socio-economic deterioration: a remote sensing and GIS based case study from Rajasthan, India*.
- Jellason, N.P., R.N. Baines, J.S. Conway and C.C. Ogbaga, 2019: Climate change perceptions and attitudes to smallholder adaptation in Northwestern Nigerian Drylands. *Soc. Sci.*, **8**(2), 31.
- Ji, M., J. Huang, Y. Xie and J. Liu, 2015: Comparison of dryland climate change in observations and CMIP5 simulations. *Adv. Atmospheric Sci.*, **32**(11), 1565–1574, doi:10.1007/s00376-015-4267-8.
- Ji, Z., G. Wang, M. Yu and J.S. Pal, 2018: Potential climate effect of mineral aerosols over West Africa: Part II—contribution of dust and land cover to future climate change. *Clim. Dyn.*, **50**(7), 2335–2353, doi:10.1007/s00382-015-2792-x.
- Jia, G., E. Shevliakova, P. Artaxo, N. De Noblet-Ducoudré, R. Houghton, J. House, K. Kitajima, C. Lennard, A. Popp, A. Sirin, R. Sukumar, L. Verchot, 2019: Land–climate interactions. In: *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems* [P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D.C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, J. Malley, (eds.)]. In press.
- Jia, H., et al., 2015: Field monitoring of a LID-BMP treatment train system in China. *Environ. Monit. Assess.*, **187**(6), 1–18.
- Jiao, Q., et al., 2016: Impacts of Re-Vegetation on Surface Soil Moisture over the Chinese Loess Plateau Based on Remote Sensing Datasets. *Remote Sens.*, **8**(2), 156.

- Jiao, W., et al., 2021: Observed increasing water constraint on vegetation growth over the last three decades. *Nat. Commun.*, **12**(1), 3777, doi:10.1038/s41467-021-24016-9.
- Jnandabhiram, C. and P. Sailen, 2012: Water stress effects on leaf growth and chlorophyll content but not the grain yield in traditional rice (*Oryza sativa* Linn.) genotypes of Assam, India II. Protein and proline status in seedlings under PEG induced water stress. *Am. J. Plant Sci.*, **2012**.
- Johnsen, K.I., 2016: Land-use conflicts between reindeer husbandry and mineral extraction in Finnmark, Norway: contested rationalities and the politics of belonging. *Polar Geogr.*, **39**(1), 58–79, doi:10.1080/1088937X.2016.1156181.
- Jones, S.M. and D.S. Gutzler, 2016: Spatial and Seasonal Variations in Aridification across Southwest North America. *J. Climate*, **29**(12), 4637–4649, doi:10.1175/jcli-d-14-00852.1.
- Kamali, B., D. Houshmand Kouchi, H. Yang and K.C. Abbaspour, 2017: Multilevel drought hazard assessment under climate change scenarios in semi-arid regions—A case study of the Karkheh river basin in Iran. *Water*, **9**(4), 241.
- Kaptué, A.T., L. Prihodko and N.P. Hanan, 2015: On greening and degradation in Sahelian watersheds. *Proc. Natl. Acad. Sci. U. S. A.*, **112**(39), 12133–12138, doi:10.1073/pnas.1509645112.
- Karmaoui, A., M. Messouli, Y.M. Khebiza and I. Ifaadassan, 2014: Environmental vulnerability to climate change and anthropogenic impacts in dryland, (pilot study: Middle Draa Valley, South Morocco. *J. Earth Sci. Clim. Chang.*, (S11), 1, doi:10.4172/2157-7617.S11-0.
- Kattumuri, R., D. Ravindranath and T. Esteves, 2015: Local adaptation strategies in semi-arid regions: study of two villages in Karnataka, India. *Clim. Dev.*, **5**(29), 1–14, doi:10.1080/17565529.2015.1067179.
- Kattumuri, R., D. Ravindranath and T. Esteves, 2017: Local adaptation strategies in semi-arid regions: study of two villages in Karnataka, India. *Clim. Dev.*, **9**(1), 36–49, doi:10.1080/17565529.2015.1067179.
- Kergoat, L., F. Guichard, C. Pierre and C. Vassal, 2017: Influence of dry-season vegetation variability on Sahelian dust during 2002–2015. *Geophys. Res. Lett.*, **44**(10), 5231–5239, doi:10.1002/2016gl072317.
- Kgope, B.S., W.J. Bond and G.F. Midgley, 2010: Growth responses of African savanna trees implicate atmospheric [CO<sub>2</sub>] as a driver of past and current changes in savanna tree cover. *Austral. Ecol.*, **35**(4), 451–463, doi:10.1111/j.1442-9993.2009.02046.x.
- Klinger, R. and M. Brooks, 2017: Alternative pathways to landscape transformation: invasive grasses, burn severity and fire frequency in arid ecosystems. *J. Ecol.*, **105**(6), 1521–1533, doi:10.1111/1365-2745.12863.
- Kong, Z.-H., L. Stringer, J. Paavola and Q. Lu, 2021: Situating China in the Global Effort to Combat Desertification. *Land*, **10**(7), 702.
- Koubi, V., 2019: Climate change and conflict. *Annu. Rev. Polit. Sci.*, **22**(1), 343–360, doi:10.1146/annurev-polisci-050317-070830.
- Koutroulis, A.G., 2019: Dryland changes under different levels of global warming. *Sci. Total. Environ.*, **655**, 482–511, doi:10.1016/j.scitotenv.2018.11.215.
- Kožmińska, A., et al., 2019: Responses of succulents to drought: comparative analysis of four *Sedum* (Crassulaceae) species. *Sci. Hort.*, **243**, 235–242, doi:10.1016/j.scienta.2018.08.028.
- Krätli, S. and N. Schareika, 2010: Living Off Uncertainty: The Intelligent Animal Production of Dryland Pastoralists. *Eur. J. Dev. Res.*, **22**(5), 605–622, doi:10.1057/ejdr.2010.41.
- Kumar, M., 2016: Impact of climate change on crop yield and role of model for achieving food security. *Environ. Monit. Assess.*, **188**(8), 465, doi:10.1007/s10661-016-5472-3.
- Kusserow, H., 2017: Desertification, resilience, and re-greening in the African Sahel – a matter of the observation period? *Earth Syst. Dynam.*, **8**(4), 1141–1170, doi:10.5194/esd-8-1141-2017.
- Kust, G.S., O.V. Andreeva and D.V. Dobrynin, 2011: Desertification assessment and mapping in the Russian Federation. *Arid Ecosyst.*, **1**(1), 14–28, doi:10.1134/S2079096111010057.
- Lamers, J.P., K. Michels and P.R. Feil, 1995: Wind erosion control using windbreaks and crop residues: local knowledge and experimental results. *Tropenlandwirt J. Agric. Trop. Subtrop.*, **96**(1), 87–96.
- Le Polain de Waroux, Y. and E. Lambin, 2012: Monitoring degradation in arid and semi-arid forests and woodlands: The case of the argan woodlands (Morocco). *Appl. Geogr.*, **32**, 777–786, doi:10.1016/j.apgeog.2011.08.005.
- Le, Q.B., E. Nkonya and A. Mirzabaev, 2016: *Biomass productivity-based mapping of global land degradation hotspots Economics of land degradation and improvement—A global assessment for sustainable development*. ISBN 978-3319191676. 55 pp.
- Léauthaud, C., et al., 2015: Revisiting historical climatic signals to better explore the future: prospects of water cycle changes in Central Sahel. *Proc. Int. Assoc. Hydrol. Sci.*, **371**, 195–201.
- Lewis, S.C. and J. Mallela, 2018: A multifactor risk analysis of the record 2016 Great Barrier Reef bleaching. *Bull. Am. Meteorol. Soc.*, **99**(1), S144–S149, doi:10.1175/BAMS-D-17-0074.1.
- Li, Z., L. Chen, M. Li and J. Cohen, 2018: Prenatal exposure to sand and dust storms and children's cognitive function in China: a quasi-experimental study. *Lancet Planet. Health*, **2**(5), e214–e222, doi:10.1016/S2542-5196(18)30068-8.
- Li, Z., et al., 2015: Potential impacts of climate change on vegetation dynamics in Central Asia. *J. Geophys. Res. Atmos.*, **120**(24), 12345–12356, doi:10.1002/2015jd023618.
- Lickley, M. and S. Solomon, 2018: Drivers, timing and some impacts of global aridity change. *Environ. Res. Lett.*, **13**, doi:10.1088/1748-9326/aae013.
- Lima, M., D.A. Christie, M.C. Santoro and C. Latorre, 2016: Coupled socio-environmental changes triggered indigenous aymara depopulation of the semiarid Andes of Tarapacá-Chile during the late 19th-20th centuries. *PLoS ONE*, **11**(8), e160580.
- Liu, J., et al., 2019: On knowledge generation and use for sustainability. *Nat. Sustain.*, **2**(2), 80–82, doi:10.1038/s41893-019-0229-y.
- Louhaichi, M. and A. Tastad, 2010: The Syrian Steppe: Past Trends, Current Status, and Future Priorities. *Rangelands*, **32**(2), 2–7, doi:10.2111/1551-501X-32.2.2.
- Louvain, C., 2019: *Natural disasters 2018*. Centre for Research on the Epidemiology of Disasters CRED, Brussels, Belgium, 8.
- Lovich, J.E., et al., 2014: Climatic variation and tortoise survival: has a desert species met its match? *Biol. Conserv.*, **169**, 214–224, doi:10.1016/j.biocon.2013.09.027.
- Lu, N., et al., 2018: Research advances in ecosystem services in drylands under global environmental changes. *Curr. Opin. Environ. Sustain.*, **33**, 92–98, doi:10.1016/j.cosust.2018.05.004.
- Ma, J., H. Hung and R.W. Macdonald, 2016: The influence of global climate change on the environmental fate of persistent organic pollutants: a review with emphasis on the Northern Hemisphere and the Arctic as a receptor. *Glob. Planet. Change*, **146**, 89–108, doi:10.1016/j.gloplacha.2016.09.011.
- Mach, K.J., et al., 2019: Climate as a risk factor for armed conflict. *Nature*, **571**(7764), 193–197, doi:10.1038/s41586-019-1300-6.
- Maestre, F.T., et al., 2015: Increasing aridity reduces soil microbial diversity and abundance in global drylands. *Proc. Natl. Acad. Sci.*, **112**(51), 15684–15689, doi:10.1073/pnas.1516684112.
- Mahmoudi, P., D. Kalim and M.R. Amirmoradi (eds.), *Investigation of Iran Vulnerability Trend to Desertification with approach of climate change*. Second International Conference on Environmental Science and Development IPCBEE. IACSIT Press, Singapore, 63–67.
- Mandumbu, R., C. Mutengwa, S. Mabasa and E. Mwenje, 2017: Predictions of the Striga scourge under new climate in Southern Africa. *J. Biol. Sci.*, **17**, 192–201.
- Manga, V., A.K. Jukanti and R. Bhatt (2015.), *Adaptation and selection of crop varieties for hot arid climate of Rajasthan*. International Journal of Plant Sciences 4(4):2319–38241
- Manlay, R.J., et al., 2004: Spatial carbon, nitrogen and phosphorus budget of a village in the West African savanna—I. Element pools and structure of



- a mixed-farming system. *Agricultural Systems*, **79**(1), 55–81, doi:10.1016/S0308-521X(03)00053-2.
- Manzoni, S., M.H. Ahmed and A. Porporato, 2019: Ecohydrological and Stoichiometric Controls on Soil Carbon and Nitrogen Dynamics in Drylands. In: *Dryland Ecohydrology* [D'Odorico, P., A. Porporato and C. Wilkinson Runyan(eds.)]. Springer, Cham.
- Maranz, S., 2009: Tree mortality in the African Sahel indicates an anthropogenic ecosystem displaced by climate change. *J. Biogeogr.*, **36**(6), 1181–1193, doi:10.1111/j.1365-2699.2008.02081.x.
- Marchesini, V.A., R. Giménez, M.D. Nosetto and E. G. Jobbágy, 2017: Ecohydrological transformation in the Dry Chaco and the risk of dryland salinity: Following Australia's footsteps? *Ecohydrology*, **10**(4), e1822, doi:10.1002/eco.1822.
- Marin, A., et al., 2020: Productivity beyond density: A critique of management models for reindeer pastoralism in Norway. *Pastoralism*, **10**(1), 9, doi:10.1186/s13570-020-00164-3.
- Martorell, C., D.M. Montañana, C. Ureta and M.C. Mandujano, 2015: Assessing the importance of multiple threats to an endangered globose cactus in Mexico: Cattle grazing, looting and climate change. *Biol. Conserv.*, **181**, 73–81.
- Masiokas, M.H., et al., 2019: Streamflow variations across the Andes (18°–55°S) during the instrumental era. *Sci. Rep.*, **9**(1), 17879–17879, doi:10.1038/s41598-019-53981-x.
- Masubelele, M.L., M.T. Hoffman and W.J. Bond, 2015a: Biome stability and long-term vegetation change in the semi-arid, south-eastern interior of South Africa: A synthesis of repeat photo-monitoring studies. *S. Afr. J. Bot.*, **101**, 139–147, doi:10.1016/j.sajb.2015.06.001.
- Masubelele, M.L., M.T. Hoffman and W.J. Bond, 2015b: A repeat photograph analysis of long-term vegetation change in semi-arid South Africa in response to land use and climate. *J. Veg. Sci.*, **26**(5), 1013–1023, doi:10.1111/jvs.12303.
- Maurer, G.E., et al., 2020: Sensitivity of primary production to precipitation across the United States. *Ecol. Lett.*, **23**(3), 527–536.
- Mazhar N, Shirazi SA, Stringer LC, Carrie RH, Dallimer M 2021. Spatial patterns in the adaptive capacity of dryland agricultural households in South Punjab, Pakistan, *Journal of Arid Environments* 194, 104610, <https://doi.org/10.1016/j.jaridenv.2021.104610>
- Mbow, C., C. Rosenzweig, L.G. Barioni, T.G. Benton, M. Herrero, M. Krishnapillai, E. Liwenga, P. Pradhan, M.G. Rivera-Ferre, T. Sapkota, F.N. Tubiello, Y. Xu, 2019: Food Security. In: *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems* [P.R. Shukla, J. Shee, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D.C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, J. Malley, (eds.)]. In press.
- Mbow, C., et al., 2014: Achieving mitigation and adaptation to climate change through sustainable agroforestry practices in Africa. *Curr. Opin. Environ. Sustain.*, **6**, 8–14, doi:10.1016/j.cosust.2013.09.002.
- Mekonnen, D., E. Bryan, T. Alemu and C. Ringler, 2017: Food versus fuel: examining tradeoffs in the allocation of biomass energy sources to domestic and productive uses in Ethiopia. *Agric. Econ.*, **48**(4), 425–435, doi:10.1111/agec.12344.
- Meynard, C.N., M. Lecoq, M.-P. Chapuis and C. Piou, 2020: On the relative role of climate change and management in the current desert locust outbreak in East Africa. *Glob. Change Biol.*, **26**(7), 3753–3755, doi:10.1111/gcb.15137.
- Mganga, K.Z., N.K.R. Musimba and D.M. Nyariki, 2015: Combining Sustainable Land Management Technologies to Combat Land Degradation and Improve Rural Livelihoods in Semi-arid Lands in Kenya. *Environ. Manage.*, **56**(6), 1538–1548, doi:10.1007/s00267-015-0579-9.
- Michels, K., J.P.A. Lamers and A. Buerkert, 1998: Effects of windbreak species and mulching on wind erosion and millet yield in the Sahel. *Experimental agriculture*, **34**(4), 449–464, doi:10.1017/s0014479798004050.
- Middleton, N., 2018: Rangeland management and climate hazards in drylands: dust storms, desertification and the overgrazing debate. *Nat. Hazards*, **92**(1), 57–70, doi:10.1007/s11069-016-2592-6.
- Middleton, N., 2019: Variability and trends in dust storm frequency on decadal timescales: Climatic drivers and human impacts. *Geosciences*, **9**(6), 261, doi:10.3390/geosciences9060261.
- Middleton, N. and U. Kang, 2017: Sand and Dust Storms: Impact Mitigation. *Sustainability*, **9**(6), 1053–1053, doi:10.3390/su9061053.
- Middleton, N.J., 2017: Desert dust hazards: A global review. *Aeolian Res.*, **24**, 53–63, doi:10.1016/J.AEOLIA.2016.12.001.
- Mirzabaev, A., J. Wu, J. Evans, F. García-Oliva, I.A.G. Hussein, M.H. Iqbal, J. Kimutai, T. Knowles, F. Meza, D. Nedjraoui, F. Tena, M. Türkeş, R.J. Vázquez, M. Weltz, 2019: Desertification. In: *Climate Change and Land: an IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems* [P.R. Shukla, J. Shee, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D.C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacemi, J. Malley, (eds.)]. In press.
- Mirzabaev, G., 2016: *Benefits of action and costs of inaction: Drought mitigation and preparedness—a literature review*. World Meteorological Organization and Global Water Partnership. Integrated Drought Management Programme Working Paper No. 1, Geneva, Switzerland.
- Mishra, A.K. and V.P. Singh, 2010: A Review of Drought Concepts. *J. Hydrol. Reg. Stud.*, **391**, 202–216, doi:10.1016/j.jhydrol.2010.07.012.
- Missirian, A. and W. Schlenker, 2017: Asylum applications respond to temperature fluctuations. *Science*, **358**(6370), 1610–1614, doi:10.1126/science.aao0432.
- Mohamed, N., B. Abdou, M. Fadul and S. Zakieldeen, 2016: Ecological Zones Degradation Analysis in Central Sudan during a Half Century Using Remote Sensing and GIS. *Adv. Remote. Sens.*, **5**(04), 355–371, doi:10.4236/ars.2016.54025.
- Montagné, P., et al. (2016.), *Bois-énergie domestique, démographie et urbanisation : situation après vingt-cinq années de gestion forestière des néo-communs au Sud-Niger*. In : Communs et Développement. Paris : AFD, 14 p. Conférence Internationale de l'AFD. 12, Paris, France.
- Morgan, J.A., et al., 2004: Water relations in grassland and desert ecosystems exposed to elevated atmospheric CO<sub>2</sub>. *Oecologia*, **140**(1), 11–25, doi:10.1007/s00442-004-1550-2.
- Moridnejad, A., N. Karimi and P.A. Ariya, 2015: Newly desertified regions in Iraq and its surrounding areas: Significant novel sources of global dust particles. *J. Arid Environ.*, **116**, 1–10.
- Morton, J. and D. Barton, 2002: Destocking as a Drought-mitigation Strategy: Clarifying Rationales and Answering Critiques. *Disasters*, **26**(3), 213–228, doi:10.1111/1467-7717.00201.
- Mote, P.W., et al., 2018: Dramatic declines in snowpack in the western US. *Npj Clim. Atmospheric Sci.*, **1**(1), 2, doi:10.1038/s41612-018-0012-1.
- Mottaleb, K.A., et al., 2017: Benefits of the development and dissemination of climate-smart rice: ex ante impact assessment of drought-tolerant rice in South Asia. *Mitig. Adapt. Strateg. Glob. Change*, **22**(6), 879–901, doi:10.1007/s11027-016-9705-0.
- Munday, C. and R. Washington, 2019: Controls on the Diversity in Climate Model Projections of Early Summer Drying over Southern Africa. *J. Climate*, **32**(12), 3707–3725, doi:10.1175/jcli-d-18-0463.1.
- Munson, S.M., A.L. Long, C.S.A. Wallace and R.H. Webb, 2016a: Cumulative drought and land-use impacts on perennial vegetation across a North American dryland region. *Appl. Veg. Sci.*, **19**(3), 430–441, doi:10.1111/avsc.12228.
- Munson, S.M., et al., 2016b: Decadal shifts in grass and woody plant cover are driven by prolonged drying and modified by topo-edaphic properties. *Ecol. Appl.*, **26**(8), 2480–2494, doi:10.1002/eap.1389.

- Munson, S.M., et al., 2012: Forecasting climate change impacts to plant community composition in the Sonoran Desert region. *Glob. Change Biol.*, **18**(3), 1083–1095, doi:10.1111/j.1365-2486.2011.02598.x.
- Münzel, T., J. Lelieveld, S. Rajagopalan and A. Daiber, 2019: Contribution of airborne desert dust to air quality and cardiopulmonary disease. *Eur. Heart J.*, doi:10.1093/eurheartj/ehz216.
- Musil, C.F., U. Schmiedel and G.F. Midgley, 2005: Lethal effects of experimental warming approximating a future climate scenario on southern African quartz-field succulents: a pilot study. *New Phytol.*, **165**(2), 539–547, doi:10.1111/j.1469-8137.2004.01243.x.
- Myers, S.S., et al., 2017: Climate Change and Global Food Systems: Potential Impacts on Food Security and Undernutrition. *Annu. Rev. Public Health*, **38**(1), 259–277, doi:10.1146/annurev-publhealth-031816-044356.
- Myhre, G.D., et al., 2013: *Anthropogenic and Natural Radiative Forcing* Stocker, T. F. D., Q. G., K. Plattner, M. Tignor, S. K. Allen, A. J. Boschung, N. Y., X. V., Bex and P. M. Midgley. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.
- Navarro-Cerrillo, R.M., et al., 2020: Competition modulates the response of growth to climate in pure and mixed *Abies pinsapo* subsp. *Maroccana* forests in northern Morocco. *For. Ecol. Manag.*, **459**, 117847, doi:10.1016/j.foreco.2019.117847.
- Nikam, V.R., R. Singh and A. Chinchmalapure, 2016: Salt tolerant varieties: A biological intervention to manage saline and sodic environment and sustain livelihoods. *J. Soil Salin. Water Qual.*, **8**(1), 37–44.
- Nkrumah, F., et al., 2019: Recent Trends in the Daily Rainfall Regime in Southern West Africa. *Atmosphere*, **10**(12), 741.
- Nori, M. and I. Scoones, 2019: Pastoralism, uncertainty and resilience: global lessons from the margins. *Pastoralism*, **9**(1), 1–7.
- Noyola-Medrano, C. and V.A. Martínez-Sías, 2017: Assessing the progress of desertification of the southern edge of Chihuahuan Desert: A case study of San Luis Potosi Plateau. *J. Geogr. Sci.*, **27**(4), 420–438, doi:10.1007/s11442-017-1385-5.
- Nyangena, J. and A.W. Roba, 2017: *Funding adaptation in Kenya's drylands*. International Institute of Environment and Development (IIED), <https://pubs.iied.org/pdfs/17418IIED.pdf>, available on 06.03.2022
- Nyantakyi-Frimpong, H. and K. Bezner, 2017: Land grabbing, social differentiation, intensified migration and food security in northern Ghana. *J. Peasant Stud.*, **44**(2), 421–444, doi:10.1080/03066150.2016.1228629.
- O'Connor, T.G., J.R. Puttick and M.T. Hoffman, 2014: Bush encroachment in southern Africa: changes and causes. *Afr. J. Range Forage Sci.*, **31**(2), 67–88, doi:10.2989/10220119.2014.939996.
- Obeng-Odoom, F., 2017: Unequal access to land and the current migration crisis. *Land Use Policy*, **62**, 159–171, doi:10.1016/j.landusepol.2016.12.024.
- Okpara, U.T., L.C. Stringer and M. Akhtar-Schuster, 2019: Gender and land degradation neutrality: A cross-country analysis to support more equitable practices. *Land Degrad. Dev.*, **30**(11), 1368–1378, doi:10.1002/ldr.3326.
- Okpara, U.T., L.C. Stringer, A.J. Dougill and M.D. Bila, 2015: Conflicts about water in Lake Chad: Are environmental, vulnerability and security issues linked? *Prog. Dev. Stud.*, **15**(4), 308–325, doi:10.1177/1464993415592738.
- Oliver-Smith, A., 2010: *Defying displacement: Grassroots resistance and the critique of development*. University of Texas Press, Austin.
- Olsson, L., H. Barbosa, S. Bhadwal, A. Cowie, K. Delusca, D. Flores-Renteria, K. Hermans, E. Jobbagy, W. Kurz, D. Li, D.J. Sonwa, L. Stringer, 2019: Land Degradation. In: *Climate Change and Land: An IPCC special report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems*. [P.R. Shukla, J. Skea, E. Calvo Buendia, V. Masson-Delmotte, H.-O. Pörtner, D. C. Roberts, P. Zhai, R. Slade, S. Connors, R. van Diemen, M. Ferrat, E. Haughey, S. Luz, S. Neogi, M. Pathak, J. Petzold, J. Portugal Pereira, P. Vyas, E. Huntley, K. Kissick, M. Belkacem, J. Malley, (eds.)]. In press.
- Olsson, L., L. Eklundh and J. Ardö, 2005: A recent greening of the Sahel—trends, patterns and potential causes. *J. Arid Environ.*, **63**(3), 556–566, doi:10.1016/j.jaridenv.2005.03.008.
- Asem, O. and W.Y. Roy, 2010: Biodiversity and climate change in Kuwait. *Int. J. Clim. Chang. Strateg. Manag.*, **2**(1), 68–83, doi:10.1108/17568691011020265.
- Opp, C., M. Groll, H. Abbasi and M. A. Foroushani, 2021: Causes and Effects of Sand and Dust Storms: What Has Past Research Taught Us? A Survey. *J. Risk Financial Manag.*, **14**(7), 326.
- Orr, B., et al. (ed.), *Scientific conceptual framework for land degradation neutrality. A report of the science-policy interface*. United Nations Convention to Combat Desertification (UNCCD), Bonn, Germany.
- Orr, B.J., et al., 2017b: *Scientific Conceptual Framework for Land Degradation Neutrality. A Report of the Science-Policy Interface*. Bonn, Germany, <https://www.unccd.int/publications/scientific-conceptual-framework-land-degradation-neutrality-report-science-policy>, available on 06.03.2022.
- Osbahr, H., P. Dorward, R. Stern and S. Cooper, 2011: Supporting agricultural innovation in Uganda to respond to climate risk: linking climate change and variability with farmer perceptions. *Exp. Agric.*, **47**(2), 293–316, doi:10.1017/S0014479710000785.
- Owain, E.L. and M.A. Maslin, 2018: Assessing the relative contribution of economic, political and environmental factors on past conflict and the displacement of people in East Africa. *Palgrave Commun.*, **4**(1), 47–47, doi:10.1057/s41599-018-0096-6.
- Painter, T.H., et al., 2010: Response of Colorado River runoff to dust radiative forcing in snow. *Proc. Natl. Acad. Sci.*, **107**(40), 17125–17130, doi:10.1073/pnas.0913139107.
- Pan, N., et al., 2021: Rapid increase of potential evapotranspiration weakens the effect of precipitation on aridity in global drylands. *J. Arid Environ.*, **186**, 104414, doi:10.1016/j.jaridenv.2020.104414.
- Park, C.-E., et al., 2018: Keeping global warming within 1.5°C constrains emergence of aridification. *Nat. Clim. Change*, **8**(1), 70–74, doi:10.1038/s41558-017-0034-4.
- Passos, F.B., et al., 2018: Savanna turning into forest: concerted vegetation change at the ecotone between the Amazon and “Cerrado” biomes. *Braz. J. Bot.*, **41**(3), 611–619, doi:10.1007/s40415-018-0470-z.
- Patel, S.K., A. Sharma and G.S. Singh, 2020: Traditional agricultural practices in India: an approach for environmental sustainability and food security. *Energy Ecol. Environ.*, **5**(4), 253–271, doi:10.1007/s40974-020-00158-2.
- Pérez-Sánchez, R.M., E. Jurado, L. Chapa-Vargas and J. Flores, 2011: Seed germination of Southern Chihuahuan Desert plants in response to elevated temperatures. *J. Arid Environ.*, **75**(10), 978–980, doi:10.1016/j.jaridenv.2011.04.020.
- Péron, G. and R. Altwegg, 2015: Twenty-five years of change in southern African passerine diversity: nonclimatic factors of change. *Global Change Biology* **21**(9), 3347–3355, doi:10.1111/gcb.12909.
- Piao, S., et al., 2019: Characteristics, drivers and feedbacks of global greening. *Nat. Rev. Earth Environ.*, **1**, 14–27.
- Piao, S., et al., 2020: Characteristics, drivers and feedbacks of global greening. *Nat. Rev. Earth Environ.*, **1**(1), 14–27, doi:10.1038/s43017-019-0001-x.
- Piao, S., et al., 2015: Detection and attribution of vegetation greening trend in China over the last 30 years. *Glob. Change Biol.*, **21**(4), 1601–1609, doi:10.1111/gcb.12795.
- Pieri, C., 1989: *Fertilité des terres de savanes: bilan de trente ans de recherche et de développement agricole au sud du Sahara*. Ministère de la Coopération, CIRAD-IRAT, Paris, France. 444 pp.
- Pierre, C., et al., 2018: Impact of Agropastoral Management on Wind Erosion in Sahelian Croplands. *Land Degrad. Dev.*, **29**(3), 800–811, doi:10.1002/ldr.2783.
- Polley, H., H.S. Mayeux, H.B. Johnson and C.R. Tischler, 1997: *Viewpoint: Atmospheric CO<sub>2</sub>, Soil Water, and Shrub/Grass Ratios on Rangelands*. Vol. 50.
- Portnov, B.A. and U.N. Safriel, 2004: Combating desertification in the Negev: dryland agriculture vs. dryland urbanization. *J. Arid Environ.*, **56**(4), 659–680, doi:10.1016/S0140-1963(03)00087-9.
- Prävälje, R., 2016: Drylands extent and environmental issues. A global approach. *Earth Sci. Rev.*, **161**, 259–278, doi:10.1016/j.earscirev.2016.08.003.



- Pu, B. and P. Ginoux, 2017: Projection of American dustiness in the late 21st century due to climate change. *Sci. Rep.*, **7**(1), 5553–5553, doi:10.1038/s41598-017-05431-9.
- Quets, J.J., et al., 2017: Emergence, survival, and growth of recruits in a desert ecosystem with vegetation-induced dunes (nebkhas): A spatiotemporal analysis. *J. Arid Environ.*, **139**.
- Quirk, J., C. Bellasio, D. Johnson and D. Beerling, 2019: Response of photosynthesis, growth and water relations of a savannah-adapted tree and grass grown across high to low CO<sub>2</sub>. *Ann. Bot.*, **124**, 77–90, doi:10.1093/aob/mcz048.
- Rajaud, A. and N. d. Noblet-Ducoudré, 2017: Tropical semi-arid regions expanding over temperate latitudes under climate change. *Clim. Change*, **144**(4), 703–719, doi:10.1007/s10584-017-2052-7.
- Rasul, G., Q.Z. Chaudhry, A. Mahmood and K.W. Hyder, 2011: Effect of Temperature Rise on Crop Growth & Productivity. *Pak. J. Meteorol.*, **8**(5).
- Reed, M.S. and L.C. Stringer, 2016: *Land degradation, desertification, and climate change : anticipating, assessing, and adapting to future change*. Routledge, 184–184. ISBN 978-1849712712. Oxfordshire, England, UK
- Reed, M.S., et al., 2015: Reorienting land degradation towards sustainable land management: Linking sustainable livelihoods with ecosystem services in rangeland systems. *J. Environ. Manag.*, **151**, 472–485, doi:10.1016/j.jenvman.2014.11.010.
- Reed, S.C., et al., 2012: Changes to dryland rainfall result in rapid moss mortality and altered soil fertility. *Nat. Clim. Change*, **2**(10), 752–755, doi:10.1038/nclimate1596.
- Reed, S.C., M. Delgado-Baquerizo and S. Ferrenberg, 2019: Biocrust science and global change. *New Phytol.*, **223**(3), 1047–1051, doi:10.1111/nph.15992.
- Reichhuber, A., et al., 2019: *The Land-Drought Nexus: Enhancing the Role of Land-Based Interventions in Drought Mitigation and Risk Management. A Report of the Science-Policy Interface*. United Nations Convention to Combat Desertification (UNCCD), Bonn.
- Reij, C. and D. Garrity, 2016: Scaling up farmer-managed natural regeneration in Africa to restore degraded landscapes. *Biotropica*, **48**(6), 834–843, doi:10.1111/btp.12390.
- Reij, C., G. Tappan and A. Belemvire, 2005: Changing land management practices and vegetation on the Central Plateau of Burkina Faso (1968–2002). *J. Arid Environ.*, **63**(3), 642–659, doi:10.1016/j.jaridenv.2005.03.010.
- Renwick, K.M., et al., 2018: Multi-model comparison highlights consistency in predicted effect of warming on a semi-arid shrub. *Glob. Change Biol.*, **24**(1), 424–438, doi:10.1111/gcb.13900.
- Reynolds, J.F., et al., 2007: Global Desertification: Building a Science for Dryland Development. *Science*, **316**(5826), 847–851, doi:10.1126/science.1131634.
- Riddell, E.A., et al., 2019: Cooling requirements fueled the collapse of a desert bird community from climate change. *Proc. Natl. Acad. Sci.*, **116**(43), 21609–21615, doi:10.1073/pnas.1908791116.
- Rivera, J.A. and O.C. Penalba, 2018: Spatio-temporal assessment of streamflow droughts over Southern South America: 1961–2006. *Theor. Appl. Climatol.*, **133**(3), 1021–1033, doi:10.1007/s00704-017-2243-1.
- Robbins, P., 2020: *Political ecology : a critical introduction*. Wiley Blackwell. New Jersey, USA.
- Rochdane, S., et al., 2012: Climate Change Impacts on Water Supply and Demand in Rheraya Watershed (Morocco), with Potential Adaptation Strategies. *Water* **4**(4), 28–44, doi:10.3390/w4010028.
- Rodríguez-Catón, M., R. Villalba, A. Srur and A.P. Williams, 2019: Radial Growth Patterns Associated with Tree Mortality in *Nothofagus pumilio* Forest. *Forests*, **10**(6), 489.
- Rodríguez-Morales, M., et al., 2019: Ecohydrology of the Venezuelan páramo: water balance of a high Andean watershed. *Plant Ecol. Divers.*, **12**(6), 573–591, doi:10.1080/17550874.2019.1673494.
- Rohde, R.F., et al., 2019: Vegetation and climate change in the Pro-Namib and Namib Desert based on repeat photography: Insights into climate trends. *J. Arid Environ.*, **165**, 119–131, doi:10.1016/j.jaridenv.2019.01.007.
- Rosan, T.M., et al., 2019: Extensive 21st-Century Woody Encroachment in South America's Savanna. *Geophys. Res. Lett.*, **46**(12), 6594–6603, doi:10.1029/2019gl082327.
- Rowell, D.P., C.A. Senior, M. Vellinga and R.J. Graham, 2016: Can climate projection uncertainty be constrained over Africa using metrics of contemporary performance? *Clim. Change*, **134**(4), 621–633, doi:10.1007/s10584-015-1554-4.
- Rudgers, J.A., et al., 2018: Climate sensitivity functions and net primary production: A framework for incorporating climate mean and variability. *Ecology*, **99**(3), 576–582, doi:10.1002/ecy.2136.
- Runhaar, H.A.C., et al., 2016: Prepared for climate change? A method for the ex-ante assessment of formal responsibilities for climate adaptation in specific sectors. *Reg. Environ. Change*, **16**(5), 1389–1400, doi:10.1007/s10113-015-0866-2.
- Russo, S., A. F. Marchese, J. Sillmann and G. Immé, 2016: When will unusual heat waves become normal in a warming Africa? *Environ. Res. Lett.*, **11**(5), 54016.
- Rutherford, M.C., L. Powrie and R. Roberts, 2000: *Plant Biodiversity: Vulnerability and Adaptation Assessment*. South Afr. Ctry. Study Clim. Change Natl. Bot. Inst, Claremont South Afr.
- Rutherford, W.A., et al., 2017: Albedo feedbacks to future climate via climate change impacts on dryland biocrusts. *Sci. Rep.*, **7**(1), 44188, doi:10.1038/srep44188.
- Sahour, H., M. Vazifedan and F. Alshehri, 2020: Aridity trends in the Middle East and adjacent areas. *Theor Appl Climatol* **142**, 1039–1054 (2020). <https://doi.org/10.1007/s00704-020-03370-6>.
- Salih, A.A.M., M. Baraibar, K.K. Mwangi and G. Artan, 2020: Climate change and locust outbreak in East Africa. *Nat. Clim. Change*, **10**(7), 584–585, doi:10.1038/s41558-020-0835-8.
- Sandford, S., 1983: *Management of pastoral development in the Third World*. Wiley, Chichester West Sussex ; New York.
- Sangaré, M., et al., 2002a: Influence of dry season supplementation for cattle on soil fertility and millet (*Pennisetum glaucum* L.) yield in a mixed crop/livestock production system of the Sahel. *Nutr. Cycl. Agroecosyst.*, **62**(3), 209–217, doi:10.1023/A:1021237626450.
- Sangaré, M., S. Fernández-Rivera, P. Hiernaux and V. Pandey, 2002b: Effect of groundnut cake and P on millet stover utilisation and nutrient excretion by sheep. *Trop. Agric.* **79**(1):31-35
- Sanogo, O.M., 2011: *Le lait, de l'or blanc ? Amélioration de la productivité des exploitations mixtes cultures-élevage à travers une meilleure gestion et alimentation des vaches laitières dans la zone de Koutiala, Mali*. Wageningen Univ, Netherlands, Wageningen. 158 pp.
- Santos, M.G., et al., 2014: Caatinga, the Brazilian dry tropical forest: can it tolerate climate changes? *Theor. Exp. Plant Physiol.*, **26**(1), 83–99, doi:10.1007/s40626-014-0008-0.
- Savage, M., et al., 2009: *Socio-economic impacts of climate change in Afghanistan*. Stockholm Environment Institute, Oxford, UK, <https://www.weadapt.org/sites/weadapt.org/files/legacy-new/placemarks/files/5345354491559sei-dfid-afghanistan-report-1-.pdf>. Accessed 2020.
- Scheff, J. and D.M.W.W. Frierson, 2015: Terrestrial aridity and its response to greenhouse warming across CMIP5 climate models. *J. Climate*, **28**(14), 5583–5600, doi:10.1175/JCLI-D-14-00480.1.
- Schlecht, E., P. Hiernaux, F. Achard and M.D. Turner, 2004: Livestock related nutrient budgets within village territories in western Niger. *Nutrient Cycling in Agroecosystems*, **68**(3), 199–211, doi:10.1023/b:fres.0000019453.19364.70.
- Schwilch, G., H.P. Liniger and H. Hurni, 2014: Sustainable Land Management (SLM) Practices in Drylands: How Do They Address Desertification Threats? *Environ. Manage.*, **54**(5), 983–1004, doi:10.1007/s00267-013-0071-3.
- Scoones, I., 2009: Climate Change and the Challenge of Non-equilibrium Thinking. *IDS Bull.*, **35**, 114–119, doi:10.1111/j.1759-5436.2004.tb00144.x.
- Sendzimir, J., C.P. Reij and P. Magnuszewski, 2011: Rebuilding resilience in the Sahel: regreening in the Maradi and Zinder regions of Niger. *Ecol. Soc.*, **16**(3) :1, doi:http://dx.doi.org/10.5751/ES-04198-160301.

- Sengupta, N., 2002: Traditional vs modern practices in salinity control. *Econ. Pol. Weekly*, **37**(13), 1247–1254.
- Sharma, D.K., et al., 2015: *Assessment of production and monetary losses from salt-affected soils in India*. ICAR-Central Soil Salinity Research Institute. Haryana, India
- Sharma, D.K. and A. Singh, 2015: Salinity research in India: Achievements, challenges and future prospects. *Water Energy Int.* **58**(6):35–45
- Sharma, P. and A. Singh, 2017: *ICAR-Central Soil Salinity Research Institute Annual Report 2016–17*.
- Sharma, P.C., M.J. Kaledhonkar, K. Thiimmappa and S.K. Chaudhari, 2016: *Reclamation of waterlogged saline soils through subsurface drainage technology*. ICAR-CSSRI/Karnal/ Technology Folder/ 2016/02.ICAR-CSSRI, Karnal, Haryana, <https://krishi.icar.gov.in/jspui/bitstream/123456789/3676/1/Reclamation%20of%20Waterlogged.pdf>, available on 06.03.2022.
- Sharratt, B., et al., 2015: Implications of climate change on wind erosion of agricultural lands in the Columbia Plateau. *Weather. Clim. Extrem.*, **10**, 20–31.
- Shikuku, K.M., et al., 2017: Prioritizing climate-smart livestock technologies in rural Tanzania: A minimum data approach. *Agric. Syst.*, **151**, 204–216, doi:10.1016/j.agsy.2016.06.004.
- Shryock, D.F., T.C. Esque and L. Hughes, 2014: Population viability of *Pediocactus bradyi* (Cactaceae) in a changing climate. *Am. J. Bot.*, **101**(11), 1944–1953, doi:10.3732/ajb.1400035.
- Singh, R.K., E. Redoña and L. Refuerzo, 2010: Plant breeding, genetics and biotechnology. In: *Abiotic Stress Adaptation in Plants: Physiological, Molecular and Genomic Foundation* [Pareek, A., S.K. Sopory, H.J. Bohnert and Govindjee (eds.)]. Springer, pp. 387–415. ISBN 978-9048131112. doi:10.1007/978-90-481-3112-9\_18. Dordrecht, Netherlands.
- Singh, R.K., et al., 2020b: Perceived Climate Variability and Compounding Stressors: Implications for Risks to Livelihoods of Smallholder Indian Farmers. *Environ. Manage.*, **66**, 826–844 (2020). <https://doi.org/10.1007/s00267-020-01345-x>.
- Sirami, C. and A. Monadjem, 2012: Changes in bird communities in Swaziland savannas between 1998 and 2008 owing to shrub encroachment. *Divers. Distributions*, **18**(4), 390–400, doi:10.1111/j.1472-4642.2011.00810.x.
- Sitch, S., et al., 2015: Recent trends and drivers of regional sources and sinks of carbon dioxide. *Biogeosciences*, **12**(3), 653–679.
- Sivakumar, M.V.K., 2005: *Impacts of Sand Storms/Dust Storms on Agriculture*. Springer, Berlin/Heidelberg, 159–177.
- Skowno, A.L., et al., 2017: Woodland expansion in South African grassy biomes based on satellite observations (1990–2013): general patterns and potential drivers. *Glob. Change Biol.*, **23**(6), 2358–2369, doi:10.1111/gcb.13529.
- Smit, I.P.J. and H.H.T. Prins, 2015: Predicting the Effects of Woody Encroachment on Mammal Communities, Grazing Biomass and Fire Frequency in African Savannas. *PLoS ONE*, **10**(9), e137857, doi:10.1371/journal.pone.0137857.
- Sommer, M., S. Ferron, S. Cavill and S. House, 2014: Violence, gender and WASH: spurring action on a complex, under-documented and sensitive topic. *Environ. Urban*, **27**(1), 105–116, doi:10.1177/0956247814564528.
- Sosa, V., et al., 2019: Climate change and conservation in a warm North American desert: effect in shrubby plants. *PeerJ*, **7**, e6572, doi:10.7717/peerj.6572.
- Spinoni, J., et al., 2015: Towards identifying areas at climatological risk of desertification using the Köppen-Geiger classification and FAO aridity index. *Int. J. Climatol.*, **35**(9), 2210–2222, doi:10.1002/joc.4124.
- Srur, A.M., et al., 2016: Establishment of *Nothofagus pumilio* at upper treelines across a precipitation gradient in the northern Patagonian Andes. *Arct. Antarct. Alp. Res.*, **48**(4), 755–766, doi:10.1657/AAAR0016-015.
- Srur, A.M., et al., 2018: Climate and *Nothofagus pumilio* Establishment at Upper Treelines in the Patagonian Andes. *Front. Earth Sci.*, **6**(57), doi:10.3389/feart.2018.00057.
- Stafford, W., et al., 2017: The economics of landscape restoration: Benefits of controlling bush encroachment and invasive plant species in South Africa and Namibia. *Ecosyst. Serv.*, **27**, 193–202, doi:10.1016/j.ecoser.2016.11.021.
- Stanelle, T., et al., 2014: Anthropogenically induced changes in twentieth century mineral dust burden and the associated impact on radiative forcing. *J. Geophys. Res. Atmos.*, **119**(23), 13,526–513,546, doi:10.1002/2014jd022062.
- Steinfeld, H., et al., 2006: *Livestock's Long Shadow: Environmental Issues and Options*. Food and Agriculture Organization of the United Nations, Rome, Italy, <http://www.fao.org/3/a0701e/a0701e00.htm>. Accessed 2020.
- Sternberg, T., 2016: Water megaprojects in deserts and drylands. *Int. J. Water Resour. Dev.*, **32**(2), 301–320.
- Stevens, N., B. Erasmus, S. Archibald and W. Bond, 2016: Woody encroachment over 70 years in South African savannas: Overgrazing, global change or extinction aftershock? *Philos. Trans. Royal Soc. B Biol. Sci.*, **371**, 20150437, doi:10.1098/rstb.2015.0437.
- Stevens, N., C.E.R. Lehmann, B.P. Murphy and G. Durigan, 2017: Savanna woody encroachment is widespread across three continents. *Glob. Change Biol.*, **23**(1), 235–244, doi:10.1111/gcb.13409.
- Stith, M., et al., 2016: A Quantitative Evaluation of the Multiple Narratives of the Recent Sahelian Regreening. *Weather. Clim. Soc.*, **8**(1), 67–83, doi:10.1175/wcas-d-15-0012.1.
- Stringer, L., et al., 2021: Climate change impacts on water security in global drylands. *One Earth*, **4**(6), 851–864.
- Stringer, L.C., et al., 2017: A New Dryland Development Paradigm Grounded in Empirical Analysis of Dryland Systems Science. *Land Degrad. Dev.*, **28**(7), 1952–1961, doi:10.1002/ldr.2716.
- Suckall, N., E. Tompkins and L. Stringer, 2014: Identifying trade-offs between adaptation, mitigation and development in community responses to climate and socio-economic stresses: Evidence from Zanzibar, Tanzania. *Appl. Geogr.*, **46**, 111–121.
- Sullivan, S. and R. Rohde, 2002: On non-equilibrium in arid and semi-arid grazing systems. *J. Biogeogr.*, **29**(12), 1595–1618, doi:10.1046/j.1365-2699.2002.00799.x.
- Sultana, P., et al., 2019: Transforming local natural resource conflicts to cooperation in a changing climate: Bangladesh and Nepal lessons. *Clim. Policy*, **19**(sup1), S94–S106, doi:10.1080/14693062.2018.1527678.
- Swann, A.L., F.M. Hoffman, C.D. Koven and J.T. Randerson, 2016: Plant responses to increasing CO2 reduce estimates of climate impacts on drought severity. *Proc. Natl. Acad. Sci. U. S. A.*, **113**(36), 10019–10024, doi:10.1073/pnas.1604581113.
- Syphard, A.D., J.E. Keeley and J.T. Abatzoglou, 2017: Trends and drivers of fire activity vary across California aridland ecosystems. *J. Arid Environ.*, **144**, 110–122, doi:10.1016/j.jaridenv.2017.03.017.
- Tabutin, D. and B. Schoumaker, 2004: La démographie de l'Afrique au sud du Sahara des années 1950 aux années 2000. *Population*, **59**(3), 521, doi:10.3917/popu.403.0521.
- Tappan, G.G., et al., 2016: *West Africa land use land cover time series: U.S. Geological Survey data release*.
- te Beest, M., J. Sitters, C.B. Ménard and J. Olofsson, 2016: Reindeer grazing increases summer albedo by reducing shrub abundance in Arctic tundra. *Environ. Res. Lett.*, **11**(12), 125013, doi:10.1088/1748-9326/aa5128.
- Thébaud, B. and S. Batterbury, 2001: Sahel pastoralists: opportunism, struggle, conflict and negotiation. A case study from eastern Niger. *Glob. Environ. Chang.*, **11**(1), 69–78, doi:10.1016/S0959-3780(00)00046-7.
- Thomas, N. and S. Nigam, 2018: Twentieth-Century Climate Change over Africa: Seasonal Hydroclimate Trends and Sahara Desert Expansion. *J. Climate*, **31**(9), 3349–3370, doi:10.1175/JCLI-D-17-0187.1.
- Thomas, R., et al., 2018: A framework for scaling sustainable land management options. *Land Degrad. Dev.*, **29**(10), 3272–3284, doi:10.1002/ldr.3080.
- Trichon, V., P. Hiernaux, R. Walcker and E. Mougou, 2018: The persistent decline of patterned woody vegetation: the tiger bush in the context of the regional Sahel greening trend. *Glob. Change Biol.*, **24**(6), 2633–2648, doi:10.1111/gcb.14059.
- Tsakiris, G., 2017: Facets of Modern Water Resources Management: Prolegomena. *Water Resour. Manag.*, **31**(10), 2899–2904, doi:10.1007/s11269-017-1742-2.

- Tsymbarovich, P., et al., 2020: Soil erosion: An important indicator for the assessment of land degradation neutrality in Russia. *Int. Soil Water Conserv. Res.*, **8**(4), 418–429, doi:10.1016/j.iswcr.2020.06.002.
- Tucker, C.J. and S.E. Nicholson, 1999: Variations in the size of the Sahara Desert from 1980 to 1997. *Ambio*, 587–591.
- Turner, M., 1993: Overstocking the Range: A Critical Analysis of the Environmental Science of Sahelian Pastoralism. *Econ. Geog.*, **69**(4), 402–421, doi:10.2307/143597.
- Turner, M.D. and P. Hiernaux, 2015: The effects of management history and landscape position on inter-field variation in soil fertility and millet yields in southwestern Niger. *Agric. Ecosyst. Environ.*, **211**, 73–83, doi:10.1016/j.agee.2015.05.010.
- Tyler, N., M. Forchhammer and N. Øritsland, 2008: Nonlinear effects of climate and density in the dynamics of a fluctuating population of reindeer. *Ecology*, **89**, 1675–1686, doi:10.1890/07-0416.1.
- UNCCD, 1994: *Elaboration of an international convention to combat desertification in countries experiencing serious drought and/or desertification, particularly in Africa*. UNCCD, Paris, 1–58.
- UNEP, 1992: *World Atlas of Desertification*. UNEP, ISBN 978-0340555125, London, UK.
- United Nations Educational, Scientific and Cultural Organization, 1979: *Map of the world distribution of arid regions*. UNESCO, Paris.
- Upton, C., 2014: The new politics of pastoralism: Identity, justice and global activism. *Geoforum*, **54**, 207–216, doi:10.1016/j.geoforum.2013.11.011.
- ur Rahman, M.H., et al., 2018: Multi-model projections of future climate and climate change impacts uncertainty assessment for cotton production in Pakistan. *Agric. For. Meteorol.*, **253**, 94–113.
- Vale, C.G. and J.C. Brito, 2015: Desert-adapted species are vulnerable to climate change: Insights from the warmest region on Earth. *Glob. Ecol. Conserv.*, **4**, 369–379, doi:10.1016/j.gecco.2015.07.012.
- Van de Steeg, J. and M. Tibbo, 2012: *Livestock and climate change in the Near East Region: measures to adapt and mitigate climate change Regional Office for the Near East [Corporate Author] RNE [Corporate Author]*. FAO, Cairo (Egypt).
- Vargas-Gastélum, L., et al., 2015: Impact of seasonal changes on fungal diversity of a semi-arid ecosystem revealed by 454 pyrosequencing. *FEMS Microbiol. Ecol.*, **91**(5), doi:10.1093/femsec/fiv044.
- Veldman, J.W., et al., 2019: Comment on “The global tree restoration potential”. *Science*, **366**(6463), eaay7976, doi:10.1126/science.aay7976.
- Veldman, J.W., et al., 2015: Where Tree Planting and Forest Expansion are Bad for Biodiversity and Ecosystem Services. *BioScience*, **65**(10), 1011–1018, doi:10.1093/biosci/biv118.
- Venter, Z.S., M.D. Cramer and H.J. Hawkins, 2018: Drivers of woody plant encroachment over Africa. *Nat. Commun.*, **9**(1), 2272, doi:10.1038/s41467-018-04616-8.
- Verner, 2012: *Adaptation to a Changing Climate in the Arab Countries: A Case for Adaptation Governance and Leadership in Building Climate Resilience*. MENA development report. World Bank, Washington, DC.
- Vidal-González, P. and B. Nahass, 2018: The use of mobile phones as a survival strategy amongst nomadic populations in the Oriental region (Morocco). *GeoJournal*, **83**(5), 1079–1090, doi:10.1007/s10708-017-9823-6.
- Vincke, C., I. Diedhiou and M. Grouzis, 2010: Long term dynamics and structure of woody vegetation in the Ferlo (Senegal). *J. Arid Environ.*, **74**, 268–276, doi:10.1016/j.jaridenv.2009.08.006.
- von Uexkull, N., M. Croicu, H. Fjelde and H. Buhaug, 2016: Civil conflict sensitivity to growing-season drought. *Proc. Natl. Acad. Sci. U. S. A.*, **113**(44), 12391–12396, doi:10.1073/pnas.1607542113.
- Wang, D.W., T.C. Gouhier, B.A. Menge and A.R. Ganguly, 2015: Intensification and spatial homogenization of coastal upwelling under climate change. *Nature*, **518**(7539), 390–394, doi:10.1038/nature14235.
- Wang, S., et al., 2020: Recent global decline of CO<sub>2</sub> fertilization effects on vegetation photosynthesis. *Science*, **370**(6522), 1295–1300.
- Wang, X., T. Hua, L. Lang and W. Ma, 2017: Spatial differences of aeolian desertification responses to climate in arid Asia. *Glob. Planet. Change.*, **148**, 22–28.
- Wang, Y., X. Yan and Z. Wang, 2016: A preliminary study to investigate the biogeophysical impact of desertification on climate based on different latitudinal bands. *Int. J. Climatol.*, **36**(2), 945–955, doi:10.1002/joc.4396.
- Ward, D., M.T. Hoffman and S.J. Collocott, 2014: A century of woody plant encroachment in the dry Kimberley savanna of South Africa. *African J. Range Forage Sci.*, **31**(2), 107–121, doi:10.2989/10220119.2014.914974.
- Warner, K., 2010: Global environmental change and migration: Governance challenges. *Glob. Environ. Chang.*, **20**(3), 402–413, doi:10.1016/j.gloenvcha.2009.12.001.
- Wassmann, R., et al., 2009: Chapter 3 Regional Vulnerability of Climate Change Impacts on Asian Rice Production and Scope for Adaptation. In: *Advances in Agronomy*. DOI: 10.1016/S0065-2113(09)01003-7, Academic Press, pp. 91–133. ISBN 00652113., Massachusetts, USA
- Webb, N.P. and C. Pierre, 2018: Quantifying Anthropogenic Dust Emissions. *Earths Future*, **6**(2), 286–295, doi:10.1002/2017ef000766.
- Weldemichel, T.G. and H. Lein, 2019: “Fencing is our last stronghold before we lose it all.” A political ecology of fencing around the Maasai Mara National Reserve, Kenya. *Land Use Policy*, **87**, 104075, doi:10.1016/j.landusepol.2019.104075.
- Wendling, V., et al., 2019: Drought-induced regime shift and resilience of a Sahelian ecohydrosystem. *Environ. Res. Lett.*, **14**(10), 105005, doi:10.1088/1748-9326/ab3dde.
- Weston, P., R. Hong, C. Kaboré and C.A. Kull, 2015: Farmer-Managed Natural Regeneration Enhances Rural Livelihoods in Dryland West Africa. *Environ. Manage.*, **55**(6), 1402–1417, doi:10.1007/s00267-015-0469-1.
- Wezel, A. and A.M. Lykke, 2006: Woody vegetation change in Sahelian West Africa: evidence from local knowledge. *Environ. Dev. Sustain.*, **8**(4), 553–567, doi:10.1007/s10668-006-9055-2.
- Wieriks, K. and N. Vlaanderen, 2015: Water-related disaster risk reduction: time for preventive action! Position paper of the High Level Experts and Leaders Panel (HELP) on water and disasters. *Water Policy*, **17**(S1), 212–219, doi:10.2166/wp.2015.011.
- Wilhite, D.A., 2019: Integrated drought management: moving from managing disasters to managing risk in the Mediterranean region. *Eur. Mediterr. J. Environ. Integr.*, **4**(1), 42, doi:10.1007/s41207-019-0131-z.
- Wilhite, D.A. and R.S. Pulwarty, 2018: *Drought and Water Crises: Integrating Science, Management, and Policy*, 2nd edn., CRC Press, ISBN 978-1138035645., Florida, USA.
- Williams, A.P., et al., 2020: Large contribution from anthropogenic warming to an emerging North American megadrought. *science*, **368**(6488), 314–318.
- Winter, J.M., P.J.-F. Yeh, X. Fu and E.A.B. Eltahir, 2015: Uncertainty in modeled and observed climate change impacts on American Midwest hydrology. *Water Resour. Res.*, **51**(5), 3635–3646, doi:10.1002/2014wr016056.
- Wu, M., et al., 2016: Vegetation–climate feedbacks modulate rainfall patterns in Africa under future climate change. *Earth Syst. Dynam.*, **7**(3), 627–647, doi:10.5194/esd-7-627-2016.
- Xu, L., N. Chen and X. Zhang, 2019: Global drought trends under 1.5 and 2 C warming. *Int. J. Climatol.*, **39**(4), 2375–2385.
- Yu, Y., et al., 2017: Observed positive vegetation-rainfall feedbacks in the Sahel dominated by a moisture recycling mechanism. *Nat. Commun.*, **8**(1), 1873, doi:10.1038/s41467-017-02021-1.
- Yuan, W., et al., 2019: Increased atmospheric vapor pressure deficit reduces global vegetation growth. *Sci. Adv.*, **5**(8), eaax1396, doi:10.1126/sciadv.aax1396.
- Yusa, A., et al., 2015: Climate Change, Drought and Human Health in Canada. *Int. J. Environ. Res. Public Health*, **12**(7), 8359–8412, doi:10.3390/ijerph120708359.
- Zeweld, W., et al., 2018: Impacts of Socio-Psychological Factors on Actual Adoption of Sustainable Land Management Practices in Dryland and Water Stressed Areas. *Sustainability*, **10**(9), 2963.



- Zhang, C., X. Wang, J. Li and T. Hua, 2020: Identifying the effect of climate change on desertification in northern China via trend analysis of potential evapotranspiration and precipitation. *Ecol. Indic.*, **112**, 106141, doi:10.1016/j.ecolind.2020.106141.
- Zhang, R., L. Xie and Z. Yan, 2019: Ecological study on biomineralization in *Pinctada fucata*. In: *Biomineralization Mechanism of the Pearl Oyster, Pinctada fucata* [Zhang, R., L. Xie and Z. Yan(eds.)]. Springer, Singapore, pp. 661–694. ISBN 978-9811314599.
- Zhang, W., et al., 2018: Impacts of the seasonal distribution of rainfall on vegetation productivity across the Sahel. *Biogeosciences*, **15**(1), 319–330, doi:10.5194/bg-15-319-2018.
- Zhang, X., et al., 2007: Detection of human influence on twentieth-century precipitation trends. *Nature*, **448**(7152), 461–465, doi:10.1038/nature06025.
- Zhao, T. and A. Dai, 2015: The Magnitude and Causes of Global Drought Changes in the Twenty-First Century under a Low–Moderate Emissions Scenario. *J. Climate*, **28**(11), 4490–4512, doi:10.1175/jcli-d-14-00363.1.
- Zhao, Y., et al., 2015: Estimating heat stress from climate-based indicators: present-day biases and future spreads in the CMIP5 global climate model ensemble. *Environ. Res. Lett.*, **10**, 84013, doi:10.1088/1748-9326/10/8/084013.
- Zhou, S., et al., 2019: Land–atmosphere feedbacks exacerbate concurrent soil drought and atmospheric aridity. *Proc. Natl. Acad. Sci.*, **116**(38), 18848, doi:10.1073/pnas.1904955116.
- Zhu, T., et al., 2013: Climate change impacts and adaptation options for water and food in Pakistan: scenario analysis using an integrated global water and food projections model. *Water Int.*, **38**(5), 651–669, doi:10.1080/02508060.2013.830682.
- Zida, W.A., B.A. Bationo and J.-P. Waaub, 2020: Re-greening of agrosystems in the Burkina Faso Sahel: greater drought resilience but falling woody plant diversity. *Envir. Conserv.*, **47**(3), 174–181, doi:10.1017/S037689292000017X.
- Zida, W.A., B.A. Bationo and J.-P. Waaub, 2020b: Re-greening of agrosystems in the Burkina Faso Sahel: greater drought resilience but falling woody plant diversity. *Envir. Conserv.*, **47**(3), 174–181, doi:10.1017/S037689292000017X.
- Zida, W.A., F. Traoré, B.A. Bationo and J.-P. Waaub, 2020a: Dynamics of woody plant cover in the Sahelian agroecosystems of the northern region of Burkina Faso since the 1970s–1980s droughts. *Can. J. For. Res.*, **50**(7), 659–669, doi:10.1139/cjfr-2019-0247.
- Zwarts, L., R.G. Bijlsma and J. van der Kamp, 2018: Large decline of birds in Sahelian rangelands due to loss of woody cover and soil seed bank. *J. Arid Environ.*, **155**, 1–15, doi:10.1016/j.jaridenv.2018.01.013.



