Advances in Water Resources 51 (2013) 326–344

Contents lists available at SciVerse ScienceDirect

Advances in Water Resources

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

Global desertification: Drivers and feedbacks

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ARTICLE INFO

Article history:
Available online 13 February 2012

Keywords:
Desertification
Land degradation
Ecohydrology
Feedbacks
Overgrazing
Soil salinity

ABSTRACT

Desertification is a change in soil properties, vegetation or climate, which results in a persistent loss of ecosystem services that are fundamental to sustaining life. Desertification affects large dryland areas around the world and is a major cause of stress in human societies. Here we review recent research on the drivers, feedbacks, and impacts of desertification. A multidisciplinary approach to understanding the drivers and feedbacks of global desertification is motivated by our increasing need to improve global food production and to sustainably manage ecosystems in the context of climate change. Classic desertification theories look at this process as a transition between stable states in bistable ecosystem dynamics. Climate change (i.e., aridification) and land use dynamics are the major drivers of an ecosystem shift to a "desertified" (or "degraded") state. This shift is typically sustained by positive feedbacks, which stabilize the system in the new state. Desertification feedbacks may involve land degradation processes (e.g., nutrient loss or salinization), changes in rainfall regime resulting from land-atmosphere interactions (e.g., precipitation recycling, dust emissions), or changes in plant community composition (e.g., shrub encroachment, decrease in vegetation cover). We analyze each of these feedback mechanisms and discuss their possible enhancement by interactions with socio-economic drivers. Large scale effects of desertification include the emigration of "environmental refugees" displaced from degraded areas, climatic changes, and the alteration of global biogeochemical cycles resulting from the emission and long-range transport of fine mineral dust. Recent research has identified some possible early warning signs of desertification, which can be used as indicators of resilience loss and imminent shift to desert-like conditions. We conclude with a brief discussion on some desertification control strategies implemented in different regions around the world.

1. Introduction

Many dryland regions around the world are affected by rapid change in vegetation cover, plant community composition, hydrologic conditions, or soil properties, which results in an overall loss of ecosystem services and poses serious threats to sustainable livelihoods. The process underlying these changes is often termed "desertification". Depending on the driver and the geographic setting, desertification can result in an increase in bare soil (up to complete denudation of the soil surface), loss of soil resources (e.g., loss of nutrients, fine soil grains, and water holding capacity), increase in soil salinity and toxicity [119,169], or shifts in vegetation composition (e.g., from perennial to annual species, from palatable to unpalatable grasses, or from grassland to shrubland [187,205,215,224]). Desertification is commonly associated with changes that persist for several decades and are presumably permanent and irreversible, at least within the time scales of a few human generations.

The term "desertification" was first used by Lavauden [107] in the context of low rangeland productivity in poorly managed land in Tunisia [56]. However, this term is more commonly credited to Aubréville [11], who noted that forest clearing in West Africa caused erosion and land deterioration or "desertification". In both cases "desertification" was used to denote the outcome of a process of land degradation induced by human action and poor land management. Since then, several authors and agencies have provided their own definition of the problem. This has led in some cases to a sterile exercise that produced a myriad of definitions and generated confusion [228].

The United Nations adopted the definition of desertification as "land degradation in arid, semi-arid and dry subhumid areas resulting from various factors, including climatic variations and human activities" [220]. Thus, the major difference with the earlier statements is that desertification can also result from climate change and not only from land mismanagement. The same definition was adopted by the Millennium Ecosystem Assessment [121]

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http://dx.doi.org/10.1016/j.advwatres.2012.01.013

with the clarification that "land degradation is in turn defined as the reduction or loss of biological or economic productivity of drylands". However, land degradation is not necessarily associated with a loss of ecosystem productivity. In Section 4.3 we will present some forms of desertification that may actually involve an increase in ecosystem productivity. The idea that desertification is associated with a persistent decrease in productivity contributes to the confusion existing around the issue of desertification and land degradation.

In recent years, the notion of desertification has been related to losses of ecosystem services resulting from the effect of anthropogenic disturbances and/or climate variations in dryland ecosystems. From this perspective desertification would be "a persistent reduction in the capacity of ecosystems to supply services… over extended periods" [121], and it would be "a result of long-term failure to balance demand and supply of ecosystem services in drylands" [121]. The major services rendered by dryland ecosystems are food security, carbon sequestration, supply of forage, fibers, wood and freshwater, maintenance of biodiversity, in addition to the recreational, cultural, and esthetic value of non-degraded dryland environments.

The view emerging from this discussion is that desertification is currently considered as the loss of the ability of a landscape to provide ecosystem services that are important to sustain life. It may result in a loss of biological and/or economic productivity, and in most cases it involves a persistent increase in bare soil at the expense of vegetation cover. Desertification does not necessarily occur at the desert margins: even dryland areas that are not at the edges of existing deserts may be prone to desertification [55].

In this paper we review some of the major mechanisms of desertification reported in different areas around the world. After a brief review of dryland hydrogeography and of current patterns of desertification (Sections 2 and 3), we analyze in detail theories of desertification based on the framework of bistable ecosystem dynamics (Section 4). Thus, we review the main feedback mechanisms of desertification (Section 4) and consider the major drivers of desertification, including climate change (Section 5), societal drivers (Section 6), soil salinization (Section 7) and rangeland degradation around watering points (Sections 8). We then discuss some environmental and human impacts of desertification (Sections 9 and 10). Because desertification may occur as a relatively abrupt process, land managers need some indicators of resilience loss and of the likelihood of an imminent shift to the desertified state. Therefore, we review some of the indicators that can be used as early warning signs of desertification (Section 11). Finally, we discuss some biophysical and socioeconomic measures for desertification mitigation and remediation (Section 12).

2. Hydrogeography of drylands

Drylands cover about 41% of the Earth's land surface and are home to about 35% of the global population [121]. Fig. 1a shows

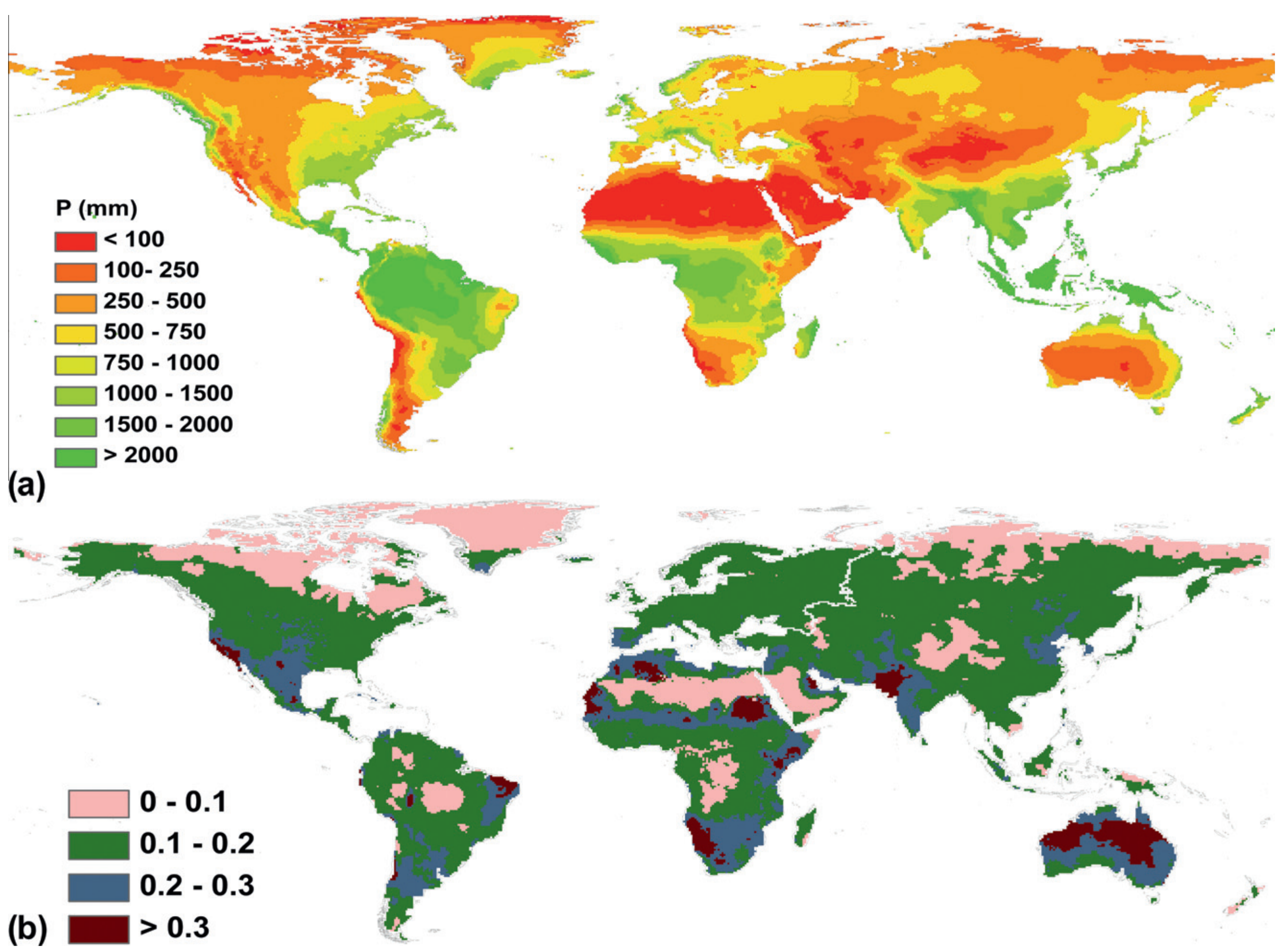

Fig. 1. (a) Global mean precipitation. (b) Coefficient of variation (NA refers to areas where no data were available). Based on the CRU TS 3.1 data, a gridded data set developed by the Tyndall Centre for Climate Change Research and the Climate Research Unit (CRU) of the University of West Anglia [125] interpolating station data with the anomaly approach [138,139]. The maps are based on data for the period 1901–2009, calculated for 0.5° by 0.5° grid.

Table 1
Typical classification of drylands on the basis of mean annual precipitation (MAP) or Aridity Index (AI = PET/P).

Climatic zone	MAP (mm yr^{-1})	AI
Hyper-Arid	<100	>12
Arid	100–250	5–12
Semiarid	250–600	2–5
Dry subhumid	600–1200	0.75–2

the global distribution of mean annual precipitation for the period 1901–2009, based on interpolated gridded rain gauge data [125]. We notice that regions with low mean annual precipitation are typically located in areas characterized by (i) *continentality*, i.e. distance from seas and oceans, which are major sources of atmospheric moisture (e.g., the Gobi desert in China); (ii) *rain shadow*, i.e., the location on the leeward side of mountain chains (e.g., the Mojave desert, in North America); (iii) *latitude*, i.e., the location in tropical regions dominated by air mass divergence associated with the patterns of the Hadley and Farrel circulations (e.g., the Sahara and Arabian deserts; the drylands of Australia and Patagonia); (iv) *proximity to cold ocean surfaces*, i.e., the location on western continental margins, in areas characterized by the persistence of air subsidence induced by a nearby cold ocean surface associated with the upwelling of deep oceanic waters (the Namib desert in Southern Africa and Atacama deserts in South America).

While rainfall is often used as an indicator of aridity (Table 1), from an ecohydrological perspective climatic conditions are better expressed in terms of water availability to plants and other organisms. Thus, the soil water content is a more representative indicator of water limitation in dryland systems. Soil moisture conditions depend on precipitation input, evapotranspirational losses, and soil properties. Thus, drylands are often defined as areas where precipitation (P) is smaller than potential evapotranspiration (PET) for most of the year. Known as *Aridity Index*, the PET/P ratio expresses the *aridity* or *dryness* of a climatic zone ([8,23]; see also Table 1). Low aridity indices during the growing season indicate the occurrence of water deficit conditions for dryland vegetation.

Dryland climates are also characterized by strong seasonal and interannual variability. Seasonal variability is typically associated with the presence of distinct dry and wet seasons, with most precipitation falling in a few wet months followed by a rainless season. This sequence of dry and wet seasons is particularly apparent in tropical drylands, where rainfall occurrence is associated with a seasonal (summertime) displacement of the Intertropical Convergence Zone (ITCZ) from the equator towards the tropics. Due to rainfall seasonality and the existence of long dry seasons, some areas of the world face conditions of limited water availability for ecosystems and societies despite their relatively high rainfall values.

Interannual rainfall variability is a recurrent feature of dryland climates and becomes particularly strong in arid regions. Fig. 1b shows a global map of the coefficient of variation (CV) of annual precipitation. We observe that areas with the strongest interannual variability of precipitation are either drylands or desert margins. While at the center of major deserts, rainfall variability is either very low – due to permanent high pressure conditions – or difficult to estimate – due to lack of rainfall measurements – most drylands exhibit a strong interannual variability of precipitation, which is mostly due to year-to-year fluctuations in the number of rainfall events rather than to variability in their magnitude (e.g., [42]). Fig. 2 shows in particular the CV of precipitation calculated using rainfall records along three major rainfall gradients on Earth. It is observed that rainfall variability increases as the mean annual precipitation decreases, consistently with the global pattern shown in Fig. 1b. Interannual climate variability determines the occurrence, duration and intensity of drought conditions.

3. Global distribution of areas affected by desertification

Drylands support a population of over 2 billion people, 90% of which live in developing countries. Some of these regions are food insecure, characterized by lowest levels of human well being [121], and prone to accelerated desertification, which puts further pressure on human societies. It has been estimated that dryland degradation costs developing countries 4–8% of their National Gross Domestic Product [219] and that a relatively large fraction of dryland population (about 135 million people in 1995 [108]) is at risk of episodic mass starvation due to land degradation.

It is estimated that desertification affects one-quarter of the world's land surface, containing one-fifth of the world's population (UNCCD). However the extent of the problem remains poorly understood [171,221,230,254]. Quantifying the extent and rate of global desertification is motivated by the increasing need to estimate long-term changes in soil productivity and global food security, assess the economic cost of soil erosion and sustainable crop production, evaluate land conservation and reclamation programs, determine the rate of suspension of dust into the atmosphere and its contribution to tropospheric aerosols, and analyze the effect of climate change scenarios on land degradation.

Estimates of areas affected by desertification show huge variations, depending on the definitions applied and methodologies used in the evaluation of land degradation [182,222,230]. Desertification is the outcome of complex interactions between biophysical and human factors, which may vary over a wide range of spatial and temporal scales, and quantifying these factors is extremely challenging [121]. Moreover, the causes and consequences of desertification are widely debated, and no consensus has been

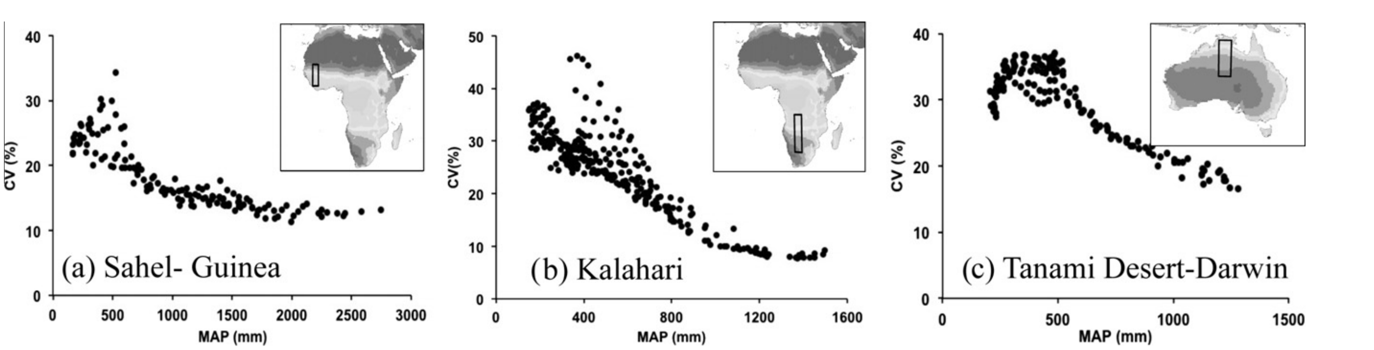

Fig. 2. Coefficient of variation of precipitation (i.e., standard deviation/mean) along the Sahel-Guinea, Kalahari, and the Simpson/Tanami Desert-Darwin rainfall gradients, based on the CRU TS 3.1 gridded data (see Fig. 1). The exact location of the transects is shown in the insets. Notice how the CV values calculated from gridded are lower than those from point measurements (see Nicholson [141]) because of the decrease in variability associated with spatial averaging.

established on adequate methods for monitoring and assessment [71,121,227].

The lack of a clear definition of desertification and of standardized techniques to measure its causes and consequences results in different estimates of its spatial extent [182,230]. Based on a comprehensive and widely used assessment of global land degradation, the Global Assessment of Human Induced Land Degradation (GLASOD) estimated that land degradation affects about 20% of dryland areas [150,254]. Some studies have indicated 10–20% (of total dryland area) as the plausible extent of dryland degradation [121,227]. However, other authors have reported different estimates ranging from 10% [109], 38% [112], 64% [54], and 71% [53], with Africa and Asia being regions of particular concern. Even though some of these figures may overestimate the real extent of the problem [109], there is a general consensus that desertification is happening at an alarming pace, contributing to the depletion of soil resources in arid and semiarid rangelands and cultivated land ([53,54,171].

4. Biophysical feedbacks of desertification

The definitions given in the previous sections indicate that desertification is caused both by climatic variations and human activities. In many cases the initial effects of human activities and aridification are sustained by some positive feedbacks between biotic and abiotic processes. These feedbacks drive the system into a downward spiral of environmental degradation and often limit the ability of the system to recover its initial state.

The relatively rapid pace of the desertification process observed in many regions around the world suggests that desertification is associated with a transition between the two stable states in bistable ecosystem dynamics. In the context of desertification theories, the two stable states would correspond to a vegetated (or "non degraded") state and an un-vegetated (or "degraded") state [36,146,149,175,232,233,240]. In other words, both the "desertified" and the vegetated states would be stable configurations of the system (Fig. 3). This means that, if a perturbation causes a transition to the desertified state, the removal of this disturbance would not necessarily allow the system to spontaneously return back to its initial configuration. Thus, when compared with systems having only one stable state (Fig. 3b), the states of bistable systems have only a limited resilience [92]; if disturbed beyond a critical threshold (e.g., by reducing the vegetation cover) these systems move toward the alternative stable state of degraded land (e.g., [234]). At that point, it would be difficult for the system to revert back to its initial state (Fig. 3b). This view of desertification is consistent with its presumable irreversibility.

The emergence of bistable dynamics is typically induced by positive feedbacks (e.g., [243]). Thus, it has been argued that the desertification process can be sustained by interactions between the biota and the physical environment. According to this classic view of desertification, an initial loss of vegetation cover triggers a self-reinforced sequence of processes that further favors a decrease in plant cover (Fig. 3c). The ability of such feedbacks to induce bistability in ecosystem dynamics has been shown by a number of minimalist process based models accounting for the impact of vegetation on rainfall regime [21,236], soil moisture [36,175], soil salinity [181], fire dynamics ([4,41], and soil erosion [146,149]. In most cases vegetation dynamics were modeled with a growth function – typically a logistic – with state dependent parameters (e.g., the carrying capacity) to account for the effect of the feedback between vegetation and its limiting resources or disturbance regime. While the standard logistic growth has only one stable state (i.e., when the system is at carrying capacity), the feedback introduces further non-linearities in the process, which can lead to the emergence of an alternative stable state (e.g., [36]).

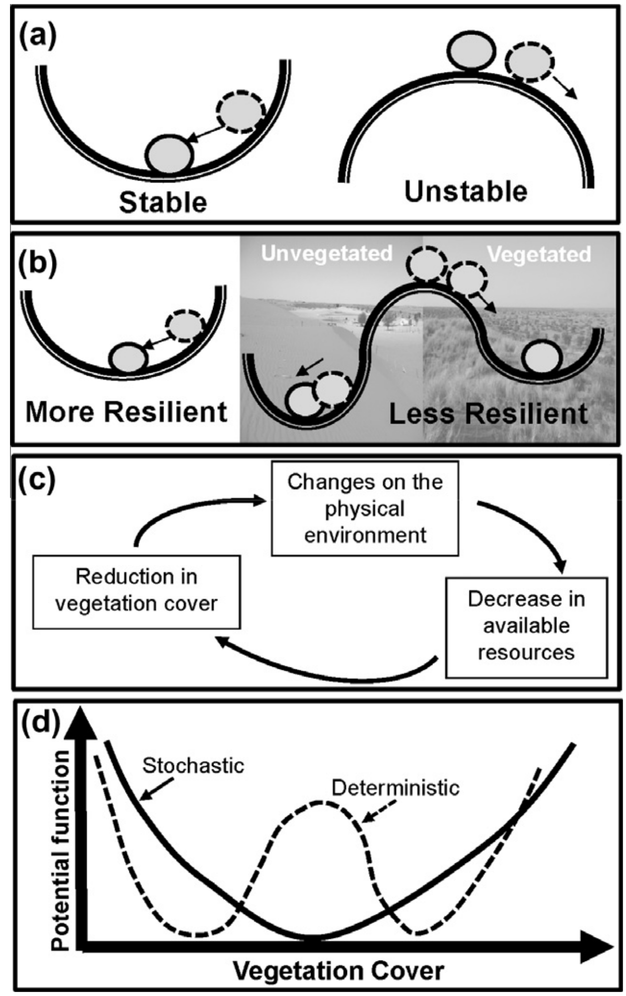

Fig. 3. Ecosystem stability and resilience. (A) A state is *stable* if, when displaced from that state, the system tends to return back to it; (B) *resilience* is an attribute of a stable state, which expresses ability of the system to recover that configuration after perturbation. Desertification is often considered as a transition to an alternative stable state in bistable ecosystem dynamics; (C) schematic representation of the typical *desertification feedbacks*; (D) "stabilizing" effect of external fluctuations: random environmental fluctuations can turn bistable deterministic dynamics into a system with only one stable state (Section 4.2).

A variety of feedback mechanisms have been invoked by a number of desertification theories. These mechanisms typically involve processes responsible for (i) changes in soil properties and land degradation; (ii) the coupling between vegetation and climate; or (iii) shifts in plant community composition.

4.1. Land degradation feedbacks

Land degradation feedbacks are typically associated with the loss of soil resources resulting from an initial reduction in vegetation cover (Fig. 4, bottom loop). Three major processes may be responsible for land degradation and loss of soil fertility: (a) the removal of nutrient-rich soil particles resulting from wind and water erosion; (b) the decrease in soil water content associated with soil compaction, decrease in soil permeability or loss of water holding capacity; or (c) the accumulation of salts and other toxic substances, which prevent vegetation re-establishment and growth.

4.1.1. Soil erosion

Soils support (directly or indirectly) most forms of life on Earth, and the loss of soil resources, accelerated by the development of agriculture and livestock grazing, has historically threatened food security and induced the collapse of some societies [50,127]. Thus, even ancient civilizations had to face environmental problems associated with loss of soil fertility resulting from the conversion of natural ecosystems into croplands or rangelands (e.g., [50,165]). A well documented case of land degradation in the modern world is associated with the development of agriculture and intensive livestock production in the Southern Great Plains of North America. In this region, land use in conjunction with drought conditions triggered major erosion events during the 1930s that led to the loss of soil resources and dramatic dust storms. To prevent further soil losses and dust storms, this region – now known as "the Dust Bowl" – has been the focus of major soil conservation practices, including the implementation of the Conservation Reserve Program (CPR). With this program, the U.S. government provided incentives to encourage farmers to convert highly erodible cropland to grassland (e.g., [223]).

Desertification problems caused by the development or intensification of agriculture are a recurrent problem in drylands. It has been reported that about 44% of global agricultural areas are located within drylands and about 15% of drylands previously used for pasture has been converted to cropland within the first half of the 20th century [121]. This conversion typically results in overgrazing of the remaining marginal lands. Moreover, intensive agriculture favors soil erosion and nutrient loss, especially when nutrients exported in harvested crops exceed those provided by atmospheric deposition, fixation, or supplied as fertilizers [228]. Land degradation is affecting extensive areas of sub-Saharan Africa [1]), Australia [70,217], the southwestern USA [24,187,224], South America [120], and Asia [253].

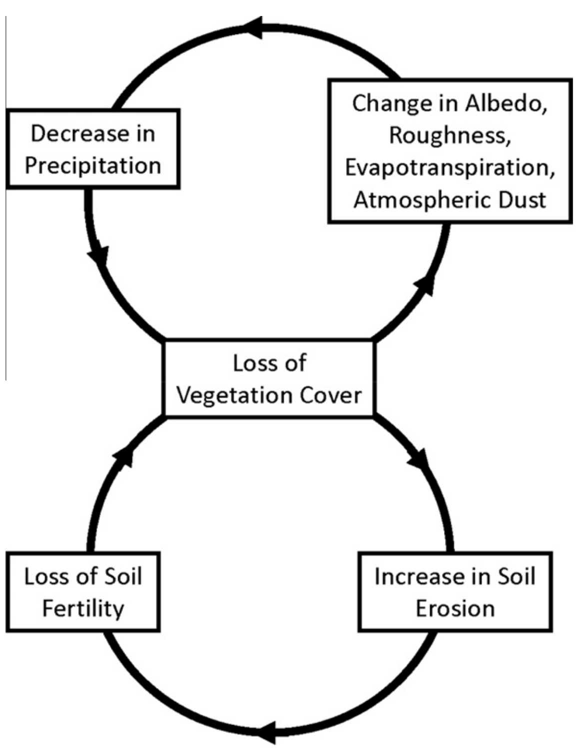

Fig. 4. Examples of desertification feedbacks. Bottom loop: the typical land degradation feedback. The exposure of the soil surface to wind and water erosion causes substantial losses of soil nutrients thereby preventing the re-establishment of vegetation (e.g., [29,187]). This type of feedback invokes the ability of vegetation to stabilize the soil surface as the mechanism that allows the system to persist either in a vegetated or in a bare soil state. Top loop: vegetation-atmosphere feedbacks.

4.1.2. Decrease in soil moisture

Other land degradation mechanisms involve losses of soil water instead of nutrients. For example, changes in soil texture and loss of water holding capacity may result from erosional losses of fine soil particles. Alternatively, land degradation may involve interactions with biotic processes, as in the case of soil moisture-vegetation feedbacks [36,77,212]. In this case, plant cover increases soil infiltration capacity or decreases evaporation from the shallow soil [188], thereby maintaining higher soil water contents under the canopy than in intercanopy areas. In both cases, the loss of vegetation cover would be associated with losses of soil water and the inability for plants to re-establish. Thus, systems affected by these feedbacks have low resilience and are susceptible to abrupt shifts to a "desertified" or degraded state [176,232]. It has been found that the strength of this feedback increases with decreasing mean annual rainfall [36].

4.1.3. Soil salinization

Loss of soil productivity may result from an increase in soil salinity, and interesting feedbacks have been documented between changes in vegetation composition, water table dynamics and salt accumulation [181]. In fact, it has been reported that in some regions the clearcutting of native vegetation and its replacement with cropland has led to a water table rise thereby enhancing soil evaporation and salt deposition [234]. Mechanisms of desertification associated with salt accumulation will be discussed in detail in Section 7.

4.2. Vegetation-climate feedbacks

Some of the early studies on desertification feedbacks were carried out by atmospheric scientists, who investigated how changes in vegetation cover associated with desertification may modify surface energy fluxes and the water balance with important implications on rainfall regime, soil moisture dynamics, and vegetation. Changes in land cover may reduce or suppress precipitation, thereby preventing vegetation re-establishment and growth (Fig. 4, top loop). The idea that a decrease in vegetation causes a reduction in precipitation can be found in the diaries of navigators and naturalists from the XVI–XVIII centuries [19]. However, quantitative studies of positive feedbacks between vegetation and precipitation became feasible only in recent times with the advent of coupled land-atmosphere models, remote sensing observations, and field measurements (e.g., [6,30,69,194,206,207]). There are three major feedback mechanisms between vegetation and precipitation. These mechanisms are associated with changes in (1) precipitation recycling (e.g., [61]), (2) surface energy balance [30,194,236,247]; and (3) dust emissions from arid landscapes [142,179].

The first type of feedback is induced by precipitation recycling, which is typically defined as the fraction of precipitation that in a certain region is contributed by moisture coming from regional evapotranspiration (e.g., [61,185,218]). Thus, a decrease in evapotranspiration induced by vegetation loss is expected to cause a decrease in precipitation recycling. This effect may lead to a positive feedback of desertification if precipitation recycling is a substantial fraction of total precipitation. To this end, a number of authors have quantified precipitation recycling using a variety of methods, including regional water balances, back-trajectory algorithms, and isotope geochemistry [51,143,183,225]. These analyses have shown that recycling – e.g., in the range 10–35%, depending on the region and its size [61] – can be important in continental regions.

The second type of feedback is due to the ability of vegetation cover to modify some surface attributes that are crucial in determining the rate of surface energy fluxes. These attributes include albedo, roughness, soil moisture, and rooting depth. The effect of vegetation on the surface energy balance was initially associated with the ability of plant cover to modify the albedo. Charney [30] noted that vegetation removal at the desert margins (e.g., the Sahel) causes an increase in land surface albedo, which, in turn, may determine surface cooling, atmospheric subsidence, and a decrease in convective precipitation. Subsequent studies built upon Charney's [30] work and highlighted some possible weaknesses. For example, it was observed that loss of vegetation cover is typically associated with changes in albedo that are much weaker than those assumed by Charney [30]; moreover areas affected by land degradation tend to exhibit an increase rather than a decrease in surface temperatures [14,15,176,245]. Soil moisture-precipitation feedbacks have been investigated both with model simulations, and data analyses [2,43,65,177,194,206]. These studies have shown that moister land surface conditions enhance precipitation, thereby maintaining a wetter soil. Thus, an initial anomaly in precipitation would be sustained by this feedback with soil moisture. Soil moisture may affect precipitation both by enhancing recycling and by modifying the surface energy balance. Through its impact on albedo and on the partitioning of the incoming solar radiation into latent and sensible heat fluxes, soil moisture affects the thickness, temperature and stability of the boundary layer, thereby providing conditions favorable for the triggering of deep convection (e.g., [62,66]). However, model simulations have shown that the sign and intensity of these feedbacks depend on the geographic location (e.g., [66]); in some cases, wetter soil surfaces may induce surface cooling and even enhance subsidence and inhibit precipitation [34]. Moreover, it has been observed that this feedback would not be able to maintain the system locked in either a dry or a wet state over time scales longer than a year. In fact, dryland soils would likely become dry during the dry season regardless of whether the rainy season has been wetter or drier than average [142]. Thus, because of the existence of a distinct dry (i.e., rainless) season, the memory of the system is reset every year, and the feedback is unable to lock the dynamics in a dry state for longer time scales.

The roughness-precipitation feedback has been investigated mostly with model simulations, which showed how the decrease in roughness associated with vegetation removal may cause a decrease in moisture convergence, thereby reducing precipitation [202]. Coupled vegetation-climate models accounting for these three feedbacks (albedo, soil moisture, and roughness) show an increase in precipitation with increasing vegetation cover (e.g., [52,69,105,236,244,246,247,249]). Most of these studies focused on desertification in the Sahel-Sahara and the Mongolia-Inner Mongolia regions (see [245] for a review). In some cases the feedback can be strong enough to induce the emergence of alternative stable states in the coupled vegetation-climate dynamics (e.g., [235,236,250]), suggesting that these regions are prone to abrupt and possibly irreversible shifts to a desertified state.

Interestingly, it has been shown that the interannual variability of "external" drivers (e.g., sea surface temperatures) may destroy this bistability and stabilize the system in an intermediate state between desert and vegetated conditions [250]. These results suggest that random environmental fluctuations may turn bistable dynamics into a system with only one stable state (Fig. 3d), thereby enhancing ecosystem resilience [17,39].

Models of atmosphere–biosphere interaction have also been used to investigate how a complete vegetation removal from the Earth planet would result in a weakening of the global water cycle with a global decrease both in evapotranspiration and in precipitation [69]. However, this change in climate would not be strong enough to prevent plant re-establishment and growth in all regions of the world. Thus, atmosphere–biosphere interactions do not seem to make the Earth planet susceptible to an irreversible shift to a globally desertified state.

Coupled vegetation-climate models have been used also to investigate past desertification events, such as the decline of the "green Sahara" in the mid-Holocene [49,155]. This research has shed light on the processes underlying the transition of this region from a vegetated to a desert state at the end of the Sahara's humid period, about 5500 years ago [21,33,105,209,210]. Model simulations contributed to the assessment of the possible stability vs. bistability of the system under current and mid-Holocene Earth's orbital conditions [21] and to show how adequate levels of environmental stochasticity may stabilize bistable systems in an intermediate state between the two stable deterministic equilibria [17].

The third type of land-atmosphere feedback involves dust emissions and is based on the effect of mineral aerosols on incoming and outgoing radiation, cloud microphysics and precipitation [123]. Loss of vegetation cover causes an intensification of dust emissions (e.g., [160]), which, in turn, may cause a reduction of precipitation and thereby impede plant establishment and growth. Dust aerosols exert a direct radiative forcing on climate. Their effect is to cause surface cooling [101,114,159], which in turn induces subsidence and reduces precipitation in dust-rich desert areas [248]. Model simulations accounting for this direct radiative forcing showed the occurrence of lower than average precipitation in the Northern Hemisphere in the high-dust decade (1980–1989) of the XX century. This lower precipitation is consistent with global estimates of the Palmer Drought Severity Index [44]. In addition to this direct radiative forcing, atmospheric dust also has two indirect effects associated with the interaction of dust with cloud microphysics. In fact, finer fractions of dust aerosols may serve as cloud condensation nuclei (CCNs). An excess in the availability of CCNs may cause a very inefficient condensation, which leads to the formation of cloud droplets that are too small to precipitate. Thus, clouds persist longer. This increase in cloudiness further contributes to surface cooling, which in turn enhances subsidence (first indirect radiative forcing); moreover, inefficient nucleation suppresses precipitation (second indirect effect). In addition, dust loadings appear to have an effect on surface winds with interesting (positive or negative) feedbacks on dust emissions [84]. Using rainfall records from the Sahel, Hui et al. [94] showed the existence of an inverse relation between precipitation and dust levels. These results confirm earlier studies on the contribution of desert dust to the Sahelian drought [142,248] and support the hypothesis of a positive desertification feedback associated with the direct and indirect radiative forcings of desert dust [179].

4.3. Feedbacks involving shifts in plant community composition

The interactions between physical and biotic processes resulting from the disturbance of native vegetation – in conjunction with large scale forcings, such as climate change, nitrogen deposition or atmospheric CO_2 enrichment – may alter vegetation composition and structure. A notable example is the encroachment of shrub species into grasslands at the expense of grass cover (e.g., [41,224]). Shrub encroachment is a widespread phenomenon that can be found in many drylands around the world [161,224]. It typically occurs with an increase in bare soil areas [13,93,187] and an increase in the rates of wind and water erosion.

Wind erosion plays a crucial role in determining vegetation structure and soil resource heterogeneity in shrub-encroached landscapes [147]. In fact, it removes soil resources from bare soil areas and deposits them in soil patches covered by shrubs. This process leads to the formation of a heterogeneous landscape with a mosaic of nutrient rich soil patches – known as "fertility islands"

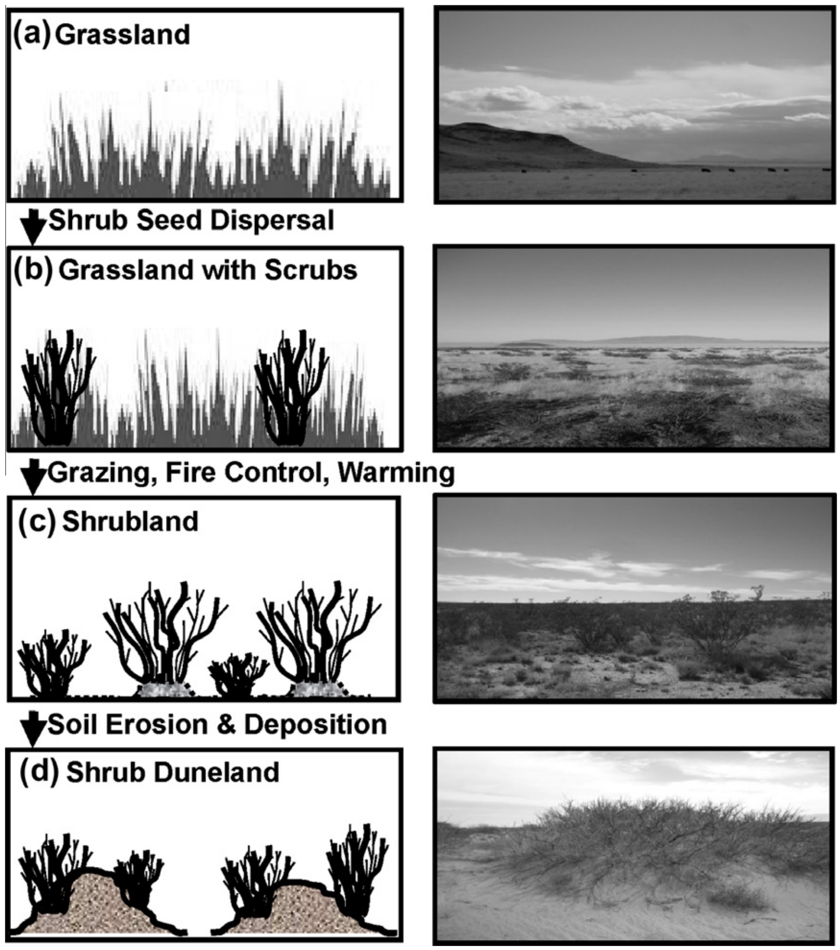

Fig. 5. Conceptual representation of stages of the shrub encroachment process reported in the southwestern US [41,146,149,164]. The initial state of the system is typically a grassland with only a few scattered shrubs. The introduction of grazers enhances shrub seed dispersal, thereby increasing the shrub density. Grazing and fire management may favor shrub encroachment by reducing (eliminating) grass biomass. The loss of grass cover leads to an increase in soil erosion in the intercanopy areas and the deposition of nutrient rich soil particles beneath shrub canopies ("fertility island" formation). On sandy soils this process leads to the formation of coppice dunes (or nebhkas) stabilized by shrubs [41].

[29] – bordered by unfertile bare soil. Due to the increase in bare soil [13,93] with respect to the initial grassland state and to the loss of ecosystem services (e.g., grazing land), shrub encroachment is often considered as a desertification process [187], which may turn arid grasslands into shrub dunelands (Fig. 5). More recently, however, some authors have argued that shrub encroachment is not necessarily associated with land degradation [59]. Because some shrublands can be more productive than the native grassland [224], in general it is not true that loss of ecosystem productivity is a distinctive attribute of the desertification.

The transition from grass to shrub dominance is often relatively abrupt and irreversible, which suggest that this change in plant community composition may be associated with a shift between stable states in a bistable system [4,41,226,240] (Fig. 5). The shift could be induced by a number of drivers, including climate warming, increase in atmospheric CO_2 concentration, nitrogen deposition, overgrazing, and fire management [7,224]. Ecosystem bistability, i.e., the existence of the alternative stable states of grassland and shrubland has been explained as the result of three different positive feedbacks [41]: (i) the erosion feedback [187] associated with the increase in bare soil and soil erosion (see Section 4.1); (ii) the fire-vegetation feedback [37,40,224], whereby an increase in shrub cover at the expenses of grasses decreases fire frequency and intensity, thereby decreasing shrub mortality and sustaining the transition to shrubland; (iii) the vegetation-microclimate feedback [38,82], whereby shrub encroachment is associated with a change in microclimate [83] and an increase in minimum nocturnal temperatures, which reduces the exposure to frost-induced mortality in cold sensitive shrub species.

A different change in plant community composition is observed in dryland ecosystems when non-native grasses invade a desert shrubland (Fig. 6). This invasion is often favored by an increase in fire frequency due to the grass fuel contributed by the invader. Because fires were not part of their evolutionary history, the shrubs are rapidly killed by fires and replaced by invasive grasses [35]. Through this positive feedback mechanism, non-native plants may change the community dynamics, enhance soil erosion, and induce desertification [162]. In fact, when annual grasses displace perennial vegetation, their ground cover can be similar to that of perennial native plants only during the growing season of wet years (Fig. 6). However, during droughts and in the course of the dry season, the invasive grasses provide only a sparse vegetation cover, thereby leaving the soil surface more vulnerable to wind erosion [162]. Moreover, the increased fire frequency may have an impact on the susceptibility of dryland landscapes to wind erosion [161].

5. Climate change as a possible driver of desertification

As noted in the introduction, desertification typically results from the compound effect of climate change and land use. Changes

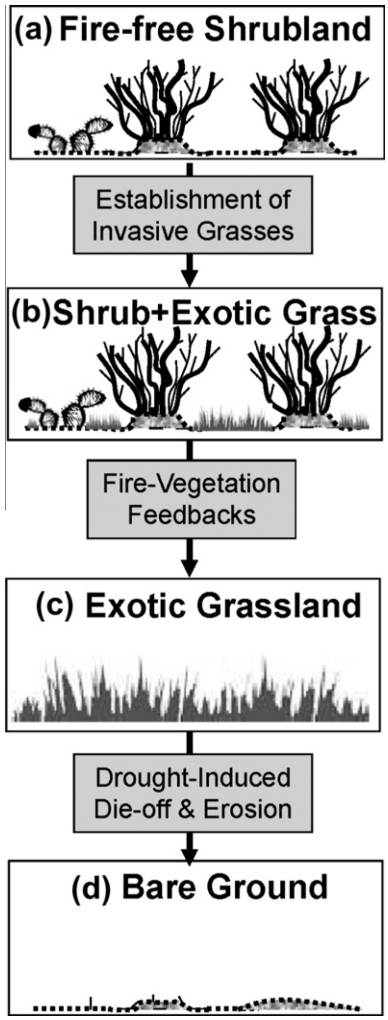

Fig. 6. Mechanism of desertification induced by grass invasions. The establishment of invasive grasses in a desert shrubland increases the fire frequency, thereby killing shrub vegetation and replacing shrubs with invasive grasses. Invasive grasses, mostly annuals, leave the soil surface exposed to wind and water erosion, particularly in during droughts.

in the global and regional patterns of precipitation can be major drivers of desertification and have historically led to the expansion and contraction of major deserts on Earth. In fact, while many of the existing deserts are very old and formed millions of years ago, most of them were affected by Pleistocene climatic changes and expanded at some point into areas that are currently much wetter (500–800 mm/yr). In those areas the temporary loss of vegetation cover can explain the formation of some of the sand seas that are currently stabilized by vegetation [74], including the Kalahari, southern Sahara, the High Plains (US), the Mega-Thar (India), the Kimberlies (Australia), and the Llanos and the Pampas (S. America). Thus, in the course of Earth's history, several regions around the world experienced the alternation of wet and dry periods. It is interesting to analyze how climate has been changing in more recent times and whether climate change studies predict an expansion or contraction of arid lands on Earth.

A number of studies have investigated ongoing aridification patterns and recent drought occurrences around the world (e.g., [192]). Global aridity has increased since the middle of the 20th century over Africa, east and southern Asia, eastern Australia, and southern Europe [45]. Global aridity associated with the rapid warming since the late 1970's is attributed to anthropogenic increases in greenhouse gas emissions [25,45,96]. The anthropogenic nature of these changes in the global patterns of precipitation was investigated in detail by Zhang et al. [252], who used simulations from fourteen climate models for 1925–1999, and found that the anthropogenic forcing has remarkable influence and explains southern hemisphere subtropics and deep tropics receiving higher precipitation while northern hemisphere tropics and subtropics receiving less precipitation.

Burke et al. [25] used the third version of the Hadley Center coupled ocean–atmosphere Global Circulation Model (HadCM3) to make some projections on future changes in global precipitation. This study predicted that up to 50% of the earth's surface will be in drought at the end of the 21st century under a "business as usual" scenario. Northern Africa, Amazonia, the United States, southern Europe, western Eurasia will become drier while central Africa, eastern Asia and high latitudes of northern hemisphere will become wetter [25,190]. Kim and Byun [102] report that by the end of the 21st century a large portion of Asia will be wetter except for West Asia, where the reduction in mean precipitation is predicted to occur between 2081 and 2100. The Asian monsoon region in Asia (East and South Asia) will experience larger interannual variability in precipitation and an increase in drought occurrence [102].

The increase in frequency of droughts poses a threat to agriculture [129]. For instance, maize production in smallholder rain-fed farms in Africa and Latin America is expected to decrease by 10% by 2055. Larger losses have been reported by other authors (see Hanjra and Qureshi [80], for a review). Extended periods of drought also cause economic losses as crops and cattle are directly affected. For example, in Australia, over 100 million sheep have died during periods of drought since 1880 [201]. With climate change, soil moisture is expected to decline during most of the year in several semi-arid regions of the world, including the southwestern United States, northeast China, Kalahari Desert and southern Australia [241]. Reduction in soil moisture and droughts are expected to lead to expansion of major deserts [25,241]. For example, subtropical deserts such as the Sahara, the Arabian, the Kalahari, the Gobi and the Great Sandy Desert are identified as the expanding deserts [251]. However, the analysis of satellite data suggests that some of these arid lands (e.g., the Sahel, the Mediterranean basin, southern Africa) are currently greening up ([85]) instead of expanding.

6. Societal drivers of desertification

In this section we consider some of the recurrent anthropogenic disturbances and societal drivers that typically contribute to desertification. The main anthropogenic causes are associated with poor land management resulting in overgrazing or unsustainable agricultural practices beyond the limits allowed by these vulnerable environments. Some of these practices enhance soil erosion or salt accumulation in the shallow soil. Land mismanagement is often due to lack of knowledge, greed, changes in the global economy, and remoteness/ marginalization (e.g., [71,121,170,172]). Marginalization may be associated with remoteness from centers of political power, i.e., disconnectedness between policy makers or centers of decisions, and the local communities affected by environmental problems. This distance prevents an adequate understanding of the problem and leads to the development and implementation of policies that further exacerbate the process of desertification. Examples of decisions that have often enhanced land degradation (Fig. 7) include the development of land tenure policies that encouraged land users to overexploit the land, changes in land succession laws (e.g., [71,163]), and a lack of protection from the exposure to (i) the demand for short-term returns without incentives for the preservation of long-term sustainability;

(ii) the risk arising from price fluctuation in the global market; (iii) loss of resilience due to lack of diversity of economical activities and products [71,87]. However, if the opening to the global economy is done effectively and protects the interests of developing dryland regions, it could lead to an increase in wealth that could be positive if used to enhance society via better education, health and technology. However, policies should be in place to protect the environment and societies from over-exploitation of natural resources and losses of tradition as well as to enable a culture of sustainable use of environmental goods and services.

From a more ecohydrological perspective, questionable land management decisions often underlie the development of infrastructures that aim to enhance crop and/or livestock production (Fig. 7). A typical example is the construction of new irrigation systems and boreholes [72]. These development programs are often based on the misconception that livestock production in dryland regions is limited by drinking water available for cattle, goats or sheep, or that crop yield is limited by a lack of water for irrigation. Thus, the drilling of a borehole would solve the problem and allow for an increase in livestock or crop production. However, a disproportionate increase in stocking rates leads to a use of the rangeland beyond its carrying capacity. Thus, the development of these infrastructures without accounting for the vulnerable nature of dryland soils favors an unbalanced intensive use of the land, which leads to desertification [238]. Moreover, as it will be discussed in Section 8, the construction of these hydraulic infrastructures has the effect of limiting the mobility of herds and crop cultivations, thereby preventing the adoption of adequate rotation schemes in the use of the land [140]. At the same time, the conversion of nomadic communities into sedentary societies limits the resilience of populations historically used to transhumance as a means to cope with land vulnerability and with the extreme interannual variability of hydroclimatic conditions [71,87,121,228]. Finally, the initial investments in these infrastructures permit short-term gains that may further enhance a detrimental intensive use of the land. In areas with limited resources and unreliable rainfall regimes, the risk of these investments is high. It may lead entire communities towards a state of poverty, which would further encourage rural societies to look at short-term production and favor land overexploitation. In Section 8 we discuss how overgrazing around artificial watering points is a major mechanism of desertification in arid rangelands.

7. Soil salinization as a driver of desertification

7.1. Global distribution of soil salinity

Soil salinization is one mechanism of land degradation that affects roughly 831 million hectares worldwide (Fig. 8), predominately in those areas located in arid and semiarid climatic zones [119,180]. Soil salinization refers to the accumulation of water-soluble salts (oftentimes NaCl) in the upper part of a soil profile to a level that impacts agricultural production, ecosystem productivity, and/or economic welfare [169]. One important form of salinity is sodicity in which Na^+ ions represent more than 15% of the exchangeable cations [180]. Sodicity alters physical properties of the soil because the swelling and dispersion of sodic aggregates destroy soil structure, reduce porosity and reduce the permeability of soils [168]. Notably, degradation brought about by sodic soils accounts for roughly 50% of the world's salt affected soils [119]. In many areas, the extent of soil salinization is increasing. For instance, 20% of irrigated land, or 45 million hectares are affected by conditions of increasing salt content [169]. This trend has been documented in a number of the major agricultural basins worldwide, including the Indo-Gangetic Basin in India [79], the Indus Basin in Pakistan [9], the Yellow River Basin in China [31], the Aral Sea Basin of Central Asia [27], the Euphrates Basin in Syria and Iraq [184], the Murray-Darling Basin in Australia [169], and the San Joaquin Valley in the United States [158,189]. It is important to point out that some semi-arid and arid areas have naturally saline soils, which is due to geologic, hydrogeological and hydromorphic characteristics of the watershed. For instance, in Western Australia many parts of the landscape are highly weathered, and the majority of the topographic relief is very shallow, which leads to a lack of substantial drainage and the accumulation of salts [32]. For agricultural systems, soil salinity not only reduces crop growth and yield but can also leave the soil in a more permanently degraded state. Dissolution of salts into surface and ground waters can lead to the degradation of these waters with concomitant effects on the systems reliant on these sources of water (e.g., [189]). Similarly, soil salinity decreases the resilience of ecosystems dependent on salt-affected soils and water resources (e.g., [234]).

7.2. Mechanisms of soil salinization

There are three major mechanisms of soil salinity formation: (i) *groundwater associated salinity*, which occurs in areas that have a shallow groundwater table (e.g., water table depth, DTW less than 2.5 m) where exfiltration via capillary action brings salts dissolved in the groundwater to the rooting-zone, and the exclusion of salts by vegetation has the potential to further increase the salinity within this zone; (ii) *non-groundwater associated salinity*, which occurs in areas that have a deep water table (e.g., DTW greater than 20 m) and poor drainage, whereby salts introduced by rain, weathering of rock, and dry deposition are stored beneath the rooting-zone; and, (iii) *irrigation associated salinity*, which occurs in areas with irrigated agriculture, where the use of poor-quality irrigation water in conjunction with insufficient leaching (i.e., low hydraulic conductivity) and relatively high evaporation rates causes the accumulation of salts in the shallow rooting-zone [169]. Sodic soils tend to result once Cl^- has been leached from the rooting zone and the positively charged sodium ions remain adsorbed to negatively charged soil particles (i.e., clay).

7.3. Adverse effects of soil salinity on vegetation

Salt accumulation decreases ecosystem and crop productivity because elevated salt concentrations can inhibit plant establishment and growth (e.g., [48,130]). To maintain water uptake from a saline soil, plants must osmotically adjust, which is accomplished by either taking up salts and compartmentalizing them within plant tissues, or synthesizing organic solutes [193]. While plants vary in their sensitivity to salt, there are two broad groups that are used to categorize a plant's tolerance to salt: halophytes and glycophytes. Halophytes are plants that have a higher salt tolerance and greater ability to store high salt concentrations in plant tissues without adversely affecting cell processes [193]. They compensate for low osmotic potentials by accumulating salt in their

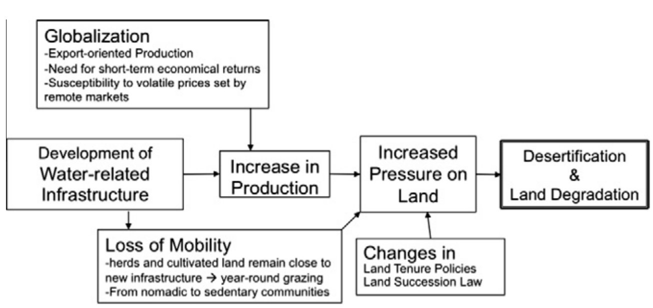

Fig. 7. Recurrent societal drivers of desertification.

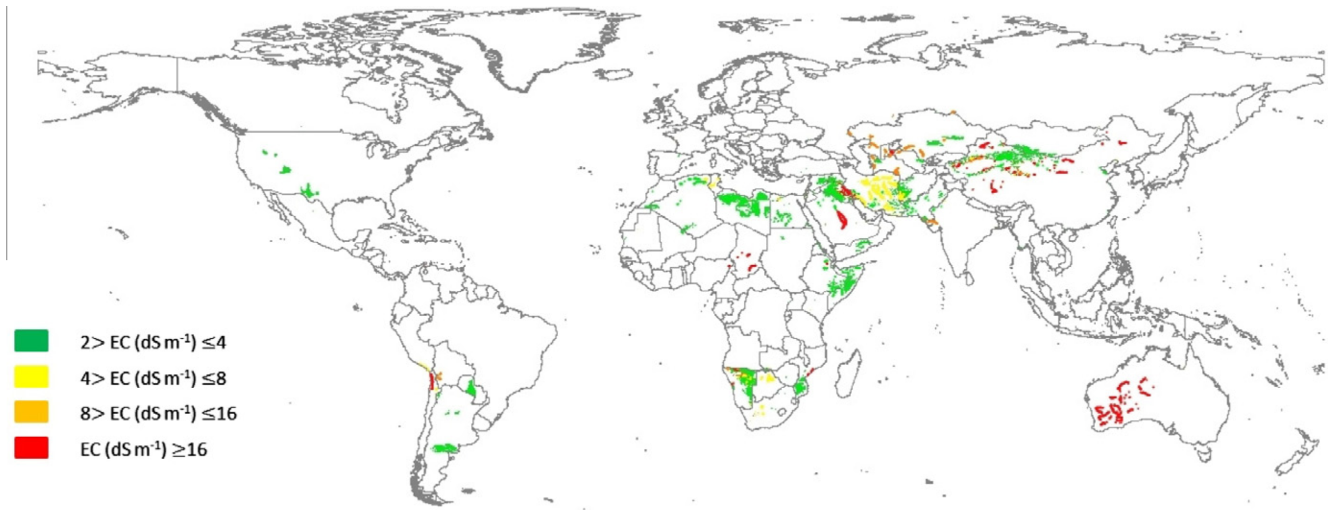

Fig. 8. Global distribution of saline soils using data from the Harmonized World Soil Database [67]. Salinity on the map is represented by electrical conductivity (dS m^{-1}) and the coloring schemes illustrate different ranges in soil salinity corresponding to the relative degree to which soil salinity constrains plant productivity.

sap cell so the osmotic potential is lower than the soil solution and water can move along an osmotic potential gradient [106]. In contrast to halophytes, glycophytes tolerate only low concentrations of salt in plant tissues before cell processes are adversely affected [106]. Sodic soils reduce crop productivity and yield due to osmotic related effects; however, sodicity also affects the plant due to a change in the soil's physical structure [158]. A change in the soil structure (such as the physical disaggregation of soil aggregates) affects water and air movement, plant-available water-holding capacity, root penetration, seedling emergence, runoff and erosion, as well as tillage and sowing operations [151]. These conditions tend to restrict water storage and transport such that soils either lack sufficient aeration immediately following a precipitation event or are too dry within a few days following the event, thereby significantly diminishing the optimal water content range for the plant [168].

7.4. Salinization feedback

Interactions between soil salinity and plant communities occur when plants are both sensitive to salt levels in the root zone and are able to modify the soil salt balance. In such cases a salt-vegetation feedback may exist, which results from the strong coupling between vegetation and water table dynamics (e.g., [5,182,234]). The interaction between vegetation dynamics and hydrologic processes modifies the soil salt balance, thereby affecting the conditions suitable for plant establishment and growth [181]. Bistable dynamics can emerge in these conditions where both a state with vegetation cover, deep water table, and low salinity, and a state with sparse or no vegetation, shallow water table and high salinity can be stable [181]. In the latter case, salts primarily accumulate due to either a rise of the water table into the rooting zone or to exfiltration (i.e., the capillarity driven upward flow of water from the water table to the surface, where it evaporates). Exfiltration brings groundwater and its dissolved salts to the surface and shallow rooting-zone. When water at the surface evaporates, salts remain at the soil surface [137]. In systems with vegetation-groundwater coupling, the removal of vegetation can cause a rise in the water table (e.g., [154]). Because exfiltration rates increase with decreasing water table depths, deforestation can lead to an increase in soil salinity that in turn can inhibit the re-establishment of vegetation in the same area. Land use decisions that accelerate the conversion of forested lands to agricultural use can also exacerbate the rate at which a shift from the fully vegetated state to the bare stable state takes place.

One such example where these bistable dynamics have been documented is in the Murray-Darling Basin in Australia. The widespread conversion from sclerophyll woodlands and forests to agricultural use resulted in a decrease in the water table depth, which caused the mobilization of salts accumulated in an unsaturated soil layer beneath the root zone and transport of these salts into the rooting zone. Once these salts have been transported into the rooting zone (via groundwater associated salinity), measures to mitigate soil salinity are not only costly, but they oftentimes require freshwater, which may be relatively scarce in arid and semi-arid areas.

8. Land degradation around artificial watering points

Subject to herbivory for millennia, much of the world's drylands are characterized by distinct wet and dry seasons (see Section 2) with highly variable mean annual precipitation (MAP; Fig. 1b) resulting in unpredictable and temporally and spatially heterogeneous periods of plant production and forage [60,165]. Until recent centuries, grazing under such conditions has consisted almost entirely of wildlife and traditional pastoralism. However, with the introduction of commercial ranching that accompanied European colonization of many parts of the world and the associated management practices that followed (e.g. water provision, fire suppression, supplementary fodder), these dynamic systems have experienced diminished function, productivity and service provision (e.g., [224]). In particular, the establishment of permanent sources of water in locations where this resource was not historically available (artificial watering points) has provided a foothold for the influx and sedentarization of humans and livestock in landscapes not typically accustomed to such sustained pressure and demand [97,103].

Traditional grazing practices emphasize herd mobility and opportunism in order to cope with the variability in climate and resource availability. Division of herds into smaller groups and relocation into neighboring territories or unused space are among the strategies employed by pastoralists that allow grazing pressure to be distributed more broadly over greater areas and that permit better access to heterogeneous resources when facing adverse conditions [60,211]. Despite these practices, pastoral herds can see large population fluctuations as a result of drought [229]. The dominance of abiotic influences on arid and semi-arid pastoral systems therefore precludes the establishment of strong influences from traditional herbivory on vegetation since livestock densities are naturally kept well below carrying capacity for rangelands with low MAP; rangeland degradation and the formation of highly impacted zones proximal to watering points is unlikely under this system of persistent yet variable livestock populations [60,174,229]. It should be noted, however, that negative environmental effects by the pastoralist system have been observed particularly when interventions by the government restrict the range of nomadic herds to communal lands, often leading to a situation in which multiple livestock owners are forced to use a common pool of limited resources (rangeland), and thus inducing an overexploitation pattern known as the "tragedy of the commons" [81,152,208].

The range of wildlife and pastoralist herds in arid and semi-arid environments is determined by distance from and availability of water, which limits the access of herds to certain pastures. This constrains the maximum realizable herd population so that dry and wet season areas experience long periods of relief and minimal impact as a result of herbivory [213]. Grazer mobility is highly variable [91,211] and dependent on a number of factors including temperature, terrain, grazer species and available forage [97]. Additionally, grazer density is strongly tied to the spatial frequency of natural or traditional watering points. Traditional hand-dug wells in Niger, for example, have limited daily water yields and can accommodate only 200–300 cattle per day [211]. Conversely, the establishment of modern artificial watering points or some other infrastructural focal point (e.g. concrete wells, boreholes, herder camps, kraals) intended to counter the unpredictability of water availability in arid and semi-arid grazing systems has significantly affected the dynamics of many of these systems by promoting increases in human and livestock populations and leading to elevated pressure on areas where no or seasonal natural water sources originally were present [97,103,213]. This allows for higher stocking rates and places unsustainable grazing pressure on the rangeland [214]. Because of unnaturally persistent grazing regardless of the climatological conditions and available grass biomass, thresholds of ecosystem resistance and resilience are often crossed leading to landscape degradation and desertification [10].

While the grazing history of a given region may exert long-term influence on the abundance and distribution of biological, chemical and physical constituents, three immediate considerations are important in determining the potential rangeland that can be impacted through grazing: (1) the distance that grazers can travel from the watering point, (2) the distance between watering points and (3) the grazing density (i.e. the number of livestock per unit area). The grazer-impacted area around a given watering point (the piosphere) generally consists of a "sacrifice zone" of severe degradation immediately surrounding the watering point [75], followed by a transition zone at intermediate distance that gradually converts to a uniformly grazed zone at increasing distance, all of which are affected by different proportions and intensities of grazing, trampling and nutrient deposition/redistribution [115,205]. Degradation is concentrated closer to a watering point because available grazing area decreases approaching the watering point [215]. The area and shape of the piosphere are highly variable between watering points and dependent on a number of biotic and abiotic factors including grazer density, available plant species, temperature and wind direction.

Sustained heavy grazing around an artificial watering point has both direct and indirect influences on the biota and on the physical/chemical properties of the impacted area. The magnitude of a shift to a degraded state around a given watering point as a result of overgrazing is largely dependent on the floral and pedological composition of a rangeland, selective grazing, livestock density and the redistribution of key nutrients. Vegetation cover, plant species composition and plant species richness are visible and important factors that can be used to quantify herbivore impact within a piosphere. Given the increased grazing pressure associated with the installation of artificial watering points, the effects of herbivory (particularly on ecosystem resilience) in the surrounding areas can be particularly pronounced [215]. For instance, in Burkina Faso, Rietkerk et al. [174] observed a transition from bare soil to patches of annual and perennial grasses to continuous vegetation cover as distance increased from the watering point. Grazing around permanent water sources along a pipeline in Namibia resulted in significant changes in grass species composition characterized by decreases in palatability and shifts from perennial to annual species [103]. Tarhouni et al. [205] saw increases in both annual and unpalatable plants and decreases in plant grazing value in areas near watering points in Tunisia. Boreholes in south-eastern Botswana saw depleted herbaceous cover and woody plant encroachment around piospheres [126]. Brooks et al. [20] examined the Mojave Desert (USA) for changes in plant species richness and composition around livestock watering sites, finding increased alien annual plant cover and decreased plant cover and species richness for both native annual and native perennial plants. While the above studies are certainly situation dependent, the general shift of vegetation composition within a landscape surrounding an artificial watering point follows two trends (Fig. 9): (1) perennials to annuals, aliens or bare soils and (2) palatable to unpalatable or toxic [205,215]. Recruitment of woody species is also an important consideration in this shift provided woody species are present in the original landscape (see Section 4.3). Selective grazing leading to decreased native plant richness can considerably alter the soil seed bank profile as well (Fig. 9), severely limiting the potential resilience of a rangeland [99]. Changes in the soil seed bank profile can also be influenced by certain seeds being deposited with dung near the watering point [22,178]. Depletion of soil resources may also result from intensive agriculture without an appropriate fallow period. It is interesting to notice how the spatial gradients in vegetation cover, plant community composition and soil properties found around watering points closely mirror temporal trends during the process of land degradation and desertification. Thus, a "space-for-time substitution" can be used to investigate the typical sequence of stages of land degradation resulting from overgrazing.

Plant cover, plant community composition and soil characteristics exert reciprocal influences on each other. Vegetation improves the quality and quantity of soil moisture and available nutrients through crust prevention, enhanced infiltration rates, and increased biological activity; its removal, in conjunction with soil compaction from trampling and rain splashing in bare or sparsely vegetated soils, enhances run-off and nutrient loss or redistribution by wind and water [76,160,161,175,188,232]. Selective grazing for perennial grass species can decrease infiltration capacity near watering points as a plant population transitions to one primarily composed of annuals [174]. Around artificial watering points, urination and dung deposition can lead to changes in the soil nutrient profile and development of nutrient gradients around artificial watering points including increased salinity, higher pH, and elevated nitrogen and phosphate levels [86,196,216]. These elevated nutrient levels largely reshape where species can establish along the grazing gradient, potentially impacting rangeland productivity. In the Nama-Karoo region of South Africa, for instance, Todd [215] reported that shallow or absent soils normally unfavorable for forb growth saw the recruitment of forb and alien species due largely to the centripetal deposition of dung within the immediate vicinity of a watering point where highly palatable, perennial plants were selectively consumed [201]. In situations where shrub encroachment is associated with land degradation from overgrazing, 'fertility island' formation (i.e. increased hetero-

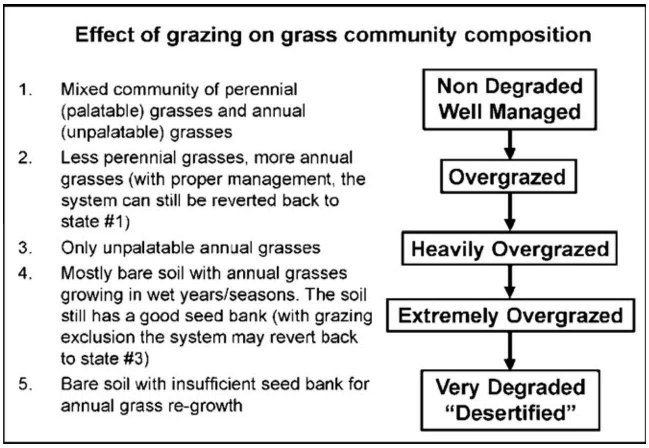

Fig. 9. Changes in dryland grass communities induced by grazing and overgrazing.

geneity in soil resource distribution by wind and water) typically occurs [160,187]. The heterogeneous distribution of soil moisture and nutrients brought about by grazing, changes in plant community composition, soil properties and hydrological processes is often a distinctive feature of landscapes undergoing desertification [10,187].

A variety of temporal and spatial factors determine the extent of grazing impact and therefore the degree to which the surrounding land is degraded, making a consensus on characterizing degradation within a piosphere difficult to reach. The high density of artificial watering points and other infrastructure within arid and semi-arid rangelands and the subsequent influx of human and livestock populations are important contributors to the desertification question. Disturbances in water and nutrient cycles as well as changes in land cover/use as a result of overgrazing not only affect the scale at which the changes are taking place but also may exert influences on larger scale processes.

9. Human impacts of desertification

Despite its impacts on over one-third of the world population, the human dimensions of desertification remain poorly understood [95,171]. As desertification is considered to be a cause and a consequence of socio-economic and political instability in developing nations, the mitigation of desertification is vital [121]. Until recently, the indicators used for desertification assessment were mostly based on biological and physical factors, while the human aspects were mostly associated with the causes of desertification [95].

Many dryland systems around the world are in constant stress due to the complex interplay of external and internal drivers (as outlined in Sections 4–8), which may render these systems unable to provide vital ecosystem services, including primary production and carbon sequestration. Further, "stressed" ecosystems lack the resilience to recover from disturbances and climatic extremes, which are predicted to occur more frequently [96]. Overall, the desertification processes at local and global scales exert enough pressure to overcome the coping mechanisms and adaptation capacities of individuals, communities and ecosystems [121,131,132]. The deteriorating livelihoods resulting from diminishing crop productivity, recurrent climatic extremes and political instability may result in large-scale human migrations, with important environmental, socio-economic and political consequences [16,133]. For example, in the case of sub-Saharan Africa, climatic disasters (the series of droughts from the late 1960s), combined with weak economies and unsustainable use of marginal resources, increased the stress on these ecosystems, which were unable to sustain the demands of the increasing human population [47]. These factors resulted in famines and large-scale human migrations [47,73,111,144]. Similarly, massive migrations from the Great Plain to the Western U.S. occurred as an effect of the "Dust Bowl" as described by John Steinbeck in "The Grapes of Wrath" (e.g., [78]). Thus, environmental degradation may be the cause or consequence of human migrations and conflicts.

"Environmental refugees" or "environmental migrants" (e.g. [58,133]) are people affected by environmental degradation (commonly by pollution or depletion) caused by anthropogenic alteration of the environment [16]. Recent estimates indicate that the number of environmental migrants has exceeded those of traditional socio-political refugees, with Sub Saharan Africa being the hot spot of environmental migrants [131–136]. However, quantifying the migrations resulting from environmental factors is extremely difficult, and the whole concept of environmental migrants is widely debated, as the decision to migrate is complex and affected by a combination of social, economic, political and environmental stressors [239].

10. Large scale implications of desertification

Desertification has important impacts not only at the local scale but also at the regional and global scales. The long-range effects of desertification modify climate, global biogeochemical cycles and human geography. In the previous sections we have discussed the impacts on climate and on global patterns of immigration/emigration associated with the displacement of environmental migrants. The impact of land degradation on regional and global biogeochemical cycles is for the most part associated with the emission of dust from arid land and with its long-range transport (e.g., [160]). In this section, we explore the large-scale implications of the dust that is produced in degraded regions and its impacts on the biogeochemistry of ecosystems affected by the deposition of this dust. The production and transport of dust from new source regions is one of the large scale effects of desertification associated with the removal of vegetation. For example, deforestation and overgrazing in Patagonia [120] and persistent droughts in Australia's deserts [89] have been recently contributing to increased wind erosion and dust mobility [98,124].

Disturbed bare soils have the lowest threshold velocities for aeolian entrainment and can be intense emitters of dust [116]. Bare soil surfaces are prone to wind erosion; the saltation of soil particles entrained in the air stream is a major mechanism for the production and suspension of fine dust sized particles [191]. The long-range transport and deposition of dust provides nutrients to terrestrial and marine ecosystems distant from the dust source. For example, Swap et al. [203] found that deposition of dust from the Sahel/Sahara was critical to the productivity of the Amazon rain forest. Droughts in the Sahel are associated with an increase in the dust transport from North Africa to the Caribbean islands [156]. Steppes of Africa and Eurasia located at the margins of major deserts are sinks for windborne phosphorous [148].

Mineral dust is one of the main sources of iron for the oceans [57]. The lack of major dust sources in the southern hemisphere has been invoked to explain the low productivity of the Southern Ocean [173]. Thus, High Nutrient, Low Chlorophyll (HNLC) waters of the Southern Ocean, where soluble iron is the limiting micronutrient [117,118], strongly rely on iron inputs from dust deposition and possible other iron sources [204]. The dependence of productivity on mineral dust inputs in this and other HNLC ocean regions has been suggested to explain the lower levels of atmospheric CO_2 during glacial maxima, when dust loads in the atmosphere were higher [113,118] due to a more intense aeolian activity in terrestrial ecosystems. This relation between atmospheric CO_2 and mineral dust concentrations is consistent with the finding of high atmospheric dust loadings coincident with low CO_2 levels in the Vostok cores [173].

11. Indicators of land degradation

The idea that desertification may emerge as a phase transition between the attractors of a bistable system, suggests that this process could exhibit a discontinuous response to environmental conditions: even small changes in environmental drivers could lead to a discontinuous response and to a shift to the desertified state (Fig. 3). These dynamics are often highly unpredictable because of the thresholds and discontinuities existing in the response to environmental conditions and anthropogenic pressure. From an ecosystem management standpoint knowledge about the proximity of the system to threshold conditions is crucial to the understanding of the likelihood of an imminent shift to the alternative (desertified) state. The distance from the threshold is a good indicator of ecological resilience, i.e., of the maximum disturbance the system could tolerate without undergoing a transition to the other stable state.

In recent years a number of theories have identified leading indicators of state change in bistable ecosystem dynamics (e.g., [186]). These methods – which have been applied to a number of different systems including the desertification associated with the decline of the "green Sahara" [46] – typically require long-term continuous measurements of the ecosystem's state with suitable temporal resolution (e.g., [28]). These measurements are used to calculate statistics that can serve as precursors of a regime shift because of the clear change they exhibit as the system approaches the bifurcation point. However, in the case of desertification the process is relatively slow and occurs at the decade-to century (or longer) timescales; long-term observations and monitoring of dryland ecosystems over these temporal scales are rare. Thus, leading indicators of state change based on theories of precursors of phase transitions appear to be of little effectiveness and limited applicability to the desertification problem. However, other indicators can be found in the system, based on changes in soil physics, hydrologic conditions or plant biology. Despite its apparent abruptness, the desertification process typically exhibits some preliminary changes that can be used as indicators of ongoing transformations along the downward pathway of land degradation. In what follows we will discuss some indicators based on changes in plant community composition, soil properties and hydrologic conditions.

As noted in the previous sections, a typical pattern of shift in grass community composition in overgrazed areas exhibits a reduction of perennial (palatable) grasses and, a subsequent loss of annual grasses (Fig. 9). The consequent increase in seasonally bare soil conditions enhances the exposure of the land surface to erosion and soil loss. As the land continues to be overgrazed, the preferential consumption of palatable perennial grasses leads to their replacement with annual grasses. As overgrazing continues, annual grasses may also decrease in density. The system can still recover as long as a viable seed bank and other fundamental soil resources still exist (Fig. 9). Thus, changes in grass community composition, seed bank abundance and viability are suitable indicators of state change that can be detected in the field and used to infer the ability of the system to recover. Similarly, changes in soil properties (e.g., soil nutrient content, water holding capacity or infiltration) along land degradation gradients around watering points provide useful indications of the severity of ongoing changes in soil resources.

The impact of desertification on the water cycle affects a number of processes, including precipitation, soil infiltration, and evapotranspiration. In the previous sections we have discussed how desertification may affect precipitation, soil infiltration capacity and soil moisture dynamics. Another obvious impact of desertification on water fluxes is associated with changes in evapotranspiration. Using a framework proposed by Falkenmark et al. [64], we can recognize that land masses receive water from the atmosphere as precipitation and lose it to the oceans as runoff and to the atmosphere as evapotranspiration, which is composed by evaporation and transpiration. From an ecohydrological perspective, evaporation is an "unproductive" water loss because it does not contribute to plant productivity; conversely, transpiration is directly coupled with plant photosynthesis and carbon assimilation. Thus, if desertification causes a loss of vegetation cover and a decrease in transpiration, its impact on the water cycle is to increase the rate of unproductive water losses to the atmosphere (i.e., evaporation). Because evaporation does not contribute to carbon sequestration nor to the production of food, fuelwood and fibers, this change in the relative importance of productive and unproductive water vapor fluxes is associated with a loss of ecosystem services and with a shift to a less desirable state. Moreover, as discussed in Section 7, evaporation tends to accumulate salts on the soil surface and within the topsoil, thereby further contributing to land degradation. Some land management techniques [63] aim at increasing transpiration at the expense of evaporation in order to favor a more productive use of water resources and enhance the provision of ecosystem services. Measurements of the relative importance of evaporation and transpiration along land degradation gradients (e.g., at different distances from a borehole) could provide interesting ecohydrologic metrics of land degradation. To this end, recent methods based on continuous measurements of the isotopic compositions of water vapor could be used [237].

12. Mitigation, control, and reversal of desertification

Adoption of desertification control measures requires identifying and monitoring early warning signs or indicators of desertification (see Section 11). Commonly used indicators [12,230] range from biophysical (land cover change, biodiversity, soil fertility), economic (declining crop yields, fodder production, household income and market efficiency), social (increase in rural–urban migration, population structural changes, decline in social solidarity, deterioration of health, increase in unemployment rates) and political (shrinking of state power, immigration-related conflicts) [95]. Monitoring involves acquisition of information through field surveys, available records, and remote sensing [12,230].

Even though desertification is often considered as an irreversible transition (at least within the timeframe of a few human generations), some measures can be adopted to reverse this process before the system reaches the stable "desertified" state. To this end both biophysical approach, and policy and socioeconomic solutions are typically used [172,199].

12.1. Biophysical solutions

In agro-ecosystems affected by desertification, enhancing food security by improving agriculture and promoting sustainable use of resources is a major step towards slowing down or reversing desertification. In this regard, biophysical solutions often involve soil erosion control, salinity remediation, grazing management, introduction of new crop varieties, improvement of existing irrigation systems, introduction of new irrigation/water harvesting technology, fire management, and/or combinations of these solutions.

In Sahelian West Africa, several strategies have been found to improve/maintain/restore soil productivity in rural agricultural lands, such as adding crop residues/mulches, leaving areas in the field fallow (in-field fallow techniques), adding livestock manures, restoring native vegetation cover and controlling soil erosion [242]

Soil conservation methods or small structures for water erosion (sheet and gully erosion) control (e.g., gravely slopes, low stone-walls, vegetation (grass) or mulch barriers) have been traditionally used in many arid regions. Control of wind erosion by mulching with crop residues and creating vegetation shelterbelts have been shown to significantly increase crop yields in the Sahel region [122,200].

Studies in rural India and in the Sudano-Sahel region of Africa have demonstrated the role of indigenous rainwater harvesting practices and new technologies like solar power drip irrigation and solar power water pumping systems as a strategy for enhancing food security and poverty reduction, as well as for improving hydrologic conditions (e.g., infiltration and ground water recharge) [26,153,231].

In the case of land degradation induced by woody plant encroachment in the Southwestern USA, Southern Africa and Australia, a combined strategy of prescribed fires and managed grazing is found to enhance recovery of native grasslands. (e.g., [161]). Vegetation restoration projects in denuded landscapes aim at rangeland regeneration while preventing soil erosion. Grazing management using seasonal enclosures to control livestock mobility resulted in increased vegetation cover and species richness in arid grasslands of northeastern China [100]. In the Thar Desert of Northwestern India, grazing restriction on vegetated sand dunes resulted in erosion reduction and enhanced growth of palatable plant species. This strategy was found to be critical during drought periods, by preventing heavy vegetation mortality on grazing restricted vegetated dunes [104]. In the Chihuahuan Desert (USA), the removal of grazers for an extended period of time led to increases in soil nutrients and soil infiltration [3]. The relocation of watering points to areas less susceptible to erosion has slowed the degradation of vegetated dunes in Patagonia [18]. However, the key to recovery is to decrease grazing pressure at watering points.

The management of grazers in Australia is suggested as a solution to desertification [198] Recently alert systems were put in place to provide early warning of potential droughts, and a policy of having 'farm management deposits' was introduced to secure the ranchers' losses during periods of drought [199].In the case of salinity related desertification in Northwestern India and Western Australia, a combination of location specific techniques such as growing salt tolerant trees to provide bio drainage, adopting salinity adapted crops, and adding chemical amendments have been used as relatively efficient salinity remediation techniques [68,195,197]. Selecting crops that are less sensitive to both saline and waterlogged conditions can aid in mitigating the adverse effects of salinity (e.g., [180]). For those systems affected by groundwater associated salinity, drainage systems can be used to reduce the amount of water that percolates beneath the rooting zone. Management practices that reduce the amount of salts input to the soil via irrigation may include either switching between or combining saline irrigation water with fresh water, which is especially important in semi-arid and arid areas where water is a limiting resource [90]. Leaching of salts accumulated within the rooting zone with low salinity water is one common practice that is used to combat soil salinity [157]. However, it is important to point out that in arid regions, where water is not available to leach these accumulated salts, soil salinization can be irreversible [180,181]. Additionally, salinization can be irreversible in areas with shallow, saline groundwater tables that have shallow topographic relief, long groundwater residence times and are located at long distances from potential discharge points.

Measures to reduce soil sodicity generally differ from those used to reduce soil salinity. These include: applying gypsum or lime in the case of acidic sodic soils or a combination of both measures. Phytoremediation is another option that has been shown to be an effective mechanism to reduce soil sodicity (e.g., [158]). In general, the basis behind these management options to reduce sodicity is that the excess Na^+ is displaced by Ca^{2+}, which aids in leaching the sodium from the root zone.

12.2. Socioecomic solutions

The success of biophysical remediation and mitigation measures depends on the existence of favorable societal conditions [121,173,219]. Local participation and "stakeholder involvement" appear to be crucial [12]. Attempts to enhance the participation of local populations include providing incentives to solicit local stakeholder involvement and providing extension and training facilities for the local communities [12,219]. Enhancing the economic and social well-being of dryland communities in a sustainable manner is vital for desertification control. In many drylands affected by desertification, the potential local resources have not been fully utilized because of lack of knowledge and planning, social issues, conflicts, land-use rights and high investment costs. Optimum use of natural resources can be achieved by providing economic incentives, targeting long-term private and public investments, promoting diversification of income and livelihoods, investing on renewable energy, creating efficient marketing systems, and conducting problem-oriented research [12,110]. Integrating local knowledge and indigenous resource conservation practices are often found to be critical for the long-term success of desertification control programs [95]. The above steps will guarantee food security and poverty reduction as well as strengthen the adaptive capacity of dry lands to climate change and desertification [12,95].

The mitigation and reversal of desertification can be favored by community involvement or improvement of societal resilience. Some examples of initiatives along these lines include farmer-lead tree regeneration programs in Niger aiming at improving crop yields, food security, and biodiversity, while modifying the microclimate and reducing agro-ecosystem vulnerability to droughts [167,219]; integration of local and scientific knowledge for adaptation to rangeland degradation in the Kalahari [166]; risk management in sub-Saharan African pastoral systems through diverse traditional institutions that support households suffering from livestock loss from droughts and disease [128,219]; implementation of an index based nation disaster insurance for post-disaster relief in Ethiopia [88,219]; income diversification by harvesting and marketing non-timber forest products in Senegal [128] or by marketing livestock products in Tibet [145].

13. Conclusions

It has been estimated that about 25% of dryland areas around the world are affected by desertification. This process has major effects on the environment and societies, including soil erosion, increases in the frequency and magnitude of dust storms, reduction of vegetative cover, change in plant community composition, or the loss of land productivity, biodiversity and food security. While some of these factors are commonly used as indicators of ongoing land degradation, not all of them occur in every desertified region. Desertification often leads to major societal changes including increased levels of poverty, starvation, land abandonment and migration from degraded rural areas to major cities and foreign countries (e.g., [16,133,228]).

Combating desertification is crucial to the reduction of global poverty as well as to the mitigation of biodiversity loss and human induced global climate change [121]. Future climate change scenarios are expected to exacerbate the progression of desertification worldwide, through precipitation variability, increased drought frequency and persistence of dry conditions [96]. Moreover rapid population growth is predicted to occur in dryland regions, coupled with an ever-increasing demand for natural resources, which are already scarce. Prevention and mitigation of desertification involves understanding the causes and feedbacks, monitoring and assessing the progression, and designing and implementing site-specific management strategies. Improving human well-being in areas affected by desertification is an integral component of desertification mitigation programs and is often based on traditional knowledge coupled with new technology adoption and with close involvement of local communities [121]. Major policy interventions and management approaches are needed for integrated soil, water and vegetation cover management in these regions.

Research in ecohydrology, soil science, and climatology has contributed to the understanding of drivers of desertification. Despite their different background and research approaches, desertification scientists tend to look at this process as a transition between metastable states in bistable ecosystem dynamics. According to this view, ecosystems prone to desertification exhibit two alternative stable configurations: a vegetated and a degraded (i.e., "desertified") state. The emergence of bistable dynamics is typically induced by a positive feedback between ecosystems and their limiting resources, environmental conditions, or disturbance regime. Examples of desertification feedbacks include the self-sustained interaction between the state of the system (e.g., vegetation cover) and (i) climate or precipitation regime; (ii) soil resources or soil suitability for plant growth (land degradation feedbacks); (iii) disturbances affecting plant community composition; (iv) societal and economic drivers. The transition between states can be associated either with aridification patterns resulting from regional or global climate change, or with land use dynamics that induce over-exploitation (e.g., overgrazing around watering points) or poor management decisions (e.g., soil salinization). Recurrent drivers of land use change include demographic pressure, changes in land tenure and land succession law, and the development of fixed infrastructures – e.g., a well – all of which can place unsustainable demands on the socioecological system.

Acknowledgements

We thank Yo Matsubara for her help with the analysis of the CRU-TS 3.1 data sets (Fig. 1).

Support from the US National Science Foundation (grants #EAR0746228; DEB0743678; DEB0717360; EAR0838218; DEB0620482) is gratefully acknowledged. We thank Sally Thompson (University of California) and three anonymous reviewers for their criticism.

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