4.20 Desertification of Rangelands

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Glossary

Alternative states Ecosystems with similar climate and soils, yet different species, interactions, and processes.

American Southwest The arid region (<25 cm rainfall per year) of the United States that includes the three hot deserts (Chihuahuan, Sonoran, Mojave).

Desertification The broad-scale shift from productive, native perennial grasslands or savannas to dominance by native or non-native annuals, unpalatable herbaceous and woody plants, and/or increasing amounts of bare ground.

Grassland Ecosystem where the vegetation is dominated by grasses and other herbaceous (nonwoody) plants, such as forbs.

Invasive species native or non-native species that have increased dramatically in an ecosystem as a result of changes in climate and/or human activities.

Novel ecosystem Ecosystem comprised of different species, interactions, and processes not possible under current conditions and not reflected in past systems.

Savanna Ecosystem characterized by a mixture of grasses and woody plants (shrubs, trees) where the woody plants are sufficiently small or widely spaced so that the canopy is not closed. The open canopy allows sufficient light to reach the ground to support the herbaceous layer of grasses.

Shrubland Ecosystem dominated by short (typically <8 m tall) woody plants often with many stems.

Soil inorganic carbon (carbonate) Compounds in the soil containing carbon that are not created by living organisms, but are derived from minerals in the Earth. The most common form of carbonate in dryland soils is calcium carbonate ($CaCO_3$) that forms when minerals are leached by rainwater from upper layers of the soil and accumulate in lower layers. Hardened deposits of calcium carbonate are called caliche.

Soil organic carbon Compounds in the soil containing carbon material derived from decaying vegetation, bacterial growth, and metabolic activities of living organisms or chemicals.

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4.20.1 Introduction

Arid and semi-arid grasslands and shrublands (i.e., dryland ecosystems) comprise nearly 40% of the Earth's land surface and influence the livelihood and well-being of one-fifth of the world's human population (Reynolds and Stafford Smith 2002). Plants and animals associated with these ecosystems often exist near their physiological limits such that slight increases in temperature, decreases in precipitation amount, or shifts in seasonality can have disproportionately large effects relative to those in other ecosystems. Furthermore, changes in the abundance and cover of vegetation in these drylands can have profound effects on soil erosion and exchanges of energy and water between the land surface and the atmosphere; these bottom-up effects can intensify stresses associated with climate and act to initiate self-reinforcing changes in vegetation (feedbacks). As a result, arid and semi-arid grasslands are highly susceptible to desertification – the broad-scale shift from productive, native perennial grasslands or savannas to dominance by native or non-native annuals, unpalatable herbaceous and woody plants, and/or increasing amounts of bare ground. As reviewed in this chapter, these ecosystem modifications have significant consequences for myriad ecosystem provisioning, regulating, supporting, and cultural services via their influence on carbon storage, biodiversity and forage production, spread of invasive non-native species, the partitioning of hydrological budgets, wind and water erosion, and land surface influences on atmospheric chemistry and weather. The social aspects of the vulnerability of these ecological systems to change are discussed in Ojima et al. (in press, see Chapter 4.17).

Desertification is the result of cumulative threats that interact in time and space (Figure 1). Each threat operates on ecosystems at local scales that can propagate to influence broad-scale dynamics with consequences for ecosystem services. Carbon dioxide enrichment (CO_2), nitrogen (N) deposition, and climate are broad-scale; regional threats that constrain or amplify effects of finer-scale threats and responses to weather events (Figure 2). These local threats include the following:

1. Extreme weather events (drought, flood, wind storms)
2. Land use (human preemption of landscapes, including suburbanization, dryland farming and fragmentation)
3. Land management (primarily livestock grazing, noxious plant management)
4. Establishment and spread of non-native species

Both the broad-scale drivers and local threats are changing through time such that the future of drylands is highly uncertain. For example, surface air temperatures are increasing in some regions for at least part of the season, and atmospheric CO_2 levels are increasing globally, yet global climate models disagree on how precipitation will change in magnitude, seasonality, and even direction (increase, decrease) in drylands. Nitrogen deposition may increase or decrease in the future depending on the source of nitrogen inputs into the atmosphere and the geographic location (e.g., proximity to cities). Local threats are also changing, and in many cases these changes are nonlinear through time and space, and depend on interactions among broad-scale drivers, land surface and ecological characteristics, policy decisions, and local management practices.

In the future, interactions among broad-scale drivers and localized threats are expected to increase the likelihood of creating alternative ecosystem states (e.g., grass states shrub states; perennial plant states annual plant states, etc.). When coupled with changes in atmospheric chemistry, such as CO_2 concentrations and N-loading, these threats are likely to create 'novel ecosystems' (ecosystems comprised of different species, interactions, and processes not possible under current conditions and not reflected in past systems). These alternate states will have different consequences for ecosystem services. Our challenge in this chapter is to determine the vulnerability of different ecosystem services to changes in drivers and ecosystem states, with a focus on the American Southwest. In addressing this challenge, we first sought to (1) briefly describe key ecosystem services in drylands, (2) identify and articulate the consequences of desertification to each ecosystem service (historical to current-day perspective), and (3) explore the vulnerability of each ecosystem service to future state-change effects if existing threats intensify and new threats emerge. We then synthesize this information to determine the threats expected to have the greatest future impact (positive–negative) on desertification and ecosystem services for alternative states, and provide potential actions for mitigation. We conclude with recommendations for land managers, policy makers, and other stakeholders.

4.20.2 Effects of Desertification on Ecosystem Services

4.20.2.1 Regulating Services

4.20.2.1.1 Energy Exchange and Land–Atmosphere Interactions

Understanding how various drivers of environmental change interact to affect the Earth's energy balance is one key to understanding the future state of the Earth system and how humans will need to adapt in order to live more sustainable. Energy balance is the difference between the total incoming and total outgoing energy within the Earth's atmosphere, because the Earth receives almost all of its radiation from the sun – an energy balance of 0 means that all incoming radiation from the sun equals all outgoing radiation. If energy balance increases above 0, the Earth's atmosphere will warm, and it will cool if the energy balance falls below 0. This balance is closely met on the annual average, but intraannual values are not. Many factors control how much energy from the sun arrives at the Earth's surface each year (e.g., sun spots, orbital patterns of the Earth, clouds), how the radiation reaching the surface is reflected or absorbed (e.g., soil color, snow cover, vegetation type and density, soil moisture content), and the extent to which it is trapped or re-emitted back into space by greenhouse gases. The influence of these factors (known as radiative forcing potential) can be assessed for their respective capacity to alter energy balance (Baldochi, in press see Chapter 4.10).

Properties and processes controlling radiative forcing potential in dryland ecosystems have received increased scientific attention for at least three reasons: (1) Arid landscapes with low vegetative cover and high bare ground cover are typically a net sink for radiation and a net source of heat energy to the atmosphere; (2) the land surface area covered by arid landscapes

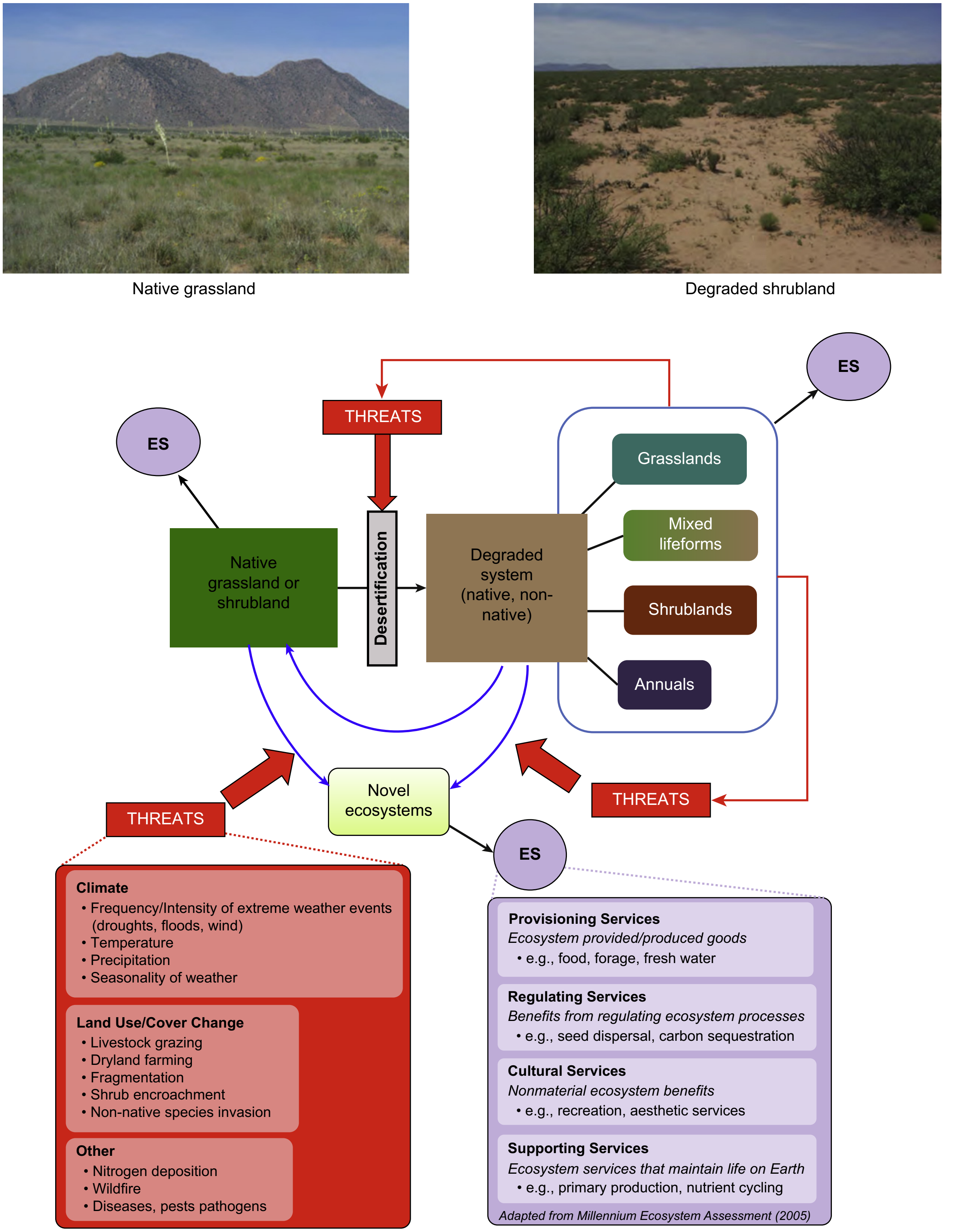

Figure 1 Historically, the predominant state change in arid and semi-arid regions globally was associated with desertification, the broad-scale conversion of perennial grasslands, shrub-steppe, and savannas to systems dominated by xerophytic, unpalatable shrubs on degraded soils or to annuals on degraded soils. Desertification results from cumulative, interacting threats that may intensify with regional climatology. Degraded systems, in turn, would be vulnerable to future threats that may lead to alternative states, including novel ecosystems. Future threats would also influence the rate and extent to which management can repair or restore degraded systems to prior and more desirable states. As state changes occur, ecosystem services (ES) would be impacted. (Photos from Jornada USDA-LTER photo library.)

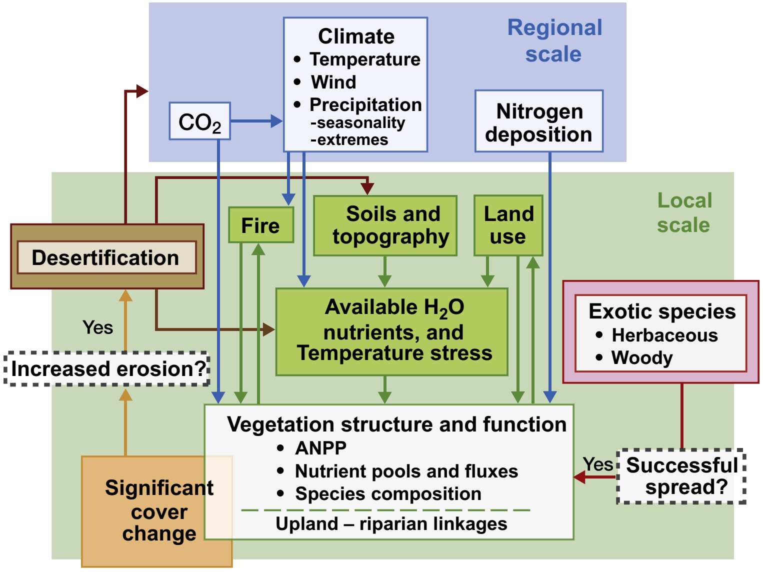

Figure 2 Organizational framework for interpreting climate, land cover effects, and their feedbacks on desertification of dryland ecosystems at local and regional scales (Ryan et al. 2008).

is increasing globally with desertification (Archer 2010); and (3) ecosystem states accompanying desertification (Figure 1) positively reinforce and sustain altered microclimatic conditions of desertified states, thereby making it difficult to restore former ecological states such as grasslands. Additionally, many arid regions such as the American Southwest could become drier and experience more extreme climatic events, such as prolonged droughts and flooding events (Seager et al. 2007). Impacts of increasing human populations, altered land use, and introduced species are expected to interact with climate to influence land–atmosphere interactions with feedbacks to climate and sustainability of drylands in the future. Understanding the sustained and cumulative impacts, and potential tipping points associated with such change remains an urgent challenge to researchers, policy makers, and land managers.

Consequences of Desertification for Energy Exchange and Land–Atmosphere Interactions

Transitions between grasslands and shrublands can alter the energy balance of arid landscapes over relatively large areas (Figure 3; Beltran-Przekurat et al. 2008; Nair et al. 2007). Due to the typically lower vegetation cover and greater reflectivity of soil compared to plants, sparsely vegetated shrublands reflect a larger amount of incoming radiation than grasslands with a lower albedo (Kurc and Small, 2004). When water is lost from soils (evaporation) and plants (transpiration), cooling can occur because energy is dissipated as water transitions from a liquid to a gaseous state (latent heat exchange). This loss of energy to the atmosphere depends on a number of factors, including soil physical properties and moisture content, leaf area within the plant canopy, and the capacity of air masses within the canopy to mix with air above it. The latter is controlled by factors such as wind speed, roughness, and vertical structure of the plant canopy.

Many differences in the partitioning of surface energy balance between grasslands and shrublands depend on the differences in the biology between grasses and shrubs, such as their physiology and timing of growth (C_4 grasses in summer, C_3 shrubs in spring and fall), their root distributions (shallow-rooted grasses can be more coupled to precipitation compared with deep-rooted shrubs that access stored water), and canopy structure (dense bunchgrasses, open shrub canopies). Thus, impacts of shrub encroachment on energy balance can differ among desert systems (Eldridge et al. 2011), and the dynamics at one site do not necessarily translate to others. The need for a more robust understanding of the consequences of land cover change on ecosystem energy balance is a key motivation for desertification research.

Land cover changes that modify surface energy balance affect a gamut of local to global ecosystem goods and services. On a local scale, the increased heat storage associated with depleted soil moisture and altered land surface properties in shrublands can promote water stress and limit photosynthesis in grasses, thereby reducing their productivity, biomass (see Section 4.20.2.3.1), and forage production (see Section 4.20.2.2.2), while creating conditions conducive to the establishment of unpalatable, xerophytic shrubs. In shrublands, soil moisture is likely to be reduced at greater depths due to the deeper penetration of shrub roots compared to grasses (Gibbens and Lenz 2001). Because of the large expanses of shrublands, these local effects manifest to impact landscape to regional scale processes, including sensible and latent heat exchange, heat storage, and surface water balance. These changes can influence and potentially alter regional climate by depleting atmospheric moisture, decreasing cloud cover, and increasing drought cycles as well as modifying radiative forcing potential.

Threats to Future Trends in Energy Exchange and Land–Atmosphere Interactions

Changes in surface energy balance, accompanying and underpinning future stresses of desertification have the

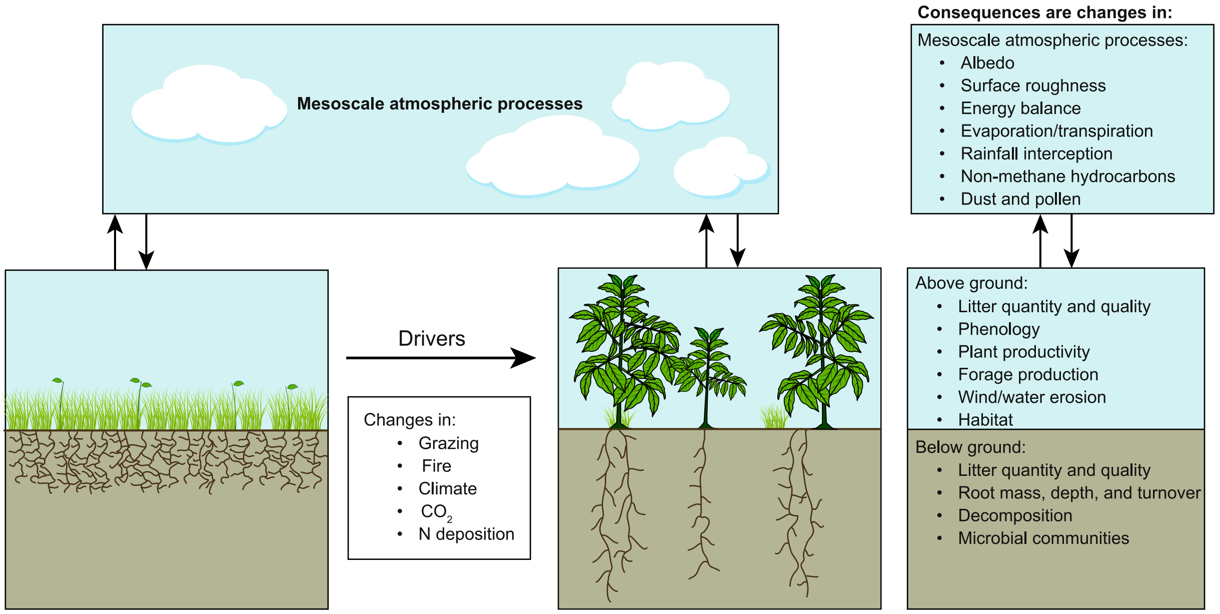

Figure 3 Drivers interact to influence state changes from grass to woody plant dominance with potential consequences for changes in above and below ground ecosystem structure and function, and land surface–atmosphere interactions. Carbon sequestration by plant–soil–microbial processes occurs both above and below ground (Archer 2010).

potential to affect a range of stakeholders over a sustained period of time, due to the broad spatial extent of these changes and the reinforcing feedbacks associated with altered ecosystem states. Warmer, drier conditions accompanying grassland to shrubland conversion would reinforce the displacement of relatively palatable mesophytic grasses by unpalatable xerophytic shrubs with reductions in overall plant productivity, livestock carrying capacity, and vegetation cover (Fredrickson et al. 1998; Barger et al. 2011; Peters et al. 2011). Associated with these changes would be the opportunity for invasion from exotic species, and altered human well-being and health through the increased capacity for dust storms – especially during periods of prolonged drought forecast for the region (see Section 4.20.2.3.2). At a larger scale, reductions in atmospheric uptake potential or enhanced radiative forcing potential of shrublands (see Section 4.20.2.1.2) may result in increased reliance on ecosystems in other bioclimatic zones to uptake carbon dioxide.

4.20.2.1.2 Carbon Storage (Organic, Inorganic)

The amount of carbon released into the atmosphere each year via fossil fuel combustion is estimated at 5.5 Pg (IPCC 2007). While this is a small component of the annual global carbon budget, the cumulative effects on the atmosphere can be quite important. Since 1850, the atmospheric concentration of carbon dioxide (CO_2) has increased from 275 ppm to more than 390 ppm. This increase in atmospheric CO_2 and other greenhouse gases (GHG) is a major contributor to documented increases in average global surface temperature (1 °C since 1900), and is hypothesized to have major impacts on regional climate (Seager et al. 2007). Substantial resources have been devoted to developing GHG mitigation technologies to reduce emissions; however, carbon sequestration in natural and managed ecosystems remains the only economically viable means of removing carbon from the atmosphere (Pacala and Socolow 2004; but see Section 4.20.4). Vegetation, via photosynthesis, takes up carbon in the form of CO_2 from the atmosphere, converts this greenhouse gas into complex organic structures, and then transfers it into the soil with the death and decomposition of plant leaves, roots, and stems. This organic plant debris is then converted to other stable carbon compounds via microbial assisted processes. The regulation of climate via CO_2 sequestration by plant–soil–microbial processes (Figure 3) is an important ecosystem service threatened by desertification where both the levels of stored soil carbon and the capacity to increase its storage are diminished. In addition, many drylands are heavily grazed and the carbon removed by grazers is exported off-site. Here we discuss both organic and inorganic soil carbon that are important in arid and semi-arid regions of the world, including the American Southwest.

The amount of organic (readily exchangeable) carbon stored in soils and vegetation globally exceeds 2000 Pg (1 Petagram = 10^{15} g = MMT). Soils contain 1400–1600 Pg of organic carbon, and vegetation is estimated to contain 500–600 Pg (IPCC 2007). Of this total amount, about 120 Pg moves back and forth between the soil–vegetation complex and the atmosphere on an annual basis (flux). By comparison, oceans with the largest pool contain about 38 000 Pg and the atmosphere contains about 750 Pg. Dryland ecosystems contain approximately 363 Pg of carbon (Post et al. 1982). This pool of carbon is equal to the amount stored in croplands and wetlands combined (370 Pg), and is only slightly less than pools associated with forest ecosystems (470 Pg). Although drylands represent a significant portion of the global soil carbon pool, managing them for an increase in storage is a challenge. For any specific unit of land, high spatial variability and year-to-year changes in factors controlling carbon flux (precipitation, temperature) make management highly uncertain, and prediction and measurement difficult and expensive. At larger scales, the same problems are confounded by the vast areas involved, and make credible accounting systems and the policies and programs they support difficult to construct.

Inorganic carbon, stored as calcium carbonate ($CaCO_3$), is also a significant portion of the global carbon budget (Figure 4(a)). The global amount exceeds 940 Pg, making it the third largest carbon pool (Eswaran et al., 2000). Inorganic carbon exists in arid and semi-arid soils as light colored subsoil horizons that develop when small calcite crystals (2–10 μm) are precipitated in the pore spaces between sand and silt particles. The longer a dryland soil has been exposed to weathering at the Earth's surface, the greater the amount of inorganic carbon in its subsoil.

The role that inorganic carbon plays in the global carbon cycle, especially with respect to carbon storage, is more complicated than organic carbon because it depends on the

(a)

(b)

Figure 4 (a) Inorganic carbon (shown as light colored layer at variable depths), stored as calcium carbonate ($CaCO_3$), is a significant portion of the global carbon budget. Lee Gile and John Hawley in background (Photo from Jornada USDA-LTER photo library). (b) High connectivity of bare areas in shrublands compared to grasslands results in higher runoff and greater losses of nutrients and sediments (photo credit: Brandon Bestelmeyer (USDA)). (c) A massive dust storm moves across Phoenix on 5 July 2011. Photo by Dave Seibert/The Arizona Republic (http://www.azcentral.com/photo/Community/PhoenixCentral/19441). (d) Prescribed fire is an important tool used to prevent shrub encroachment into arid and semi-arid perennial grasslands. Photo credit: Guy McPherson (University of Arizona).

(c)
(d)


Figure 4 (*Continued*).

calcium biogeochemical cycle. A lexicon to explain how and when different types of inorganic carbon are formed is still developing. For example, 'Soil Carbonate' is the broadest category and refers to the total amount of carbonate in soil. This category is subdivided into 'Lithogenic Carbonate' (carbonate particles physically derived from limestone or similar bedrock) and 'Pedogenic Carbonate' (carbonate crystals precipitated from solutions in the soil). If the source of calcium in pedogenic carbonates is from preexisting carbonate minerals, such as particles of limestone, there is no gain in carbon storage with its formation. This is because the amount of carbon dioxide (CO_2) consumed to form carbonic acid, which reacts with and dissolves the limestone particles, is the same amount of CO_2 released upon the formation of pedogenic carbonate (Monger and Martinez-Rios 2000). However, pedogenic carbonates whose calcium is derived from silicate minerals is a potentially strong sink for atmospheric CO_2 because the carbon in the $CaCO_3$ precipitate is derived from CO_2 respired from roots and microbes; this CO_2 could otherwise leave the soil and return to the atmosphere.

Consequences of Desertification for Carbon Storage

Drylands with low plant production (see Section 4.20.2.3.1) and low organic soil carbon are vulnerable to extreme weather events (e.g., drought) and disturbance, such as livestock overgrazing (**Figure 1**). Desert grasslands in the American Southwest are typically net carbon sinks. With conversion to shrublands, arid lands tend to become net carbon sources (Barger et al. 2011), and adversely affect air quality by increasing dust loading and the concentration of volatile organic carbon compounds (see Section 4.20.2.3.2). Cases where shifts from grass to shrub dominance do not change the total amount of organic carbon in the soil pool have also been documented. In these instances, the spatial distribution of soil organic carbon (SOC) is strongly impacted, with SOC becoming concentrated beneath shrub canopies with very little SOC in bare soil gaps between plants. This shift in the distribution of SOC has important consequences for soil properties that feed back to influence the availability of water and nutrients to plants, animals, and microbes (see Section 4.20.2.2.1) and the nature of land surface–atmosphere interactions (see Section 4.20.2.1.1).

Desertification also poses a threat to inorganic carbon storage, which contains roughly 10 times more carbon than the amount in soil organic matter. When desertification reduces plant production, the amount of CO_2 respired into the soil and the abundance of microorganisms, which are partially responsible for the precipitation of $CaCO_3$, decline (Monger et al. 1991). In addition, desertification causes erosion and exhumes subsoil horizons. When wind and water erosion expose long-buried inorganic carbon to the geochemical environment at the land surface, $CaCO_3$ can break down and contribute CO_2 to the atmosphere (Serna-Perez et al. 2006; Tamir et al. 2011).

Threats to Future Trends in Carbon Storage

The net storage or loss of carbon in an ecosystem is the balance between carbon uptake by plants and carbon released by plant and microbial respiration. Because levels of soil organic matter are inversely related to mean annual temperature in many arid regions, increases in regional temperature would promote losses of soil carbon to the atmosphere, exacerbating increases in atmospheric CO_2. This accelerated carbon liberation might be compounded by declines in levels of carbon sequestration, which would decrease with decreasing rainfall. Grazing by livestock is the predominant land use in drylands. Excessive grazing is detrimental to plant productivity and can further accentuate declines in soil organic matter. Land management can contribute to the mitigation of radiative warming from atmospheric CO_2 by adjusting practices to increase or protect the amount of carbon (C) stored in soils and vegetation. In particular, stocking at sustainable levels to maintain desirable shrub:grass ratios, responding quickly and decisively to drought to avoid degradation, and developing and implementing technologies, such as appropriate plant materials, reseeding methods, and management guidelines to restore degraded areas could increase soil carbon storage at approximately 0.15 Gt year^{-1} over the next 100 years (Thomson et al. 2008). Although this level of potential C sequestration is relatively low per unit of land area compared to other land-use categories, the vast land area in drylands and strong positive correlation between increased sequestration and other desirable benefits makes sequestration worth pursuing. However, by far the most effective strategy, given the potential for desertification-induced losses of soil carbon in rangelands, is to develop tools, policies, and programs to identify arid lands at risk before they are seriously degraded, and to implement management to halt or reverse the degradation.

4.20.2.2 Provisioning Services

4.20.2.2.1 Water Quality and Quantity

An optimum quantity and quality of water are needed to maintain natural and human ecosystems. The way that land, water, and atmospheric resources in drylands are exploited or developed can have serious effects on ecosystem provisioning and regulating services related to water. Landscapes in drylands are organized into watersheds of different sizes, ranging from small headwater or upland basins to larger watersheds that encapsulate the valley floor. As such, watersheds are critical for water provisioning and use in the American Southwest. However, drylands are continually operating under conditions of limited water availability since evapotranspiration demand greatly exceeds low precipitation amounts. As a result, dryland ecosystems have evolved to maximize their efficient use of water, although episodes of drought or flooding can significantly alter the balance between water availability and ecosystem function.

Many landscape characteristics in drylands, including the spatial distributions of plants and animals, are shaped by the availability and distribution of water and the timing of its delivery. As a result, hydrologic conditions can vary substantially over short distances, with common occurrences of ephemeral channels and isolated perennial reaches fed by shallow groundwater or springs. Although these riparian features occupy less than 1% of the entire landscape, they have disproportionately large impacts on ecosystem productivity and biological diversity. Water availability and its influence on the landscape also have a direct impact on atmospheric conditions, which can lead to short- and long-term feedbacks to weather and climate (see Section 4.20.2.1.1).

The natural scarcity of water in drylands, coupled with the ever-increasing demands for water from rapidly expanding human populations, constitutes a major challenge in watershed management. Stakeholders affected by inadequate amounts and quality of water in drylands include ranchers and pastoralists (livestock), farmers (crops), ecologists (natural vegetation), and the public (recreation, wildlife, residents). As suburban or urban land uses proliferate, additional stakeholders include towns and cities (and their residents) who become important users of water, as agricultural or land-use rights are transferred. These stakeholders can also impact water in drylands through effects of grazing, mining, and urbanization activities on the natural landscape. Mining in the Southwestern United States in particular, has reduced water availability and impacted its quality in areas adjacent to and downstream of excavations.

Consequences of Desertification for Water Supplies

Desertification and the encroachment of woody plants into grasslands have direct impacts on the distribution of water and its quality within landscapes (Huxman et al. 2005). Since plant–water relations are bidirectional, a change in the dominant plant functional type can result in a myriad of impacts and feedbacks in the water, carbon, nutrient, and sediment cycles. Above and below ground plant characteristics affect local radiation, rainfall interception, root water uptake, soil moisture redistribution and litter and soil production, among other processes (Figure 3). Higher overall evapotranspiration losses occur when shrublands replace grasslands as a result of larger bare areas and greater plant water use efficiency of shrubs compared with grasses (Dugas et al. 1996). A greater demand for water by shrubs decreases overall water availability, with subsequent impacts on soil moisture, runoff generation, groundwater recharge, and transport of dissolved and particulate matter by water. Shrublands on sandy soils located on level topographic positions have been found to use most or all of the water from precipitation, while grasslands allow some deeper recharge. By contrast, the shift from grassland to shrubland on slopes and rocky soils can increase the amount of runoff and rates of water erosion. The connectivity of bare areas is typically greater in shrublands compared to grasslands, resulting in higher runoff and greater losses of nutrients and sediments (Figure 4(b)). This, in turn, translates into losses of soil fertility, the dissection of landscapes into rills and gullies, and increased sediment loads to downstream locations. The latter is the major cause of reductions in water quality in drylands. Interactions at the plant-to-patch scale in grasslands and shrublands aggregate to basins and watersheds, thus affecting water, nutrient, and sediment yield in broader areas.

Finally, dust emitted from desert regions, due to human activities and desertification, has the potential to impact mountain snow hydrology (Painter et al. 2010). Dust deposited on snow can significantly impact the amount of solar radiation absorbed by the snow, increase the rate of melt, and the rate at which meltwater is produced and delivered to river systems. These changes have the potential to impact water management and decrease the amount of water in major river systems (e.g., the Colorado River).

Threats to Future Trends in Water Quantity and Quality

Desertification adversely impacts water and sediment yield. Plausible changes in the intensity, duration, and frequency of precipitation events would accentuate these impacts. For example, the balance between grasses and shrubs which affects numerous ecosystem services is influenced by the amount, timing, and seasonality of precipitation and the size of rainfall events (e.g., Good and Caylor 2011). Should they occur, shifts between summer and winter precipitation or changes in the frequency of extreme storm events that deliver precipitation in short, intense pulses would be expected to tip the balance between grasses and shrubs either directly or indirectly via higher surface runoff, accelerated erosion, and changes in soil moisture and groundwater storage and recharge regimes. Higher temperatures would reduce the effectiveness of rainfall by increasing evaporative demands while concomitantly increasing water requirements and levels of physiological stress in plants and animals. This combination of increased runoff, increased soil evaporation, and reductions in plant performance would alter ecosystem rain-use efficiency.

Increases in convective storm intensity would increase the incidence and magnitude of surface runoff events and associated erosion. This, in turns, would lead to reductions in soil depth (critical for water storage) and fertility on upland sites and hence forage production (see Section 4.20.2.2.2) and ecosystem productivity (see Section 4.20.2.3.1). Particulates and nutrients in the sediments carried in these runoff events would be transported in ephemeral channels and eventually end up in playas or streams where water quality and the life span of man-made structures aimed at capturing water (e.g., ponding dikes, stock dams, and reservoirs) could be reduced.

4.20.2.2.2 Food and Fiber

Drylands contribute significantly to annual global food and fiber production owing to their extensive geographic extent on all continents. About 37% of the total annual global value of food and fiber production originates from drylands. One-half of this value is livestock products, primarily from extensive grazing of cattle, sheep, and goats, and one-half of livestock production globally each year is harvested from drylands used as grazing lands. In addition, about 10% of non-livestock food and fiber production (e.g., cereal grains and cotton) are produced from rain-fed systems in drylands. The remaining dryland food production originates from irrigated systems.

Of the two billion people living on drylands, about 800 million are farmers engaged in food and fiber production. Livestock ownership sustains about 675 million rural poor, predominately in the developing countries of the world. Estimates are that one in ten humans is involved in animal husbandry. Livestock are thus important economic assets and sources of income for rural people on all continents, except Antarctica. Although per capita demand for meat products may be at saturation levels within developed countries, demand for meat products is on the rise within developing countries, including China, Korea, and Brazil (Steinfeld et al. 2010). Demands for meat products are projected to increase 2–3% per annum. Globally, meat production is increasingly from intensive, confined systems, but extensive dryland production systems are the source of many of the animals that are 'finished' in confined systems and will continue to supply local meat demands and sustain rural economies, irrespective of a country's economic status. Domesticated ruminants are well suited to both the biophysical and the socioeconomic conditions inherent to drylands.

In the American Southwest, the issue of food and fiber production from drylands has become less relevant over recent decades, despite growing global demands described above. The use of these lands for food and fiber production has diminished significantly from peak livestock numbers in the mid-twentieth century (Fredrickson et al. 1998). At present, it is common for public land allotments to be unused by livestock. These declines are mirrored across North America: cattle, sheep, and goat numbers (expressed as animal units) have declined by over 25% since 1979. In addition, recent rancher surveys reflect other characteristics of an industry in decline, including increased age of primary owners, smaller herd sizes, and growing importance of non-economic rationales for ownership, such as lifestyle and recreational motivations.

Consequences of Desertification for Food and Fiber

Desertification has had less of an impact upon food production than expected based on meat production. Ruminants have wide dietary preferences, and maintain inherent capacities to digest cellulose regardless of the dietary sources of forage. At least 10–20% of drylands globally are degraded through desertification processes, yet animal production has continued to increase. For example, the dramatic increases over the last two decades in goat numbers, averaging nearly 1.2 million additional goats around the world each month, in part reflect adjustments of meat production systems to altered landscapes and altered socioeconomic conditions. Certainly, degraded conditions due to overgrazing have caused significant reductions in capacities of drylands to produce forage with resulting losses in meat production at certain times on all continents, over the past century. However, the widespread impacts of overgrazing upon food production have likely been overestimated. In addition, within local regions where overgrazing has more recently resulted in degraded conditions, policies have often been implemented to constrain, if not outright ban, continued livestock grazing (Estell et al. 2012).

Threats to Future Trends in Food and Fiber

Degradation associated with land conversion and salinization is expected to influence drylands more so than livestock grazing. Farming on lands marginally suited for crops has been, and will likely continue to be, a major source of land degradation. Cereal production will likely need to increase by 0.5 billion tons per year over the next two decades owing to the demands of increasing human populations. In lieu of unit-area production increases on lands currently being cropped, this increase in crop production would be supplied by conversion of drylands. These drylands will be poorly suited for cropping, owing to thin, rocky soils on steep slopes, and low, variable, and unpredictable precipitation. A high rate of crop failure on such lands makes them susceptible to soil erosion and subject to high rates of abandonment.

The world food economy is being driven by continuing dietary shifts toward consumption of meat products. However, this shift will affect drylands differently than in the past. Impacts of the late nineteenth and early twentieth centuries were typically the result of excessive livestock stocking rates. The current settings and drivers are different. Given the saturation of per capita meat demand in developed countries, fewer livestock will graze drylands of Australia, North America, and Europe. Concurrently, as seen in recent decades, livestock numbers will continue to increase on the Asian and African continents where per capita meat demand continues to increase, although likely at a decelerated rate in coming decades. However, the demand for meat will be increasingly serviced by swine and poultry, and these more intensive livestock production systems will require increased reliance on and production of cereal grains. This demand for grains will drive conversion of drylands to cropland agriculture, and will place additional land area at risk for desertification. Reliance on traditional free-ranging livestock production systems will continue to decline, and will lead to shifts in the valuation of drylands for supplying other goods and services.

These shifting land uses represent opportunities to enhance the supply of other goods and services, but will require increased attention to valuing goods and services other than traditional food and fiber production. An often overlooked requirement of this valuation will be the need for methods to accurately assess benefits that result when management practices change to enhance the supply of these alternative goods and services.

4.20.2.3 Supporting Services

4.20.2.3.1 Plant Production, Carbon and Nitrogen Cycling

Primary production is a central process in the functioning of an ecosystem by which plants capture energy coming from the sun and transform it into chemical energy for microorganisms, animals, and humans. The flow of energy from the sun and back to outer space is coupled to the carbon cycle in most ecosystems. Plants capture carbon dioxide from the atmosphere and convert it to chemical energy (carbon based compounds, called carbohydrates) using light energy from the sun along with water and soil nutrients. This process is known as photosynthesis in plants, and the measurement of its magnitude represents ‘primary production’ in ecosystems. Primary production is estimated by assessing changes in plant mass over a known period of time (weight of biomass per unit area of land per unit of time (e.g., kg/ha/year)).

In drylands, plant production is limited by water availability, and nitrogen (N) is the second most important limiting factor. Average annual plant production increases with annual precipitation across a range of grasslands and shrublands located throughout the central and western United States. Dryland ecosystems with extremely low precipitation are most frequently limited by water availability, except during short periods of time after precipitation events when they can become limited by N availability. Water and N cycles are closely linked because their availability controls the activity of microorganisms and plants, which are sources and sinks of reactive N. However, the response of plants and microbes to water availability is not in synchrony because of their differential sensitivity to water availability (Schwinning and Sala 2004). For example, droughts negatively affect plant uptake more than they affect microbial mineralization. Thus, during dry periods, arid ecosystems tend to accumulate nitrate, which is one of the most common forms of mineral N in soils. During wet periods, however, mineral N concentration in soils is lower than in dry periods mostly as a result of increased demand by actively growing plants.

Primary production is a supporting ecosystem service (Figure 1) necessary for the production of all other services. Humans benefit from primary production indirectly because provisioning, regulating, and cultural services depend on it. In drylands, the major provisioning service is food production, and the growth of livestock and wild animals upon which humans depend is directly related to the abundance of plant biomass or primary production, and is related to forage production (see Section 4.20.2.2.2). Similarly, most regulating services depend on primary production that affects plant cover of the land surface, which in turn affects albedo and water balance and thus regulates climate (**Figures 2 and 3**; see Section 4.20.2.1.1). Primary production also affects disease regulation (see Section 4.20.2.3.5). For example, increased fall–spring precipitation associated with the El Niño phenomenon results in an increase in primary production in the American Southwest that leads to an explosion of deer mice (Peromyscus spp.), the rodent vector of the hantavirus (Yates et al. 2002). Primary production directly affects carbon sequestration (see Section 4.20.2.1.2) because it represents the major input of organic carbon into the relatively stable soil organic matter pool. Respiration of plant roots and decomposition of plant material provide the CO_2 needed to form pedogenic carbonates, which are a strong C sink in drylands (see Section 4.20.2.1.2).

Consequences of Desertification for Plant Production

Primary production is a relatively resilient ecosystem supporting service. However, even subtle changes in the nature of primary production can have major impacts on provisioning and regulating services. Desertification affects provisioning ecosystem services, such as food production, first by changes in species composition and species abundance. A replacement of palatable and grazing sensitive species by unpalatable, grazing resistant species has a relatively small effect on primary production (Peters et al. 2011), but may have a disproportionately larger effect on livestock production (Fredrickson et al. 1998). Grazing of herbaceous plants is often accompanied by the encroachment of unpalatable shrubs that feed back to reduce forage, and hence livestock production. In cases where perennial herbaceous plants give way to annual plants, production becomes less predictable and confined to narrow windows of time that correspond to the short life-span of annual plants (weeks to months). These short bursts of productivity can reduce soil water and nutrients needed by perennial plants that can be competitively displaced from the ecosystem. Furthermore, these annual plants produce far more biomass than animals can consume. When they complete their life cycle and die, they generate large amounts of fine, dry litter that is highly combustible. This increase in litter can dramatically alter the fire regime compared to historic levels (see Section 4.20.2.3.3). Grazing-induced reductions in perennial plant productivity and cover also expose the soil surface to erosional forces that then feed back to further accentuate degradation (see Sections 4.20.2.1.1 and 4.20.2.3.2). Erosion of the soil by wind caused by human activities and desertification processes that cause emission of nutrient-rich dust particles have the potential to change the biogeochemical properties of soils by reducing fertility (e.g., Okin et al. 2001; Neff et al. 2005; Li et al. 2007).

Planting of non-native grasses to restore desertified grasslands and improve forage production for livestock has been a long tradition in the drylands of North America. The US Department of Agriculture has maintained active research programs aimed at screening, breeding, propagating, and introducing plant materials collected from other parts of the world. In the Southwest United States, perennial grasses from Africa, notably Lehmann lovegrass and buffelgrass, were widely planted in the mid- to late 1900s. Since that time, they have expanded spatially to the point where they now threaten biodiversity across much of the region (see Section 4.20.2.3.4).

Threats to Future Trends in Plant Production

Because plant production is governed by both water and nitrogen, changes in one or both of these drivers in the future would impact patterns in production and the services that depend on it. Directional decreases in precipitation, such as an increase in the frequency, intensity, and duration of drought, would result in decreases in plant production. These decreases would be particularly so for perennial grasses and would likely make additional areas susceptible to shrub invasion and desertification (Fredrickson et al. 1998). Increases in precipitation, combined with sustained livestock grazing, would accentuate effects of dry periods on transitions from grasslands to shrublands. By contrast, directional increases in precipitation may have unexpected effects in shrublands that are commonly perceived as highly resistant to change. A 5-year wet period resulted in a nonlinear increase in grass production in shrublands as a result of grass seedling establishment and growth (Peters et al. 2011). Because large grass production was maintained even in subsequent dry years, this wet period may have initiated a state change reversal from shrublands to grasslands that has not been observed over the past 150 years. Subsequent wet periods are expected to result in similar state change reversals. Increase in nitrogen to these systems from atmospheric deposition would also favor grasses that are currently nitrogen limited, compared with shrubs, such as mesquite that can fix their own nitrogen.

Clearly, changes in land use have effects on regional climate (Pielke et al. 2011; Avila et al. 2012), as well as effects on plant production. Although conversion of grazing land to agricultural land through water redistribution may have positive short-term effects on plant production, the long-term impacts on water quality and quantity, and trade-offs with increasing human demands for water (see Section 4.20.2.2.1) may limit the feasibility of these land conversions in the future.

4.20.2.3.2 Air Quality

Air quality impacts all inhabitants of dryland regions. The atmosphere is comprised of gases, as well as, very small solid or liquid particles known as aerosols. One of the most obvious aspects of air quality is visibility, which is a function of both the amount and type of aerosols in the air. The most important contributor to low visibility in drylands is mineral dust, which is produced when strong winds strip particles from non-vegetated surfaces in the landscape, and a portion of those particles become suspended in the air column (Okin et al. 2006). Large dust storms result in significant reductions in visibility, and create hazards to both air and road travel (**Figure 4(c)**). Reports of major traffic accidents along roads and highways are common from dryland regions. Dust can also contribute significantly to vehicle and aircraft maintenance costs.

Dust can have a profound impact on human health (see Section 4.20.2.3.5). For instance, Coccidioidomycosis (known as valley fever) is a sometimes fatal disease caused by a fungus endemic to the American Southwest that is transported on dust (e.g., Kolivras and Comrie 2003). Desert regions with significant dust can frequently violate health standards for respirable material (PM10 and PM2.5, particulate matter less than 10 μm and 2.5 μm, respectively), and desert dust has been positively linked to hospitalization of children due to asthma.

Consequences of Desertification for Air Quality

Desertification often leads to either a reduction in vegetation cover or a reorganization of that cover so that the size of unvegetated gaps and amount of bare ground between vegetation increases. These larger bare gaps are more prone to wind erosion and the dust emission that accompanies it. Unvegetated areas made directly by humans, whether roads, construction sites, or off-highway vehicle tracks, also contribute to dust emission, particularly when the disturbance is aligned with the prevailing wind direction. Soil surface disturbance of natural desert stabilizers (biological and physical crusts, desert pavements) due to agricultural, recreational, and grazing activities has resulted in large increases in dust production in the Southwestern United States since 1850 (Neff et al. 2008). Drought, by reducing plant cover and production (see Section 4.20.2.3.1), can also result in large bare areas and hence increased dust emission. Aerosols and gaseous components in smoke significantly impact air quality and can be linked, in some cases, to desertification. For instance, throughout much of the Sonoran Desert, shrub communities that evolved in the near-absence of fire are being invaded by warm-season grasses that can sustain high enough fuel loads to result in wildfire (see Section 4.20.2.3.3) (D'Antonio and Vitousek 1992). In these areas, smoke and gas emissions due to fire would have been, in the absence of this form of desertification, a rare occurrence. Dust emissions following these fires would be elevated until vegetation cover is restored.

Finally, many desert plants are known for having strong scents, a common indicator of the emission of volatile organic carbon (VOC) compounds from their leaf surfaces. Mesquite and creosote bush are common shrubs that have increased throughout the American Southwest with overgrazing by livestock and drought that led to broad-scale desertification. These shrubs are strong producers of VOCs compared with grasses. In their gas phase, VOCs from desert vegetation can contribute to anthropogenic emissions and lead to air quality standards being exceeded. Furthermore, VOCs can produce liquid aerosols that reduce visibility while enhancing the longevity of GHGs and radiative forcing (see Section 4.20.2.1.1).

Threats to Future Trends in Air Quality

The two largest threats to air quality in drylands in the future are changes in land use and possible changes to drier conditions. Changes in land use that increase bare ground on soils susceptible to wind erosion would undoubtedly create an increased frequency of poor air quality in drylands. Similarly, an increase in periods of drought that reduce vegetation cover would lead to an increased occurrence of dust emission events.

4.20.2.3.3 Disturbance Regimes: Wildfire

Wildland fire is commonly perceived as a threat to human life, property, and, in some cases, ecosystem services. Many people believe that fires should be prevented and, if they do occur, that rehabilitation and restoration actions may be warranted. It is less appreciated that fire historically played a major role in maintaining ecosystems in their current, natural, or otherwise desired condition (e.g., Johnston and Klick 2012). Ecosystems are affected by fire at various levels of intensity and patterns of burning (e.g., within and among years and across landscapes). The fire regime, or the magnitude, temporal, and spatial characteristics of fire, partially defines many ecosystems. Like many other agents of natural disturbance (e.g., extreme weather events, pest outbreaks), fire regimes can promote biodiversity, heterogeneity, and dynamic ecosystem stability. Fire regimes are also a very strong natural selection factor that influences the evolution and distribution of species. When fire regimes are altered, populations, communities, and ecosystems can be affected along with the services they provide.

Role of Fire in Desertification with Consequences for Ecosystem Services

Dryland ecosystems have a characteristic fire regime that both affect, and are affected by, the composition and structure of vegetation. In grasslands of the American Southwest, the pre-Anglo-European settlement fire regime was one of moderate intensity surface fires carried by perennial grasses in late summer when plants were dormant and primary production (see Section 4.20.2.3.1) was at its peak 28 (**Figure** 4(d)) (McPherson 1997). Livestock grazing beginning in the mid-1800s, and landscape fragmentation and fire suppression activities during the mid- to late 1900s, reduced the amount and continuity of grass fuels and hence the frequency and extent of fires (Allen, 2007). With less fire, woody species expanded into areas where frequent fire previously excluded them, resulting in a decline in grasslands and an increase in areal extent of shrublands. As woody plant abundance increased, grass production further decreased, while bare ground increased, further reducing the probability that fire would start and spread, thus providing a positive feedback that reinforced the maintenance or increase in woody plant abundance (Ravi et al. 2007). The replacement of grasslands by shrublands following cessation of fire in drylands results in lower levels of primary production (see Section 4.20.2.3.1), lower carbon sequestration potential (see Section 4.20.2.1.2), and higher cover of bare ground; all of which feed back to influence the region's climate (see Section 4.20.2.1.1) and impact air and water (see Sections 4.20.2.2.1 and 4.20.2.3.2) resources.

By contrast, shrublands and savannas were historically characterized by less frequent and patchier fires compared to grasslands. Longer intervals between fires allowed shrubs and trees to establish and grow sufficiently large to survive surface fires. Removal of fine fuels by livestock grazing and suppression of fire had less dramatic effects on these fire regimes.

Threats to Future Fire Regimes

Fire alone may not be sufficient to maintain native perennial grasslands under all conditions. Fire regimes depend on fine-fuel production by grasses, and influence the capacity for grasslands to persist only if livestock grazing regimes, soils, and climate are conducive to the establishment and growth of perennial grasses. Threats associated with desertification that affect soil fertility and the distribution of soil nutrients, or that result in reduced soil moisture levels during the summer, can reduce grass productivity and cover, thus reducing fire frequency and intensity, and increasing the chances of woody plant encroachment.

Similarly, soil nutrient loss and horizontal homogenization in shrublands invaded by non-native grasses may prevent re-establishment of shrubs. Changes in the amount and season of lightning can also affect the frequency and seasonality of fire, and the balance of grasses versus woody plants. Landscape fragmentation can isolate patches of fuels, and limit the size and spread of wildfires; thus muting the potentially positive effects in maintaining grassland or negative effects in maintaining shrub steppe and woodlands. However, fragmentation may also facilitate the application of prescribed fire during the summer season by providing pre-established fuel breaks that make individual fires easier to manage. Increased nitrogen deposition and elevated concentrations of atmospheric carbon dioxide can promote the establishment and dominance of non-native plant species, which can affect fire regimes if they alter the structural and seasonal characteristics of fuels (Brooks et al. 2004).

In addition, invasions by non-native grass species have had tremendous effects on fire regimes. Non-native perennial grasses, such as Lehmann lovegrass and buffelgrass, and annual grasses, such as red brome, have increased the mass and continuity of fuels and decreased the time required for post fire fuels to return to conditions that can carry subsequent fire. These changes have increased the frequency and extent of fires in shrub steppe such that native woody species cannot persist and non-native grasslands now predominate. These conversions of vegetation types and fire regimes have concomitant negative effects on individual species and overall biodiversity (Ravi et al. 2009).

4.20.2.3.4 Biodiversity

Biodiversity refers to the range of variation found among microorganisms, plants, fungi, and animals. Biodiversity is typically measured using numbers of species in an area and how rapidly the identity of species changes over space and time. Biodiversity indirectly affects ecosystem processes, such as net primary production (see Section 4.20.2.3.1), decomposition (see Section 4.20.2.1.2), biological control of pests (see Section 4.20.2.3.5), and even physical processes affected by plants such as water and wind-driven soil erosion (see Sections 4.20.2.2.1 and 4.20.2.3.2). Biodiversity is also an important basis for sustenance, recreation, and spirituality for people who inhabit or visit drylands. Stakeholders with direct interests in biodiversity include hunters, naturalists, tourists, exurban homeowners, and ranchers. These stakeholders may have differing values for particular species comprising biodiversity, including species that are: game (mule deer, scaled quail), threatened with extinction (Chiricahua leopard frog, Chihuahua Scurfpea), pests (coyotes, woodrats, certain shrubs), regulators of ecosystem processes (termites, grasses), or recreation (native birds, wildflowers). These varying values guide how biodiversity is managed in drylands (see Section 4.20.2.4.1).

Consequences of Desertification for Biodiversity

Biodiversity in drylands is strongly influenced by the high variability in stress (e.g., temperature) and resource availability (e.g., water and plant production) over time and space, particularly when compared with other ecosystem types (Stafford Smith and McAllister 2008). Dryland species often have specific adaptations that allow them to tolerate or avoid resource scarcity and stress, and certain species are highly specialized to particular conditions. Land uses, including variations in grazing pressure, conversion of wildlands or rangelands to crop agriculture, and urbanization interact with environmental variability and species adaptations to cause changes in biodiversity. Of particular concern, desertification associated with past heavy livestock grazing has reduced grassland associated species when shrubs or bare ground dominate ecosystems (Archer 2010; Eldridge et al. 2011). Similarly, historically shrub-dominated ecosystems and their associated flora, fauna, and microorganisms were altered when invasive annual grasses become dominant (Ravi et al. 2009). In such cases, biodiversity of a specific functional group of organisms (e.g., ants or breeding birds) may be reduced or the identity of species may change with no net loss of species numbers at a local scale (**Figure 5(a)**). Often, however, certain species decline in abundance, so these species become the focus of biodiversity concerns and management efforts (**Figure 5(b)**).

Threats to Future Trends in Biodiversity

In general, the extensive loss of formerly widespread habitat types due to past agricultural practices or non-native species invasions focuses management attention on the preservation and restoration of currently rare habitat types and their dependent species, such as reducing shrub cover to promote open perennial grasslands in the Southwestern United States (Archer et al. 2011). New challenges to rare habitat types in drylands are also emerging, including increasing aridity, and solar and wind energy development that is increasingly focused in drylands, and conversion of the more humid portions of drylands to crop agriculture (see Section 4.20.2.2.2). Mapping, model-based forecasting, careful land-use planning, and monitoring will need to be carefully coordinated as such novel conditions expand in order to prevent the additional loss of biodiversity elements.

4.20.2.3.5 Disease, Pests, Pathogens

The fate of disease in a changing environment is a significant and complex question for scientists and decision-makers alike. For human disease, outbreaks and altered patterns of disease are linked to both biophysical and social factors as part of coupled natural-human systems. Infectious diseases, those that are transmissible and caused by pathogens such as viruses, bacteria, fungi, protozoa and parasites, are particularly susceptible to interactions between ecosystems and human-related changes in land use and cover. Often, these pathogens are associated with a vector species that is part of the transmission cycle. Diseases and human health issues of particular importance in the American Southwest include valley fever (*Coccidioidomycosis*), Hantavirus, plague, and West Nile virus.

Consequences of Desertification to Disease, Pests, and Pathogens

Disease and its outbreaks can be depicted in an epidemiological triangle, comprising the environment (e.g., habitat, climate), a host (e.g., humans), and a pathogen (e.g., malaria parasite). Where applicable, the middle of the triangle includes a vector (e.g., mosquito, rodents, and ticks) that connects all three points of the triangle (Comrie 2007). The impacts of planned or unforeseen interactions among natural and human systems can alter relations across the triangle. Amplified disease threats can

Figure 5 Biodiversity can be increased, decreased, or unchanged with desertification that depends on focal species of interest: (a) pronghorns (*Antilocapra americana*) at the USDA ARS, Jornada Experimental Range, USA, are considered of 'least concern' by the IUCN red list of threatened species, and (b) banner-tailed kangaroo rats (*Dipodomys spectabilis*) are ecosystem engineers of the native grasslands in the American Southwest that are considered 'near threatened' by the IUCN red list of threatened species as a result of desertification and shrub invasion. Photos credit: Andrea Campanella (New Mexico state University).

occur through new combinations of suitable conditions (e.g., restricted vector habitat, urbanization) leading to increases in the pathogen or vector populations or via greater host exposure. Importantly, disease outbreaks can also occur if key regulating services provided by the ecosystem (Figure 1) are diminished (Irwin and Ranganathan 2007). For example, desertification can change surface water availability, abundance of mosquito predators, and temperature, all of which affect the effectiveness of the mosquito as a disease vector.

Several kinds of regulating services provided by ecosystems are relevant to disease and pathogens in drylands. For example, riparian systems promote clean water by acting as a biofilter for fecal pathogens in streams that cause waterborne diseases. Ecosystems generally have checks and balances in place where predators maintain populations of vector species in dynamic equilibrium. These balances can be upset by processes such as desertification (MEA 2005). Thus, a reduction in regulating ecosystem services can create conditions that lead to proliferation of vectors as pests (e.g., ticks, rodents, and mosquitoes) and the pathogens they carry.

Vectors and pathogens often create problems that result from the proximity of humans to locations where regulating ecosystem services have been diminished or removed. Urban areas provide the most prominent set of examples where highly altered, simplified, or exotic ecosystems cannot self-regulate in natural ways. For example, mosquito habitat in cities is often associated with water for irrigation or rainwater that collects in and around human habitation. Because mosquitoes in these environments are not part of a naturally regulated ecosystem, the potential for unchecked growth in vector populations is large. A complementary example is human exposure to Hantavirus, where rodent populations surge following high rainfall and abundant food supply (Yates et al. 2002). In subsequent average or dry years, human exposure to the virus increases as infected rodents seek food close to human dwellings.

Threats (or Opportunities) to Future Trends in Disease, Pests, and Pathogens

The biggest opportunities for the spread of disease at local scales are from landscape changes that modify the habitat for pathogens and their vectors. At regional and continental scales, the range of pathogens and vectors is associated with extremes of temperature and precipitation (Comrie 2007), such as frosts or changes in timing and duration of wet–dry spells. An example is dengue fever, currently in northern Mexico, but not yet in the Southwestern United States. The mosquito vector *Aedes aegypti* is present in the Southwest, but the pathogen is not endemic. It is unknown whether dengue will expand northward if the region's temperature and moisture environments change. The trajectory for these kinds of shifts in ecosystem services is inherently complex, and depends on changes in human activity, as well as the biophysical impacts of desertification within the climate system.

4.20.2.4 Cultural Services

4.20.2.4.1 Esthetics and Recreation

Non-material benefits obtained from ecosystems represent cultural services (e.g., esthetic and recreational experiences, cultural heritage, sense of place; Figure 1). Cultural services include and are shaped by human perceptions and preferences, recreational experiences, interpersonal displacement, and tolerance levels, and conflicts and benefits accrued to individuals in a landscape. Human evolutionary history has instilled strong adaptive biases that influence current perceptions and preferences with respect to visual landscapes and biological needs (Ulrich 1977). These adaptive biases and bonds between humans and their environment are strong and inherited, and are the basis for the proposition that esthetic satisfaction stems from the spontaneous perception of, and interaction with, landscape features. Explicit inclusion of cultural services is thus a key, but under appreciated, component of effective natural resources monitoring and management.

Cultural services have intrinsic value but also play a central role in determining the ecosystems, which people are disposed to value and protect, or to degrade or develop for other purposes. Perceptions of cultural services can be an important, albeit intangible, factor in public support of resource use, management, and policy. Alternatively, landscape or social conditions can change to have negative effects on desired cultural services that lead to undesirable conditions, declining recreation experience levels, conflicts among stakeholders, and eventually degraded environmental conditions. For example, increasing use in Saguaro National Park (Arizona) with associated physical impacts and competition between recreational groups (horse riders and hikers) diminished the recreation experience for each group and forced land managers to close trails, thus resulting in reduced opportunities.

Cultural ecosystems services are less understood and explored than other services, and are more difficult to quantify. Cultural services provide for human physical, mental, spiritual, social, cultural, and economic well-being, all of which are determined by a variety of traditional and changing perceptions, beliefs, attitudes, behaviors, needs, values, and influences. The provision of cultural services must take into account past, present, and possible future influences of humans on ecosystems.

Cultural services depend heavily on the relationship between humans and their environments. Recreational experience, for example, requires landscape settings that meet certain expectations in terms of the services they provide. Landscape settings such as lakes, meadows, and mountains provide unique experience opportunities, and humans are linked to each setting for a variety of reasons. Wildlands provide opportunities to explore and engage in nature, and to derive historic, spiritual, esthetic, and educational values. Cultural services in wildlands are observed in different ways: backpackers seek solitude, commercial outfitters earn income, mountain climbers seek danger and risk, and naturalists derive satisfaction from seeing and identifying plants and animals. Ecosystems providing cultural services also generate broader public support for conservation management. For example, the Cabeza Prieta Wilderness Area is Arizona's largest wilderness area, but is visited by very few humans. This primitive wilderness area is a symbolic refuge of nature that some suggest should be preserved and protected for inherent ecological, esthetic, and symbolic value. There is cultural value to many in knowing this type of landscape continues to exist.

Consequences of Desertification for Cultural Ecosystem Services

If desertification continues, there would be dramatic threats to the quantity and quality of cultural services available in drylands. With changing biodiversity (see Section 4.20.2.3.4 Biodiversity), the loss of wildflower production could result in lost recreation opportunities and the overall quality of the recreation experience. Increased human-related impacts, such as social trail and recreation site impacts would provide increased opportunities for invasive and non-native plant species.

Threats and the Future of Esthetics and Recreation

Significant threats to cultural services are associated with human use impacts and reductions in recreation opportunities. High quality recreation experiences often decline with increasing human population densities. Crowding, excessive numbers of visitors, and their associated impacts coupled with harsher environmental conditions affect the ability of these systems to sustain cultural services. For example, increased human use along the US – Mexican border in Organ Pipe National Monument in the Sonoran Desert, Arizona, has already led to a proliferation of trails and traffic on these fragile landscapes (**Figure 6**) (Sharp and Gimblett 2009). An increase in temperature and water stress on plants and animals would exacerbate the degradation from current human-caused impacts. The extent and severity of impact in disturbance-sensitive drylands suggest some of these environments may never recover (Sharp and Gimblett 2009). Climate impacts cultural services: weather influences visitor experiences and affects recreation choices, utility maximization, and net amenity benefits. Summer and winter season lengths determine the availability and quality of certain recreation opportunities, such as hunting, fishing, bird watching, and scenic viewing.

A critical challenge will be to provide cultural services, while at the same time balancing the protection of rapidly changing, declining, or degrading natural resources. A clear set of management objectives will be needed within the context of the many environmental changes underway (Cole et al. 2008). A more holistic paradigm that explicitly identifies and comprehensively incorporates cultural services is required. One such approach

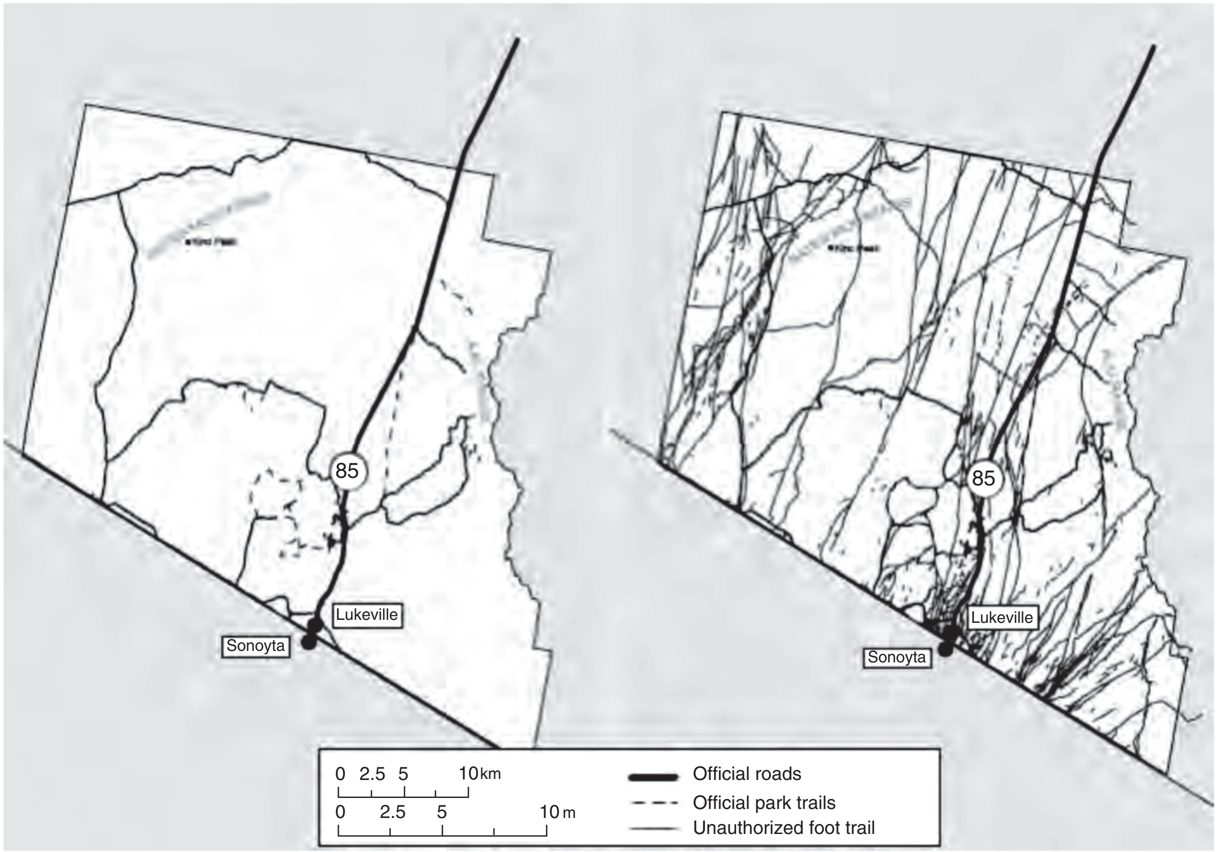

Figure 6 Increased human use along the US – Mexican border in Organ Pipe National Monument in the Sonoran Desert has led to a proliferation of trails and traffic on an already stressed landscape. Left: Official roads and recreational trails within Organ Pipe Cactus National Monument boundaries. Right: Official routes overlain with unauthorized routes that have resulted in severe loss of vegetation, erosion, unnecessary widening, gullying throughout Organ Pipe. These unauthorized routes will take years, if ever, to recover from such impacts. From Sharp, C., and R. Gimblett, 2009: Assessing border-related human impacts at organ pipe cactus national monument. *Conservation of Shared Environments: Learning from the United States and Mexico*, L. Lopez-Hoffman, E. D. McGovern, R. G. Vardy, and K. W. Flessa, Eds., University of Arizona Press, 226–40. (Permission granted from University of Arizona Press to publish figure: 12-1-2011.)

couples human and natural systems to rules governing land-use decisions, ecological models of landscape change, and decision support systems mimicking local landowners, recreational users, and resource management agencies (Scott et al. 2010a,b). This ongoing project attempts to understand complex utilitarian processes in human-dominated, semi-arid river systems and seeks to define the linked influences of climate, hydrology, societal practices and esthetic values, and any changes over time – on the social and ecological resilience of riparian corridors of two desert river systems: the Rio Sonora in Mexico and the San Pedro River, which originates at the same watershed boundary in Mexico, but flows northward into Arizona. Improved understanding of these complex processes provides a foundation for exploring what types of human occupancy and resource use may be possible, given climatic constraints set by a semi-arid ecosystem. In emphasizing the riparian-corridor ecotone, this project is exploring the nature and extent of combined societal and hydro-ecological changes under differing scenarios.

Public lands and protected areas, in general, are receiving a greater level and diversity of human activities and total visitation use than in historical times. This increase in demand leads to the question of whether public lands will have the ability to provide high quality cultural services now and into the future. Maintaining high quality cultural services, while protecting ecosystem integrity, remains at the heart of many contentious, confrontational, and highly scrutinized land-use planning and management processes that will continue into the future.

4.20.3 Potential Actions for Mitigation

4.20.3.1 Can Payments for Ecosystem Services Mitigate Desertification?

The growing awareness of the value of ecosystem services to society, and the increasing concern about threats to their continued provisioning, is catalyzing a new paradigm – viewing ecosystems as assets to be managed. As discussed above, drylands in the American Southwest provide a diverse array of services that support human life, food and fiber, clean drinking water, climate regulation, recreational experiences, wildlife habitat, and others (Havstad et al. 2008; Skaggs 2008). With the notable exceptions of food and fiber, the rest are public goods that have remained largely outside economic markets. Historically, the Farm Bill and other government programs have provided incentives to landowners for the protection of public goods. In the last decade, more and more conservationists, landowners, and natural resource managers are considering the concept of 'Payments for Ecosystem Services' (PES), as a way of providing market-based incentives to protect these goods. The objective of this section is to define PES and describe how it might be used to create incentives for preventing desertification and protecting the non-market goods provided by drylands. The questions addressed are: What types of PES programs are there and how they might be used to mitigate desertification? What are the short-term prospects for implementing PES programs in the American Southwest? And finally, given the vast public lands in the Southwest, how can PES be implemented on these lands? Payments for ecosystem services are market-based approaches in which users of ecosystem services directly compensate providers (i.e., landowners and managers) for their protection and supply. PES combines a positive incentive (if you improve and protect a resource, you can get paid by others to do so), with a negative incentive (if you impact a resource, you must or should pay for it) (Goldstein et al. 2011). Further, PES places the responsibility to pay for and protect ecosystem services on the individuals and private sector entities using the services. Ideally, PES should create payments for measurable outcomes (e.g., tons of carbon dioxide sequestered, volume erosion reduced, acreage of invasive vegetation removed) in contrast to government programs that provide incentives for changing management practices (e.g., grants for installing a fence to protect a waterway (CEAP 2011; Briske 2011)).

There are four types of PES programs that could be used to minimize or mitigate desertification in Southwestern grasslands. First, carbon programs provide payments to landowners and managers for undertaking management practices that reduce the loss of plant and soil carbon stocks (see Section 4.20.2.1.2). Second, water programs pay both upstream private landowners and public land managers for controlling erosion and grazing in order to promote higher air quality (see Section 4.20.2.3.2) and increase the quality and quantity of water delivered downstream (see Section 4.20.2.2.1). Third, biodiversity programs provide payments to landowners for the protection and/or restoration of a specified amount of habitat for target species (see Section 4.20.2.3.4) – such practices could include actions to mitigate desertification. Finally, there are bundled payments that combine carbon, water, and biodiversity benefits.

All programs require one of three market vehicles. First, compliance markets are created by regulation (e.g., Endangered Species Act, Clean Water Act). Second, voluntary markets occur when entities participate of their own volition – typically businesses to burnish a 'green' corporate image or private groups wishing to become 'carbon neutral.' Third, government-mediated payment programs (e.g., Farm Bill) use public funds to pay landowners for protecting or enhancing ecosystem services.

4.20.3.2 What Are the Prospects for PES in the US Southwest?

Despite the keen interest around the world in implementing PES programs, there are very few examples in arid regions and fewer yet in the Southwestern United States (Goldstein et al. 2011). Several years ago, observers of PES likely would have considered carbon programs to offer the greatest promise. However, failure to enact cap and trade (a federal regulatory driver for a nation-wide carbon offset program) led to the closures of the Chicago Climate Exchange in 2010 and its Sustainably Managed Rangeland Soil Carbon Sequestration Offset Project (Gosnell et al. 2011). Biodiversity markets in the form of mitigation banks to protect species habitat offer some promise: according to a recent report (Madsen et al. 2010), the habitat of at least 119 species in the United States is protected by mitigation banks. Arguably, the greatest promise for the Southwest lies in water programs, where municipal utilities enter into contractual agreements with upstream landowners or managers. An example of the potential for PES to align the interests of ecosystem service users and public land managers is the recently formed partnership between Denver Water, the utility that serves the city and surrounding suburbs, and the US Forest Service. Denver Water recently entered into a 5-year, $33 million partnership with the Forest Service to fund erosion control and wildfire prevention activities in its publicly managed upstream watershed. While some have questioned why the utility should pay a federal agency, the organizations argue that Denver Water is paying for additional land management practices specifically designed to protect and enhance water quality. Similar programs have been discussed in locations in the Southwest.

To date, there are few concrete examples of PES being used to combat desertification and degradation of drylands in the Southwest. In the absence of federal regulation on greenhouse gas emissions, it seems unlikely that carbon markets will emerge as a tool to mitigate dryland degradation, though state-level efforts (particularly in California) are continuing to keep some opportunities open. As biodiversity and water-based PES programs expand across the United States, it will be important for all stakeholders, land managers, private owners, civil society, and academia to carefully evaluate the opportunities that PES provides, and to tailor programs to meet the interconnected goals of preventing and mitigating desertification with protecting ecosystem services.

4.20.4 Recommendations for Land Managers, Policymakers, and Other Stakeholders

The effects of desertification and the threat of future effects upon ecosystem goods and services provided by drylands have important implications and lessons for land managers, policymakers, and other stakeholders who can be impacted. At the center of these implications is the knowledge that using general principles, even if derived from thorough research and peer reviewed analyses, will have limited application to any specific landscape and any specific emerging threat to any combination of goods and services. Actual management practices applied or policies implemented will have to be contextualized to the specifics of a landscape. For example, research may have identified the typical capacity of an ecosystem to produce a sustainable level of a particular good, such as livestock products. However, the vagaries of climatic drivers and resulting primary production for a particular ecosystem will negate the application of that average capacity to any specific time frame. In addition, generalizations based on past or recent research and experience may be irrelevant for 'novel ecosystems' developing under future conditions. Management programs need to be agile. Management actions need to be increasingly adaptive, and the policies supporting or constraining those actions need to be sufficiently flexible to readily accommodate adaptive adjustments.

Recognition of the need for adaptive management and flexible policies impacts the general principles that guide management. In the past, extraction of combinations of goods and services from drylands was guided by the principles of proper limits to use by livestock, proper distribution and timing of this use across landscapes, and proper types of livestock matched to a landscape and its forages. However, specific uses and combinations of uses change over time. Reductionist science has serious limits in identifying proper uses and combinations of uses for all landscapes in dynamic environments with numerous changing and interacting drivers. These principles, employed ineffectively on all continents for the past century, now need to be replaced.

Principles guiding resource managers need to be based on the simple concept that the central element to all of these goods and services, threatened or not, is the basic commodity of land. Within this concept is the recognition that 'land' is heterogeneous on many levels, and management principles and policies need to be designed and implemented based on this knowledge. The principles guiding management actions and policies should be rooted in the technology that classifies land based on similarities and differences with respect to climate, soil, landscape position, prior histories of management, and inherent vegetation dynamics – the ecological site and its description (Bestelmeyer et al. 2009). The cardinal principles of land management are then the proper descriptions of a site's (1) potential to provide goods and services (which may be predicated on prior history), (2) current status, (3) suite of possible future trajectories in response to management practices and environmental conditions, and (4) monitored responses to those practices and conditions. These principles are very different than those utilized in the past, and the prior principles certainly contributed to the threatened and degraded conditions currently in existence.

Two key issues emerge from the recognition of the need for a new set of guiding principles. First, the successful application of these principles requires that institutions of management and policy improve their ability to learn from and adapt to the information derived from site-specific responses. Management practices, and the policies that guide them, need to be redesigned to dynamically accommodate specific lessons learned. These institutions need mechanisms where they can be informed by data and associated analyses. These mechanisms will require that landscapes have diverse and detailed data layers that are accessible, transparent, timely, and suitably described by metadata (Peters 2010). The infrastructure to support data-informed management actions and policies is not yet appropriately interactive and integrative, but these barriers can be overcome.

Second, conducting science to collect and organize data to inform land management and policy will require considerably different methodologies than used in the past. Issues related to climate change and desertification have forced ecologists and most resource managers to quantify patterns and processes at spatial scales more extensive than those addressed previously: how landscapes, land surfaces, and the atmosphere interact across a broad range of scales. This new science includes, but goes far beyond, the traditional highly controlled experimental designs of our reductionist past. It recognizes the need for research to (1) span multiple levels of organization in ecological hierarchies (reductionist approach) balanced by research aimed at understanding how mechanisms and processes at a given scale play out at broader scales over longer times (holistic approach), and (2) be interdisciplinary. For example, it has been stated that soil science has been "brilliantly informed by reductionist physics and chemistry, poorly informed by biology, ecology and geography, and largely uniformed by the social sciences" (Swift 1999). The science challenge now is less controlled, much more variable, and yet much more applied (Sayre et al. 2012). It is a science that employs management as an experimental, hypothesis-testing tool, e.g., the scientific method is applied in the testing of the effects of management practices as they are applied, or have been applied, in the field. It is a science that provides the types of data that can inform both management actions and policies geared toward heterogeneous landscapes under dynamic drivers, and that can learn and adapt as conditions warrant.

Finally, given the uncertainty of future climatic conditions, continued spread of exotic organisms, increasing global demand for an array of goods and services, and impacts of other drivers, it is important that policy makers and managers maintain and utilize mechanisms that can inform and focus science priorities. One possible mechanism to employ is future plausible scenarios generated by science-based models, worst-case historical and recent paleo–conditions, and sequences of events developed from linking together subsets of extreme events (such as the two most extreme droughts in the historical record placed in sequence). This mechanism can both prepare and direct management and policy actions. These scenarios can then be refined and employed in management and policy, and thus serve to maintain communication among scientists, policy makers, and managers relative to information needs and their relevance to the emerging problems of the future. A key recommendation for policy makers and managers is to more strongly employ and maintain linkages with scientists in shaping and focusing their priorities and their hypotheses to be tested.

4.20.5 Summary

Desertification, the broad-scale conversion of perennial grasslands to dominance by annual plants or xerophytic shrubs, and the attendant consequences to ecosystem services, has affected arid and semi-arid regions globally over the past several centuries. This state change is expected to continue in the future. It is generally well recognized that desertification is a cumulative threat that explicitly includes both climatic (e.g., drought) and land-use drivers (e.g., livestock overgrazing and inappropriate conversions of rangeland to cropland). However, a basis for ranking the relative importance of these drivers is lacking for many locations. In addition, the emergence of additional drivers (e.g., non-native forbs and grasses) modifying historic fire regimes will result in even more complex dynamics in the future. Questions remain: (1) How do these multiple drivers interact through time and space to influence grass–shrub dynamics? (2) When is the region's climate versus land use expected to be the primary driver governing ecosystem dynamics? (3) Where are management actions expected to be the most effective given variability in climate? (4) How would specific ecosystem services be impacted, and (5) What are trade-offs in positive versus negative effects when considering bundles of services?

Clearly, climate can have unanticipated effects, in particular for dryland regions with low and variable precipitation and high temperatures in the growing season. However, any change in climate statistics would be operating across diverse landscapes that include a mosaic of human-dominated and natural states, each governed by different drivers and susceptible to different threats. Accounting for the separate and interactive effects of these threats on grassland–shrubland transitions will be necessary as we move forward into a difficult to predict, if not unknown, environmental world.

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