Traversing the Wasteland: A Framework for Assessing Ecological Threats to Drylands

DAVID L. HOOVER, BRANDON BESTELMEYER, NANCY B. GRIMM, TRAVIS E. HUXMAN, SASHA C. REED, OSVALDO SALA, TIMOTHY R. SEASTEDT, HAILEY WILMER, AND SCOTT FERRENBERG

Drylands cover 41% of the Earth's terrestrial surface, play a critical role in global ecosystem function, and are home to over two billion people. Like other biomes, drylands face increasing pressure from global change, but many of these ecosystems are close to tipping points, which, if crossed, can lead to abrupt transitions and persistent degraded states. Their limited but variable precipitation, low soil fertility, and low productivity have given rise to a perception that drylands are wastelands, needing societal intervention to bring value to them. Negative perceptions of drylands synergistically combine with conflicting sociocultural values regarding what constitutes a threat to these ecosystems. In the present article, we propose a framework for assessing threats to dryland ecosystems and suggest we must also combat the negative perceptions of drylands in order to preserve the ecosystem services that they offer.

Keywords: global change, arid, semiarid, vulnerability, perception

"Wasteland" as defined by the Merriam-Webster Dictionary:

1. barren or uncultivated land
   // a desert wasteland
2. an ugly often devastated or barely inhabitable place or area
3. something (such as a way of life) that is spiritually and emotionally arid and unsatisfying

What is a dryland?

Drylands encompass a diverse array of ecosystems—deserts, steppe, savannas, chaparral, shrublands, grasslands, and rangelands, yet all are unified by a scarcity of water (figure 1). The global extent of drylands covers around 41%, or 60 million square kilometers, of the Earth's terrestrial surface, an extent that is projected to increase by 11%–23% by the end of this century (figure 1; Safriel and Adeel 2005, Huang et al. 2016, Prăvălie 2016). Approximately 38% of the world's population lives in these arid and semiarid regions, in both rural and urban communities, including some of the world's largest cities (e.g., Mexico City, Cairo, and Delhi) and poorest villages (EMG 2011). Drylands are water limited ecosystems: The aridity index is below 0.65 such that annual evaporative demand is at least 1.5 times greater than precipitation (figure 1; Safriel and Adeel 2005). The lack of water limits both vegetation growth and soil development (Weil and Brady 2016), often resulting in landscapes with low productivity and plant cover (Aguiar and Sala 1999, Klausmeier 1999), as well as young, developing soils with little organic matter (Delgado-Baquerizo et al. 2016, Augusto et al. 2017).

Water limitation is the predominant feature of drylands, and life exists where and when water is available. Rivers, streams, and their floodplains provide a source of water and nutrients in these resource limited environments, creating hotspots for biodiversity and providing physical and biological connectivity for many species, as well as fluxes of materials and energy (Belnap et al. 2005, Sabo et al. 2005, Harms and Grimm 2008, McKenna and Sala 2018). Some of the earliest complex civilizations developed along the banks of dryland rivers, including in Mesopotamia (3500 BCE), between the Tigris and Euphrates Rivers; in Egypt (3000 BCE), in the Nile River Valley; and in China (2070 BCE), along the Hueng He (Redman 1999). Along with spatial heterogeneity of water availability, dryland organisms have adapted to extreme temporal variability in water, including cycles of droughts and deluges (Smith and Cribb 2009, Greenville et al. 2012, Greenville et al. 2017). Within hours to days after rainfall interrupts dry periods, seemingly depauperate landscapes can experience a burst of biological activity as dormant soil microbes and plants become active. This rapid biotic shift drives ecosystem processes

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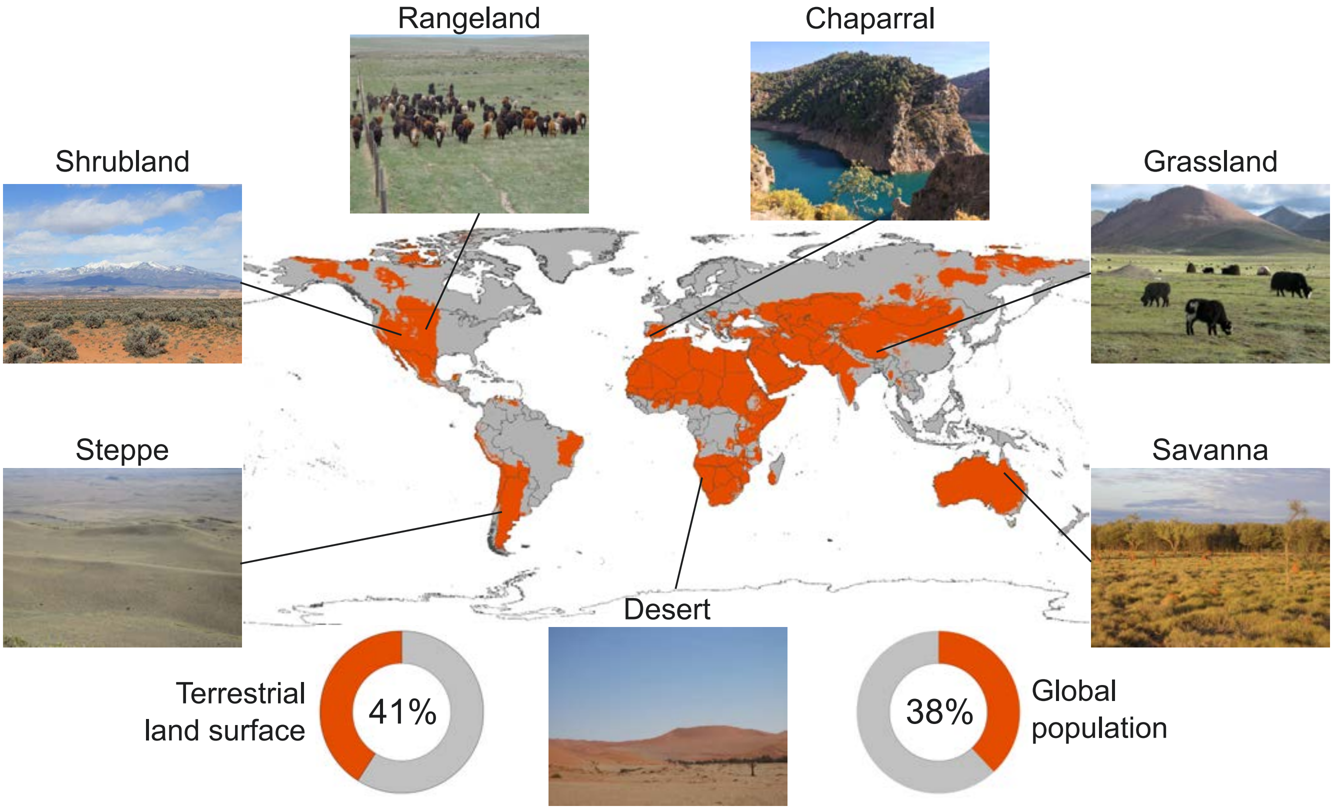

Figure 1. Drylands of the world. Drylands are water-limited ecosystems found throughout the world and include many ecosystem types. They cover 41% of the terrestrial land surface and are home to 38% of global population (Safriel and Adeel 2005, EMG 2011). Drylands (orange on the map) are defined as regions where the aridity index (ratio of annual precipitation to potential evapotranspiration) is below 0.65 (Trabucco and Zomer 2009). Photographs: Rangeland, Melissa Johnson, USDA-ARS; chaparral, Jesse Bayer; grassland, Kelly Hopping, Boise State University; savanna, desert, and steppe, Nick Webb, USDA-ARS).

(Belnap 2006, Jenerette et al. 2008, Collins et al. 2014) and influences global climate by altering fluxes of carbon dioxide (CO_2) and gaseous forms of nitrogen (NO, N_2O, N_2) between the land surface and atmosphere (Sponseller 2007, Poulter et al. 2014, Ahlström et al. 2015, Homyak et al. 2016, Ma et al. 2016).

In addition to playing dominant roles in regulating Earth's biogeochemical cycles, drylands provide important supporting, provisioning, and cultural services (Safriel and Adeel 2005). Although these landscapes feature sparse vegetation cover, primary production, and soil formation are key supporting services of dryland ecosystems (Safriel and Adeel 2005). For example, loss of vegetation cover due to overgrazing, climate change, species invasions, or fire has been linked to an increase in soil erosion by water and wind (McAuliffe 1994, Neff et al. 2008, Polyakov et al. 2010, Sankey et al. 2012), with wide-ranging regional hydrological impacts (Painter et al. 2007). Of the two billion people who live in drylands, 90% are in developing countries, and about half rely directly on local ecosystem provisioning services for food and fiber (Safriel and Adeel 2005, EMG 2011). Globally, livestock production accounts for 65% of the land use in drylands, and 25% is used for irrigated and rain-fed croplands (EMG 2011). Finally, drylands provide important cultural services, such a source of cultural identity and diversity, as well as landscapes for recreation and tourism (Safriel and Adeel 2005).

Although many organisms and societies have adapted to the extreme conditions of drylands, myriad of global change drivers threaten the ecological structure and functioning of these arid and semiarid ecosystems and, in turn, the many services they provide. Increased intensification of agriculture in drylands for developing nations has the potential to greatly alter the socioeconomic and ecological structure of these regions. Arid systems are recognized as potential poverty traps (Carpenter and Brock 2008). This is, in part, not only because overexploitation of resources has short-term consequences, but also because these actions affect long-term stabilizing feedback loops associated with resource provisioning (e.g., Narisma et al. 2007). Within more developed regions, some drylands may also have important agricultural value, but have increasingly been used by a

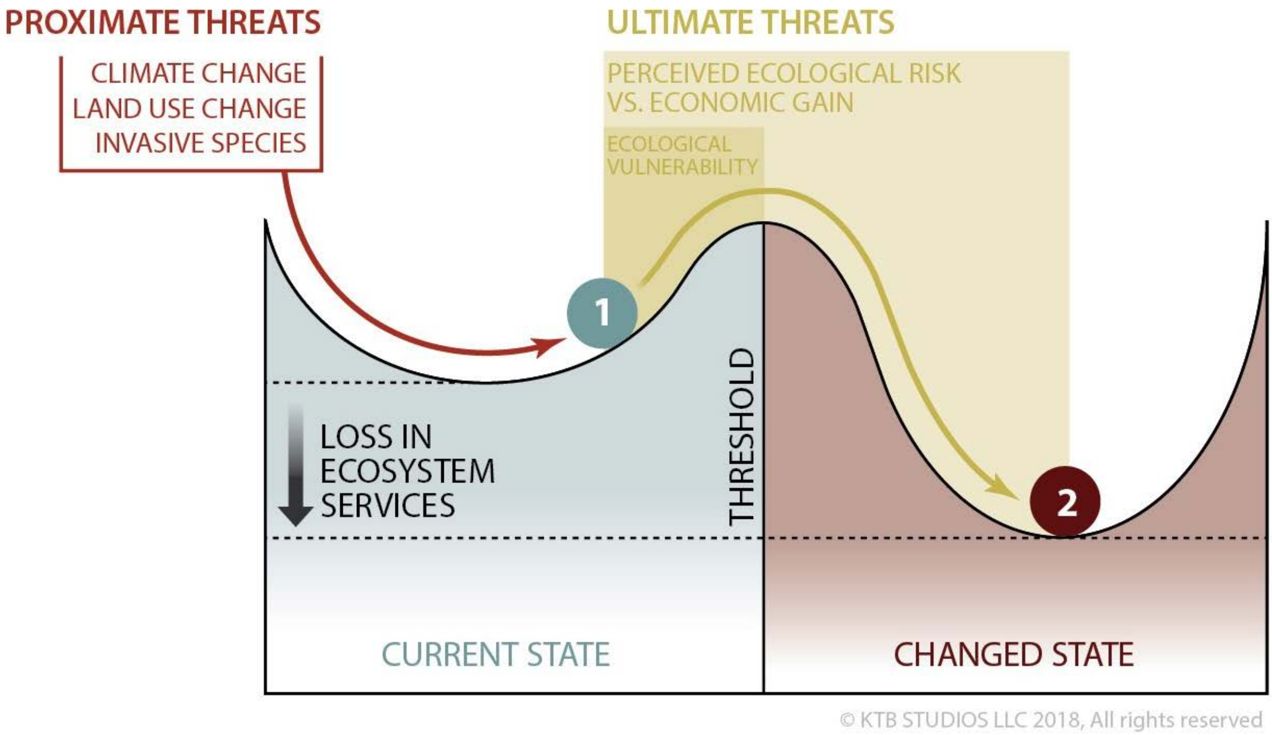

Figure 2. A conceptual framework for threats to dryland ecosystems. Drylands are unique in that proximate threats, such as climate change, land use change, and invasive species, are exacerbated by ultimate threats including ecological vulnerability to state change, and the societal perception of drylands. Using a ball-and-cup diagram, we illustrated how proximate threats are drivers, individually and interactively, that push the current state of the ecosystem (1) toward a threshold. The ecological vulnerability of the system will govern its proximity to the threshold (e.g., resistance) and the ability to return to the original state after perturbation (resilience). Once a threshold is crossed, the new state (2) can lead to a loss in ecosystem services. Management decision making is influenced by the perception of the dryland, specifically the ecological risk (i.e., likelihood of state change and loss in ecosystem services) versus economic or other value-based gains.

diverse set of stakeholders for mining, oil and gas extraction, off-road vehicular recreation, hunting, ecotourism, conservation efforts, urban and suburban growth, and solar and wind farms (e.g., Copeland et al. 2017). With so many uses, managing these ecosystems in the face of change represents a significant challenge. In the present article, our primary objective is to present a conceptual framework for assessing ecological threats to drylands in a changing world. We define ecological threats to drylands as either proximate or ultimate, providing examples of each and describing how they interact. We conclude with suggestions on how to shift the narrative on drylands to combat the negative perceptions of these landscapes in order to preserve the ecosystem services that they offer.

What are ecological threats to drylands?

Here, we define an ecological threat as a potential driver of undesirable state change, a definition contingent on the relationship between global change drivers, ecological responses, as well as the perception and values of diverse stakeholders (figure 2). As with all ecosystems on Earth, drylands face numerous proximate threats or those with an immediate, causal relationship between the force driving change and an ecological response. What makes drylands unique is that ultimate threats—the higher-level ecological, evolutionary, and social contexts in which drivers act—strongly exacerbate proximate threats. Ultimate threats in drylands are the vulnerability to state change of these ecosystems, the perceptions of drylands as “wastelands” and other false narratives that have influenced decision-making and management (figure 2).

Proximate threats, including climate change, land-use change, and invasive species, interact with biophysical properties and processes in drylands to influence multiple aspects of ecosystem structure and functioning. Furthermore, the interaction among global change drivers may lead to ecological impacts that are greater than those caused by the sum of single drivers (Scheffer et al. 2015). Therefore, proximate threats, alone and in combination, may push dryland ecosystems beyond their limits, with large and potentially irreversible changes (figure 2). Indeed, rapid plant mortality has been observed in drylands in response to simultaneous

Figure 3. Proximate threats to drylands. (a) Climate change—massive tree die-off with global change type drought. Photograph: Craig D. Allen, US Geological Survey. (b) Land conversion—pasture converted from woodland to buffelgrass. Photograph: Brandon Bestelmeyer. (c) Invasions—introduced cheatgrass produces a continuous mat of fine fuel that greatly facilitates frequent fires in areas formerly occupied by shrubs and bunch grasses. Photograph: Jeff Mitton, University of Colorado Boulder. (d) Interactions—urbanization and climate change. Photograph: Nancy B. Grimm.

interacting climate change drivers (Breshears et al. 2005, Hamerlynck and McAuliffe 2008, Overpeck and Udall 2010).

Ultimate threats to drylands may exacerbate proximate threats, resulting in impacts that are more abrupt and persistent. Many drylands have high vulnerability to state change owing to their evolutionary, environmental, and management history. Once a threshold is crossed and a new state is reached, recovery may be difficult or impossible, because variable precipitation regimes and low soil fertility impede regrowth and biophysical feedback loops, maintaining the alternate state (figure 2; Reynolds et al. 2007, D'Odorico et al. 2013, Bestelmeyer et al. 2015, Maestre et al. 2016). In addition to the ecological vulnerabilities of drylands to global change drivers (Flombaum et al. 2017), the perception of drylands as wastelands has influenced their management and governance (Davis 2016). Assessing a threat therefore requires identifying what constitutes an undesirable ecological state change; desirability is a normative term dependent on the sociocultural values of diverse stakeholders and decision makers.

Proximate threats to drylands

We define a proximate threat to drylands as a global change driver with an immediate, causal relationship with an ecological response or state change. Climate change, land-use and land-cover change, and nonnative species are proximate threats with independent and interactive effects on dryland ecosystems (figure 2).

Climate change. Drylands are considered hotspots of climate change, with rising temperatures, more variable precipitation, and an increase in extreme events (IPCC 2014, Huang et al. 2017). Over the past century, one of the greatest increases in temperature worldwide has been observed in drylands, because surface warming in drylands has been 20%–40% higher than humid lands (Huang et al. 2017). As warming continues, expanding drylands are predicted cover over half of the global land surface by the end of the century (Fu and Feng 2014, Huang et al. 2016). Observed and predicted trends in mean annual precipitation have been less clear, with some regions getting wetter and others drier. Beyond changes in mean precipitation, increases in precipitation variability, shifts in precipitation seasonality, and increases in the frequency and magnitude of drought are projected to occur in drylands (IPCC 2014, Sloat et al. 2018). The combined effects of increasing temperatures and altered precipitation will likely reduce water availability (i.e., through large changes in soil moisture), as well as change when and where water is available.

Forecasted changes in climate portend large ecological and sociological impacts (EMG 2011, Maestre et al. 2016). Vegetation responses to climate change have already been documented globally and suggest that plant functional types may be differentially affected, leading to large changes in community composition and key ecosystem services, such as forage availability, carbon storage, and erosion (e.g., Ravi et al. 2010, Poulter et al. 2014, Ruppert et al. 2015). Extreme drought in drylands can push key species or plant functional types past critical thresholds, leading to widespread mortality (figure 3a; Breshears et al. 2009), as can warming (Munson et al. 2011, Ferrenberg et al. 2015).

Climate change, particularly as it affects water balance or the potential for increased precipitation variability, may have exceptional impacts on aquatic ecosystems in drylands. Rivers, streams, lakes and ponds, reservoirs, and springs are the enigmatic ecosystems of drylands because they are defined by the one feature that is limiting elsewhere: water. For large rivers, their status is intimately tied to human water use and decision-making, but for small streams, springs, ponds, playas, and wetlands, reductions in precipitation coupled with increased evapotranspiration at higher temperatures represent an existential threat (Grimm et al. 1997, Ye and Grimm 2013). Most of the projected expansion of drylands will occur in developing countries, such as China, India, Iran, and South Sudan, many of which are undergoing rapid population growth (Huang et al. 2016). This trend will exert further pressure on these ecosystems as their demand for resources far exceed the ecological carrying and restoring capacities of the land (Wang et al. 2012, Huang et al. 2016).

Land-use and land-cover change. Most of the land area used for livestock production (i.e., rangelands) occurs in dryland biomes (Asner et al. 2004, Sayre et al. 2017). The development of unsustainable livestock production systems has resulted in widespread, persistent shifts in plant functional types worldwide (Stafford Smith et al. 2007, Todd and Hoffman 2009, Bestelmeyer et al. 2018, Jamsranjav et al. 2018). Grazing management practices have been improved in some dryland areas, whereas in others, recent disruptions of pastoral governance systems, changing climate, and ongoing increases in livestock numbers are causing ongoing state changes (Todd and Hoffman 2009, Basupi et al. 2017, Fernández-Giménez et al. 2017). Because many drylands are relatively unproductive for cropland agriculture (when compared with more humid environments), they have escaped historical episodes of widespread conversion from rangeland or wildland uses to cropland (Ramankutty and Foley 1999).

Recent changes in climatic, economic, and technological drivers have accelerated land conversion in drylands. For example, large-scale conversion of semiarid savannas and forests to croplands in Argentina, Bolivia, and Paraguay continues unabated since the 1970s, because of increasing global demand for soy and beef, genetically modified seeds in combination with no-till techniques and increased rainfall, all occurring in the context of weakly enforced regulations governing deforestation (figure 3b; Le Polain de Waroux et al. 2016). Urbanization in rangelands is also occurring, primarily adjacent to existing cities (Bestelmeyer et al. 2015, Allington et al. 2017) and associated with energy development and mining (Allred et al. 2015, Sternberg and Chatty 2016, Copeland et al. 2017). Land conversion in drylands may have unintended ecological and societal effects, such as fragmentation with respect to rangeland management operations (e.g., use of fire), impacts on wildlife, and air quality (Sayre 2002, Sacchi et al. 2017).

Nonnative species. Dryland ecosystems have been recipients of invasive species capable of wholesale transformations of landscapes. Both deliberate and accidental introductions of nonnative organisms in drylands have occurred over the past 200 years. Many of these introductions have altered community composition, ecosystem functioning, and disturbance regimes (e.g., Mack 1981, Brooks et al. 2004). For example, the southwestern United States witnessed an explosion and monoculture of several species of Eurasian saltcedar (*Tamarix* spp.), a plant that can crowd out native plants in dryland riparian corridors and has high rates of water use (relative to native vegetation), with large economic impacts. This multimillion dollar problem was blamed for changes that were probably caused by—or at least exacerbated by—water impoundments in the West. This riparian invader and putative water thief is now in decline because of proactive management and intentional introductions of a beetle used for biological control, but such successes in terms of reversing invasive species impacts are few and may carry unintended consequences. For example, the decline in saltcedar because of the beetle is now itself a large concern, because saltcedar provided habitat to the endangered southwestern willow flycatcher and other wildlife that cannot be replaced sufficiently (Hultine et al. 2010). Another dramatic example is exotic plant invasions by both annual (figure 3c; Bradley et al. 2017) and perennial grasses (McDonald and McPherson 2011) that contribute to spread of wildfires where fires were once rare or almost nonexistent or exacerbate the effects of drought on native species (Alexander Eilts and Huxman 2013). The effect of these introduced species is therefore to transform woodland and savanna communities into grasslands.

Interaction among proximate threats. So far, we have identified three individual proximate threats with direct effects on dryland ecosystems. However, these drivers of change don't exist in isolation but, instead may interact in additive and nonlinear ways, leading to complex feedback loops. A prime example of interacting proximate threats to drylands is urbanization and climate change. Urbanization concentrates people and their infrastructure in relatively small areas, bringing on a host of changes to the biophysical environment, such as increased impervious surface, an urban heat island with higher nighttime temperature, alteration of hydrologic flowpaths, importation of exotic plants, reduction in native biodiversity, and profound changes in biogeochemical cycles (figure 3d; Paul and Meyer 2001, Pickett et al. 2001, Kaye et al. 2006, Grimm et al. 2008, Seto et al. 2012). But changes are not restricted to the local urban environment; the impacts of cities' demand for resources—particularly water—and emission of air and water pollutants extend far beyond city limits (Luck et al. 2001, Ramaswami et al. 2012). Drylands tend to be slightly more urbanized than continental averages and the urban area percentage is growing (Balk et al. 2012). By 2025, urbanization percentages in drylands will grow to 55% globally, with an 84% increase for North America; 70% and 75% for Europe and South America, respectively; and 51% for both Africa and Asia (Balk et al. 2012). In the developed world, urbanization in drylands has been driven by the attractions of a moderate climate and economic opportunity, whereas urban centers in developing world often attract local rural migrants during times of resource scarcity (Balk et al. 2012).

The biggest challenge in the convergence of urbanization and climate change is that projections for most drylands are for increased severity and frequency of drought, greater variability in precipitation, and higher temperatures (Cayan et al. 2010, IPCC 2014). This threatens urban populations with ever-greater water scarcity when capacity to adjust through technological development may be compromised by the rapidity of urban growth in the less-developed world (McDonald and McPherson 2011, Balk et al. 2012) and competing demands in the developed world (Gober 2010). Because dryland cities rarely rely on neighboring rural areas to supply their needed resources but instead have vast ecological footprints, these impending compromises open up the very real possibility of increased interregional and international conflict.

Ultimate threats to drylands

We define ultimate threats to drylands as the higher-level ecological, evolutionary, and social factors that exacerbate proximate threats. Vulnerability to ecological state change and false perceptions are both ultimate threats to dryland ecosystems.

Vulnerability. Organisms in drylands are often assumed to be less vulnerable to global change than those from more humid ecosystems because they are adapted to and survive in such harsh environments (Gonzalez et al. 2010, Seddon et al. 2016). However, a number of ecological and evolutionary factors can make drylands highly vulnerable to state change (Reynolds et al. 2007, Stafford Smith and McAllister 2008). We define *vulnerability* as the capacity of an ecosystem to withstand pressures from drivers of state change, dependent on several factors, including the likelihood of exposure, the sensitivity of the system (i.e., resistance), and the recovery or adaptive capacity of the ecosystem (i.e., resilience; De Lange et al. 2010, He et al. 2018). Therefore, the most vulnerable ecosystems are those with a low resistance and/or resilience to a proximate threat (or threats) and high probability of exposure (box 1). As we previously noted, drylands are being increasingly exposed to numerous direct and interacting proximate threats, so the risk of exposure is already high and perhaps even increasing. An important question remains: Are the organisms and communities of these ecosystems resistant or resilient to such exposure?

Ecological resistance and resilience are based on past environmental conditions selecting for given traits within populations, and shaping current community assemblages. Such ecological legacies are driven by biotic, soil, and geomorphic processes operating at various spatiotemporal scales (Morton et al. 2011, Monger et al. 2015). Evolutionary theory predicts that organisms and ecosystems should be least sensitive to environmental conditions that vary the most in their environment (Janzen 1967, Flombaum et al. 2017). Although dryland organisms are adapted to high variability in precipitation and water availability, climate change may alter hydrological regimes in ways that exceed the adaptive capacity of certain species or plant functional types or significantly influence species interactions, leading to large changes in community composition and altered ecosystem functioning (Breshears et al. 2016). Dryland ecosystems are also sensitive to atmospheric nitrogen additions (but less responsive than more humid lands; Yahdijan et al. 2011), which can lead to modest increases in productivity, as well as effects on plant species composition. Furthermore, adaptations that provided resistance or resilience to historical environmental conditions can become maladaptive in response to changes in precipitation regimes (Reed et al. 2012) or lead to counterintuitive responses (Kimball et al. 2010).

Given the potentially low ability to recover from disturbance, drylands may be most vulnerable to novel disturbance regimes that can lead to state changes (box 1; Flombaum et al. 2017). Dryland pastoral and agricultural activities can rapidly lead to persistent ecosystem degradation when they exceed a dryland system's capacity for production and soil development or nutrient cycling, respectively (Parr et al. 1990). For example, the combined influences of increasing atmospheric CO_2 concentration, twentieth century climate change, and livestock grazing have collectively promoted transitions from grassland to shrub-dominated landscapes across the world (Cingolani et al. 2005, Okin et al. 2009, Ravi et al. 2010, D'Odorico et al. 2012). As grass cover declines, and aboveground vegetation becomes more regularly distributed, plant-soil feedback loops lead to the concentration of nutrients and biological activity around the base of shrubs and depletes nutrients and activity in soil interspaces (Schlesinger et al. 1990). These processes have

Box 1. Ultimate threats to drylands: Ecological vulnerability.

Ecological vulnerability is the capacity of an ecosystem to withstand pressures from drivers of change, and is dependent on exposure risk, and the resistance and resilience of the ecosystem. Drylands are being exposed to a growing number of global change drivers (proximate threats). As a case study, we focus on the Colorado Plateau, a semiarid dryland in the southwestern United States.

Climate change. Droughts, altered precipitation seasonality, and warming temperatures have been linked to observed or forecast changes for the Colorado Plateau (Seager et al. 2007, USGCRP 2017). Both observation and experimental evidence suggest that such changes in climate will lead to reduced perennial grass cover as well as biological soil crusts (Munson et al. 2011, Ferrenberg et al. 2015). The loss of both vegetation and soil surface communities may increase vulnerability of these ecosystems to soil erosion via wind and water movement. Photograph: Killi Quinn, US National Parks Service.

Land-cover change. Oil and natural gas extraction has expanded rapidly across the Colorado Plateau in recent decades with roughly 90,000 extraction-related sites being reported (Nauman et al. 2017). Well pad sites can remain highly degraded even after a half-century of time for recovery (Minnick and Alward 2015). Restoration efforts have made little difference in the overall recovery of well-pads, highlighting the recalcitrant nature of state changes in drylands (Nauman et al. 2017). This very poor recovery in both passive and active restoration highlights the vulnerability of the Colorado Plateau to land-use change. Photograph: Jeff Mitton, University of Colorado Boulder.

Grazing. Roughly 90% of the Colorado Plateau is open to livestock grazing. The abundance of large, native-herbivores is historically low across the Colorado Plateau, leading to vegetation systems that are not adapted to grazing. Many perennial grasslands across the Colorado Plateau shifted to shrublands in the 1800s because of livestock grazing (Schwinning et al. 2008). Grazing has also negatively affected biological soil crusts leading to increased soil erosion and susceptibility to exotic plant invasions. Given low resilience of the vegetation, chronic aridity, and loss of soil fertility and stability, grassland recovery from overgrazing is slow or nonexistent (Schwinning et al. 2008). Photograph: Mike Duniway, US Geological Survey.

been recognized to affect 43% of Africa (Reich et al. 2001), up to 70% of Australia (Pickup 1998) and the huge semiarid regions that border true deserts in the Arabian Peninsula, Southeastern and Central Asia (Wang et al. 2008, Heshmati and Squires 2013), and semiarid regions in South America (Tomasella et al. 2018). These above- and below–ground transitions can increase wind and water erosion of soils leading to additional degradation (Ravi et al. 2010), a positive feedback that can maintain the system in the altered state.

Perception. The management of drylands has been influenced by a long history of misconceptions about theses ecosystems and their people (box 2; Mortimore et al. 2009). Drylands are often perceived as barren landscapes with little economic value owing to their harsh climates, low productivity, and remoteness from markets and political centers (Stafford Smith 2008, Mortimore et al. 2009, Middleton et al. 2011). In reality, people and societies have lived and thrived in drylands for thousands of years, and

Box 2. Ultimate threats to drylands: Perception.

The following are common misconceptions about drylands:

- Drylands are wastelands, needing society to add value such as agriculture, mining, or solar farms.
- Because of low rates of productivity, rainfall, and nutrients, drylands have little impact on global biogeochemical cycles or energy balance.
- Drylands are mostly inhabited by poor people that are degrading and exploiting land.
- Restricting mobility of grazing will reduce dryland degradation and desertification.
- Technological innovations combined with stronger centralized governance will improve conditions for drylands inhabitants and allow for better land management.

today these ecosystems account for much of the world's grain and livestock production (Middleton et al. 2011). The role of drylands at regional to global scales is often under–appreciated. Given their massive spatial extent, drylands exert a major influence on global energy balance and biogeochemical cycles. For example, high surface albedo in many drylands has a large impact on the global radiation budget and therefore climate (Alkama and Cescatti 2016, Rutherford et al. 2017). Drylands also play a significant role in the global carbon cycle by affecting interannual variability in the terrestrial carbon sink (Ahlström et al. 2015). For instance, 60% of the global carbon sink anomaly in 2011 was attributed to increased carbon uptake in Australia during an abnormally wet period (Poulter et al. 2014). Misconceptions about drylands also extend to the people that live there. The traditional livelihoods and land use of pastoralists in drylands are often viewed as inefficient and damaging to natural ecosystems, resulting in false narratives that influence governance and management. As a result, practices and technologies developed in more humid ecosystems have been imposed in drylands in an attempt to diminish the effects of natural variability of these systems, rather than using approaches built on local knowledge or aiming to enhance existing adaptive capacities (Middleton et al. 2011).

Compelling, simple narratives have transformed polices, management, and perception of drylands. Two historical examples, the desertification narrative in the Sahel region in the 1970s and the tragedy of the commons narrative in rangelands of the American West, illustrate how simple stories, supported by the science of the time, can have large impacts on the fate of dryland ecosystems. The desertification narrative first evolved in the late nineteenth century in North Africa, arising from a misunderstanding of the ecological potential of drylands (i.e., they were believed to have once been forested like Europe) and the erroneous attribution of the nonequilibrium dynamics of drylands to mismanagement (Davis 2016). This desertification narrative was expanded throughout the world in the 1970s (Charney 1975), leading to policies intended to minimize variability and heterogeneity in the environment. In addition to Africa, desertification has been identified as a problem linked to poor land management in countries such as Iran, India, and China (Misra 2009, Varghese and Singh 2016, Zhang and Huising 2018). The tragedy of the commons narrative (Hardin 1968) suggests that if a pasture is shared by a community of herders, it will head toward inevitable ruin because of individual selfish actions. This concept has dominated twentieth century rangeland science and had large impacts on approaches to resource management in the American West, which has turned to privatization, central governance, and fences as solutions.

Although these narratives are simple and compelling, they are largely based on invalidated science. Both Desertification and the Tragedy of the Commons narratives were influenced by theories that ecosystems would inevitably reach an equilibrium or "climax" state (Mortimore et al. 2009). Such equilibrium states were the targets for management at broad scales, and variability and heterogeneity in the environment were minimized. Today, ecology and rangeland science are underpinned by nonequilibrium dynamics and resilience theory, characterized by concepts of nonlinear, less predictable dynamics and the potential for multiple stable states (e.g., Holling 1973, May 1977). The assumption that contemporary grazing alone pushed Sahelian and American Western rangelands away from equilibrium conditions has given way to alternative interpretations. In the case of the Sahel, vegetation change was largely attributed to changes in sea surface temperature that altered climatic patterns (rather than land use); in fact, recent shifts in rainfall have led to a regreening of the region (Dardel et al. 2014). In the American West and elsewhere, sociologists, anthropologists, and historians have invalidated many of Hardin's (1968) conclusions that communal property careens toward inevitable ruin and environmental destruction (Ostrom 1990). Nonetheless, oversimplified narratives of the past have shaped a persistent negative perception of drylands and their inhabitants.

Shifting the narrative

It is important that scientists are aware of the profound impact of simple narratives and find creative but informative

Figure 4. Solutions: Knowledge coproduction. The transition of Mongolia from a communist to democratic society in the early 1990s was accompanied by a disruption to pastoral management systems (Fernandez-Gimenez et al. 2017). The privatization of livestock in communal rangelands has led to ever increasing livestock numbers, reductions in forage availability and productivity, and an increased vulnerability of livestock and herders to weather extremes. A nongovernmental organization funded by the Swiss government, Green Gold Mongolia, in 2006 initiated the "resilience-based rangeland management" program. This approach features community-based development of rangeland "state and transition models" that describe the mechanisms of changes in vegetation and accompanying management responses (Bestelmeyer et al. 2017). These models are used to interpret monitoring data gathered with support of government agencies. Information on rangeland states is used to design grazing management strategies intended to increase rangeland production and animal quality. The models and monitoring serve as a foundation for local governance of rangeland conditions, and is being widely adopted across Mongolia (Densambuu et al. 2018). Photograph: Brandon Bestelmeyer.

ways to challenge them. All ecosystems on Earth face numerous threats from global change, but drylands are unique in that proximate threats are exacerbated by the ultimate threats of vulnerability and societal perception. Variability in climate, heterogeneity of the landscape, and remoteness of many populations are common characteristics of drylands. Although many pastoral communities have adapted their livelihoods to dealing with such environmental uncertainty, development over the past century has largely ignored local knowledge and undermined sustainable practices, making these communities more vulnerable to climate change. For example, migratory grazing practices that can exploit the temporal and spatial variability in forage quality have been replaced with more sedentary and privatized livestock production, managed by systems of centralized governance (Behnke and Mortimore 2016). Land management that can adapt to climate variability and landscape heterogeneity, and balance the values of multiple stakeholders to implement desired management outcomes, may provide a path forward to sustainable drylands. Knowledge coproduction, with scientists collaborating with stakeholders to develop research questions and analyze data, has a much higher likelihood of affecting decision making because the stakeholders have more faith in the data, which are at relevant spatial and temporal scales for management (figure 4; Meadow et al. 2015). Furthermore, indigenous and local knowledge systems can provide valuable insights into practices for sustainable ecosystem management (Tengö et al. 2014), and may help guide research (figure 4).

One of the greatest threats to drylands is the perception of drylands as fragile and largely degraded landscapes in need of human intervention to bring value. False narratives that have led to this perception need to be replaced with accessible, science-based narratives that convey the complexity of dryland ecosystems. Improved communication with educators, land managers, policy makers, and the general public will help shift this perspective. Indeed, when looking at Merriam-Webster's definition of a wasteland, the allusions to deserts are common. The example provided for the "barren or uncultivated land" definition of a wasteland is a *desert* wasteland. A second wasteland definition is "a way of life that is spiritually and emotionally *arid* and unsatisfying."

To inhabitants of drylands, these negative connotations of deserts and arid environments often do not ring true. Deserts mark the location of our first civilizations and currently support the livelihoods of billions of people (Millennium Ecosystem Assessment 2005). Nevertheless, a perception of drylands as wastelands affects the way we make decisions about these ecosystems, and the way we prioritize land use and management. Many of these considerations have to do with values that will vary by group, but all of these considerations would likely benefit from a shift away from a narrative describing drylands as wastelands. In order to address the ultimate threats to dryland sustainability, we propose a conscious shift in our dryland perspectives to more accurately represent the diversity of ecosystems and organisms unique to drylands and the range of services drylands provide. Avoiding deliberate and inadvertent representations of drylands as useless or barren is the first step toward greater investment in the management of arid and semiarid ecosystems. Highlighting the utility and beauty of drylands in outreach and education can help ensure their sustainability.

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David L. Hoover (david.hoover@ars.usda.gov) and Hailey Wilmer are affiliated with the US Department of Agriculture (USDA) Agricultural Research Service (ARS) Rangeland Resources and Systems Research Unit, Crops Research Laboratory, in Fort Collins, Colorado. Brandon Bestelmeyer is affiliated with the USDA-ARS Jornada Experimental Range, in Las Cruces, New Mexico. Nancy B. Grimm and Osvaldo Sala are affiliated with the School of Life Sciences, Julie Ann Wrigley Global Institute of Sustainability, at Arizona State University, in Tempe, Arizona. Travis E. Huxman is affiliated with the Department of Ecology and Evolutionary Biology at the University of California, Irvine. Sasha C. Reed is affiliated with the US Geological Survey, Southwest Biological Science Center, in Moab, Utah. Osvaldo Sala is affiliated with the Global Drylands Center, at Arizona State University, in Tempe. Timothy R. Seastedt is affiliated with the Department of Ecology and Evolutionary Biology at the University of Colorado, in Boulder. Scott Ferrenberg is affiliated with the Department of Biology at New Mexico State University, in Las Cruces.