Beyond desertification: new paradigms for dryland landscapes

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The traditional desertification paradigm focuses on the losses of ecosystem services that typically occur when grasslands transition to systems dominated by bare (unvegetated) ground or by woody plants that are unpalatable to domestic livestock. However, recent studies reveal complex transitions across a range of environmental conditions and socioeconomic contexts. The papers in this Special Issue illustrate how an improved understanding of these dynamics is generating more robust paradigms, where state changes and regime shifts occurring within the context of changes in land use and climate are modified by landform and antecedent conditions. New and emerging technologies are being used to characterize and evaluate processes and outcomes across various scales and levels of organization. At the same time, developments in education are taking advantage of these new perspectives to improve the ecological literacy of future generations, and to better inform land-management decisions. A framework that integrates these perspectives provides a more comprehensive approach for understanding and predicting dryland dynamics.

Front Ecol Environ 2015; 13(1): 4–12, doi:10.1890/140276

Challenges to existing paradigms – the set of practices or universally recognized achievements or perspectives that define a scientific discipline at any particular period of time – are fundamental to the progress of scientific knowledge (Kuhn 1962). While these challenges have always been part of science, the frequency and number of successful challenges to traditional paradigms across many ecosystem types may be higher now than at any time in the past (eg Naeem 2002). Innovative knowledge-generating technologies acting in concert with new forms of communication among scientific disciplines are leading to a more complete understanding of Earth as a coupled human–natural–physical system operating at multiple, interacting scales. This new information and deeper understanding drives paradigm shifts in numerous ecological subdisciplines, by identifying shortcomings – including inconsistencies – that must be addressed and resolved.

In a nutshell:

- The traditional desertification paradigm focuses on shifts from grasslands to dominance by unpalatable woody plants separated by bare areas, with a concurrent loss of ecosystem services
- Challenges to this paradigm have arisen from observations across a variety of interacting spatial and temporal scales under a range of socioeconomic contexts
- New perspectives are emerging that account for spatial connectivity in resources interacting with legacies of past environmental conditions and current patterns in land use; these approaches improve interpretation and prediction of regime shifts
- A framework that integrates these paradigms can be used to assess ecosystem services, inform land-management decisions, and improve the ecological literacy of future generations living on these lands

Advances in sensor technologies – as well as improvements in modeling, sample analysis methodologies such as genome sequencing (Cohen *et al.* 2009; Porter *et al.* 2009; Luo *et al.* 2011), and data management – are increasing the spatiotemporal extent and resolution of studies while facilitating access to and analysis of large datasets (Peters 2010; Michener and Jones 2012). The spatial scale for observing underlying mechanisms has progressed from individual- or plot-scale studies to examinations conducted at much finer scales (eg point-based sensors, cellular-level micro-arrays); at the same time, airborne and space-based imagery allow for integration of this information at broader (regional to global) scales (eg Hasselquist *et al.* 2010; Ponce-Campos *et al.* 2013). Likewise, short-term fluctuations can now be distinguished quantitatively from long-term directional changes through the availability of instruments measuring and data/proxies covering short (near real-time), medium (decades to centuries), and long (paleo records) time frames (Jackson 2001; Moran *et al.* 2008; Porter *et al.* 2009).

By expanding the depth and breadth of scientists' scales of study, such innovations have enabled paradigms associated with various levels of biological organization, from genes to the biosphere, to be challenged (Jones *et al.* 2006). Accordingly, equilibrium views that predominated until the mid-20th century have been replaced by perspectives accounting for non-equilibrium dynamics that include linear and non-linear behaviors with thresholds, bifurcation points, alternative states, regime shifts, tip-

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ping points, cross-scale interactions, hierarchies of scale, nested hierarchies, and panarchies (eg Pickett *et al.* 1992; Gunderson and Holling 2002). Recognition of the importance of interdisciplinary interactions has also increased (eg Collins *et al.* 2011). The 21st century may arguably be one of the most exciting in terms of the number and variety of fundamental shifts in how ecologists and environmental scientists think about and study their surroundings. These advances assume that scientists can effectively condense and interpret the "data deluge" and direct it to constructively challenge existing perspectives and to develop new ones (Peters *et al.* 2014).

Figure 1. *Land-cover change on the Santa Rita Experimental Range in Arizona. Areas characterized by semi-desert grassland in the early 1900s are now dominated by unpalatable shrubs and succulents (images in public domain are available from http://ag.arizona.edu/SRER/photos.html; compiled by R Wu).*

Elements of the "desertification" paradigm, the subject of this Special Issue, have dominated the scholarly literature on arid and semiarid ecosystems (ie drylands) since the 1980s (eg Verstraete 1986). Definitions of desertification vary, but it is generally considered to be a persistent and severe broad-scale reduction in biological productivity that results from interactions among land use, climate, and societal factors (Verstraete *et al.* 2009). This widespread loss of productivity has occurred globally in tropical, temperate, and high-latitude bioclimatic zones, often through the conversion of perennial grasslands and savannas to systems dominated by xerophytic (adapted to arid environments) woody plants or bare ground (Figure 1). Positive feedbacks between woody plants and soil properties at local scales can propagate across dryland landscapes and lead to broad-scale regime shifts that persist through time (Schlesinger *et al.* 1990; Scheffer and Carpenter 2003). As a consequence of these shifts in land cover and lifeform dominance, these landscapes have traditionally been viewed as degraded, delivering reduced ecosystem services, when compared with historical grasslands and savannas (Reynolds *et al.* 2007).

Globally, many dryland landscapes experienced marked changes in vegetation structure and ecosystem processes over the past 150 years; for any particular location, the proposed explanations for such changes – including intensification of grazing or overgrazing by livestock, drought and climate change, reduction in fire frequency, and changes in atmospheric chemistry and small animal (eg rabbit) populations (Havstad *et al.* 2006) – are numerous and often controversial. Assigning primacy to a given factor is complicated by interactions between factors (eg livestock grazing reduces grass biomass and removes fine fuel, thereby reducing fire intensity and frequency, both of which have positive effects on woody plants) and the occurrence of stochastic trigger events, such as extreme weather, that can either promote woody plant recruitment (during a wet period) or lead to grass mortality (during a drought). These synergistic interactions can overwhelm the effects of individual drivers (Scheffer *et al.* 2001). Trigger events and positive feedbacks can create threshold behaviors and non-linear ecosystem responses that are challenging to understand and predict (Rietkerk and van de Koppel 1997). Human activities have long been regarded as important determinants of desertification (Reynolds and Stafford Smith 2002). Despite this recognition, the role of humans relative to other biotic and abiotic factors is poorly understood, and will likely assume greater importance as environmental conditions change and human population densities increase.

■ A case study from the Chihuahuan Desert

Research over the past decade has generated insights into desertification and the dynamics of desertified systems within the context of global change. Here, we trace the historical changes and challenges to the traditional desertification paradigm, using the Chihuahuan Desert – the largest "hot" desert in North America – as a case study. This region exemplifies the changes that have occurred across dryland landscapes globally over the past 1000 years. The Chihuahuan Desert was selected because land-survey data are available from as early as 1858, and extensive site-based data are readily available from one of the oldest ecological research sites in the US (dating back to 1912), the 78 000 ha Jornada Experimental Range (hereafter "the Jornada"), operated by the US Department of Agriculture, and from the adjoining 22 000 ha Chihuahuan Desert Rangeland Research Center (dating back to 1928), operated by New Mexico State University. The Jornada has also served as a US National Science Foundation (NSF) Long Term Ecological Research (LTER) site since 1982 (http://jornada-www.nmsu.edu/).

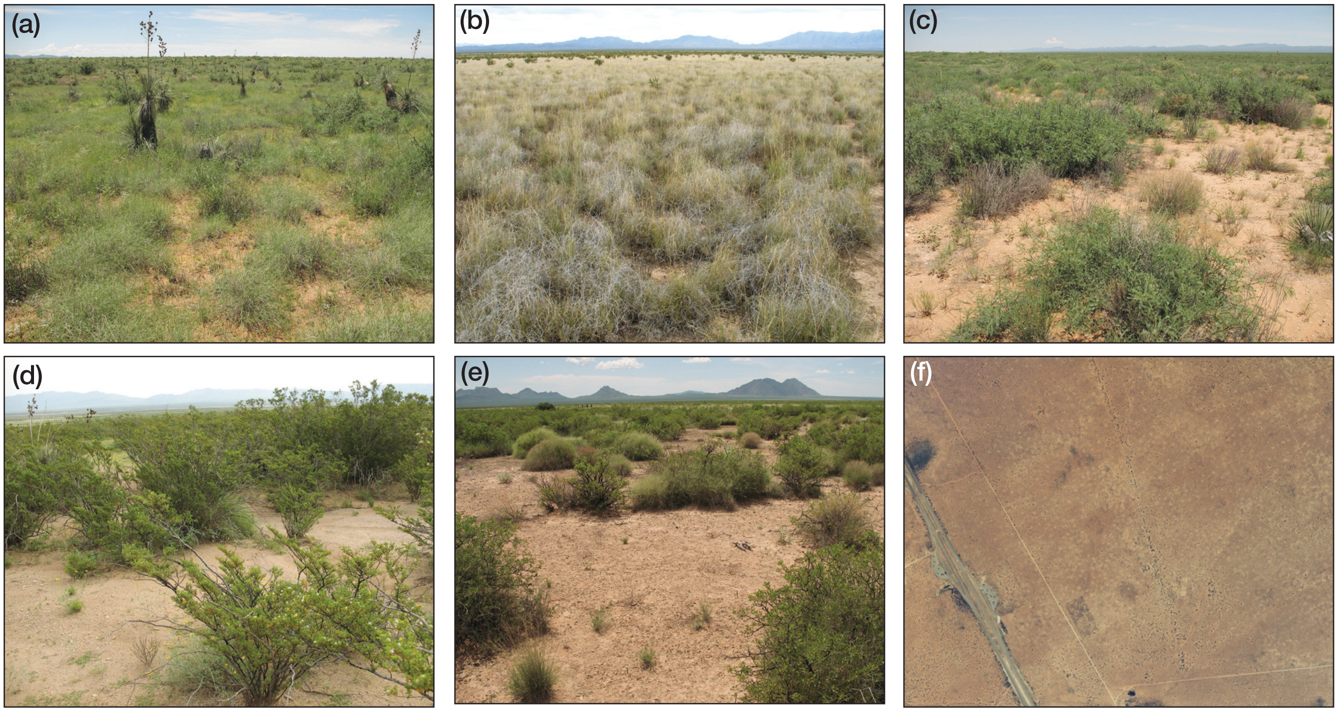
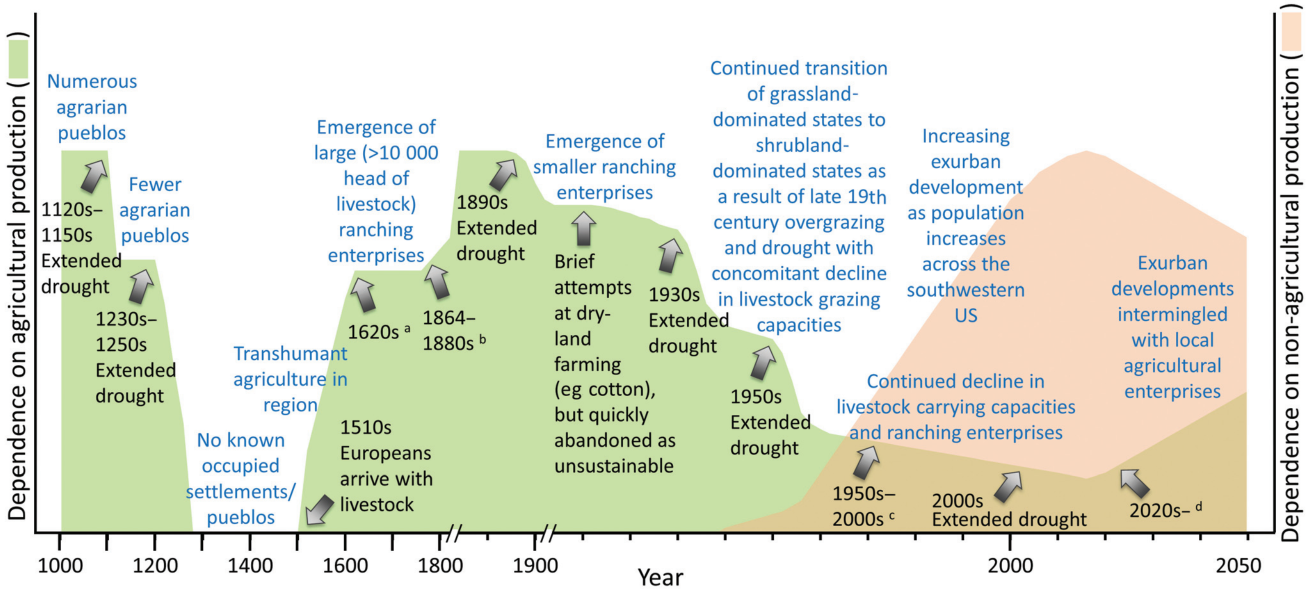


Figure 2. *Typical Chihuahuan Desert plant communities at the Jornada site. (a) Perennial grasslands on loamy sands (dominated by black grama [*Bouteloua eriopoda*] and dropseeds [*Sporobolus flexuosus*]); (b) grasslands in playas that flood intermittently are dominated by perennial grasses (tobosa grass [*Pleuraphis mutica*] and burrograss [*Scleropogon brevifolius*]); (c) shrublands (primarily honey mesquite [*Prosopis glandulosa*]) on sands and loamy sands, and piedmont slope (bajada) shrublands on silty and gravelly soils dominated by (d) creosotebush (*Larrea tridentata*) with scattered grasses on the upper bajada, or (e) tarbush (*Flourensia cernua*) with scattered grasses on the lower bajada. (f) Mesquite plants distributed by humans and animals using the historic El Camino Real have expanded into the surrounding grassland. Images from Jornada USDA-LTER photo library (Jornada.nmsu.edu).*

The Chihuahuan Desert is a warm, high-elevation desert; at the Jornada, elevation averages 1600 m above sea level, with monthly temperatures ranging from 13°C in January to 36°C in June, and mean annual precipitation of 24 cm, the bulk of which (> 60%) falls in the summer monsoon season (1 July to 1 October). Similar to other areas in the Chihuahuan Desert, the Jornada consists of repeating geomorphic units defined by a combination of physical features (landforms), soils, and vegetation properties (Havstad *et al.* 2006). These geomorphic units currently support five major ecosystem types (Figure 2). We use information from the Jornada to illustrate how the desertification paradigm developed to explain changes in these ecosystem types through time, why this perspective prevailed, and how it is now being challenged.

Although the US Southwest has experienced a major transition between C_4 grassland and C_3 shrubland at least three times over the past 10 000 years, the most recent transition – between the mid-1800s and mid-1900s – occurred at a much faster rate than previously (Van Devender and Spaulding 1979). This transition actually began in 1000 CE, a period when an agricultural lifestyle influenced by periodic drought predominated (Figure 3; Stuart 2000). Humans lived in pueblos (permanent settlements), the population sizes of which expanded and contracted depending on weather-driven variations in food supply. Three multidecadal droughts, beginning in the early 11th century and extending through the late 13th century, led to widespread abandonment of pueblos (Benson *et al.* 2007). Agriculture rebounded in the 1500s, and localized overgrazing was recorded along the El Camino Real, the historic overland route established between Mexico City and Santa Fe, in present-day New Mexico. The movement of livestock (including horses) along this route also facilitated the transport and redistribution of seeds of woody plant species, which contributed to their establishment and expansion into the neighboring desert grassland (Figure 2f).

Throughout the 19th century, most of the northern Chihuahuan Desert – much of which now lies within the contemporary boundaries of the US – was composed of perennial grassland with isolated patches of shrubs (Dick-Peddie 1999). In 1858, 80% of the Jornada was dominated by perennial grasslands (Peters *et al.* 2012), similar to much of the southwestern region (Grover and Musick 1990). This large expanse of grasslands attracted both farmers and ranchers. Federal government policies, as well as the development of railroads and technologies for fencing and water development, promoted settlement (Figure 3), and by the late 1800s, large cattle ranches were common and overgrazing was prevalent. A series of multiyear droughts (in the 1890s and 1930s) and severe winters (1880s), combined with an influx of homesteaders, led to smaller ranching/cropping enterprises. Dryland



[a] 1620s El Camino Real route established from Chihuahua to Santa Fe with first reports of localized overgrazing.

[b] 1864–1880s Original Homestead Act, water drilling and fencing technologies introduced, railway transportation established, banking investments available for western settlements.

[c] 1950s–2000s Use of non-renewable technologies in an attempt to stabilize agriculture with minimal success due to focus on production rather than aridity and regional propensity for extended severe droughts.

[d] 2020s– Adoption of climate-smart agricultural production practices.

Figure 3. *Millennial transitions between agricultural (green, brown) and non-agricultural (pink) human activities (blue text) and examples of key drivers of those transitions (black text and arrows) at the Jornada site in southern New Mexico. Transitions anticipated over the next 40 years include incorporation of agricultural activities within exurban developments and adoption of climate-smart agricultural production practices and technologies, such as the use of dryland-adapted Criollo cattle.*

agriculture was attempted, but was largely unsustainable. By the time of the major drought of the 1950s, nearly half of the landscape of the Jornada and many other locations had transitioned from perennial grassland to xerophytic shrubland (Peters *et al.* 2012). Despite subsequent reductions in stocking rates and the implementation of progressive livestock management practices, woody plant expansion continued until 1998, by which time only 8% of the Jornada landscape remained grass-dominated (Gibbens *et al.* 2005).

■ Development of the desertification paradigm

The transformation of a landscape from a productive perennial grassland to a desertified shrubland characterized by large areas of bare ground – over a relatively short period of time, as occurred in the Jornada – is a phenomenon that has been widely observed and well-documented throughout the southwestern US (Figure 4). This grassland-to-shrubland transformation became a model for the study of desertification because it occurred during a time period when research sites and land-management agencies were being established, active research was being conducted, and human population density was increasing in the region. The desertification process was therefore witnessed by many people across a large region over a similar time frame, allowing data to be collected and generalizations to be made.

This traditional desertification paradigm has persisted in large part because ecosystem-level changes were well documented by researchers, and occurred within two to three generations of researchers, land managers, and practitioners. Thus, the memory of land cover in the mid-to-late 1800s and its subsequent changes were passed down and maintained within the human population and are part of computational databases within the scientific community. Remnant grasslands are still available for study within the region (Hochstrasser *et al.* 2002). Finally, the current shrub-dominated landscapes are often resistant to change, thus leading to studies characterizing tipping points and thresholds in desertification processes (Bestelmeyer *et al.* 2011).

■ The need for a more comprehensive framework

Although the traditional desertification model exemplified by the Jornada has persisted, the continued debates and controversies pertaining to the drivers of dryland dynamics around the globe have reinforced our perception that this paradigm is not sufficiently robust. More than a century of ecological research in dryland environments has indicated – at a minimum – the importance of context, including location, to dynamics. New perspectives need to explicitly account for the ecological implications of location, how the past influences the present,

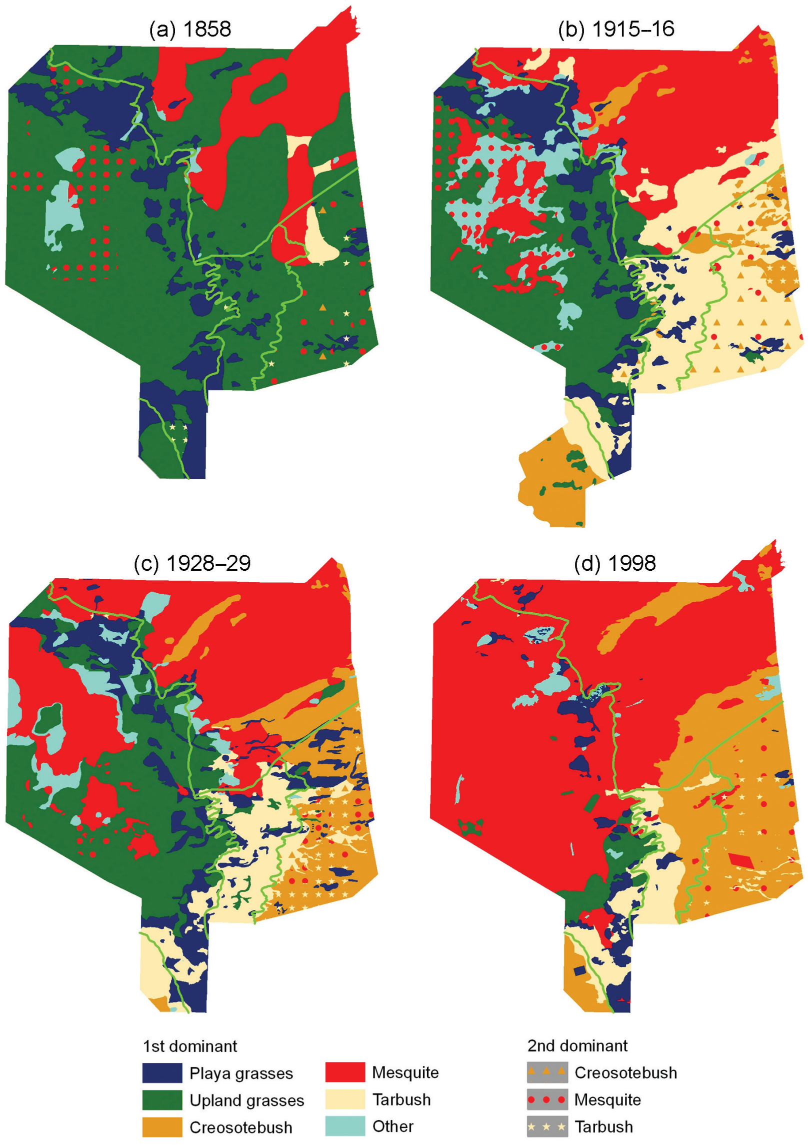


Figure 4. *Land-cover change in the Chihuahuan Desert at the Jornada site in New Mexico, 1858–1998 (modified from Gibbens* et al. *2005). During this period, uplands dominated by black grama grasses transitioned to one of three shrub communities (mesquite, tarbush, or creostotebush), and shrub communities transitioned from one to another (eg tarbush to creosotebush).*

and how spatial interrelationships change through time to drive further change.

Complex transitions

Long-term data show that the desertification of the Jornada landscape was the result of multiscale spatial–temporal interactions. We suggest that an explicit accounting of these interactions will explain and resolve what have previously been regarded as exceptions to, inconsistencies in, and limitations of the desertification paradigm. Six observations illustrate this point (Table 1). First, desertification can occur even in the absence of livestock grazing (Peters *et al.* 2006). Second, the Jornada grasslands present in 1858 have been transformed into a landscape consisting of spatially distinct communities, dominated by one of three shrub functional types (N_2-fixing, winter deciduous honey mesquite [*Prosopis glandulosa*]; evergreen creosotebush [*Larrea tridentata*]; and winter deciduous tarbush [*Flourensia cernua*]; Figure 4). This suggests that pattern–process relationships acting on similar initial vegetation can result in divergent dynamics and outcomes when occurring on geomorphic units with different soils and topographies. Third, transitions among different shrubland types have occurred through time (eg from deciduous tarbush to evergreen creosotebush on the eastern upper bajadas [an alluvial plain at the base of a mountain range formed by the coalescing of alluvial fans] between 1915 and 1928; from low to high densities of N_2-fixing deciduous mesquite since 1928 on the western sand sheet). This emergence of different shrublands suggests important functional changes beyond those represented in the traditional desertification paradigm. Fourth and fifth, after a series of wet years, the following outcomes are suggested by observed increases in the abundance of both native perennial grasses (on shrublands occupying former grasslands) and non-native grasses (in native grasslands): for the former, regime-shift reversals may occur, although the processes and climatic events required for long-term persistence of grasses are unknown (Peters *et al.* 2012); for the latter, future land-cover states may be different from past ones (Yao and Peters 2014). Sixth, at the regional scale, drought and human population increases are expected to shift land-use patterns from agriculture and ranching to multiple uses, particularly in developed countries. Landscapes will increasingly consist of mosaics of exurban development intermingled with local climate-smart agricultural enterprises that are informed by the past, but adapted for future conditions. Climate-smart agriculture is defined as systems of production that sustainably increase both agricultural outputs and incomes, build resilience to climate change, and reduce greenhouse-gas emissions. For example, the southwestern US is predicted to experience increased annual ambient temperatures, with an increased number of days with temperatures above 35° C. These conditions will reduce primary production in many locations and will reduce capacities for secondary production through traditional rangeland livestock production. Adaptations through the incorporation of livestock genetics will be necessary to maintain the nearly $70-billion annual animal agriculture business in the region. One possibility is the use of Criollo cattle, which were introduced to arid environments of North America by the Spanish in the early 16th century (Peinetti *et al.* 2011). This livestock breed is well-adapted to drylands, with reduced forage intake requirements and extremely limited requirements for other inputs, such as water. Though Criollo cattle are small and atypical for classic US feedlot industry standards, the animal industry is beginning to adapt production systems to accommodate their genetics, and market demand is increasing. These types of industry adaptations are necessary to impart resilience for US agriculture in response to the realities of changing climates.

Because the traditional desertification paradigm is too narrow in scope to accommodate the six changes summarized in Table 1, a broader framework – one that accounts for new types and patterns of land use and novel environmental conditions – is needed to improve our understanding of local-scale dryland dynamics (Figure 5). Papers in this Special Issue, described briefly below, illustrate how an understanding of these dynamics is generating more comprehensive perspectives where state changes and regime shifts are occurring within the context of changes in land use and climate. New paradigms are emerging in six areas (legacies, spatial connections, land-use context, ecological literacy, ecosystem services, and new technologies) that, when integrated into a new framework, provide a more robust approach for understanding and predicting dryland dynamics.

Legacies

In this issue, Monger *et al.* (2015) present a new generalized legacy paradigm, in which historical perspectives play a major role in explaining various phenomena spanning multiple scales and disciplines. For example, the effects of the Medieval Warm Period (approximately 900–1300 CE) are still reflected in today's vegetation patterns (Weems and Monger 2012), while previous-year precipitation markedly influences current-year primary production (Sala *et al.* 2012). The power of the legacy perspective is that it provides a context for the interdisciplinary collaboration and rapid scientific progress that occur when tools and conceptual frameworks developed within one discipline are adapted for use in others.

Spatial connections

Drylands are characterized by low but variable precipitation, infrequent and intense thunderstorms, sparse vegetation, and exposed ground surfaces. As such, they are prone to the redistribution of biological materials, soil, and nutrients by wind and water. The traditional desertification paradigm emphasizes fine-scale processes at the plant and interspace scale, and watershed-scale perspectives on the extent of wind and water erosion across the landscape (Schlesinger *et al.* 1990, 2000). However, there are important phenomena that cannot be explained with this conceptual framework (Peters *et al.* 2006). In this issue, Okin *et al.* (2015) address this gap with a perspective based on the concept of structural and functional "connectivity",

Table 1. Observations from the Jornada Basin illustrating the limitations in the current grassland to shrubland desertification paradigm

Observation	*Evidence from the Jornada site*
1. Desertification occurs in the absence of livestock grazing	Shrub encroachment has occurred within long-term cattle exclosures (Peters *et al.* 2006)
2. Spatial variation in soils and topography dictate the pattern, extent, and dynamics of desertification	Spatially distinct communities dominated by contrasting shrub functional types (nitrogen-fixing, winter deciduous honey mesquite; evergreen creosotebush; winter deciduous tarbush) now occur on what was once homogeneous grassland (Figure 4)
3. Lumping desertified states as "shrubland" ignores dynamic transitions among shrub growth forms that have consequences for ecosystem structure/function	Upper bajadas transitioned from deciduous tarbush to evergreen creosotebush between 1915 and 1928, and nitrogen-fixing deciduous shrubs (mesquite) have increased since 1928 (Figure 4)
4. Regime-shift reversals can occur (eg shrubland → grassland)	Native perennial grasses have recently increased in shrub communities occupying former grasslands (Peters *et al.* 2012, 2014)
5. Invasive species and anthropogenic drivers are creating novel ecosystems	Non-native grasses have recently increased in abundance after a series of wet years (Yao and Peters 2014)
6. Changes in land use beyond natural ecosystems to multiple uses	At the regional scale, continued drought and an increasing human population are expected to lead to a marked regional shift in land use from agriculture and ranching to exurban development, outdoor recreation, and multiple uses (Buenemann and Wright 2010)

Notes: These were historically regarded as exceptions and inconsistencies. We suggest that an accounting of multiscale spatial–temporal interactions and land uses will create a more robust framework, capable of accounting for such observations (Figure 5).

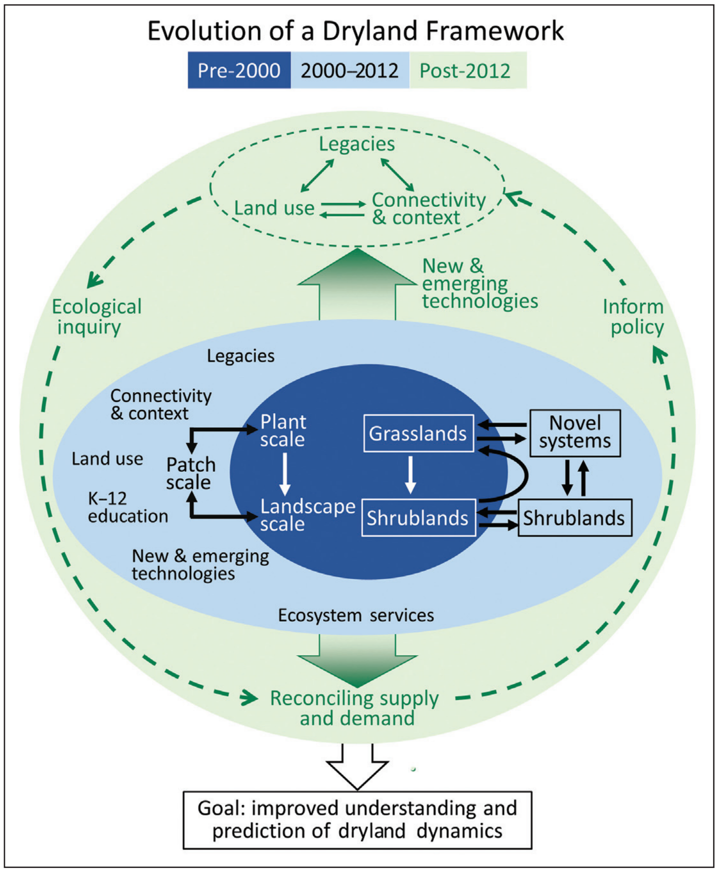


Figure 5. *Evolution of a dryland framework based on case studies at the Jornada site in the Chihuahuan Desert, New Mexico. Early perspectives (dark blue area) focused on the grassland to shrubland transition, and emphasized either plant- or landscape-scale research. Later research (light blue area) focused on the patch scale and accounted for transitions among communities dominated by different shrub species and transitions to novel systems. Recent research, reviewed in this Special Issue (green area), is broadening the framework to incorporate new perspectives and new technologies to promote ecological inquiry and inform policy that will affect the ability of drylands to provide services to society, and to improve understanding of and predictions about dryland dynamics.*

which relies on the patch scale to link plant-level processes with landscape-scale patterns. Their model demonstrates the importance of connected pathways in promoting the sustainable management and restoration of drylands.

Land-use context

The importance of the term "desertification" is internationally recognized (UN-DDD 2014). Yet the use of desertification as a catch-all concept for diverse types of change obscures both underlying causes and potential solutions. Bestelmeyer *et al.* (2015a) suggest a framework that distinguishes between various changes – equilibrium, non-equilibrium, ecological state, and regime shifts – and integrates state change, regime shifts, and land-use change. This new framework views desertification as state changes or regime shifts occurring within the context of specific land-use categories (eg rangeland, cropland, urban) that vary in space and time in response to environmental and socioeconomic drivers. Their framework accommodates the array of context-specific analyses needed to identify appropriate management and policy responses for either preventing or reversing undesirable change. This perspective helps managers prioritize the deployment of limited resources to areas where goals and objectives have the greatest chance of being realized.

Ecological literacy

Ecologists are increasingly engaging in global-scale research, conducted through partnerships among scientists from many disciplines. To be successful, participants within these collaborations require extensive organizational abilities, interdisciplinary training, and strong communication skills. Graduate school programs in recent years have sought to develop a new generation of scientists possessing such perspectives and skills. However, Bestelmeyer *et al.* (2015b) – also in this issue – argue that activities cultivating these novel skill-sets should be introduced and propagated much earlier in the educational system, beginning in kindergarten through the 12th grade (K–12). Accordingly, the authors propose a new ecological inquiry paradigm, wherein information presented in textbooks and the classroom is proactively integrated with hands-on, team-oriented research projects including both outdoor and laboratory components.

Ecosystem services

Ecologists, hydrologists, and range managers have evaluated the consequences of desertification for the provisioning of ecosystem services (Havstad *et al.* 2007). These assessments were conducted from the point of view of determining which services would be supplied and how they could contribute (directly and indirectly) to improve human well-being. Yet in this issue, Yahdjian *et al.* (2015) note that the provisioning of ecosystem services that are not demanded or used by stakeholders adds little to human well-being and should therefore be a low priority in research, management, and policy considerations. Furthermore, demand for ecosystem services is dynamic and can change markedly over time for social, cultural, or political reasons. The framework proposed by Yahdjian *et al.* (2015) attempts to reconcile supply and demand, and suggests that land-management decisions recognize the need for this reconciliation among different stakeholders.

Emerging technologies

Traditional approaches to data collection, management, and analysis for dryland research relied on short-term, plot-scale studies characterized by a relatively small number of spatially distributed, infrequently sampled plots. Monitoring data captured from these sites were then used for landscape- and watershed-scale assessments and management decisions. Here, Browning *et al.* (2015) present an emerging research paradigm, typified by multi-investigator studies, carried out across many sites, spatial and temporal scales, and biological levels of organization. This approach is achieved by applying existing technologies in novel ways and implementing new analytical techniques. Within this framework, large, disparate datasets are integrated within interactive technological settings that encourage and reward data sharing, exploration, and interpretation. This framework will be pivotal for improving decision making for sustainable resource management.

Concluding remarks

The traditional view of desertification simplistically characterizes dryland degradation as a loss of net primary productivity and soils, often accompanied by a transition from grassland to shrubland dominance. However, evidence points to a more nuanced, location-dependent dynamic in which dryland responses to interacting climatic and anthropogenic drivers can be explained and predicted. These dynamics demand a more robust and comprehensive framework that integrates a suite of new paradigms that can accommodate conservation and management of the world's diverse drylands. Though more complex, the framework summarized in Figure 5 and reviewed in detail by the papers in this Special Issue is based on newly available knowledge, technologies, and computational capabilities.

The foundation for this new framework is based on clear descriptions of ecological states and transitions of those states at sites within a defined biophysical region. Boundaries of biophysical regions and the ecological sites within them can be identified using knowledge of climate, regional geomorphology, and ecology. An example within the US is the US Department of Agriculture's Major Land Resource Areas (MLRAs), which consists of approximately 325 well-defined biophysical regions. One MLRA encompasses the northern Chihuahuan Desert of southern New Mexico, and includes about 40 unique ecological sites, defined on the basis of vegetation and soils. Characterization of the ecological states and transitions unique to individual sites or groups of similar sites within this (or any) MLRA would be conducted with the proposed desertification framework (Figure 5). These characterizations would then serve as a basis for hypothesis testing and assessment of climate-change impacts and land-use/land-conservation, at the scales at which land management is practiced and policy is implemented (Sayre *et al.* 2012).

Acknowledgements

Funding was provided by the NSF to the Jornada Basin Long Term Ecological Research Program through New Mexico State University (DEB-1235828). DPCP and KMH acknowledge the USDA-ARS (#6235-11210-007) for ongoing support; SRA acknowledges support from the Arizona Agricultural Experiment Station (ARZT- 1 360540-Hl 2- 99).

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