Connectivity and Scale in Dryland Ecosystems

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Arid and semiarid ecosystems, sometimes summarized as "drylands," occupy approximately 45 percent of terrestrial ecosystems and are expected to expand under climate change. Unlike mesic systems, where moisture is only rarely limiting, dryland ecosystems are characterized by frequent periods of water shortage punctuated by more or less isolated rain events (figure 1) that drive episodes of biological activity (Noy-Meir 1973). This pulse–reserve paradigm has dominated the theoretical underpinnings of aridland ecology for decades (Reynolds et al. 2004, Collins et al. 2008). Updated conceptual frameworks have attempted to generalize the model to focus on pulse dynamics, as well as expand the spatial and temporal scales of pulse dynamics theory (Schwinning and Sala 2004, Collins et al. 2014). Most recently, ecologists and ecohydrologists have recognized that biophysical processes and interactions during dry periods, such as the relationship between vegetation cover and wind erosion, also have significant consequences for dryland dynamics and stability.

This issue of *BioScience* includes a special section that contains four articles on connectivity and multiscale processes in dryland ecosystems. These articles unite theory with fundamental long-term research to improve understanding and enable better management of these highly dynamic ecosystems. Connectivity measures the ability of materials (soil nutrients, seeds) to move from one place to another in the landscape as a function of the strength of factors that cause movement (wind, water). A fifth article in the section discusses the challenges and prospects for developing and maintaining formal education programs built around educational philosophies that change on political timescales. Together, these articles integrate biological and physical processes at multiple spatial and temporal scales to enhance our ability to predict how these systems will respond under a more arid and variable future climate (Cook et al. 2015).

The bulk of the articles center on the long research history of drylands research at the Jornada Experimental Range (JER) in southern New Mexico. The JER has been a US Department of Agriculture (USDA) Agricultural Research Service site since 1912. It was originally established to help range managers and ranchers understand the causes and consequences of overgrazing, drought, soil erosion, and loss of forage plants on rangeland productivity. In 1982, the JER became part of the National Science Foundation's (NSF) Long-Term Ecological Research Program. The NSF supports fundamental research in science, engineering, and education. As a consequence, the JER has enjoyed a long history of research that has evolved over the decades from primarily focusing on forage and cattle production to developing an understanding of the fundamental drivers of aridland ecosystem dynamics and how these apply to rangeland management and sustainability. In a recent issue of *BioScience*, Hughes and colleagues (2017) documented the enduring value of long-term research for management and policy. The history of long-term research at the JER nicely illustrates that point.

Indeed, in recognition of its impactful research history, the USDA named the JER as one of its 10 original Long-Term Agricultural Research sites (Robertson et al. 2008).

One requirement of the NSF's LTER program is information management, an activity that has grown in complexity over time from simply curating (documenting, storing, and managing) data sets to enhanced discovery and integration of multiple data streams. Taking advantage of developments in ecoinformatics, Peters and colleagues (2018) propose new levels of data-model integration with data drawn from multiple sources to understand and predict cross-scale interactions in dryland systems. In this contribution to the special section, the authors summarize three examples of this data integration process that differ in complexity and scale: (1) primary production in wet versus dry periods at the local scale, (2) landscape-scale dynamics in Great Plains agroecosystems during historic drought, and (3) continent-scale spread of livestock disease. Peters and colleagues (2018) note that historical research at the JER focused on processes driving dynamics *within* geomorphic units (grassland, shrubland). Although this leads to a better understanding of within-system dynamics, it does not account for connectivity and cross-scale interactions. By combining a variety of data sources, they show how this new approach can generate a "landscape knowledge map" through nonlinear extrapolations of site-based temporal and spatial measurements to predict net primary productivity at the landscape scale. Peters and colleagues (2018) conclude that expanding outward in this manner generates general knowledge applicable to dynamics of arid systems globally. This can then feed back to the design of additional observational and experimental studies that incorporate scale, connectivity, and nonlinear dynamics.

In the following paper, Okin and colleagues (2018) present a conceptual framework that integrates vegetation productivity, aeolian transport, and

Figure 1. A summer monsoon rain event in central New Mexico. Intense, localized storms such as this have tremendous erosive power that can connect multiple components of aridland landscapes. Photograph: Scott L. Collins.

hydrologic connectivity at the hillslope (local) scale and links their effects on dryland processes under anticipated climate changes. Hydrologic connectivity is a function of runoff, which increases exponentially with rainfall amount. As was noted earlier, water dynamics in drylands are well studied both conceptually and empirically, but dry periods are often longer than wet periods within and between growing seasons. As a consequence, connectivity also occurs during dry periods via aeolian forces. Vegetation structure has a significant influence on the strength of aeolian and hydrological forces. Okin and colleagues (2018) predict that a more extreme climatic regime will favor shrubs over grasses. This will lead to lower vegetation cover on the soil surface, resulting in a more connected landscape at the hillslope scale with increased losses in soil, nutrient, and water resources through both hydrological and aeolian processes. These authors argue that, under climate change, woody plant encroachment may become irreversible.

Alternative stable state theory predicts that two or more ecological states can exist under a range of similar environmental conditions (Bestelmeyer et al. 2011). However, if environmental drivers push the system past a tipping point, it will transition from one state to another. Much of this theory has been built around rapid shifts in aquatic systems, such as lakes and coral reefs. But many terrestrial systems exhibit alternative stable states that are characterized by slow rather than rapid processes, along with less-well-defined thresholds or tipping points (Ratajczak et al. 2017). This is well illustrated by woody plant encroachment in dryland ecosystems (D'Odorico et al. 2012). In their special section contribution, Brandon Bestelmeyer and colleagues (2018) address three (mis) conceptions or "oversimplifications" about dryland state transitions: (1) They are controlled by livestock grazing and drought, (2) they represent land degradation, and (3) restoration back to a grassland state is impossible. The transition from grass to shrub state is often called desertification, implying a general decline in ecosystem services. According to historical data, landscapes in the southwestern US are thought to have been mosaics of grasslands, mixed grass–shrub areas, and shrublands as a function of historical conditions, management, and abiotic drivers. The authors argue that woody plant encroachment and desertification are not the same thing, and that under rare climatic circumstances, it is possible to return shrub-dominated areas to a grassland state. Bestelmeyer and colleagues recommend managing for a landscape mosaic reflective of historical conditions, because the different components provide complementary ecosystem services. They note that most transitions are a function of social–ecological processes, and studies within that theoretical context are rare but much needed.

In the next article, submitted independently of the special section articles, Wilcox and colleagues (2018) take up that challenge. These authors focus on woody plant encroachment in the southern Great Plains, which offers a slightly more mesic perspective in which fire plays a larger role in grass–shrub interactions than it does in the more arid desert Southwest. Wilcox and colleagues (2018) use a press–pulse framework (Collins et al. 2011) that integrates cultural, social, and biophysical processes regarding the use of fire management to control woody plant encroachment. Once again, the dynamics of the social–ecological system are a function of connectivity at the landscape scale fostered by human decision-making processes. Wilcox and colleagues (2018) note, however, that knowledge of the social domain lags well behind understanding of the biophysical realm. Yet, understanding and integrating these processes has important consequences for pastoral societies and livestock production, which are the foundations of many rural economies. Because the press–pulse framework is not explicitly mechanistic, these authors encourage the development of agent based models or more complex systems models that can generate quantitative predictions on how these landscapes will develop in the future as both social and biophysical drivers change.

In 1998, the LTER Network introduced the Schoolyard LTER program to integrate LTER science with K–12 education. Some of the goals of the Schoolyard LTER are to use research resources to enhance science learning; develop long-term research sites on or near schoolyards; and to promote outdoor, inquiry-based learning (*https://lternet.edu/committees/education*). The final contribution to the Special Section by Stephanie Bestelmeyer and colleagues (2018) describes the many aspects of the Jornada LTER Schoolyard LTER program. The goal of the JER Schoolyard program is to infuse more local ecological content into the K–12 curriculum. The K–12 educational environment is nearly as dynamic as the dryland ecosystems in which the JER is embedded. Over the years, this program has evolved to deliver changing content under an unpredictable educational system. Bestelmeyer and colleagues (2018) describe and assess the impacts of six trends that have changed in emphasis over time: (1) field trips, (2) inquiry-based instruction, (3) schoolyard ecology, (4) new science education standards, (5) reduction in science instruction time, and (6) twenty-first-century learning. The success of this program is illustrated by the growing number of student participants along with increasing requests by teachers for program content and resources.

In summary, we are pleased to present this set of articles that further develop a solid conceptual foundation for drylands research at multiple spatial and temporal scales. Although much has been learned about the formidable role of abiotic processes in drylands, as well as the consequences of dryland state transitions, much more theoretical and empirical research is needed to derive a predictive understanding of dryland dynamics as a complex social–ecological system. Yet, this conceptual advancement is crucial if we are to sustainably manage these globally widespread and expanding ecosystems.

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