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A Holistic View of an Arid Ecosystem: A Synthesis of Research and Its Applications

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A primary objective of the Jornada Basin research program has been to provide a broad view of desert grassland ecology. Architects of the program, especially scientists with the Jornada Basin Long-Term Ecological Research (LTER) program, felt that existing ecological data sets were usually of too short a duration and represented too few ecosystem components to provide a foundation for predicting dynamics in response to disturbances (NSF 1979). This recognition gave rise to the LTER approach—using long-term and multidisciplinary research at particular places to advance a holistic and broad-scale but also mechanistic view of ecological dynamics. Such a view is essential to applying ecological research to natural resources management (Golley 1993; Li 2000). In this synthesis chapter we ask: What has this approach taught us about the structure and function of a desert grassland ecosystem? How should this knowledge change the way we manage arid ecosystems? What gaps in our knowledge still exist and why?

The Jornada Basin LTER was established in 1981 with the primary aim of using ecological science to understand the progressive loss of semiarid grasslands and their replacement with shrublands. This motivation echoed that which initiated the Jornada Experimental Range (JER) 69 years earlier. The combined, century-long body of research offers a unique perspective on several core ideas in ecology, including the existence of equilibria in

ecosystems, the role of scale, landscape heterogeneity and historic events in ecosystem processes and trajectories, and the linkage between ecosystem processes and biodiversity. From this perspective, we examine key assumptions of this research tradition, including the value of the ecosystem concept and the ability to extrapolate site-based conclusions across a biome. The Jornada Basin research program is also uncommon in its close ties to long-term, management-oriented research. The research questions first asked by the U.S. Forest Service and later by the Agricultural Research Service (ARS), such as how to manage livestock operations, frame much of the Jornada Basin research. This allows us to consider the contributions of this research and synthesis toward answering management questions.

The Jornada Basin Ecosystem

The research presented in this volume suggests that the Jornada Basin (rather than the individual watersheds within it) provides a reasonable delineation of an "ecosystem object" (in a narrow sense, as in Golley 1993), or perhaps a meta-ecosystem (Loreau et al. 2003), in which internal connections are relatively strong across several compartments (e.g., hydrologic and eolian fluxes and animal movements). Of course, there are fluxes into and out of the basin (chapter 9) and the basin is also part of a greater whole.

Within the basin, the patch has served as the fundamental unit of organization. The patch includes plants and their associated interspaces (Schlesinger et al. 1990). Feedbacks between plants and soil comprising a patch (chapter 5) lead to patch persistence in the face of abiotic forces (e.g., erosion) that may otherwise tend toward patch disintegration. Disturbances and regeneration of vegetation lead to changes in patch identity (e.g., a grass or shrub patch) and location over time (White and Pickett 1985).

Past and current Jornada research suggests there are general rules by which patch mosaics (and their effects) are organized within landscapes via geomorphic patterning (Ludwig and Cornelius 1987; McAuliffe 1994; Wondzell et al. 1996; see also chapter 16). Because research conducted in different parts of the landscape can be compared and connected via these rules, we review past results following a multiscale landscape-geomorphic framework (figure 17-1). Although the elements of the framework are specific to parts of the Jornada Basin and the Chihuahuan Desert, the processes it represents are observed throughout the Basin and Range Physiographic Province of North America and in other topographically diverse, arid systems of the world (Gile et al. 1981; McAuliffe 2003). These patterns are the foundation for understanding the spatially interactive mechanisms of ecosystem change described in chapter 18. In the sections that follow, we summarize four key insights derived from Jornada research that contribute to this framework and elaborate on the questions asked at the inception of this research program.

Plant–Soil–Animal Feedbacks Govern Patch Transitions

Perhaps one of the most significant contributions of the Jornada Basin program to date is the recognition that several parallel feedbacks govern changes in the characteristics of patches (Schlesinger et al. 1990). Nowhere are these feedbacks more evident within the Jornada Basin than in the progression of grass-to-shrub transitions. Schlesinger and Schmidt (chapter 5) succinctly describe such transitions as a reconfiguration of biotic activity toward shrubland. A host of interactions have been identified that regulate the rate and nature of transitions.

There is historical evidence that variability in the magnitude and coincidence of multiple stressors, particularly extended drought periods cooccurring with instances of overgrazing by
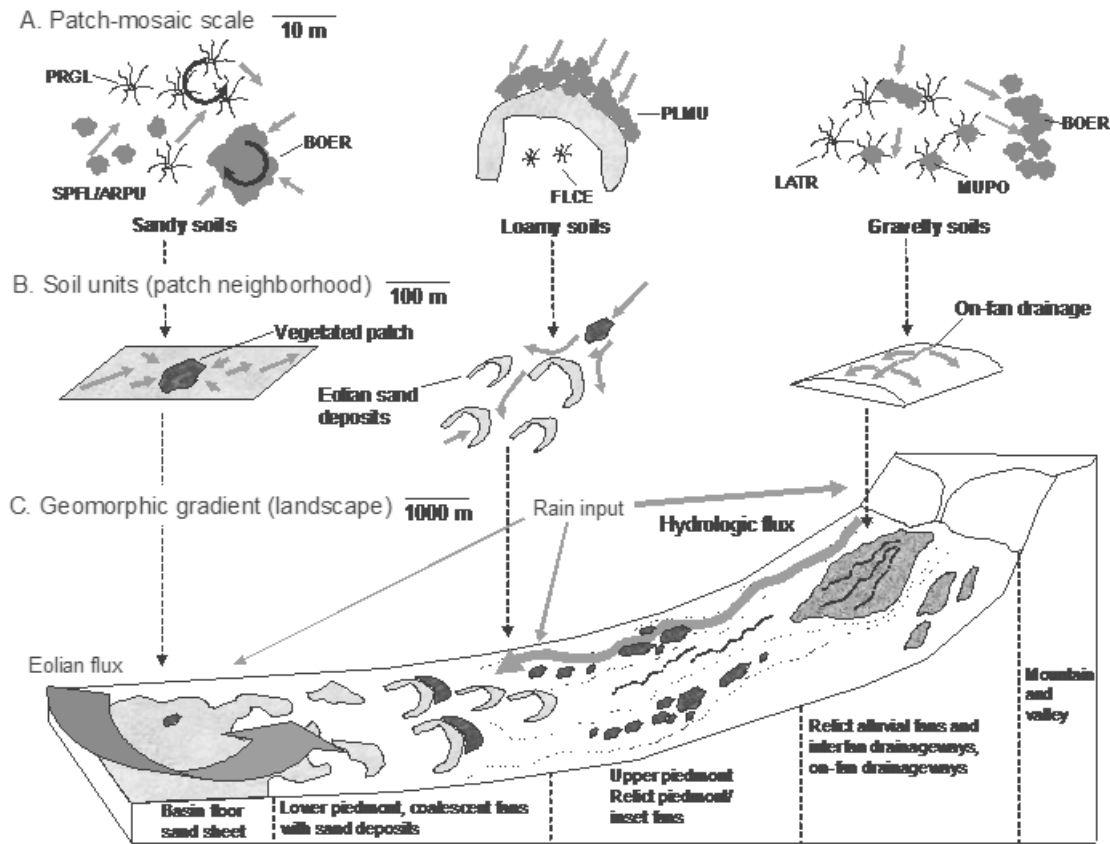
Fig. 17-1. A graphical framework describing of the relationships of plants and material fluxes occurring on common geomorphic surfaces at the Jornada

livestock, have led to episodic losses of grass patches. These periods include years during the early 1890s, 1910s, 1930s, and 1950s (chapters 10 and 13). Climate records reveal that these droughts varied with respect to the combination of rainfall and temperatures (chapter 3), and this produced varying effects on vegetation. Summer droughts associated with increased frequencies of El Niño periods (featuring high winter rainfall) over the past century may have favored shrub establishment and survival at the expense of perennial grasses (Brown et al. 1997; see also chapter 3). It is unclear why particular patches of certain species (e.g., black grama, *Bouteloua*

eriopoda) are lost while others of the same species survived during a given drought episode

(Gibbens and Beck 1988). Consequently, current approaches to explaining patterns in the

Jornada Basin's long-term quadrat data have emphasized landscape context in addition to patch

characteristics (chapter 10).

Unlike grasses, locally invading shrubs are little affected by livestock and can access

deeper, more reliable sources of soil water than can grasses (Burgess 1995; Gibbens and Lenz

2001; see also chapter 6). Thus, shrubs are more likely to survive periodic droughts and

capitalize on the space and resources made available as grasses decline. Once shrubs, particularly

honey mesquite (*Prosopis glandulosa*) and creosotebush (*Larrea tridentata*), become established

in a patch, a number of characteristics favor their persistence. Mesquite, for example, is less

reliant on N mineralization (which declines by half as grasslands change to shrublands) due to its

ability to fix nitrogen. Additionally, shrub physiognomy slows rainfall impact at the soil surface,

thus reducing local erosional losses under shrubs when compared to interspaces (Whitford et al.

1997; see also chapter 7). This process may also lead to a grass–shrub symbiosis when grass

cover is low because shrubs create stable microenvironments for grass establishment and

persistence. Understory grasses further reduce raindrop impact and promote local infiltration

(Abrahams et al. 2003).

Though not fully understood, current concepts hold that major vegetation transitions at

the Jornada are related to changes in soil water availability and its interaction with

decomposition and nutrient availability (Gutierrez and Whitford 1987a), which differs from other

LTER sites (Lauenroth et al. 1978; Van Cleve et al. 1996; Shaver et al. 2001). Differences in C

and N cycling patterns can be viewed as both consequences and drivers of vegetation change.

Shrubland states may be sustained, for example, by increasingly localized production and

nutrient cycling occurring in resource islands found beneath shrub patches (Schlesinger et al.

1990). Thus the interplay of rainfall patterns, soil degradation, and variable nutrient limitation in

space and time may regulate the pace of vegetation change.

Resource island stability leads to the accumulation of material that is physically

redistributed from interspaces between shrubs. In addition, biotic redistribution by animals

attracted to resource islands, such as rodents, lagomorphs, birds, and ants, may be important

(e.g., Dean et al. 1999). In contrast, the potential activity of termites, which are the major animal

contributors to nutrient cycling, is little affected by changes associated with grass–shrub

transitions (chapter 12). On many soils, termites appear to be ubiquitous and recruit rapidly to

litter sources during favorable climatic conditions (Nash et al. 1999). Only extreme soil

degradation associated with the formation or exposure of cemented soils in shrub interspaces

seems likely to restrict termite activity. The patch-level consequences of biotic effects on nutrient

cycles are as yet only partly understood.

Changes in vegetation physiognomy associated with shrub encroachment may favor

populations of rodents and lagomorphs, leading to increased herbivore pressure on seedlings and

the reproductive parts of adult grass and shrub plants (Nelson 1934; see also chapter 12). This

effect may limit plant recruitment (figure 17-1). On the other hand, increased small mammal

densities may increase rates of biopedturbation, improve rates of water infiltration in interspaces,

and increase the likelihood of seed germination (Whitford and Kay 1999). For a given patch of

mesquite shrubland, it remains unclear (1) whether biotic or abiotic limitations to grass recovery

in shrub interspaces are most important and (2) whether particular taxa, such as small mammals,

have a net positive, negative, or neutral effect on grass abundance at the patch scale.

Existing plot-level aboveground net primary productivity (ANPP) data in grasslands and

shrublands suggest that reconfiguration of biological activity has not led to reductions in energy

capture (assuming similar initial potential) at broader scales. A shift from grass to shrub

dominance appears to involve changes in the identity of the producers, rather than a significant

change in the overall ANPP production rates (Huenneke et al. 2002; see also chapters 5 and 11,

this volume). Furthermore, because existing measurements do not consider belowground

productivity, it is possible that total productivity (TNPP) and carbon sequestration are greater in

shrublands than in grasslands (see House et al. 2003). Existing data, however, suggest that

grasslands and shrublands have similar efficiencies with respect to the use of N and water,

despite strong differences in how these nutrients are acquired (Reynolds et al. 1997; see also

chapter 8). If borne out, this conclusion would support the view that TNPP is a constant property

of the Jornada ecosystem (at least at the basin scale) that is constrained by energy and resource

availability rather than species or functional group composition (Enquist and Niklas 2001;

Brown 2004).

Variable Fluxes Drive Landscape Organization (and Reorganization)

The characteristics and dynamics of patches are clearly related to the movement of organisms

and materials across the landscape. Although Jornada researchers have recognized this for some

time with regard to particular processes (Schlesinger and Jones 1984; Wondzell et al. 1996;

Gillette and Chen 2001), the means to measure and interpret interactions among these processes

in a spatially explicit fashion have only recently become available (chapter 18). Nonetheless, the

influence of the spatial organization of geology, soils, and plant communities on material

redistribution at several spatial scales can be described in nonexplicit terms. Three vectors have been examined in detail at the Jornada: wind, water, and animals.

The influence of regional weather patterns is modified by the basin's internal spatial organization that in turn creates additional spatial patterning. For example, in exposed areas north of the Doña Ana Mountains, the southwesterly erosive winds have organized mesoscale spatial patterns of sand accumulation and erosional deflation (chapter 2) that influence soil texture, the depth of petrocalcic horizons, and thus plant community development and responses to disturbance (chapter 6). Within these zones at finer scales, erosive wind direction affects the spatial organization of mesquite shrubs and patterns and rates of grass mortality (Okin and Gillette 2001). In turn, the preponderance of honey mesquite on the extensive sandy basin floor results in a net flux of dust out of the basin (chapter 9). Similarly, the position of small mountain ranges interacts with moisture arriving to the basin at different times of year to create multiyear spatial patterning in rainfall amounts (chapter 3).

The precipitation arriving to different parts of the basin surface is redistributed across different distances and in different directions, depending on soil properties and slope. Localized water redistribution on the sandy areas of the basin floor may produce "spots" where petrocalcic horizons are absent ("playettes"; chapter 2) and aboveground plant production and grass cover are high relative to surrounding areas. Vegetation bands or "stripes" may be produced on the gentle slopes and loamy soils of lower piedmont positions (see Aguiar and Sala 1999). In upper piedmont positions, the distribution of surface flow alternates between narrow channels and broader beads that create yet another form of spatial regularity in plant community structure (chapter 7).

Although little moisture is available for groundwater recharge in the basin, rainfall events producing significant run-off lead to surface water transfers among landforms (Phillips et al. 1988; see also chapter 7). These transfers may be critical determinants of plant community patterns. Run-in water may be a significant factor in maintaining productive tobosa (*Pleuraphis mutica*) grasslands in lower piedmont and marginal basin floor positions (Herbel and Gibbens 1989; see also chapter 6). The soils of these areas may also accumulate unusually high amounts of organic carbon (chapter 4). Historical decreases in grass cover in upslope positions may have allowed increased surface water runoff, resulting in increasing cover downslope over the same period (Herbel et al. 1972). Although we currently have few spatially explicit data at suitable scales of space and time to examine, it is likely that basin-scale vegetation change can be understood as much by the redistribution of water as by local, within-patch changes emphasized in earlier work (Noy-Meir 1985; see also chapter 18).

Both wind and water fluxes interact with vegetation to drive changes in nutrient distributions and production (Breshears et al. 2003; see also chapters 5 and 11). For example, under historical grassland conditions on sandy soils, internal N cycling is generally much greater (50 kg N/ha/yr) than new inputs (< 3 kg N/ha/yr). Mesquite dominance increases both the rate of symbiotic N fixation as well as redistribution within and outside of the basin due to wind flux. The change in cycling and redistribution of nutrients and water across the basin results in highly variable ANPP estimates such that basin-scale averages are difficult to assess. Consequently, current plot-scale measurements are ill equipped to detect the effects of basin-scale redistribution of key nutrients. It is possible that ANPP reductions at one scale are coupled with stability or even increases at other scales.

Like abiotic vectors, livestock have variable effects across the landscape. The distribution of fences, anthropogenic resources (livestock water tanks, mineral supplements), and patches dominated by different plant species influence livestock movements and their consequent effects on plants. Preferred dominant grasses, including dropseeds (*Sporobolus* spp.), black grama, and threeawns (*Aristida* spp.) are associated with sandy and gravelly soils, resulting in a tendency for livestock to aggregate in these areas. Heavy use of such areas, especially during drought, leads to rapid and persistent grass loss (chapter 13), further concentrating livestock movements to remaining preferred patches and eventually to less preferred species, depending on grass phenological state. These positive feedbacks and associated soil degradation can lead to nonlinear rates of grass loss and erosion across landscapes (van de Koppel et al. 2002). Soil degradation is exacerbated when preferred grass species are dominant and associated with erosion-susceptible landforms and soils. Fences and anthropogenic resources can be used to regulate the spatial distribution of livestock to minimize negative impacts, but short-term, mesoscale climatic variability imposes dynamic changes in the vulnerability of grass patches to extinction and has proven difficult to track effectively (and economically).

High Soil Heterogeneity Governs Basin-Level Variation in Key Processes

Geological and geomorphic processes create a template of soil differentiation and potential interconnections among soil units (Gile et al. 1981; McAuliffe 1994). Geomorphology strongly influences the nature of patch-level feedbacks and the rates and directions of fluxes within the Jornada Basin as well as fluxes into and out of the basin. There has been significant progress in recognizing that these linkages explain a wide range of ecological phenomena (Wondzell et al. 1996; see also chapters 2, 6, 9, and 14). These linkages will be explored more fully in the next

phase of Jornada research (chapter 18).

The modern structure of the Jornada Basin has been traced from the depositional environments of Paleozoic basins and seas, Oligocene volcanism, block uplifts and basin subsidence from the Miocene to the present day, the extension of the Rio Grande Rift, the arrival of the river, and shifts in its location as well as the destination of the sediments it carried. In comparison to some other arid landscapes (Stafford Smith and Morton 1990), landforms and soils of the region are young, and their properties are determined by ongoing climatic cycles that drive shifting rates of erosion, deposition, soil formation, and soil destruction.

These processes have produced several strong gradients in soil properties at several scales and a high degree of spatial organization in plant communities (Wierenga et al. 1987). For example, the sedimentary bedrock alluvium on the eastern side of the basin and the alluvium derived from the ancestral Rio Grande in the central and western basin floor are primarily sands, and this pattern has a major influence on the patch dynamics and feedback behaviors described earlier. Within these areas, variation in the depth and development of calcium carbonate–rich soil horizons exerts a strong influence on soils and vegetation. In other areas, the presence of clay-rich horizons can have important positive effects on grass persistence (Gibbens and Beck 1987), and the development of these horizons may be reduced in the presence of high amounts of calcium carbonate in parent materials (Gile et al. 1981). The shift from rhyolite and monzonite to limestone-derived parent materials across the southern portion of the basin yields shifts in the availability of calcium carbonate as well as rates of weathering, and this affects the composition of plants, the identity of encroaching shrub species, and grass–shrub–animal interactions. Thus, the consequences of land use history are a function of both disturbance intensity and the inherent

variation in geology and soils.

Biodiversity Exhibits Both Vulnerability and Resilience in a Dynamic Landscape

The processes structuring vegetation and soils in the Jornada Basin can be linked to some biodiversity patterns. The effects of grassland–shrubland transitions on ANPP, for example, are mirrored to some extent by their effects on biodiversity (Brown et al. 1997). Some elements of animal diversity appear not to respond to transitions, others decrease, and others increase in abundance. The net change in summary diversity measures may be low (e.g., Bestelmeyer and Wiens 2001b), but there is some turnover and loss of grassland obligate species, in some cases balanced by colonization of shrubland obligates (Naranjo and Raitt 1993; Pidgeon et al. 2001; see also chapter 12). Some grassland birds present at the time of European colonization may have already been driven regionally extinct and the fauna generally impoverished (Pidgeon et al. 2001). For taxa such as ants, however, the Jornada landscape may be more diverse than desert grasslands with few shrubs due to the abundance of native (and even rare) shrub-associated species (Bestelmeyer et al. 2005). Thus, shrub invasion may have enhanced certain aspects of animal species diversity.

The mosaic of vegetation and soil properties imparts a high degree of beta diversity for ants, lizards, and rodents across the Jornada Basin (chapter 12), but these patterns have been poorly examined for most taxa. Drought dynamics are superimposed on this mosaic to create strong spatiotemporal variability in resources used by animals. This leads to strong variation in population densities over time. Patterns of apparent local extinction and recolonization in some taxa (e.g., the hispid cotton rat, *Sigmodon hispidus*, occupying playa grasslands) suggest that meta-population dynamics may impart resilience to local species diversity in the Jornada

ecosystem. As yet, however, there are not enough data on dispersal or patch occupancy for any species to evaluate the potential for habitat fragmentation to reduce species diversity. Consequently, it is not clear what kinds of habitat changes (e.g., exurban development, degrees of shrub encroachment) would produce habitat fragmentation for particular species.

Implications for Ecological Theory and a Long-Term Research Approach

Long-term ecological studies are inherently limited by the questions and concepts that framed them at the time studies are initiated. Emerging from a research tradition derived from the International Biological Programme (IBP) of the 1970s, early Jornada research placed an emphasis on understanding whole ecosystems in terms of their component parts. These parts were typically trophic levels (represented by particular taxonomic groups) that exchanged and stored energy within a bounded ecosystem following the Lindeman ecosystem paradigm. It was hoped that data on biomass and energy flux through species populations could be assembled in systems models to predict dynamic behavior of the ecosystem and that these relationships could be generalized across "wide regions" (Golley 1993).

Jornada research initiated in the 1980s preserved the emphasis on production and trophic structure but recognized the need for more detail on the mechanisms underlying vegetation change. These studies, many of which are described in this volume, provide a detailed, multifaceted view of processes associated with desertification. Nonetheless, we recognize that this aggregate reductionist view continues to be constrained by (1) the small-scale, nonhierarchical, and spatially inexplicit nature of many observations and experiments; and (2) the opportunistic (and unfulfilled) integration of results across ecosystem components and individual investigators. These limitations were recognized by Eugene Odum at the inception of

the IBP (Golley 1993), but the concepts and technologies to act on them are still maturing.

Indeed, the need to address these limitations and develop holistic approaches spawned the

subdiscipline of landscape ecology (Wiens 1999). This volume represents a first step in the

development of an integrated, multiple-scale approach for the Jornada.

Nonetheless, with the benefit of recent conceptual advances and the new approaches

being taken by the Jornada Basin research group, we can evaluate some long-held assumptions

that have guided the practice and interpretation of some LTER research, including (1) patch-

based correlations of physical and biological variables can be used to characterize ecosystem

dynamics, (2) measurements of ongoing processes explain current patterns of ecosystem

organization, and (3) site-specific conclusions can be generalized within and across biomes.

The Value of Patch-Based Correlations Is Limited

Different processes with different inherent scales of action influence patches at particular points

within the Jornada. Thus, the value of correlations between local vegetation and local soil

properties is limited. For example, satellite imagery and geomorphic studies reveal that the

dynamics of northern basin floor positions are governed by eolian fluxes of soil from the border

of the Rio Grande Valley, but these fluxes are buffered to the south by the Doña Ana Mountains

such that dominant structuring processes become more localized. The importance of these

distinctions is likely to vary with time and climatic conditions. Due to this spatiotemporal

variation in processes, broad vegetation classifications such as those employed in the NPP

experiment (Huenneke et al. 2002) that are not spatially stratified and sufficiently replicated are

bound to miss or obscure important differences in basin ecosystem properties.

Historical Events Exert a Powerful Influence on Ecosystem Processes

Much about the structure of the Jornada ecosystem cannot be explained by studies of contemporary processes. Historical events, including the effects of prehistoric Native American settlements and ranching enterprises of the eighteenth and nineteenth centuries, may have altered the long-term trajectory of localities by initiating desertification processes that continue to unfold. These effects are often unrecognized (and unrecognizable). The influence of sequential historical events on the spatial distribution of species confounds explanations based solely on the present-day species–environment relationships (Neilson 1986; Swetnam et al. 1999; Motzkin et al. 2002). Jornada Basin vegetation is clearly not in equilibrium at any scale, and its changing patterns are a product of both historical events and ongoing processes.

Generalizations about Arid Rangeland Behavior Are Inherently Limited

In addition to the processes just noted, much of the apparent uncertainty regarding the behavior of rangelands stems from a failure to account for regional differences in climate, spatially dominant soils, and the traits of plant species contained within broad functional groups (such as shrubs and grasses). A comparison of three patterns described by Walker (2002) for a generic rangeland with Jornada patterns serves to underscore this point.

Generic Pattern 1: Vegetation on Sandy Soils Is More Resilient than on Clayey Soils

The sandy loam and loamy sand soils of the Jornada were dominated by grasses in recent history and most have been converted to eroding shrubland, whereas clay loam soils often continue to be dominated by the original, dominant grasses (Gibbens and Beck 1988). One reason for this discrepancy is that Walker considered examples in which sandy soils were (apparently) originally dominated by shrubs. If we were to consider the behavior of postthreshold shrubland states at the Jornada, we would also consider them to be very resilient. From the point of view of

historical composition (and the threats to remaining grasslands), we regard sandy soils as weakly resilient. The mechanisms underlying the Jornada's inconsistency with Walker's generalization are probably related to grazing history, differences in the palatability and life history of dominant grasses, and the relative landscape positions of sandy and clayey soils (Rietkerk et al. 1997).

Generic Pattern 2: Climatic Variation and Disturbance Reverse Grassland-Shrubland Transitions

In some rangelands, high interannual variation in rainfall constrains shrub dominance because drought causes woody plant mortality and recovery of shrubs is slow when compared to grasses. Even when woody plants establish under ideal conditions of wet years and fire absence to form even-aged stands, age-related senescence leads to grass reestablishment (Walker 2002). These mechanisms maintain a dynamic savanna structure over the long-term.

Our understanding of the Jornada situation does not conform to this pattern. Recruitment of mesquite on sandy soils may be episodic, but drought-induced or age-related mortality of adults is rarely observed (Goslee et al. 2003). Dominant shrub species (mesquite and creosotebush) are well equipped to survive drought (Reynolds et al. 1999a), and mesquite may live at least 60 years on the Jornada (Goslee et al. 2003) and up to 200 years elsewhere (McClaran 2003). Consequently, vegetation change has been directional and contagious with shrublands filling in grassland areas and not retreating over the Jornada's century-long record. Velvet mesquite (*Prosopis velutina*) shows a similar pattern in southeastern Arizona (McClaran 2003), even as other shrubs (burroweed, *Isocoma tenuisecta*) conform to Walker's pattern.

Generic Pattern 3: Over Sufficiently Long Time Scales There Is One Domain of Attraction

Grassland–shrubland transitions may appear to involve thresholds separating two domains of

attraction over shorter time scales, but a single domain of attraction toward savanna may be

revealed over sufficiently long periods, 40–50 years (Walker 2002; Valone et al. 2002). This is

likely to be true in certain cases, even within some Chihuahuan Desert grasslands, but there is no

evidence that this is universally true. Some grass–shrub transitions have lasted for at least a

century and current processes indicate many will last much longer. Domains of attraction may

shift due to the interplay of plant life history, soil degradation and loss, and climate change

(Westoby 1980). Resilience times within a domain and the existence of alternative domains are

highly variable across the Southwestern United States and within particular landscapes

(Bestelmeyer et al. 2003a).

The Interface of Ecology and Rangeland Management

Although a primary focus of years of work in the Jornada Basin was to examine ecological

processes and mechanisms underlying desertification, the dominant rangeland management

theories of this period also contributed to the design, analysis, and interpretation of our

experiments. Indeed, one of the primary goals was to determine the role of livestock grazing in

the conversion of desert grasslands to shrublands (chapter 1). In turn, the assumption that an

improved understanding of ecological processes would result in improved management serves as

a basis for current rangeland research and applications. In this vein, we contrast the prevailing

ideas that guided rangeland management (and its consequences) over the past century with what

we now believe given hindsight and Jornada science.

Historical Ecological Assumptions

There are three cornerstone ideas that have underlain rangeland management decisions over the

past century. First, it was implicitly assumed that Chihuahuan Desert grasslands possessed a

level of resilience to grazing pressure similar to that of other grasslands in North America. This notion led to early management practices based on the notion that the decline of grass abundance following temporary overgrazing could be reversed during periods of increased rainfall without any reduction in livestock use intensity. Although domestic livestock grazing had been present in the Jornada Basin since the 1500s, the emergence of ranching as a commercial enterprise did not take hold until the latter part of the nineteenth century (chapter 13). The practitioners of this new culture immigrated to the Jornada Basin from the mesic prairies to the east and brought their concepts of grassland ecosystem behavior with them. The next century of grazing management practice, policy, and research were affected by those concepts.

Second, many believed that the primary challenge facing ranchers, researchers, and policy makers was to establish a grazing capacity (maximum stocking rate [ha/animal/year] possible, year after year, without reducing forage to vegetation and other resources; Holechek et al. 1998a) (Jardine and Forsling 1922). A conservative stocking rate was viewed as an appropriate strategy for coping with spatial and temporal climatic variability because "attempts to adjust stocking rate to this highly variable basis of forage have had disastrous results. A breeding herd built up to use most of the forage crop in good or even average years cannot be maintained in dry years" (JER field-day report 1948 unpublished). Using a conservative strategy, adequate forage would be available in most (but not all) years. It was assumed that ungrazed forage produced during favorable years would be available to protect soil or be used as a forage reserve in drought years. It was also implicitly assumed that the infrequent periods of overuse would not have long-term consequences.

Third, many assumed that a more equitable spatial distribution of livestock grazing

pressure would reduce instances of overuse of forage where animals had previously concentrated and underuse in areas that animals had avoided (Jardine and Forsling 1922). Thus new parts of the landscape were made available for grazing, and provisions of nutrients and fencing have been used to distribute livestock more evenly across the forage resource, presumably reducing impacts on any given point. More recently, Herbel and Nelson (1969) advocated the opportunistic rotation of livestock among pastures to take advantage of spatially variable rainfall, plant production, and plant phenological stage, for example, flowering of soapweed (*Yucca elata*). Although these strategies accounted for spatial and temporal variation in the vulnerability of forage plants, they did not account for the fine scale of this variation. Most reasonably sized management units encompass significant spatial variability in soil properties, soil resource levels, and vegetation at the patch or patch-mosaic scale. Typical livestock grazing behavior (as currently managed) results in full utilization of all palatable forage in patches before moving to the next forage patch (Bailey et al. 1996; Fuhlendorf and Smeins 1997). Therefore, the livestock use in any forage patch is largely inelastic to stocking rate and improved animal distribution.

Recognition of Heterogeneity, Thresholds, and Economic Constraints

We now know that management strategies based on the preceding assumptions have led to stocking rates that were too high at many places and in several periods, and this has led to the episodic loss of grass patches and, cumulatively, to desertification. Thus, it is important to ask what could have been done differently and, more important, how can the remaining grasslands be sustained? Foremost, it is clear that grazing capacity fluctuates greatly and stocking rates must be tightly controlled and adjusted rapidly from year to year given the high spatial and temporal variability in forage production. This idea is reflected in Herbel and Nelson's (1969)

recommendations. This system sets objectives for pasture condition rather than animal

production. Nonetheless, most grazing systems employed then, as today, have stocking rates

based on a relatively fixed grazing capacity.

Due to the high spatiotemporal variability of NPP and threshold behavior, it has been

argued that maintaining acceptable levels of forage harvest through even moderate droughts

would have required an unrealistic level of economic flexibility on the part of individual

ranchers. This suggests that ranchers could not have heeded Herbel and Nelson's advice in the

late 1800s unless they changed their basic operations and their principle reliance on a cow-calf

production system. Even today, creative management alternatives such as light stocking rates,

fall calving season, and integration of complementary enterprises are strongly encouraged to

sustain ranching in the Southwest (Ruyle et al. 2000).

Recent advances in technologies for tightly controlling animal distribution without

fencing (Anderson 2001; Provenza 2003) offer hope that some economic constraints to

sustainable grazing can be overcome. In addition, the identification and use of cattle breeds that

minimize production costs and provide greater market flexibility during drought may facilitate

opportunistic management by ranchers. Although technology offers improved tools for

management, ecological solutions that are not tied to socioeconomic innovations are unlikely to

stem the tide of grass loss.

This should not imply that all remaining grasslands can be preserved even if such

approaches are successful. Current applications of chemical, mechanical, and management

technologies to interdict degrading processes offer little chance of success when the mechanisms

driving degradation derive from regional and landscape scales (chapters 14 and 18). Historical

events may have catalyzed current degradation rates and be independent of subsequent livestock

management (Jardine and Forsling 1922; Campbell 1929). Our understanding of soil–plant

feedback processes and multiscale redistribution of soil resources (chapter 5) implies that simply

treating one symptom (e.g., shrub increase) does little to mitigate grassland loss, especially in the

short term, over which most economic analysis is performed.

A basic understanding of ecological processes is a prerequisite for reasonable decisions

by land users. Ecological site descriptions offer a means of communicating how processes vary

over time and among climate regions, landforms, and soils (USDA NRCS 1997). At the core of

the descriptions, state-and-transition models summarize how particular processes discussed in

this volume combine to produce reversible and difficult-to-reverse vegetation and soil changes

(Bestelmeyer et al. 2003a) as well as indicators of these processes (Ludwig et al. 2000). By

specifying such processes and their indicators, land users can evaluate management actions in

light of the recognition of soil and vegetation heterogeneity at several scales, linkages with

surrounding areas, and the likelihood of threshold behavior in vegetation dynamics.

Social Change and New Management Challenges

Two of the conclusions offered by John Wesley Powell in "Report on the Lands of the Arid

Region" delivered to Congress in 1878 were that Western lands have distinct limits set by their

aridity and cannot be appropriately managed if arbitrarily dissected into fractions by the political

conventions of the day (de Buys 2001). In one sense, the history of research in the Jornada Basin

has reaffirmed and refined these conclusions. We now understand variability in primary

production, its low extremes, and the roles of scale in our use of this ecosystem. Our resource

management institutions and principles recognize the necessity of working within biological

limits, but social, economic, and administrative constraints often prevent actions based on this knowledge (Ruyle et al. 2000).

In a socioeconomic setting where property rights are paramount, management of Western lands by fractions has persisted since the nineteenth century, despite Powell's recommendation, with widely reported consequences for biodiversity and human welfare. Lately, however, creative alternatives have emerged around the Western United States that allow resource management to be coordinated over ecologically appropriate regional scales while accommodating ownership of fractions. Examples include grass banks and land management cooperatives. Our Jornada Basin program and other, regional long-term research (e.g., the Santa Rita Experimental Range in southeast Arizona) can contribute to these efforts by identifying the processes driving (or constraining) vegetation dynamics on particular soils, the role of linkages between areas, and thus the appropriate extents for management coordination.

As the biological and economic realities of traditional rangeland management have become clearer, the role of the land manager has changed. Public and private land managers that dealt exclusively with livestock-based agriculture are increasingly faced with urban–exurban populations seeking scenic amenities, including working agricultural landscapes. In New Mexico, as in much of the Intermountain West, there is a shift from traditional agriculture toward an economy based on services and professional industries (Rasker et al. 2003). For most communities in these regions, future growth will be tightly linked to environmental quality, an amenity often used by industry to attract employees. Nonetheless, livestock grazing continues to be a dominant land use in these regions. The increasing diversity of land uses imposes new values and criteria with respect to the acceptable structure and composition of ecosystems. New

land uses also introduce novel processes to particular areas, such as the introduction of nonnative

species and habitat fragmentation by roads and houses that increase the demand for information

(e.g., the behavior of animal species; Maestas et al. 2003) that has not been a focus of past

Jornada Basin research. It is critical that we adjust our scientific resources to track these

changing needs.

Conclusions

The contributions of Jornada Basin research to our understanding of desertification processes,

particularly at the patch scale, are profound. This work has been instrumental in directing

desertification research across the globe. Perhaps even more important, the long-term

multidisciplinary approach has described remarkable variability of desert grassland ecosystem

function, and its causes, across space and time. This perspective reinforces the need to develop

scientific and management concepts and methods that account for the unexpected magnitude of

ecological variability (Shrader-Frechette and McCoy 1993; O'Neill 2001; Archer and Bowman

2002; Simberloff 2004). We are implementing both long-term ecological research and proactive

management strategies in the light of this realization (chapter 18). This will require (1)

measurements that are not only spatially explicit and long-term but embedded in a process-based

logic that makes use of spatial and temporal information, (2) observations of processes that can

be linked across scales of space and time, (3) approaches that link mechanistic studies at long-

term research sites to regional variations in pattern, and (4) monitoring and management

strategies that can be adapted to the socioeconomic constraints and ecological processes

regulating change in particular localities. These requirements, in turn, indicate that we must

adopt truly interdisciplinary approaches in addition to multidisciplinary approaches that were

formerly emphasized. We now have the tools to realize the convergence of ecosystem ecology, research, and landscape ecology foreseen by Eugene Odum 40 years ago. Cultivating the institutional structures to achieve this remains a significant challenge, but it is a challenge we are attempting to meet.