

How Can Science Be General, Yet Specific? The Conundrum of Rangeland Science in the 21st Century

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Abstract

A critical challenge for range scientists is to provide input to management decisions for land units where little or no data exist. The disciplines of range science, basic ecology, and global ecology use different perspectives and approaches with different levels of detail to extrapolate information and understanding from well-studied locations to other land units. However, these traditional approaches are expected to be insufficient in the future as both human and climatic drivers change in magnitude and direction, spatial heterogeneity in land cover and its use increases, and rangelands become increasingly connected at local to global scales by flows of materials, people, and information. Here we argue that to overcome limitations of each individual discipline, and to address future rangeland problems effectively, scientists will need to integrate these disciplines successfully and in novel ways. The objectives of this article are 1) to describe the background, historical development, and limitations of current approaches employed by these disciplines; 2) to describe an integrated approach that takes advantage of the strengths and minimizes the weaknesses of these individual approaches; and 3) to discuss the challenges and implications of this integrated approach to the future of range science when climate and human drivers are nonstationary. This integration will be critical for applying range science to the management of specific land units; will contribute to and benefit from the development of general ecological principles; and will assist in addressing problems facing society at regional, continental, and global scales.

Resumen

Un reto muy crítico para los científicos en pastizales es proveer de información para toma decisiones de manejo de unidades de tierra donde hay pocos o nulos datos. Las disciplinas de ciencia del pastizal, ecología básica y ecología global usan diferentes perspectivas y enfoques con diferentes niveles de detalle para extrapolar la información y el conocimiento de lugares bien estudiados a otras unidades de tierra. Sin embargo, estos enfoques tradicionales se espera que sean insuficientes en el futuro porque los humanos y el clima generan cambios en magnitud y dirección, especial heterogeneidad en cubierta del suelo y sus usos se incrementa y los pastizales llegan a estar con en escala local y global por el flujo de materiales, personas e información. Aquí discutimos que para sortear las limitaciones de cada disciplina de manera efectiva y atender los problemas de los pastizales, en el futuro los científicos necesitaran integrar de manera novedosa y exitosa estas disciplinas. Los objetivos de este artículo son 1) describir los antecedentes, desarrollo histórico y limitaciones de los enfoques actuales empleados por estas disciplinas, 2) describir un enfoque integrado que resalte las fortalezas y minimice las debilidades de cada enfoque en lo particular y 3) discutir los retos e implicaciones de este enfoque integrado en el futuro de la ciencia del pastizal cuando el clima y los humanos son conductores no pasivos. Esta integración será crítica para aplicar la ciencia del pastizal para el manejo específico de unidades de tierra y contribuirá para el beneficio en el desarrollo de principios ecológicos y también direccionar los problemas que enfrenta la sociedad a escalas regional, continental y global.

Key Words: downscaling, extrapolation, global ecology, integration, nonstationarity, spatial heterogeneity

INTRODUCTION

Understanding, managing, and predicting rangeland dynamics are reaching crossroads where approaches used in the past will be insufficient and inaccurate in the future as the physical, biological, technological, and social environments change in novel and unforeseen ways (Millennium Ecosystem Assessment [MEA] 2003; Intergovernmental Panel on Climate Change [IPCC] 2007). Traditionally, range scientists obtain detailed, site-specific information to characterize the spatial and temporal heterogeneity of rangelands (Sayre et al. 2012 [this issue]). This site-specific information can be applied to other locations by extrapolating small plots to different conditions, broader spatial

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extents, and longer time periods, and downscaling environmental driver information. Tools such as remote sensing can be used to characterize broad spatial extents with accuracy at finer scales determined by the resolution of the sensor (Blanco et al. 2008, 2009; Williamson et al. 2012). Both the contextualization and the remote-sensing approach assume homogeneity in space at certain scales and stationarity in time. However, managed rangelands and unmanaged natural areas are becoming increasingly smaller parts of landscapes as the human population continues to grow, and urban and suburban areas expand spatially (Grimm et al. 2008), and many rangelands are being converted to other land uses, including cropland and for wind and solar energy. Connections among locations, both contiguous and nonadjacent, can overwhelm local processes to govern dynamics, yet these connections are often not included in current approaches (Peters et al. 2006, 2008). Thus, these approaches are insufficient, as both the physical drivers and biotic responses change in nonlinear and interactive ways beyond the historic realm of variability (Milly et al. 2008).

Alternatively, any location of interest could be intensively sampled, yet this is not feasible or even desirable for all rangelands globally. Technological advances, such as sensors and imagery, are increasing the availability of some types of data, even in remote locations, yet this information needs to be strategically collected and applied with minimal error, and integrated with other sources of data to be useful at scales relevant to management (e.g., pasture to landscape unit) (Peters 2010).

Here we argue that alternative approaches drawn from related disciplines will need to be integrated with traditional range science approaches to address these future challenges. These alternative approaches differ from each other in four interrelated aspects: 1) the *goal*, ranging from understanding general principles about how ecosystems function to making recommendations and predictions for specific locations; 2) the *perspective*, ranging from top down, where broad-scale dynamics are downscaled to specific locations, to bottom up, where location-specific information is extrapolated to other locations or to broader spatial extents; 3) the *degree of detail sampled*, more detail is needed when measured responses are highly contingent on location-specific information; and 4) the *role of humans*, varying from merely recipients of ecosystem services to both drivers of rangeland dynamics and recipients of these services. Combinations of these four aspects are represented by three disciplines (range science, basic ecology, global ecology) related to rangeland dynamics. We present these disciplines and associated approaches as end points while recognizing individual researcher variability within each discipline and acknowledging that differences among approaches and concepts are less defined now than in the past.

Range science studies are characteristic of one approach where specific locations are intensively studied with sufficient detail to inform, via extrapolation, management decisions at other locations with similar characteristics. It is often difficult to develop generalizations from these studies because the results are highly contingent on location-specific details that may not occur in very many locations (Lawton 1999). This approach is of interest to land managers who solve problems for particular land units under alternative scenarios that include humans as both drivers of rangeland dynamics and recipients of their services (e.g., Ash et al. 1994; Boyd and Svejcar 2009).

Ecologists interested in developing general patterns and principles within and among ecosystem types often use less-detailed studies conducted at multiple locations. Cross-site comparisons of responses can elucidate commonalities across different types of ecosystems, including rangelands (e.g., Svejcar et al. 2008; McIver et al. 2010). In the United States, this approach is typically used to study natural, unmanaged systems where human impacts are minimized. Results from these studies are often inaccurate when extrapolated to specific locations because insufficient information is collected to represent location-specific heterogeneity (e.g., Sala et al. 1988; Lauenroth and Sala 1992).

A third approach used by the emerging discipline of *global ecology* is based on studies of many locations where broad spatial extents are represented by aggregating drivers and responses across land units with similar properties, such as with imagery; thus location-specific spatial contingency is low. The goal is to pose and potentially solve problems at regional to global scales that explicitly include humans as both drivers and recipients. This approach is used to address problems that affect similar locations across regions, continents, and the globe where little comparable information may be available for all locations (e.g., Del Grosso et al. 2008; Gonzalez et al. 2010).

None of these approaches alone is sufficient to address the complexity of problems and issues facing range scientists today and in the future. Our goal is to describe an approach that integrates the strengths of these individual approaches in order to provide improved recommendations to land managers (Fig. 1). In this article, we 1) briefly describe the background, historical development, and limitations of each traditional approach; 2) describe an integrated approach that takes advantage of the strengths and minimizes the weaknesses of each individual approach; and 3) discuss the challenges and implications of this integrated approach to the future of range science when climate and human drivers are nonstationary. Our intent is not to provide a prescriptive approach for land managers or range practitioners, but rather an approach is described to allow range scientists to better integrate data, information, and analytical tools in order to make more informed recommendations for management.

TRADITIONAL APPROACHES

Intensive sampling to predict location-specific dynamics

Developing detailed understanding of selected locations in order to predict their dynamics and inform management decisions forms the underlying approach for range science. In the United States, and in many other parts of the world (e.g., Asia, South America, Australia, southern Africa), range science concepts are historically linked with the Clementsian framework where potential natural vegetation is a function of long-term average climate (Clements 1916, 1928, 1936; Sayre et al. 2012 [this issue]). The Clementsian-based approach was adapted for management applications by Sampson (1919) and Dyksterhuis (1949, 1958) by including grazing as a driver that affects variability in vegetation through time. By including managed grazing by domestic livestock, this approach explicitly: 1) includes humans as both drivers of system dynamics and recipients of rangeland services, and 2) focuses on location-

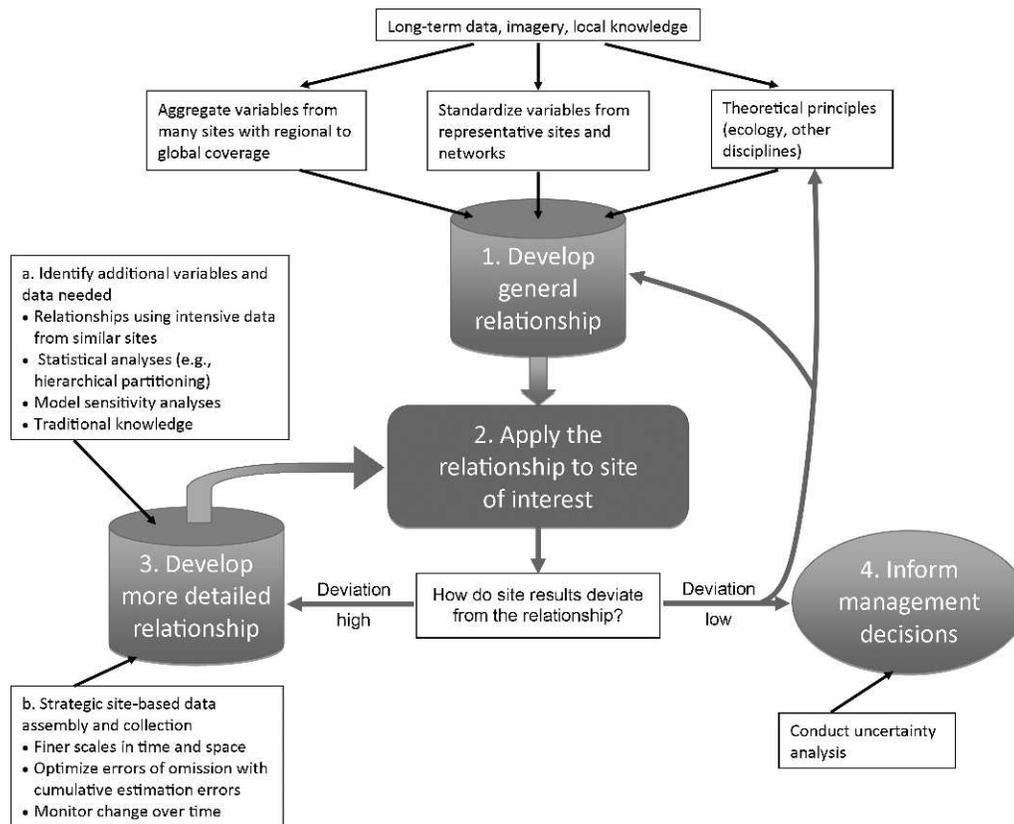


Figure 1. Integrated approach for informing management decisions that links theory and development of general relationships from ecology with broad-scale patterns and drivers from global ecology, and sampling and assembly of intensive site-based data from range science. This integrated approach results in a strategic addition of variables and data at the spatial and temporal resolutions required for management with feedbacks to inform theory and data collection and acquisition. Long-term field-based data, imagery across broad spatial extents, and local ecological knowledge are key sources of information.

specific conditions that affect forage for livestock. This climax approach was applied to rangelands globally throughout the last half of the 20th century (Heady 1975; Stoddart et al. 1975; Tainton 1981), and led to the range site concept popular in the 1970s and 1980s (Shiflet 1975).

By the 1980s, range scientists began developing state-and-transition models (Westoby et al. 1989) based on nonequilibrium concepts from ecological theory (Holling 1973; May 1977; Strong et al. 1984; Wiens 1984). These models include sufficient detail about an individual location to understand its dynamics (Whitford et al. 1998; Tongway and Hindley 2000; Brown et al. 2002; Pyke et al. 2002; Ludwig et al. 2004; Briske et al. 2005), and to inform management decisions about similar locations (e.g., Ash et al. 1994; Bestelmeyer et al. 2004). Generalities across rangelands of similar type are developed from site-based details (Bestelmeyer et al. 2003, 2004).

Simulation models provide an alternative way to develop detailed understanding of specific locations. However, in some cases, model results are so specific to a certain location that the results are not applicable anywhere else. Alternatively, the model parameters can be obtained by combining data from multiple sources such that the resulting formulation does not represent real locations. For example, a model of soil water dynamics has been used to predict the climatic and soil conditions required for recovery of perennial grass seedlings following shrub invasion or disturbance in rangelands. Because soils can be very heterogeneous by depth, reflecting local

development and weathering, field-based soils with heterogeneous properties by depth have been used to simulate establishment for specific locations (e.g., Peters 2000; Peters et al. 2010). These results are contingent on location-specific information, such as buried soil horizons and hardened petrocalcic layers, that modify soil water content in variable ways to affect establishment ($R^2=0.46$) (solid line, Fig. 2). This relationship can be used to explain local patterns in establishment where these specific soils exist, but have little utility in predicting establishment for other locations on different soil profiles. Alternatively, standard soils have been used as input parameters where soil properties are homogeneous for all layers (e.g., sandy clay loam throughout) (e.g., Lauenroth et al. 1994; Minnick and Coffin 1999). Relationships between modeled values of establishment and soil texture are often significant with low unexplained variation ($R^2=0.92$) (dashed line, Fig. 2), but may not capture dynamics at a given site. Although these relationships can be used to improve understanding about controls on processes, soils are not naturally homogeneous-by-depth such that these relationships have little utility for management. Modelers are often faced with this conundrum of either simulating specific locations with high level of details and little relevance elsewhere or parameterizing models with data from many locations such that the aggregated model output is not accurate for any particular location. Clearly, an integrated approach is needed that accounts for both specificity and generality.

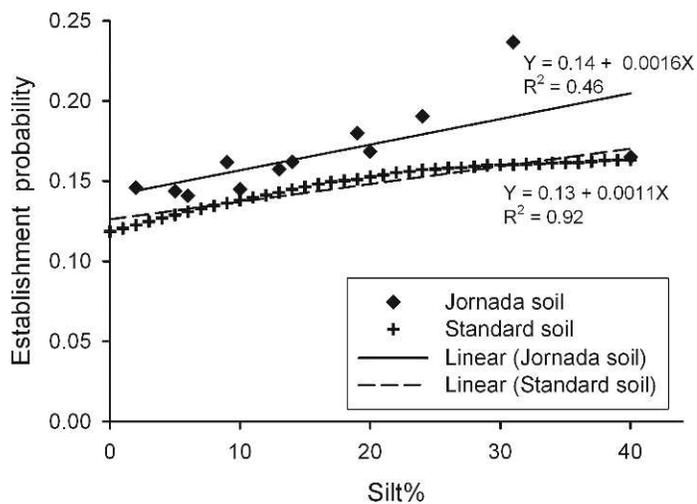


Figure 2. Simulation results of establishment probability of the dominant grass (*Bouteloua eriopoda*) in the Chihuahuan Desert are compared for profiles using field-based and standard soil properties. The SOILWAT simulation model (Parton 1978, modified by Peters 2000) was used to simulate daily soil water content by layer using daily precipitation and temperature, and monthly climatic and vegetation parameters (152 g m^{-2} biomass) for 2,000 yr of weather based on 80 yr of historical data from the Jornada ARS-LTER site in southern New Mexico, United States. A different weather is used each year, but the same sequence of years was used in all simulations. Recruitment is determined in each year by comparing simulated soil water content through time with amount and timing of soil water required for germination (0–5-cm depth) and establishment (0–30-cm depth) (Peters 2000). The number of recruitment events in each simulation was used to calculate the probability of recruitment for each soil type. We then related probability of recruitment to silt content in the 0–5-cm layer (sensu Lauenroth et al. 1994). In our first set of simulations using detailed site-based data (solid line with \blacklozenge), soil profiles were obtained by combining a landform map (Monger et al. 2006) with soil texture data from the Jornada (Monger 2006; <http://ssldata.nrcs.usda.gov>). Soil texture input by depth represented 15 unique landforms (Peters et al. 2010). In our second set of simulations (dashed line with $+$), we created 5151 standard soils by varying sand, silt, and clay by 1% increments, and using the same texture for all depths. Results are shown for the range of variation in silt content found naturally at this site (0–40%); standard soils with similar silt content in the top 5 cm were averaged to result in 3321 data points in the figure.

Sampling key properties at many locations to develop general principles

To understand patterns in nature, ecologists develop general principles and theoretical constructs (Scheiner and Willig 2011) based on either the Clementsian equilibrium concept (e.g., Tansley 1935; Leopold 1949; Odum 1959; MacArthur and Wilson 1967) or a nonequilibrium view (Gleason 1926; Curtis 1959; Holling 1973; Wiens 1984; Botkin 1990; Pimm 1991; Odum 1992).

General relationships are used to represent locations with insufficient data by assuming location-specific details are not needed to understand dynamics. For example, aboveground net primary production (ANPP) is a key determinant of forage quality and quantity available to domestic and wild herbivores (McNaughton et al. 1989) that is time- and labor-intensive to sample and predict at temporal and spatial scales relevant to management (Oesterheld and McNaughton 2000; Sala and Austin 2000). One approach to prediction is to use the

relationships between long-term mean ANPP and long-term mean annual precipitation based on many locations across North America (Sala et al. 1988) and other geographic areas (McNaughton et al. 1989). However, this spatial model results in an underestimate of ANPP in dry years and an overestimate in wet years compared with a relationship between ANPP and annual precipitation using a time series for an individual location (Lauenroth and Sala 1992; Paruelo et al. 1999). Thus, general models provide a reasonable understanding of the controls of ANPP in time and space at regional to continental scales, but they do not help range managers adjust stocking densities or grazing schemes of an individual rancher allotment.

Another example is the use of small sample sizes at a few locations to represent terrestrial biome properties (Holdridge 1947; Whittaker 1975; Buis et al. 2009). Environmental networks are based on the same premise: the International Biological Programme in the 1970s, the US Long Term Ecological Research Program beginning in the early 1980s (e.g., Burke et al. 1991; Hobbie et al. 2003), and emerging networks in the United States (e.g., National Ecological Observatory Network [Keller et al. 2008]) and abroad (e.g., Australian Terrestrial Ecosystem Research Network [Interim Biogeographic Regionalisation of Australia] (IBRA) 2005; Bastin and the Australian Collaborative Rangeland Information System–Management Committee (ACRIS-MC) 2008) attempt to generalize site-based results to biomes. However, individual sites often do not represent the range of variability of their biome: the Shortgrass Steppe site in northern Colorado represents only 23% of the climate, soils, and land use of the shortgrass steppe biome (Burke and Lauenroth 1993).

Historically, most ecologists in the United States preferred to study natural systems where human impacts are minimal, and humans were seen solely as recipients of services provided by ecosystems. More recently, many of the continental-scale programs explicitly include human drivers in their study designs (National Research Council [NRC] 2001; Millennium Ecosystem Assessment [MEA] 2003; Keller et al. 2008; Collins et al. 2011). Because these programs are place-based with many investigators, they occur along a gradient of contingency from intensively studied locations to representative locations depending on an individual investigator's interests. Corresponding to this gradient is a range of individual investigator goals, from solving problems at certain locations to developing general principles.

Aggregating key properties from many locations for regional-scale dynamics

Global ecology is emerging as an approach that uses information from many specific locations to address regional to global-scale problems that explicitly include humans as both drivers of ecosystem dynamics and recipients of ecosystem services (e.g., The Global Land Project.¹ Because comparable data are not available globally, the information is condensed, summarized, or aggregated to allow comparisons or predictions for large areas. This approach often uses spatial analysis of imagery or results from simulation models to create aggregate maps showing general patterns or to derive relationships among drivers and responses (e.g., Reynolds and Stafford Smith 2002;

¹<http://www.globallandproject.org>

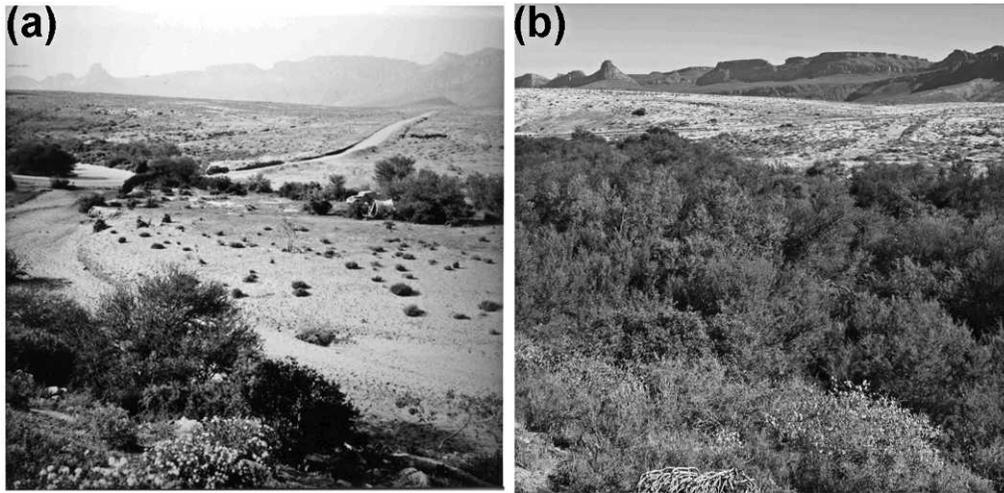


Figure 3. Increase in *Acacia karroo* in the Wiedouw River and relatively stable cover of the rangeland beyond the river channel between: (a) 1939 and (b) 2007. (Photo credits: M. R. Levyns and M. T. Hoffman). Reprinted with permission from Hoffman and Rohde (2011).

Zak et al. 2008). Downscaling of these relationships is used to predict dynamics for additional locations with little data.

However, these estimates often have low accuracy for specific locations, and can provide results that contradict fine-scale studies with greater detail. For example, a regional habitat modeling approach based on general principles suggested a loss of ca. 40% of the bioclimatically suitable extent of semiarid rangelands of the Succulent Karoo biome in South Africa by 2050 with a future change in climate (Midgley and Thuiller 2007). These results are at odds with current trajectories of vegetation change for the region based on fine-scale information that includes historical legacies and the role of humans and land management at particular sites (Hoffman and Rohde 2007; Rohde and Hoffman 2008; Hongslo et al. 2009; Hoffman and Rohde 2010, 2011). A widespread increase in cover of native Karoo species has occurred over the past 100 yr (Fig. 3). These differences between approaches have important management and conservation implications. For example, policy based on a decrease in spatial extent of the biome would emphasize *ex situ* propagation, seed storage, and species translocation efforts (Midgley and Thuiller 2007). However, if vegetation cover is driven by site-specific historical land use practices, such as grazing and herd mobility (Todd and Hoffman 2009; Anderson et al. 2010), then efforts to maintain stocking rates, develop appropriate management strategies, and formulate appropriate land tenure regimes should be emphasized.

INTEGRATED APPROACH

We recommend an approach that integrates the traditional approaches in novel ways that can be used to build a forward-looking science enterprise to account for future changes in drivers (climate, humans) and responses of the many components of rangelands, including services provided to humans (Fig. 1). We illustrate this approach by predicting forage production on a particular land unit for which little site-based data are available. Long-term field-based data, imagery at multiscales, and local ecological knowledge (LEK) are critical underpinnings to the approach. The four steps in the approach include developing general relationships based on basic

principles and site information, and then applying these relationships to locations of interest. The aim is to use these relationships to make valid predictions for specific locations and to aid management decisions. If location-specific predictions deviate greatly from expected results, then additional data are sought to improve relationships. If obtaining additional data is not possible, then the types and levels of uncertainty are estimated for the predictions.

The first step is to develop general relationships between a response variable of interest (e.g., forage production) and key environmental drivers based on principles derived from theory and a general understanding about how rangelands function (Fig. 1). Theory, previous experience, and local sources of knowledge can be used to determine the critical drivers to be measured, analyzed, or simulated. Traditional approaches used by ecologists, such as analysis of standardized forage production data (approximated by ANPP for grasslands) and a small set of drivers from many sites selected to represent different types of rangelands, are useful here (e.g., Sala et al. 1988). Sites in these historic analyses were selected based on data availability such that parts of the country and globe are underrepresented. Standardized ecological data collected from emerging networks in the United States (e.g., NEON) and elsewhere (e.g., country and continental-based networks in the International LTER [ILTER]²) will be instrumental in the future to fill gaps in coverage for rangeland sites globally. Integration with other approaches will be needed for broader spatial extents beyond individual sites. For example, spatially and temporally aggregated variables used by global ecologists to develop relationships between forage production (and other response variables) and regional to global drivers can be used to provide more continuous spatial coverage. Approaches from related disciplines can also be used. Macroecology or geographical ecology approaches to explain patterns in species richness have not traditionally been applied to rangeland research (Kerr et al. 2007; Kühn et al. 2008). Because these approaches search for scale-dependent relations between driver and response variables, and test predictions in large, spatially-

²www.ilternet.edu

referenced data sets across scales (e.g., Brown 1995, 1999; Rahbek 2004; Rangel et al. 2006), they have much to offer to prediction of dynamic ecosystem variables for rangelands at broad scales, such as plant production (Bradley 2009).

The second step is to apply this general relationship between forage production and a small set of explanatory drivers to the location of interest (Fig. 1). Because these drivers are often aggregate values of climate (e.g., annual precipitation, mean monthly temperature) and soil properties, it is possible to obtain estimates for many particular locations from on-line resources, such as the National Climate Data Center for global climate weather stations,³ the PRISM climate mapping system,⁴ and the Natural Resources Conservation Service for broad-scale soil classifications in the United States.⁵ Predictions of forage production from these general relationships can be compared with data collected on site. If the estimated forage production values have a small deviation from predicted (i.e., high R^2 value), then much of the variation in production is explained by these drivers, and management decisions can be informed about livestock density and distribution. However, in most cases, a general relationship is a poor predictor of site-specific production, for reasons discussed previously, and the process continues to the next step.

The third step is to include additional detail into the forage production-climate relationship to improve its predictive capability (Fig. 1). In this step, the first task is to identify key explanatory variables and associated data needed to improve the relationship. These variables can be identified in a number of ways: 1) use relationships developed using intensive data collected at similar locations; for example, significant relationships between forage production and variables such as topographic position, grazing intensity, and annual precipitation from one location would indicate that these same variables can be used for other locations in the region; 2) use statistical analyses, such as hierarchical partitioning and stepwise regression, to identify key variables for different locations and at different spatial scales (Yao et al. 2006); 3) use sensitivity analyses of simulation models to determine the variables that model output is most sensitive to (Paruelo et al. 2008); and 4) use traditional knowledge sources and personal experience to provide important insights to key drivers (Sayre et al. 2012 [this issue]).

It will also be necessary to determine the level of aggregation needed when including additional variables at increasingly finer scales. For example, we used a hierarchical analysis to determine the level of aggregation needed to predict cover of exotic annual grasses (EAG) (e.g., *Bromus* sp. and *Schismus* sp.) in three climatically determined deserts in North America (hot Mojave Desert [winter rain], cool Colorado Plateau [summer rain], and the cool Great Basin [winter rain]). We intensively sampled soils and vegetation (ca. 400 locations total) across a range of soil types, elevations (as a proxy for local precipitation), and EAG cover (J. Belnap, unpublished data). The relationship with the lowest predictive power ($R^2=0.08$) occurred at the largest level of aggregation when all sites were included in the analysis (Fig. 4). At one lower level of aggregation, separate regressions

developed for each desert analyzed separately improved model predictions ($R^2=0.20-0.48$). The best resolution was obtained when sites within a desert were divided into three elevational groups ($R^2=0.41-0.99$). Further examination showed the importance of soil factors, and in particular phosphorus [P] availability, to EAG cover (circled locations in Fig. 4b). These results show that EAG cover can be predicted using a separate relationship in each desert type, but predictions can be improved at finer scales relevant to management with additional information on elevation and P availability. This hierarchical analysis can also be used to identify sites where more intensive sampling is needed for additional variables.

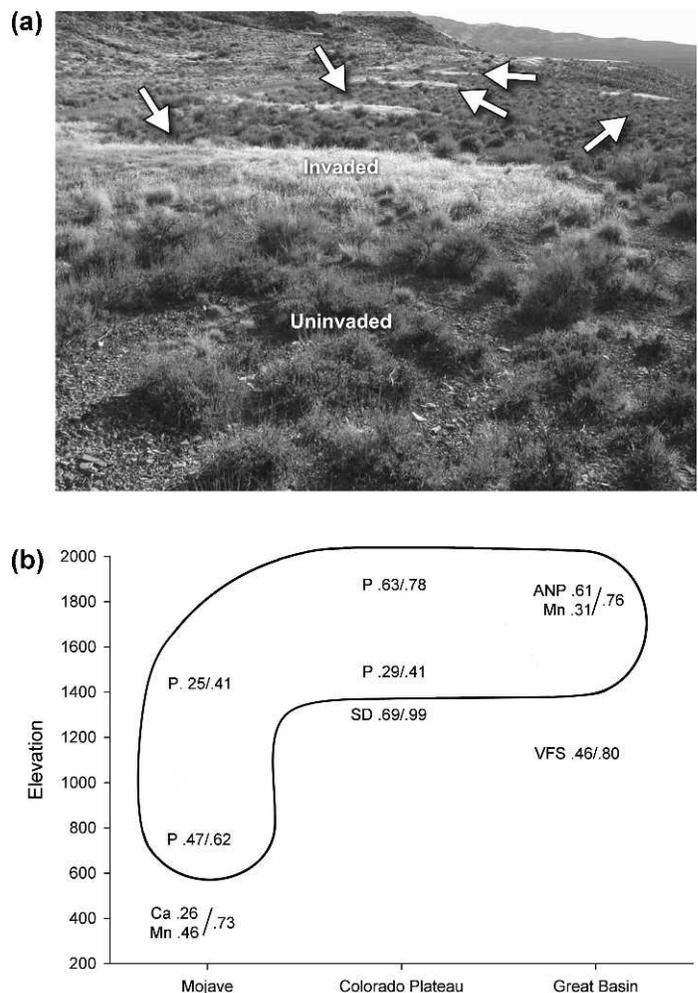


Figure 4. (a) Exotic annual grass (EAG) invasions in western US rangelands often occur in distinct patches (as indicated by arrows) that are not necessarily related to disturbance. (b) Dominant R^2 values for soil variables in stepwise regression models for different deserts and elevational classes. Ca = calcium, Mn = manganese, P = factors associated with phosphorus availability (e.g., ANP [the buffering capacity of the soil, thus indicating levels of calcium carbonates and other P-binding compounds in the soil]); SD = soil depth; VFS = very fine sand. The second value in the ratio is the total R^2 for the regression model (e.g., P 0.25/0.41 = P has an R^2 of 0.25, whereas the total model has an R^2 of 0.41). The placement of factors along the y axis represents the midpoint of the elevational class within each desert (elevational classes were created for the use of a two-step cluster analysis and thus were not the same for each desert). Circled locations show the importance of P availability to EAG cover.

³<http://www.ncdc.noaa.gov/oa/ncdc.html>

⁴<http://www.prism.oregonstate.edu>

⁵<http://soils.usda.gov>

KEY CHALLENGES

The second task in the third step is to use this information to collect and assemble site-based data strategically to characterize key drivers of forage production at spatial and temporal scales relevant to management (Fig. 1). This data collection can include fine-resolution imagery (e.g., MODIS: Williamson et al. 2012, unmanned aerial vehicles [UAV]: Rango et al. 2009; Laliberte and Rango 2011), historical data on vegetation reconstruction and land use (Gibbens et al. 2005; Hoffman and Rohde 2011), long-term data to distinguish short-term variability from long-term trends (Peters 2010; Peters et al. 2012), and monitoring data to observe changes over time (Herrick et al. 2005). The degree of detail included should optimize total error by offsetting errors of omission (decrease with more detail) with estimation errors (accumulate as more variables and data points are added) (O'Neill 1973).

The more detailed, improved relationship developed by strategically adding site-based detail to the general relationship for forage production can then be reapplied to predict production at the site of interest (Fig. 1). When sufficient detail has been added that estimated forage production values have a small deviation from predicted values (i.e., high R^2 value), then the fourth step occurs and livestock density and distribution can be adjusted. This process is iterative in that additional detail can be added until the deviation reaches an acceptable value. At the point when management decisions can be informed, then the site-based relationship can also be used to guide theory development and to provide new insights into the rich behavior of forage production on rangelands to help explain deviations from the general relationship. There may be locations where insufficient quality, quantity, and type of data are available to provide predictions with high confidence at temporal resolutions appropriate for management. For these locations, uncertainty analyses can be conducted to determine the level and type of uncertainty in predictions based on data availability in the relationship (Gardner et al. 1981; Minor et al. 2007).

This iterative process is not trivial, and will place demands on resources. However, Web-based technologies can reduce these demands in the future. Technologies will be needed to allow scientists to easily enter, access, and manipulate data relevant to land management units of interest and concern. Tools will also be needed to allow scientists to view and visualize results of alternative management options as environmental conditions change through time. Many of these technologies are currently under development or are actively being used by scientists and land managers to address specific questions with few data sources⁶ or to compare data from many sources across locations.⁷ Incorporating technological advances from other disciplines, including computer science, engineering, and information theory⁸ will be critical to move range science and management forward. A full suite of tools that allow seamless integration of on-site data with theoretically based relationships derived from many locations and future climate and land management scenarios is needed before scientists from everywhere can take advantage of this new technology.

⁶E.g., <http://www.rightrisk.org>, <http://www.agtools.org>, and <http://www.aplan.umn.edu>

⁷E.g., <http://www.ecotrends.info>

⁸E.g., <http://www.gapminder.org> and <http://www.google.com/earth/explore/showcase/liquidgalaxy.html>

There are a number of challenges emerging over the past several decades that will continue to limit the utility of both existing approaches and our integrated approach. First, *technological advances* in ground- and space-based sensors are increasing the amount of data that can potentially be collected from any location. Although more data provide more information, there are questions as to how much and what kind of data can be effectively used for a specific problem, and concerns about the cumulative effects of measurement error that can overwhelm the benefits of additional data (O'Neill 1973; Peters et al. 2004; Urban 2005).

The second challenge is driven by *conceptual advances* leading to multiple lines of theoretical development that are converging on common problems. However, there are questions as to how to synthesize these different perspectives to apply general relationships to specific problems, and there are concerns that this synthesis may lack the level of detail needed to capture important dynamics of specific locations (O'Neill 1973; Peters et al. 2004).

The third challenge is driven by *computational advances* leading to increasingly sophisticated quantitative analyses (e.g., statistical, simulation modeling, information handling) at increasingly broader spatial extents (regions, continents) and longer temporal scales (centuries, millennia). There are questions as to how to select the most parsimonious technique when computational time is no longer limiting, and about the scientific significance of results from such complex analyses (Michener et al. 2001; Diniz-Filho et al. 2008; Overpeck et al. 2011).

The fourth challenge is driven by *communication and knowledge advances* that are increasing awareness of the Earth as a system of interconnected spatial and temporal scales where dynamics at one location, including human actions, can influence other locations. There are questions about what variables to measure to link locations at different spatial and temporal scales, and how to incorporate human behavior and impacts into the dynamics of natural systems (Peters et al. 2008; Collins et al. 2011). There are also concerns as to how to reconcile findings from detailed fine-scale studies in managed or unmanaged systems with those from studies of broad-scale dynamics that include a mosaic of land use types.

The final challenge is one of *feasibility* in using approaches for locations globally where insufficient data may be available. Incomplete information will result in recommendations with high levels of uncertainty. These levels of uncertainty for specific locations will need to be effectively communicated to those aiming to improve and restore the production and conservation value of rangelands. Historic data can be used to learn from the past (e.g., Stafford Smith et al. 2007; Stafford Smith and Cribb 2009), but modifications will be needed to reduce levels of uncertainty as environmental drivers continue to change in the future with no historic analogs (Williams and Jackson 2007). The use of electronic forms of communication will need to expand to make these tools accessible to more users, such as rangeland Web sites⁹

⁹E.g., <http://www.rangelands.org> and <http://www.austrangesoc.com.au>

on-line, open-access journals,¹⁰ and specific “discussions” on the Internet (e.g., blogs) and through social network links (e.g., Facebook).

MANAGEMENT IMPLICATIONS

The new approach discussed here builds on traditional range science, basic ecology, and global ecology approaches as a first step in integrating these technologies into a future range science that is transparent and effective at addressing problems at multiple scales, and relevant to both science and policy. This integrated approach has four key implications to rangeland management. First, this approach more directly links science and research-based findings to the management of specific locations. Second, it creates a framework for land managers to inform scientists of specific informational needs that could be addressed by research. Third, it establishes a mechanism for local knowledge, including generational knowledge of landowners to be incorporated into specific models (e.g., state-and-transition models) that characterize specific rangelands and their responses to management practices. Fourth, the resulting data (and associated analyses) for any specific location become both increasingly accessible and transparent to managers, scientists, and the general public. All of these implications address critical management needs identified in contemporary syntheses of the current state of rangeland management and its supporting sciences (see Sayre et al. 2012 [this issue]; Bestelmeyer and Briske 2012 [this issue]).

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¹⁰E.g., <http://esapubs.org/esapubs/journals/ecosphere.htm>

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