A Strategy for Rangeland Management Based on Best Available Knowledge and Information

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Abstract

Adapting what we currently know about ecosystems to a future where rangelands are changing is a new frontier in rangeland management. Current tools for knowledge discovery and application are limited because they cannot adequately judge ecological relevance of knowledge to specific situations. We propose development of integrated knowledge systems (KSs)—collections of resources (e.g., data, analytical tools, literature) drawn from disparate domains and organized around topics by process-based conceptual models. An integrated KS would define relevance by ecological attributes (e.g., soils, climate, vegetation) and location as a flexible mechanism for organizing, finding, and applying knowledge to rangeland management. A KS provides knowledge sources within a decision-making framework that defines what knowledge is needed and how it will be used to make decisions. Knowledge from a KS can identify appropriate spatial and temporal scales to address specific resource questions or objectives. Several factors currently limit KS development and implementation. These include limited interoperability of disparate information and knowledge systems; lack of consistent geographic referencing of knowledge; incomplete and inconsistent documentation of the origin, history and meaning of data and information; underexploited application of remote sensing products; limited ability to extrapolate and share local knowledge and unstructured information; and lack of training and education of professionals that can link ecological and technical fields of study. The proposed KS concept and recommendations present an opportunity to take advantage of emerging technologies and the collective knowledge of rangeland professionals to address changing ecosystems and evolving threats. If we keep on with a "business as usual" approach to finding and using information, we will struggle to meet our responsibilities as rangeland professionals.

Resumen

Adaptar lo que actualmente sabemos acerca de los ecosistemas a un futuro donde los pastizales han cambiando es una nueva frontera en el manejo de pastizales. Las herramientas que existen en la actualidad para el descubrimiento del conocimiento y su aplicación son limitadas porque no pueden juzgar adecuadamente la relevancia ecológica del conocimiento para situaciones específicas. Propusimos el desarrollo de sistemas de conocimiento integrales (KSs)—colecciones de recursos (ej., datos, herramientas analíticas, literatura) elaborado a partir de áreas diferentes y organizados en torno a temas por procesos basado en modelos conceptuales. Un KS integrado podría definir la relevancia por atributos ecológicos (ej., suelos, climas, vegetación) y la locación como un mecanismo flexible para organizar, encontrar, la aplicación de conocimiento al manejo de pastizales. Un KS provee fuentes de conocimiento dentro de un marco de toma de decisiones que define que conocimiento es necesitado y cómo va a usarse para tomar decisiones. El conocimiento de un KS puede identificar escalas espaciales apropiadas y temporales para responder preguntas de recursos específicas u objetivos. Varios factores en la actualidad limitan el desarrollo y la implementación de KS. Entre ellos encontramos: interoperabilidad limitada de información dispar y los sistemas de conocimiento. Falta de referencias geográficas consistentes del conocimiento; documentación incompleta e inconsistente de documentación de origen, historia y significado de datos e información; aplicación sin explorar de los productos de teleobservacion; habilidad limitada para extrapolar y compartir conocimiento local e información no estructurada; y entrenamiento y educación de profesionales que pueden unir los campos de estudios ecológicos y técnicos. El concepto KS propuesto y las recomendaciones son una oportunidad para aprovechar las tecnologías emergentes y el conocimiento colectivo de los pastizales para hacer frente al cambio de los ecosistemas y los riegos cambiantes. Si seguimos con un enfoque tradicional para encontrar y usar información, vamos a enfrentar serias dificultades para cumplir con nuestras responsabilidades como profesionales de los pastizales.

INTRODUCTION

Adapting what we currently know about ecosystems to a future in which rangelands are changing, and in some cases fundamentally different, is a new frontier in rangeland management. Efficient, sophisticated tools for finding relevant

morsels within the expanding morass of data and information are necessary to knowledge adaptation, but they are not sufficient. Successful application of knowledge to rangeland management in the future will also require understanding the ecological context of that knowledge so that its relevance (or perhaps more importantly its irrelevance) in a changing world can be judged. Effective rangeland management is supported by the application of information (i.e., the accumulation and synthesis of facts, observations, and experiences) and knowl-

edge (i.e., the interpretation of information for a specific purpose; Stenmark 2001; Rowley 2006; Karl 2011). For brevity, we use the term knowledge below to mean knowledge, information, and their supporting measurements and observations (i.e., data).

Historically, the decision-making process for rangeland management relied heavily on prior experience, qualitative assessments, precedence, prescriptions, and policies based on general ecological principles (see Holechek et al. 2001:chapter 2; Fuhlendorf et al. 2012 [this issue]). Formal approaches have helped structure decision making (e.g., Tomer 2010). However, three simultaneous occurrences hinder our ability to find and apply relevant knowledge to rangeland management: rapid large-scale environmental and land use changes, loss of local knowledge of ecosystems, and, ironically, the increased abundance and availability of data and information itself.

A prominent challenge facing rangeland ecologists and managers is the ability of managers to respond fast enough to rapidly changing environments. The knowledge gathered over decades of research on how rangeland ecosystems are organized and respond to management and disturbance is, in large part, tied to existing combinations of climate, land uses, and soils (Briske et al. 2005; Bestelmeyer et al. 2009; Duniway et al. 2010). Changing climatic conditions could alter these combinations and introduce novel ecosystems that may respond differently (Hobbs et al. 2006; Williams and Jackson 2007). Both climate and land uses are changing at increasing rates and at spatial scales not seen before (Peters et al. 2004, this issue) This, in turn, can cause changes in soils through processes such as increased erosion rates (see Peters et al. 2007). Also, these changes are occurring at spatial and temporal scales not typically encompassed by existing knowledge bases. In cases where land uses and conditions are changing quickly, there may not be time to study all the effects of these changes and act on the results in time to make any difference in the outcome. As a result, our knowledge of rangeland ecosystems is in danger of becoming obsolete unless we employ a new approach to 1) more rapidly generate and synthesize the knowledge necessary to support adaptive management and 2) identify what knowledge is relevant based on its ecological context.

One significant source of management-relevant knowledge is the land managers themselves (Knapp and Fernandez-Gimenez 2009a; Knapp et al. 2010). Historically, many land management decisions were rationally based almost entirely on this local knowledge, and while not always formally tested, they were highly relevant to local conditions. Unfortunately, this knowledge may be disappearing with retirement, relocation, and death. In the United States, family ranches are being subdivided and sold to individuals who seek the amenities of a Western lifestyle (Gosnell et al. 2006; Brunson and Huntsinger 2008; Mendham and Curtis 2010), but may lack the local knowledge necessary for sustainable production from these lands. Conflicts or involuntary relocations in countries with large areas of rangeland such as Kenya and Somalia have displaced entire communities (Essoungou 2010), separating populations from their ancestral homelands and potentially making whatever local knowledge is passed down less available (de Wet 1988). As we argue below, however, ownership and administrative transitions do not need to result in poorer

management. There are opportunities to capture and increase the amount of local knowledge that is retained (e.g., Knapp and Fernandez-Gimenez 2009b) as well as the knowledge necessary to decide where it is relevant (Herrick and Sarukhan 2007).

The availability of new knowledge for rangeland management is burgeoning. The earth has been monitored by airborne and satellite-based sensors with ever-increasing frequency and resolution (both spatial and spectral) since the first aerial photographs were taken from balloons in middle 19th century (Campbell 2007). Nationally consistent field-based monitoring efforts have been implemented to monitor the status and trend of natural resources (e.g., Nusser and Goebel 1997; US Forest Service 2007; Toevs et al. 2011). Databases and online applications have been developed to help scientists and managers discover and use data from different programs (e.g., Ecological Society of America Vegetation Classification Panel 2008; Dengler et al. 2011). However, data, no matter the quantity or quality, are of little value to management if they are not accessible and interoperable (Peters 2010), and many of these efforts have themselves been isolated and are thus a piecemeal approach to the problem of applying knowledge to land management. The ever-increasing array of information systems and databases are integral to successful rangeland management. In the absence of an overall approach for how disparate sources can be used together, however, they will not meet management needs.

In this paper we propose a strategy for integrating different knowledge sources (including information systems and databases) within a decision-making framework for rangeland management. We discuss the importance of applying knowledge by understanding its ecological context defined by biophysical patterns and processes. Finally, we explore some hurdles to implementing an integrated approach to knowledge application in rangeland management and recommend some concrete steps that, if adopted, can speed the realization of the kinds of systems we propose.

KNOWLEDGE SYSTEMS FOR RANGELANDS

In our experience, the knowledge used in rangeland management decision making is often limited to what has been accumulated by the decision maker or what can be found quickly through a search of literature and other information databases. This is not meant to suggest that land management staff are shirking their responsibilities, but it is an indication that the demands and time constraints placed on them often preclude exhaustive knowledge searches. However, such an ad hoc approach to finding knowledge often misses valuable information sources and leads to sources being used out of context or misinterpreted.

We propose development of integrated knowledge systems (KSs) as a more systematic approach to organizing available knowledge to help managers and researchers select the right data and methods for their situations. We define a KS as a collection of resources drawn from disparate domains that relate to a topic or theme and provide a flexible and adaptable mechanism for organizing, finding, and applying knowledge that is relevant to specific needs (Fig. 1). Different KSs may share all or a portion of knowledge from different domains, so it is important that the

sources are maintained individually and be available to any KS. A KS provides knowledge sources within a decision-making framework (e.g., Herrick et al. in press) that defines what knowledge is needed and how it will be used to make decisions (e.g., Haynes 2001 for evidence-based medicine).

Body of Knowledge

The core of a KS is a body of knowledge relevant to a question or objective (Fig. 2). In an ideal sense, this represents everything that is known about the structure and functioning of ecosystems and their constituent parts. This includes not just information sources such as databases, spatial data catalogs, imagery archives, and monitoring data but also published studies and reviews, reports, and local knowledge. These latter sources are the knowledge that has been gained through observation, synthesis, and experience and that is used to support (and adapt) management.

In part, the body of knowledge for a KS has already been assembled through the efforts of online tools like Google Scholar and Web of Science. However, the tools currently available for knowledge discovery have several important limitations that must be overcome to realize the potential for a KS to inform management decisions. First, the scope of searchable knowledge for land management is largely limited to information databases and formal presentations of knowledge (e.g., published studies, reports, synopses). This is a short-term problem, though, that will be overcome as knowledge from different sources is captured and made available (see recommendations below).

The larger limitation, however, is that current knowledge sources do not adequately represent the context of their knowledge and therefore users cannot fully judge its relevance to a specific situation. This is not a problem that is limited to natural resource management. In the practice of medicine, doctors must understand the relevance of a treatment to a patient before prescribing it, but information on the context of a treatment's clinical trials is often poor and makes it difficult to know how broadly results can be generalized (Rothwell 2005).
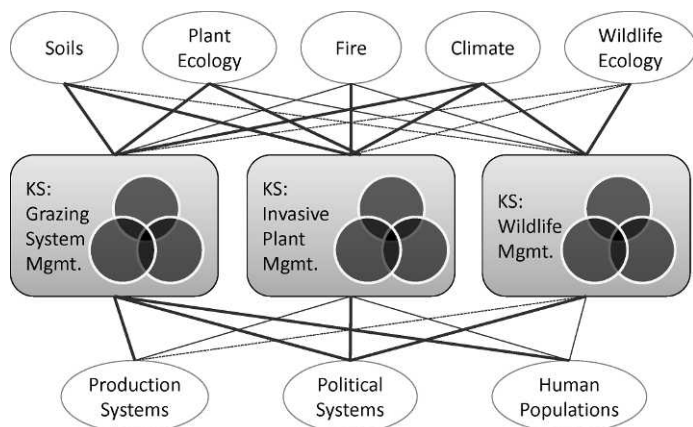

Figure 1. Knowledge systems (KS) can be created for specific topics or interests by drawing on sources from different knowledge domains (open ovals). Knowledge domains may contribute substantially or only partly to a KS depending on how relevant and broadly applicable knowledge within that domain is to the topic (represented by different weights of lines).
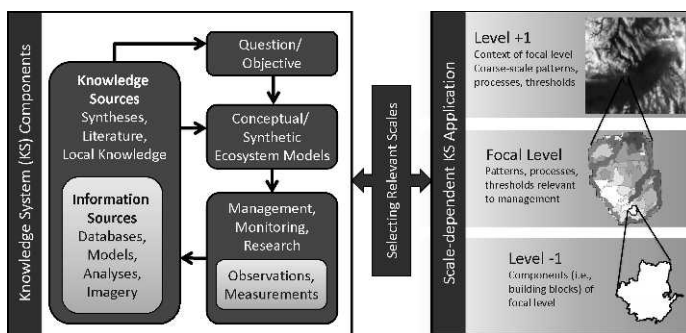

Figure 2. A knowledge system (KS) should be structured around knowledge and information sources pertinent to the KS objective. Conceptual or synthetic models of ecosystems processes and components help identify relevant knowledge and how it can be used in management, monitoring, or research. Knowledge from a KS can be used to identify appropriate spatial and temporal scales to address specific resource questions or objectives.

We propose that the relevance of knowledge to a management objective is proportional to how similar the topic, ecological context, and origin of that knowledge is to the system in question. Most current tools for searching knowledge sources focus on topics and to some extent general location (via place name). However, this represents only a small part of the context of the original source. Although many studies describe their study areas, this information is not consistent and may not include attributes important to defining relevance for a given question. What is needed is a system whereby researchers can define their own contextual criteria (based on themes such as soils or climate) to search against available knowledge sources.

Because most of the knowledge of rangeland ecosystems is place-based (i.e., comes from or pertains to specific locations), assigning geographic coordinates to knowledge sources would not only allow for more robust location-based knowledge searches but would also permit searching based on user-defined context criteria (i.e., a geosemantic search). In this manner, areas of interest on a map as well as topics could be defined to find available and relevant knowledge (e.g., "What studies have been done in this area? What studies have been done in semiarid regions with sandy soils?"). In a changing world, the knowledge that is relevant to a place and ecosystem today might not be relevant in the future (Williams and Jackson 2007). The kind of geo-semantic searching we propose could be used not only to judge relevance of existing knowledge, but also find potentially relevant knowledge based on context similarity when conditions (e.g., climates) have changed.

Management Questions and Objectives

A KS is used with a specific management need or research question in mind. This fundamental step for land management and monitoring (see Elzinga et al. 1998) identifies the problem, locations of interest, what knowledge is needed, and those sources from which that knowledge will be drawn. The management questions or objectives should be defined within a decision-making framework (e.g., Herrick et al. in press) so that it is clear how the quality of knowledge from different sources will be evaluated and ultimately the role that knowledge from a KS (and subsequent analyses) plays in

decision making (Mooney and Sala 1993; Pitelka and Pitelka 1993; McNie 2007).

Process-Based Conceptual Ecosystem Models

The knowledge in a KS becomes useful for management as it is organized around conceptual models that illustrate the effects of processes on ecosystem components relative to a scale-specific management objective. Such conceptual models characterize ecological context and define relevance criteria for a management question. Conceptual models can be used to identify important ecosystem attributes (Miller 2005), select indicators (Breckenridge et al. 1995; Karl and Herrick 2010), and define thresholds (Briske et al. 2005; Petersen et al. 2009).

Process-based conceptual models also can be used to define land-potential classes (i.e., ecological sites) and expectations of response to management or disturbance (Westoby et al. 1989; Stringham et al. 2003; Bestelmeyer et al. 2006, 2009; Duniway et al. 2010; Karl and Herrick 2010). Conceptual models are also useful for determining practical or realistic objectives in light of what is possible for a particular area and not just objectives based on current conditions (Herrick et al. 2006).

A state-and-transition models (STM) synthesized from available, suitable information (Briske et al. 2005; Bestelmeyer et al. 2010) is one form of process-based conceptual model that could be used in a KS. An STM can show how different natural processes, management actions, and disturbances affect the composition and productivity of plant communities in a land cover class or ecosystem type (Stringham et al. 2003; for an example see Petersen et al. 2009). Each component of the STM should also refer back to the data, information, and knowledge used to create the model. In this manner, STMs can have the added benefit of highlighting information gaps and directing future research. Additionally, STMs can be used to document, evaluate, and apply local knowledge (Knapp et al. 2010) that can be integrated into a KS.

Management, Monitoring, and Research

The conceptual models in a KS can be used to direct or support management and monitoring or generate hypotheses for research. STMs in particular can help define ecosystem resilience and thresholds between states (Briske et al. 2006; Petersen et al. 2009), predict possible outcomes of management actions (e.g., Forbis et al. 2006), and select indicators for monitoring (Karl and Herrick 2010). A KS also gives an outlet for the observations and measurements generated from research, management, or monitoring to not only answer specific management questions but also feed directly back into to the body of knowledge (i.e., adaptive management and learning).

SCALE-DEPENDENT APPLICATIONS OF A KNOWLEDGE SYSTEM

A critical step in supporting management decisions is identifying key spatial and temporal scales and what types of knowledge are required for each (Elzinga et al. 1998; see also Bestelmeyer et al. 2006). Two examples below illustrate how knowledge needs vary with spatial and temporal scale. First, conservation efforts for greater sage-grouse (*Centrocercus*

urophasianus) occur at different spatial scales (Wisdom et al. 2005). At the scale of local populations of sage-grouse, agricultural areas adjacent to sagebrush (*Artemisia* spp.) habitat may be an important source of food for brood rearing, especially if the quality of the native habitat limits the availability of forbs and insects (Schroeder et al. 1999). At a regional scale, however, conversion of native sagebrush steppe to cultivated agriculture is a large contributor to the decrease in sage-grouse habitat (Schroeder et al. 1999). As an example of selecting temporal scale, average growing season precipitation may be useful for deciding what types of species might be planted in a forage bank, but short- to medium-term weather forecasts and site-specific soil moisture measurements are needed to decide when to plant.

In addition to defining the appropriate scale for answering a question, knowledge is necessary at finer and coarser scales. The organizational level corresponding to the patterns and processes of primary management or research interest is defined as the focal level (Fig. 2; see also Wu 1999). Coarser-scale patterns and processes (Level +1) constrain responses at the focal level and can lead to different interpretations of data and information (Peters et al. 2004). For example, wildfires may create coarse-scale patterns within the same ecological site that cause differential responses of vegetation to grazing with distance to water. Finer-scale patterns or processes than those directly related to the management objective (Fig. 2; Level −1) define the constituents of the focal level (O'Neill et al. 1986; Wu 1999). For instance, changes in vegetation density, cover, or configuration as a result of invasive species can influence the capacity for fire to carry (Brooks et al. 2004). Many times observations or measurements are taken at this finer level. Understanding of the processes and patterns at this level is necessary to determine the correct approach for scaling those data up to the focal level (Wu and Li 2006).

Explicitly describing the focal scale as well as important scale processes above and below it adds another contextual filter for finding relevant knowledge in a KS. From a process-based model, a question or objective defines the processes of interest and the patterns in the study area related to these processes (e.g., geomorphology, disturbance and management history, land tenure). These, in turn, define focal spatial and temporal scale of the analysis (Bestelmeyer et al. 2011; Fig. 2). However, knowledge from other scales may be helpful, or in some cases necessary, to management or for inquiry at the focal scale (Allen and Starr 1982; O'Neill et al. 1986; Ahl and Allen 1996; Peters et al. 2004). Process-based conceptual ecosystem models such as STMs can be used to understand the influence of coarser- and finer-scale patterns and processes (Bestelmeyer et al. 2011) and construct a scale hierarchy to interpret existing and newly collected knowledge.

HURDLES AND RECOMMENDATIONS— REALIZING INTEGRATED KNOWLEDGE SYSTEMS

Implementing KSs will require fundamental shifts in how we store, find, access, and use data, information, and knowledge. A number of hurdles exist, though, that will limit the application of KSs. Below we discuss issues related to the

ability to find and use knowledge across a dispersed, interdisciplinary, and previously unconnected set of sources and propose a means by which to overcome them.

Interoperability

A significant challenge to implementing a KS is that many of our existing systems (i.e., subsystems or components of KSs) are isolated and not set up to share information (Peters 2010). Interoperability of systems refers to more than just sharing data and information. It requires making it easy to discover and use data, information, and knowledge in unrelated projects (Shelly and Frydenberg 2010). One example of interoperability is making data available through Web services (e.g., Natural Resources Conservation Service soil data[1] or plant taxonomy information[2]). Currently, Internet traffic capacities limit the kinds and amounts of data requests that can be handled by Web services, but this is a temporary limitation. Also, to date, the investment in data dissemination via Web services is being made mainly by entities with large data holdings. More sites where data and results from small projects and studies can be contributed and distributed via Web services are needed. While in the case of smaller projects it may not be possible to integrate and share the original observations or measurements, data summaries can be combined and made available as in the EcoTrends project[3] does for datasets from long-term ecological research sites (Peters et al. 2011).

Developing interoperable systems (and increasing interoperability of existing systems) should be a high priority. Projects and studies should be developed with collaboration and data sharing as fundamental principles. Issues such privacy concerns and data sensitivity should be decided at a project's outset and not once data have been collected. Managers and developers should actively consider how to use existing data sources and services as well as how to make their data and results available to other efforts.

Geographic Referencing

Implementing a KS is also currently hindered by options for finding relevant knowledge that are limited to topic, key word, and text searches. Although geographic searching for data and information is common, few systems exist for finding the kinds of site-specific knowledge found in published literature (or other knowledge sources) based on location.

To implement a KS, knowledge at all levels, from raw observations to syntheses, must be associated with precise geographic information and made available (with appropriate safeguards for privacy concerns) for use in other applications. Location information is routinely collected for raw observations, but then omitted from published studies, reducing the ability to search geographically for relevant information. Of the 2 335 studies published in *Rangeland Ecology & Management* (REM) and the *Journal of Arid Environments* (JAE) from 2005 to 2011, only 76.5% of studies that reported a study area included geographic coordinates; the rest included only place names (Fig. 3).
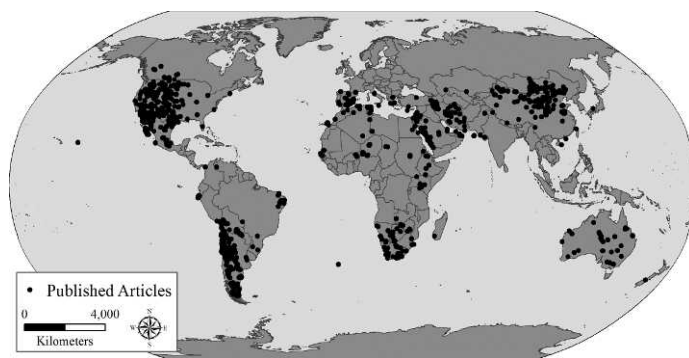
Figure 3. Locations of 1 721 studies published in *Rangeland Ecology & Management* or *Journal of Arid Environments* between 2005 and 2011. Locations were taken from the "Study Area" sections of articles (only those articles reporting geographic coordinates were mapped). No attempt was made to correct errors in reported coordinates (points located in the middle of the ocean are examples).

Geographically identifying published research and other knowledge sources opens up new possibilities for discovering and using knowledge. Researchers in medical fields are beginning to recognize the utility of geographically searching across publications to discover new health patterns (Bautista Cabello et al. 2006; Valderas et al. 2006). As a potential example for rangelands, geographically referenced studies could be used together with soil surveys to allow landowners and managers to identify previously unknown knowledge sources that are relevant to their land.

Three specific changes could greatly increase the usefulness and accessibility of rangeland knowledge. First, the format for reporting geographic information must be standardized to improve the ability to access and use geographic information and to reduce the potential for errors. Of the 1 721 REM and JAE studies from 2005 to 2011 that reported geographic coordinates, eight different coordinate formats were used. The diversity of coordinate systems makes it difficult to validate coordinate values (obvious errors were found in reported coordinates for 36 studies, or 2.1% of studies reporting geographic coordinates). Although several systems have been proposed for global location systems, we recommend adoption of the World Geodetic System of 1984 (National Imagery and Mapping Agency 1997), which is reported in decimal degrees because of its universal applicability across the globe and widespread support in a variety of hardware (e.g., global positioning system devices) and software applications. Second, journals should require authors to input standardized geographic coordinates for their studies as part of the submission process and then include this locational information as part of the article's basic citation metadata when it is published. This is similar in concept to geo-tagging of digital photographs and would permit development of applications to search and visualize literature geographically. Third, unless privacy or proprietary concerns dictate otherwise, the original field observations and locations associated with published studies should be made publically available (with adequate metadata) through journal archive sites (e.g., Ecological Archives[4]) or online

databases (e.g., VegBank[5]). This would support more in-depth syntheses (e.g., meta-analyses) that contribute to our knowledge of rangeland ecosystems.

Documentation

Documentation of the origin, history, and meaning of data and information (i.e., metadata) is crucial to being able to use it (Michener 2006), and metadata should be expected to accompany any dataset produced for management or research. Additionally, sophisticated search and analysis tools can be developed around standardized metadata formats (Jones 2007). Existing metadata standards for spatial (e.g., Federal Geographic Data Committee 1998) and nonspatial data[6] (see also Michener et al. 1997) should be widely adopted and expanded to formally include aspects important to understanding data uses and limitations such as study design and important methodological nuances that can affect data interpretation (e.g., differences between foliar and total canopy cover). In addition to documenting the origin and meaning of data, metadata standards should be adopted to describe the processes used to manipulate and analyze data (i.e., scientific work flows; Osterweil et al. 2010).

Effective Use of Remote Sensing Products

Remotely sensed imagery is an underutilized source of information and an integral component of a KS. Satellite imagery and aerial photography permit spatially explicit, broad-scale assessment of land surface conditions in a documented and consistent manner that is well-suited for assessment of rangeland patterns and processes in a hierarchical framework (Hunt et al. 2003; Washington-Allen et al. 2006; Browning et al. 2012). In addition, it provides quantitative data in a consistent and modular format from which products (e.g., estimates of ground conditions) at different scales and levels of detail can be created in either continuous (e.g., percentage of cover) or categorical (e.g., vegetation class, soil map unit) formats (Lillesand and Kiefer 1994). Despite these useful attributes, the potential of remotely sensed imagery to enhance land management decision making is not fully realized (West 2003; Butterfield and Malmstrom 2006; Washington-Allen et al. 2006). Hurdles to the routine implementation of remote sensing products into rangeland management include physical and logistical constraints of producing useful products, limited communication between remote sensing experts and land managers, and challenges in convincing land managers and owners of remote sensing's cost effectiveness (Kalluri et al. 2003; Butterfield and Malmstrom 2006).

The indicators land managers seek and those that the remote sensing community can reliably provide from moderate-resolution sensors may be different. For instance, direct estimates of herbaceous biomass as an indicator of forage production are a challenge for moderate-resolution satellite imagery in arid and semiarid regions because of modest vegetation cover and large areas of exposed bare ground (Huete and Jackson 1987). However, satellite imagery can provide consistent and well-calibrated estimates of change in the amount of photosynthetically active (i.e., green) vegetation over time to gauge response to disturbance or periods of above- and below-average rainfall (Wylie et al. 2012). The use of remote sensing to duplicate traditional field-measured indicators has yielded mixed results due to effects of scale (Booth et al. 2005; Karl and Maurer 2010; Karl et al. 2012), phenology (Lass and Callihan 1997), plant characteristics (Hunt et al. 2005), and climate dependence of results (Hunt and Miyake 2006; Reeves et al. 2006). Rather than deriving ecosystem indicators based on statistical relationships between remotely sensed data and ground measurements (e.g., Carlson and Ripley 1997; Reeves et al. 2006), effort is now being put to developing remote-sensing-specific indicators of ecosystem state and trend (e.g., Bradley and O'Sullivan 2011; Wylie et al. 2012). Ultimately, successful and routine use of remote sensing technologies for rangeland management will require improved dialogue between land management and remote sensing communities and an increased understanding of each other's respective fields (Kennedy et al. 2009).

Many land management needs can be met by available image products; however, this requires consideration of costs and benefits of existing approaches that is achievable only through clear and open discussion (Kennedy et al. 2009). The conceptual, processed-based models developed as part of a KS are a launching point for these discussions. Defining appropriate remote-sensing-based indicators at appropriate scales (Fig. 2) is a first step. These indicators may include surrogates for traditional field-measured indicators (e.g., Escuin et al. 2008, Wylie et al. 2012) or landscape-level indicators that clearly relate to important rangeland processes (e.g., Kéfi et al. 2007, 2010; Ludwig et al. 2007).

Using Local Knowledge and Unstructured Information

Data and information stored in well-defined databases (i.e., structured information) form the backbone of our current information systems. The knowledge derived from these sources, gained through experience or passed between generations, however, is largely unstructured and contained in myriad forms (e.g., scientific literature, institutional knowledge, local knowledge). Limitations to finding and accessing knowledge discussed above are even more pronounced with local or traditional knowledge because there is no system in place to effectively and consistently capture these kinds of knowledge (Huntington 2000).

Poor use of local and traditional knowledge short-circuits the KS. These types of knowledge are particularly important in ecosystems where empirically derived knowledge is sparse. Capturing and cataloging this unstructured knowledge and making it more widely available should be a priority.

Recent advancements in mobile and internet technologies have made it possible to automate the capture, retrieval, and use of local knowledge. Wikis, Web sites where content can be created or edited by a community of users, can be used to document the experiences of a group of people (e.g., Rangeland Monitoring Methods Guide[7]; Karl et al. 2011). In some cases, facilitated workshops can be used to collect, structure, and document local knowledge (e.g., Knapp and Fernandez-Gimenez 2009a, 2009b).

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[5]http://vegbank.org/vegbank/views/plot-query-bymap.jsp
[6]http://knb.ecoinformatics.org/software/eml/

[7]http://methods.landscapetoolbox.org

Local and traditional knowledge could also be captured and documented through crowd-sourcing (i.e., individual users contributing knowledge directly to a collective Web site) and by using increasingly available mobile technologies (e.g., camera phones, messaging services). For example, in just a few seconds, a land manager who observes a positive or negative response to management could snap an automatically geo-tagged photograph, upload it to a Web site where it can be recorded, communicated to neighbors, evaluated, interpreted alongside other observations, and synthesized with existing geospatial and field data.

Learning and Teaching

Computer systems needed to store, retrieve, and process rangeland data, information, and knowledge are growing ever more complex. In the KS vision described above, computing complexity could increase even more as emphasis is put on interconnected, distributed systems. At the same time, however, there is an increasing expectation for simple interfaces and tools to search for and analyze this content (i.e., "There's an app for that."). By and large scientists and managers are only trained in how to interact with high-level interfaces (e.g., spreadsheets and databases commonly found in office productivity software) and are self-taught in how ever-more-complex and interconnected computer systems process and store the underlying data (Merali 2010).

Rangeland education curricula need to be updated to keep pace with new demands being placed on rangeland professionals (Abbott et al. 2012 [this issue]). Management decisions, increasingly being litigated, must be backed up with quantitative data and defensible analyses—requiring a working knowledge of survey statistics and study design. Also, as the suite of remote sensing products and geospatial analysis techniques expands, rangeland professionals need more than a cursory knowledge of geographic information systems and remote sensing software. In some cases, rangeland professionals are developing their own software and tools—something in which few of us have any training. A lack of training in database and programming skills can at a minimum produce frustration and inefficiency and in the worst cases give false results (see Merali 2010).

The kind of rangeland professionals that can develop a KS and avail themselves of its benefits will require a diverse set of talents ranging from traditional ecology to computer programming. We need a new class of ecologists—intermediaries who can translate information needs between traditionally trained ecologists (most of us) and computer programmers, database developers, remote-sensing product creators, and statisticians (Fig. 4). These "technical ecologists" must have formal training in ecology, statistics, databases, geospatial analysis, programming, and software design, while recognizing that they will not necessarily be experts in any of these fields. Instead, they must know each field well enough to understand what is possible, facilitate in-depth work from experts in each field, and bring ideas and technologies together to create the kinds of KSs that will move rangeland management forward.

MANAGEMENT IMPLICATIONS

Evidence-based management of natural resources is predicated on learning and making use of best available knowledge (e.g.,
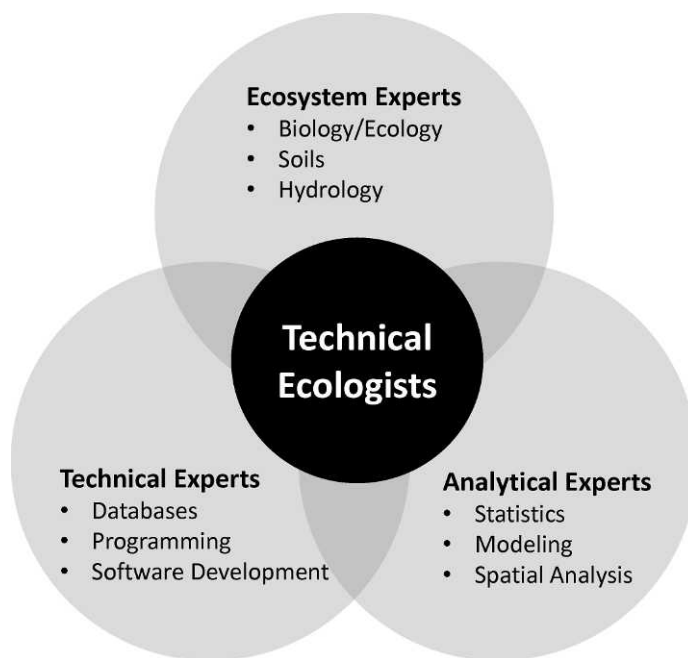

Figure 4. The field of rangeland ecology and management increasingly involves interactions between ecosystem, analytical, and technical areas of expertise. However, because experts from these fields have traditionally received little training in other disciplines, and because of increasing specialization within disciplines, a new class of professional technical ecologists is needed that can serve as intermediaries between disciplines.

Walters and Holling 1990). This approach to management has been faulted because the learning loop is often short-circuited (Lee 1999; Walters 2007), but this is a programmatic failing that can be remedied. However, if knowledge of rangeland ecosystems is lost or if relevant knowledge cannot be found or fed back into management, the foundation for evidence-based management is compromised. Rangeland management is at a critical nexus: knowledge needs to be captured, organized, and used to address changing ecosystems and evolving threats, but we now have the technological capacities and capabilities to accomplish it. Accomplishing this will require changes in how we manage and use knowledge. But if we keep on with a "business as usual" approach to finding and using information for management decision making, we will struggle to meet our responsibility as rangeland professionals.

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