Revolutionary Land Use Change in the 21st Century: Is (Rangeland) Science Relevant?

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Abstract

Rapidly increasing demand for food, fiber, and fuel together with new technologies and the mobility of global capital are driving revolutionary changes in land use throughout the world. Efforts to increase land productivity include conversion of millions of hectares of rangelands to crop production, including many marginal lands with low resistance and resilience to degradation. Sustaining the productivity of these lands requires careful land use planning and innovative management systems. Historically, this responsibility has been left to agronomists and others with expertise in crop production. In this article, we argue that the revolutionary land use changes necessary to support national and global food security potentially make rangeland science more relevant now than ever. Maintaining and increasing relevance will require a revolutionary change in range science from a discipline that focuses on a particular land use or land cover to one that addresses the challenge of managing all lands that, at one time, were considered to be marginal for crop production. We propose four strategies to increase the relevance of rangeland science to global land management: 1) expand our awareness and understanding of local to global economic, social, and technological trends in order to anticipate and identify drivers and patterns of conversion; 2) emphasize empirical studies and modeling that anticipate the biophysical (ecosystem services) and societal consequences of large-scale changes in land cover and use; 3) significantly increase communication and collaboration with the disciplines and sectors of society currently responsible for managing the new land uses; and 4) develop and adopt a dynamic and flexible resilience-based land classification system and data-supported conceptual models (e.g., state-and-transition models) that represent all lands, regardless of use and the consequences of land conversion to various uses instead of changes in state or condition that are focused on a single land use.

Resumen

La creciente demanda de alimentos, fibras y combustibles de manera simultánea con las nuevas tecnologías y la movilidad global del capital están ocasionando cambios revolucionados en el uso de la tierra en todo el mundo. Los esfuerzos para incrementar la productividad de la tierra incluyen la conversión de millones de hectáreas de pastizales a la producción de granos, incluyendo tierras marginales con bajo resistencia y resilencia a la degradación. Sostener la productividad de estas tierras requiere planeación cuidadosa del uso de la tierra y sistemas de manejo innovadores. Históricamente, esta responsabilidad se ha dejado a agrónomos y otros expertos en producción de granos. En este articulo, discutimos que los revolucionados cambios en uso de la tierra necesarios para sostener la seguridad alimentaria nacional y mundial potencialmente hacen a la ciencia del pastizal más relevante ahora que nunca. Mantener e incrementar esa relevancia requerirá de cambios revolucionarios en la ciencia del pastizal de una disciplina que se enfoca en un uso particular de la tierra o cubierta vegetal a una que considere el reto de manejar todas las tierras que en algún tiempo fueron consideradas marginales para la producción de granos. Proponemos cuatro estrategias para aumentar la relevancia de la ciencia del pastizal a un manejo global de la tierra: 1) extender nuestra conocimiento y concientización del ámbito local a tendencias globales económicas, sociales y tecnológicas con el fin de anticipar e identificar conductores y patrones de conversión, 2) enfatizar en estudios empíricos y modelaje que anticipe las consecuencias biofísicas (servicios de los ecosistemas) y sociales de cambios en la cobertura y uso de la tierra en gran escala, 3) aumentar significativamente la comunicación y colaboración con las disciplinas y sectores de la sociedad actualmente responsables en el manejo del nuevo uso de la tierra, y 4) desarrollar y adoptar un sistema de clasificación dinámica y flexible basado en la resilencia de la tierra y modelos conceptuales apoyados en datos (ejm. Modelos de Estado y Transición) que representan todas las tierras, independientemente del uso y las consecuencias en la conversión de tierras para varios usos el lugar de cambios en el estado y condición que se enfocan en un solo uso de la tierra.

Key Words: degradation, economics, food security, resilience, soil, sustainable land management

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INTRODUCTION

Rangeland science is *perceived*, by rangeland scientists and agronomists alike, to be irrelevant to croplands despite the fact that many croplands were once the world's most productive grazing lands. Combine harvesters now roll where ruminants once roamed in North America, the iconic Pampas region of Argentina is increasingly dominated by amber waves of grain, and elephants are fenced out of former rangelands in Africa. Today rangelands—and rangeland scientists—are limited largely to land that is too dry, wet, cold, steep, or infertile to support highly productive cropping systems: Ellis and Ramankutty (2008) estimate that while rangeland biomes (defined based on human use patterns) cover approximately one-third of the earth's ice-free land, they account for just 15% of terrestrial net primary production. Attempts to increase rangeland forage production via the addition of water and/or fertilizer have not been universally successful (Martin and Berry 1970; Scifres 1980; Briske et al. 2008).

There are increasing social and financial incentives to cultivate the more productive marginal agricultural lands that remain, including large areas currently managed as "rangeland." In early 2011, the *Wall Street Journal* reported that "grain prices are 'screaming' for more acres which will push farmers to convert pasture used for grazing animals to cropland and consider planting in questionable weather conditions" (Berry 2011). Annual demand for cereal grain alone is projected to increase nearly 15% (from less than 2 300 to 2 600 Mt) in just the next 10 yr (OECD-FAO 2011). The UN Food and Agriculture Organization (FAO 2003) predicts that one-half of this increase will be used for livestock feed to meet a projected 2–3% annual increase in global demand for meat products through 2030. The bulk of this meat will come from intensive grain-based production operations for poultry and swine (FAO 2003), while rangeland scientists continue to explore opportunities to intensify livestock production on remaining rangelands (Estell et al. 2012 [this issue]).

In this article, we argue that the revolutionary land use changes necessary to support national and global food security while maintaining other ecosystem services make rangeland science more relevant to sustainable land management and policy now than ever. Maintaining relevance, however, will require rangeland science to shift from a focus on a particular land use (e.g., livestock grazing) to working with other disciplines to support the development of sustainable land and landscape management systems independent of current land use. This focus must be supported by an understanding of the land and landscape properties that determine resilience, or the sustainability of the land's potential: its capacity to support ecosystem services required to meet "the needs of the present without compromising the ability of future generations to meet their own needs" (Brundtland Commission 1987). We argue that this understanding is required for *all land* currently managed as rangeland as humans continue to expand the definition of "productive lands."

Our specific objectives are to briefly 1) consider the definition of rangelands and marginal lands; 2) review the drivers of land use and cover changes on lands with the potential to support grassland, shrubland, and savanna ecosystems; and 3) explore the implications for the relevance of rangeland science. We then 4) describe several strategies to increase the relevance of rangeland science in the coming decades.

HOW ARE RANGELANDS AND MARGINAL LANDS DEFINED?

In a widely cited article, Pratt et al. (1966) defined rangelands as "land carrying natural or semi-natural vegetation which provides a habitat suitable for herds of wild or domestic ungulates." They further state that "some of the present range area has a potential for agricultural or other development, but most is destined *in the present state of technical knowledge* to remain under range use because its rainfall is scanty and erratic" (emphasis added). A recently published glossary emphasizes potential rather than current vegetation as a criterion for defining rangeland and restricts use to livestock and wildlife (Allen et al. 2011). The Society for Range Management's (SRM's) current definition follows the use of potential vegetation (Allen et al. 2011): "a type of land on which the natural vegetation is dominated by grasses, forbs and shrubs and the land is managed as a natural ecosystem." However, the Society argues that in addition to providing "valuable grazing lands for livestock and wildlife," rangelands "serve as a source of high quality water, clean air and open spaces and benefit people as a setting for recreation and economic means for agriculture, mining and communities."

More productive rangelands have historically been viewed by many societies as simply "marginal lands," which are "lands on the margin of cultivation" but often more broadly understood as all lands that are "barren, rough, inaccessible, or possessed of other undesirable characteristics or relationships" (Peterson and Galbraith 1932; see also recent review in Tang et al. 2010). The Chinese Ministry of Agriculture's definition of marginal lands available for energy crop production cites "wastelands," which include "natural grassland, sparse forestland and unused land that may be used to grow energy crops" (quoted in Tang et al. 2010).

Faced with increasing variability in climatic and economic conditions, it is likely that land use (such as "rangeland" or "cropland") as a stable, long-term categorical classification tool will become increasingly less useful. A good example is the Conservation Reserve Program (CRP) in the United States. Although the program has resulted in $\sim$15 million ha of "highly erodible land" being converted to perennial cover that can be managed as rangeland, domestic budget constraints and policies as well as global market incentives have increased pressure on landowners to convert back to grain crops.

In summary, while rangeland scientists define rangelands positively (i.e., based on cover and land use), much of the rest of the world defines them negatively (i.e., based on their limitations to cultivation). It is perhaps not surprising, then, that once those limitations are removed, these lands cease to be viewed as rangelands by nearly everyone. Even when rangeland scientists have argued for a definition based on land potential rather than current cover or use, it has been focused on potential for livestock production or wildlife habitat rather than the potential to optimize the provision of particular ecosystem services from a particular landscape or region (e.g., Pratt et al. 1966).

DRIVERS OF LAND USE AND COVER TRENDS

Drivers of land use and cover change in rangelands include growth in human population and consumption, development of new technologies, and increasing availability and mobility of global capital (Fig. 1). These drivers interact with each other and with other factors, such as land tenure, to control the rate and trajectory of land use change.

Human Population and Consumption

The earth's human population reached 7 billion in 2011. It is projected to surpass 10 billion by 2100 (United Nations 2011). Per-capita consumption of food, fiber and energy are also increasing rapidly, and most countries are seeking to increase renewable energy production. Livestock production will likely continue to dominate rangeland management in some parts of the world, such as the colder and drier regions of Asia and more arid areas in Africa, Australia, North America, and the Middle East. Even in these regions, however, proposals are being developed to implement intensive land-based mechanical systems to convert the global average 198 $W \cdot m^{-2}$ of solar energy reaching the earth's surface (Kiehl and Trenberth 1997) into a form that can be transported to energy-consuming industrial and population centers.

New Technologies

Concurrent with increased demand for "marginal" lands for food and alternative energy production is the development of technologies that can overcome many of the limitations to obtaining these services from current rangelands. In the 19th century, new technology in the form of the moldboard plow facilitated the establishment of highly productive annual production systems on the most productive rangelands of central North America, long before the establishment of rangeland science as a profession. In other areas, technology-supported transformations have been even more rapid. At the end of the 20th century, Brazil began to replicate North America's tremendous increase in per-capita and per-hectare food production on its own grasslands and savannas, thanks largely to significant inputs of lime (Klink and Machado 2005). In the Pampas of Argentina, mechanization is pushing agriculture westward into increasingly arid rangelands (Baldi and Paruelo 2008; Demaria et al. 2008; Grau et al. 2008) dominated by highly wind-erodible soils (Peña Zubiate et al. 1998).

Today, plant breeders are producing drought- and salt-tolerant genotypes, engineers are building cellulosic biomass plants, and desalination, algae production, and other technologies are making high levels of net primary production possible in even the most arid regions of the world (Fedoroff et al. 2009; International Center for Biosaline Agriculture 2011). The economic drivers of cropping currently marginal lands are often much stronger than arguments for preservation of the ecosystem services they provide as rangelands, even where there is little hope of sustaining production on these lands (Fig. 1; Fig. 2, bottom graph).

Global Capital

The availability of global capital to purchase large tracts of land and intensify agricultural production also continues to increase, accelerating land conversion throughout the world (Adesina 2010; Deininger and Byerlee 2011). Between August 2008 and April 2010 alone, 8.2% of the agricultural land in Ethiopia and 6.7% in Madagascar was purchased by foreign

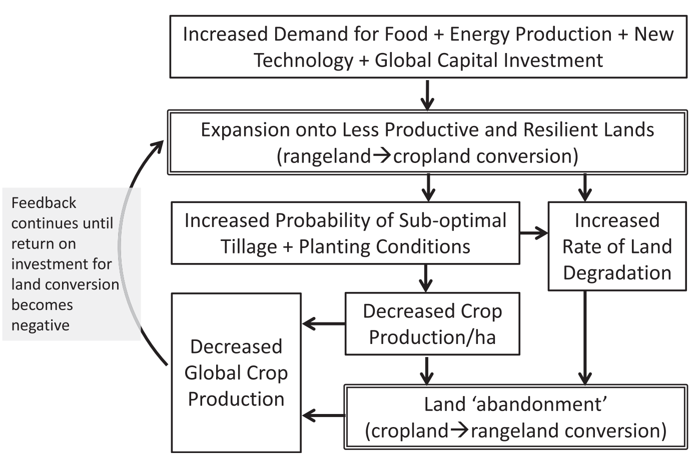

Figure 1. Increased demand for food and/or energy production can trigger a vicious cycle of increased rates of degradation and expansion onto ever less resilient lands, even when demand stops increasing.

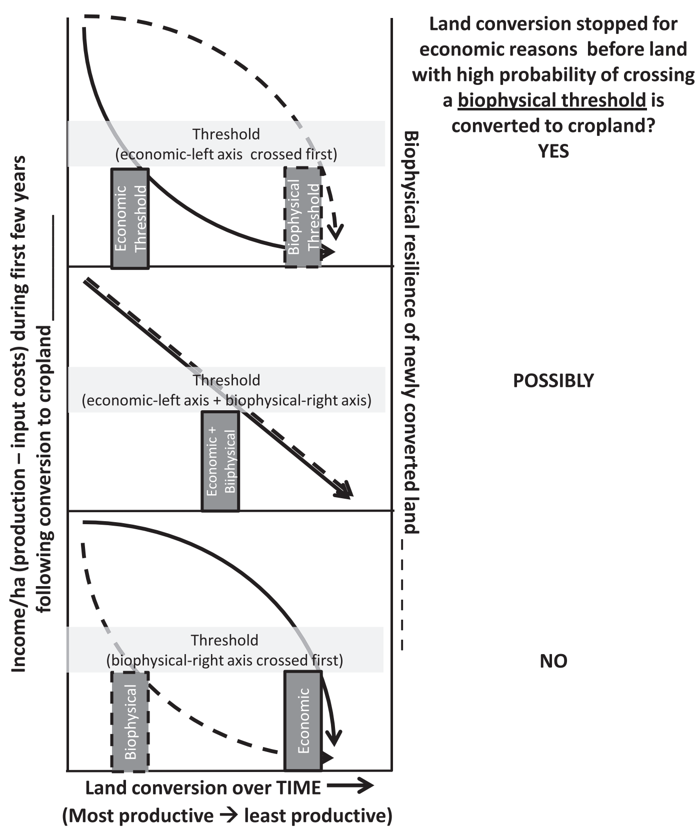

Figure 2. The relationship between the economic productivity of newly converted lands (reflected in income · ha, solid line) and the biophysical resilience of these lands (dashed line) determines whether cropping will be abandoned before (top) or after (bottom) a biophysical threshold is reached. See text for additional explanation and examples.

investors (Friis and Reenberg 2010). In an attempt to address these issues, a series of international negotiations resulted in the development of a set of voluntary guidelines on land tenure (UN World Conference on Food Security 2012). These guidelines, while nonbinding, provide guidance for both domestic and international investments and for the development of national policies related to land tenure.

In some cases, the impacts of global capital can be quite positive. For example, Hacienda La Pacifica, a highly productive 2 650-ha dual-purpose (milk and meat) livestock operation in Costa Rica, converted the majority of its irrigated (dry season) pastures to organic and reduced input irrigated rice production in the 1990s. Several years later, tilapia production was established on 67 ha of irrigated land, generating over 3 000 000 kg of fish per year. While cattle continue to play an important role in maintaining air quality (substitute for fire used by neighboring farms to remove rice crop residues), milk production has been eliminated, and beef production warrants barely a footnote in La Pacifica's ledger sheet (F. Estrada, Hacienda La Pacifica general manager, personal communication, 30 April 2012) or that of the multinational corporation that owns it. The dominant land cover is now dry forest, which provides the farm with a number of ecosystem services, including microclimate modification and biodiversity conservation, which, in turn, supports an ecotourism operation. The access of this corporation to capital and technology made possible a series of transformations that were virtually unimaginable for many of its neighbors.

La Pacifica's transformation has occurred within a relatively stable social environment, supported by a well-documented land tenure system. Where landownership and use rights are poorly defined or where land tenure is preferentially assigned to a particular group or class of individuals, rapid influxes of global capital and new technology can create or exacerbate social tensions, contributing to conflicts in addition to directly leading to conversion of marginal lands (Friis and Reenberg 2010). Ownership changes have the potential to increase or reduce sustainable land management across large areas of much of the world, especially in those areas with underexploited potential for intensified crop production.

Feedbacks and Interactions

The "Green Revolution" provides an example of how increased demand for food together with new technologies can transform landscapes at a global scale. Genetic improvement was at the heart of the 1960s green revolution, but the gains would not have been possible without other technologies, including increased use of irrigation, synthetic fertilizers, and new tillage systems. These investments were often supported by both public and private sources of global capital. The new technologies not only increased yields on prime agricultural land but also expanded the ability to produce food grains on previously "marginal" lands. The result was further expansion of cropping into many rangelands. While there have been periodic contractions in many parts of the world (e.g., Cramer et al. 2008; Morris and Monaco 2010; Morris et al. 2011), the drivers ensure that the long-term trends are inexorable (Fig. 1).

IMPLICATIONS FOR THE RELEVANCE OF RANGELAND SCIENCE

The relevance of rangeland science as a professional discipline will necessarily decline if it is perceived as applicable only to land covered by natural or seminatural vegetation that is suitable for ungulates and if rangeland scientists fail to "follow" the land into other land uses, such as crop production. This compounds an ongoing identity problem. The word "rangelands" does not have an equivalent in some languages (e.g., Spanish), and many urban dwellers do not recognize the term even in countries such as the United States, where it is widely used. An investor purchasing a landscape currently dominated by rangeland values the land for the ecosystem services it does and could provide. Some are associated with traditional rangeland uses, but others are not.

Given current trends, rangeland science will be increasingly limited to supporting management on only the world's most marginal lands, including those abandoned following the failure of crop production (Cramer et al. 2008). Development of management strategies for these degraded lands is clearly an important growth sector for rangeland science, just as health care is a growth industry for an increasingly unhealthy and aging human population. We argue, however, that rangeland science is relevant to sustaining as well as restoring land productivity, especially on those "marginal" lands that are often most vulnerable to degradation (Fig. 2). Specifically, we believe that rangeland science can help identify lands at risk of crossing an irreversible threshold and contribute to an understanding of key processes controlling resilience and to the development of sustainable land management systems that support the increased production necessary to support a global population of 9 billion by 2050. This is particularly critical for those soils where there are significant short-term economic benefits of cultivating increasingly marginal land (Fig. 2, bottom graph).

Lands that are first converted to annual crops (left side of all graphs in Fig. 2), such as the eastern Great Plains of the United States, tend to be the most productive with high resilience. Over time, increasingly marginal lands are converted. Where income declines rapidly relative to resilience with each advance into the agricultural frontier, land conversion is stopped before low-resilience land is converted (Fig. 2, top graph). An example is a precipitation gradient on a landscape dominated by flat soils with low wind erodibility, such as the Mitchell Grass Plains of northern Australia. Conversely, where income per hectare is high even on relatively low-resilience lands, such as expanding quinoa (*Chenopodium quinoa* Willd) production on the Bolivian altiplano, land with a high probability of crossing a biophysical threshold following conversion is likely to be converted (Fig. 2, bottom graph; Revista Habitat 2008). The distinctions illustrated by the differences among the three scenarios in Figure 2 are rarely considered in the allocation of conservation resources in part because of the lack of simultaneous analysis of biophysical and socioeconomic patterns and processes.

While the focus of this article is on biophysical resilience, we recognize the critical importance of socioeconomic resilience and the interdependence between biophysical and socioeconomic resilience (Stafford Smith and Reynolds 2002; Reynolds et al. 2007; Folke et al. 2010; Resilience Alliance 2012; Stockholm Resilience Institute 2012). For example, an understanding of the impacts of different drought policies on sustainable livelihoods can lead to the adoption of polices that increase regional resilience relative to drought (Nelson et al. 2008).

STRATEGIES TO INCREASE THE RELEVANCE OF RANGELAND SCIENCE

We propose four strategies to increase the relevance of rangeland science to the management of all lands in the 21st century: 1) increase our awareness and understanding of local to global economic, social, and technological trends in order to anticipate and identify drivers and patterns of conversion; 2) emphasize empirical studies and modeling that anticipate the biophysical (ecosystem services) and societal consequences of large-scale changes in land cover and use; 3) significantly increase communication and collaboration with the disciplines and sectors of society currently responsible for managing the new land uses; and 4) develop and adopt a dynamic and flexible resilience-based land classification system and data-supported conceptual models (e.g., state-and-transition models; Briske et al. 2008; Bestelmeyer et al. 2009) to represent all lands regardless of use and the consequences of land conversion to various uses instead of changes in state or condition that are focused on a single land use.

An *increased awareness of global economic, social and technological trends* is necessary to anticipate future knowledge and information needs from natural resource scientists (Herrick and Sarukhán 2007). In order to effectively target our research to maximize its impact, we need information on the drivers and current patterns of conversion and how these vary throughout the world. Rather than reacting to large-scale land use and land cover changes after they have occurred, research needs to anticipate potential changes to provide information that can be used to inform policy and management. Along with this awareness must come a recognition of the importance of developing, organizing, and sharing information so that valuable knowledge about the functioning and history of ecosystems is not lost (see also Karl et al. 2012 [this issue]).

Various frameworks, including the Dryland Development Paradigm (Reynolds et al. 2007), exist to help identify the critical social, economic, and biophysical factors limiting sustainability (e.g., Ayarza et al. 2010). These need to be applied more regularly and with greater rigor to guide research resource allocation and to avoid inappropriate application of new and existing technologies. For example, this type of analysis might have been used by international donors to avoid land degradation on the Bolivian altiplano (Revista Habitat 2008). Tractors (technology) donated by these organizations together with increased rural-to-urban migration (social), and high grain prices (economic) supported the replacement of grasslands and shrublands with cultivated quinoa production. High rates of wind erosion rapidly degrade these marginal lands following cultivation, especially during the fallows necessary for soil moisture conservation. Rangeland scientists could have contributed an understanding of how resilience varies across these landscapes and the role of connections between upland and basin areas in order to develop more sustainable alternatives.

Emphasizing empirical studies and modeling that anticipate the biophysical (ecosystem services) and societal consequences of large-scale changes in land cover and use can increase the impact of research on land management. Improved process-based models are required that accurately predict the effects of alternative land management systems on ecosystem services, including those that depend on biodiversity conservation, based on the type, timing, frequency, and intensity of disturbance (Vlek et al. 2008; Whitbred et al. 2010). These studies and models must address both short-term effects on the provision of ecosystem services and longer-term effects on the ability of the system to recover its capacity to support the provision of these services in the future (resilience).

The models and studies must account for soil, climate, topography, and landscape connectivity effects while also addressing possible adaptive responses by managers in response to dynamic input and commodity prices. They must also be accessible to managers as both users and contributors of knowledge and information (see Karl et al. 2012 [this issue]). While recent research indicates that some empirical models, such as the Soil Conditioning Index, can be successfully extended beyond the environments for which they were developed (Zobeck et al. 2007), these models cannot anticipate the effects of new management systems in novel environments, and may even limit innovation of existing management systems when they are used to guide policy (Pollan 2006). Innovative, transdisciplinary research is needed to support development and application of new models, particularly those that address effects on human livelihoods. Ironically, this may require a shift from traditional management system comparisons to more basic research focusing on ecosystem processes (see Peters et al. 2012 [this issue]).

Increasing communication and collaboration with other disciplines, breaking free from our own disciplinary biases, and placing site-based research in the context of multiple potential land uses are three of the greatest opportunities and challenges we face as natural resource scientists because of the speed and intensity of land use and land cover changes. Understanding and accepting the relevance of other disciplines while adapting and clearly communicating our own work and making our knowledge and data accessible often present personal (ego), professional, and technical challenges (Peters 2010). Fortunately, many of these disciplines have themselves begun to apply frameworks similar to those used by rangeland scientists in North America and elsewhere, (e.g., Wilhelm et al. 2010). Among agronomists, this transition also includes the concept of precision farming, which is gradually evolving to include precision conservation (Delgado and Berry 2008). Online collaborative spaces can help diverse scientists and land managers work together while using enhanced online databases, search tools, crowdsourcing and other Web 2.0 tools to ensure that they have the best available information.

While there have been innumerable calls for increased interdisciplinary research and collaboration in the natural resource sciences (e.g., Palmer et al. 2005), the value of placing both disciplinary and multidisciplinary research on a particular land use in the context of multiple potential land uses has received significantly less attention. There are, however, a number of successful examples of the application of transdisciplinary approaches in rural development through community-based natural resource management, though challenges remain (Dressler et al. 2010). The case study of Hacienda La Pacifica described above is an example of how the private sector can often complete and act on its own integrated social, economic, and biophysical analyses to create more sustainable systems. While less formal and scientifically rigorous than published examples, the quality of these analyses is reflected in the sustainability of the resulting production systems.

Developing and adopting a dynamic and flexible resilience-based land classification system and data-supported conceptual models are essential to applying relevant knowledge and information to management. The classification system and models must represent 1) all lands regardless of use and 2) the consequences of land conversion to various uses instead of changes in state or condition that are focused on a single land use. This classification system should build on the success of existing systems, including the Land Capability Classification system (Klingebiel and Montgomery 1961) and the Food and Agricultural Organization (FAO) Agroecological Zoning system (FAO 1996). However, it must go beyond these systems by more explicitly 1) addressing resilience (including both resistance and recovery processes) and thresholds, 2) addressing the potential of the land to support a wide variety of ecosystem services, and 3) taking into account spatial interactions among land use and land cover types. The rangeland "ecological site" approach, which is a core tool for rangeland management in the United States, provides a model and a starting point for development of this new system (Fig. 3). This system was developed by the US Department of Agriculture's Natural Resources Conservation Service (NRCS) and was recently adopted by the Bureau of Land Management and the Forest Service for application to rangelands. NRCS is also extending its application to other land cover types.

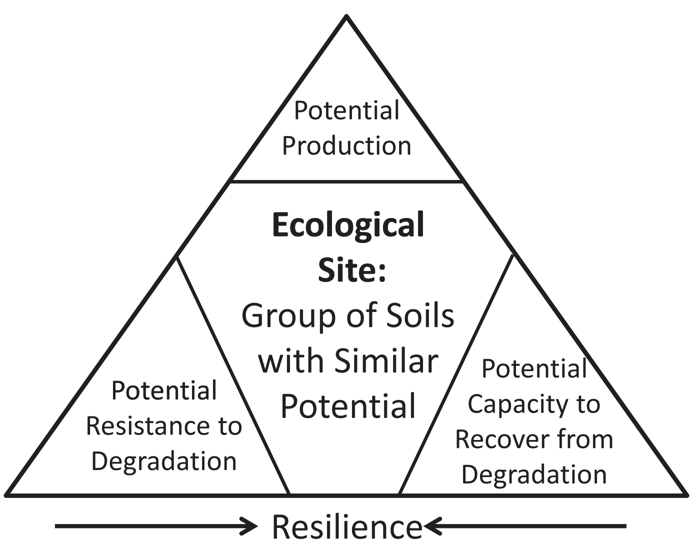

Figure 3. Potential production, resistance to degradation, and capacity to recover are integrated to define ecological sites, differentiating them from most other classification systems for land potential that focus on only potential production or degradation resistance.

The second criterion is particularly important and necessarily requires the system to be based on climate and relatively static soil properties, such as texture and depth, rather than existing vegetation. This necessarily distinguishes the ecological site approach from many existing frameworks based on current vegetation cover or "habitats." Because they are limited to current vegetation, they cannot address the land's potential to provide ecosystem services not supported by the current land cover. Many of these vegetation-based systems can, however, be used to aggregate classification units at coarser scales where they are all based primarily on climate differences.

By expanding land capability classification systems to address resilience (including resistance) and thresholds (Fig. 3), the ecological site system would allow land managers to, for example, differentiate 1) a highly erodible soil that retains its capacity to recover because of its greater depth from 2) a highly erodible but shallow soil (or soil shallow to a texture change) that, if allowed to erode beyond a certain point, will never be able to recover its ecological functions and services (Fig. 2). A more comprehensive land capability assessment protocol would also help the general public and policymakers understand the subtle difference between land that is potentially susceptible to gully erosion and permanent damage from those areas that simply have a high probability of losing soil through sheet erosion. Being able to quantitatively distinguish between different types of land could thus provide an acceptable solution to contentious interpretation debates, such as one regarding soil erosion rates in Iowa, USA, that has been highlighted in the media (Neuman 2011; *New York Times* 2011).

In addition to classifying land based on its response to management and addressing thresholds through the development of ecological site-specific state-and-transition models (Stringham et al. 2003), the ecological site system also provides a more nuanced approach to distinguishing different types of land on the basis of their potential to produce different types and amounts of vegetation. It does not, however, fully address the final two requirements: ecosystem services and interactions across the landscape. Both of these—and future changes in climate—are likely to require a more flexible and dynamic approach to the definition and interpretation of ecological sites. Integration of economics will also be essential to applying an ecological site-based system to land use planning, management, and restoration.

These four strategies can be supported by expanding university efforts to increase students' ability to support land management rather than simply rangeland management through truly interdisciplinary programs and courses. These programs need to include landscape ecology and an understanding of the multiscale, multidimensional drivers affecting global sustainability. They also need to include solid training in the fundamentals of soil science and geomorphology, including pedogenesis and plant–soil–water relations. In our experience working with recent graduates of natural resource programs, one of the most significant limitations to applying the strategies described here is a lack of understanding of the soil and topographic factors controlling production, the resistance of the land to catastrophic soil erosion, and its resilience. These concepts are often not explicitly taught in traditional soil science classes, but an understanding of basic soil science is necessary to understand them.

STRATEGIES TO INCREASE THE RELEVANCE OF RANGELAND SCIENCE: AN EXAMPLE

David Western's book *In the Dust of Kilimanjaro* (Western 2002) provides one of the best illustrations of how landscape science can inform policy and management in a constantly changing political environment driven by globally increasing demand for rangeland resources. In this book, he chronicles his evolving struggle to protect Kenya's rangeland-dependent wildlife through careful research and long-term intensive engagement with key stakeholders, from livestock herders and elephant poachers to the highest levels of the Kenyan government. His willingness to explicitly address evolving perceptions of the land and its value for humans was key to understanding the landscape-scale dynamics involving humans, water, wildlife, and livestock. This understanding directly supported the development of relevant and timely policy and management recommendations that address both ecological and social resilience. Persistence, flexibility, and an ability to reach out to multiple cultures and disciplines were—and continue to be—essential.

While Kenya's native megafauna-rich savanna may seem far from the prairies and shrublands of North America and Western's focus on wildlife foreign to managers of Argentina's pampas, his successes illustrate the value of applying, to varying degrees, each of the four strategies above. An *awareness of local to global economic, social, and technological trends* drives many of the subtle and significant shifts in his approach to both science and stakeholder engagement. His evolving understanding of and appreciation for the *societal consequences of large-scale changes in land cover* and use helped guide his targeted empirical studies of land use and land use change. His willingness to *communicate and collaborate with other disciplines* and other cultures allowed him to rapidly shift his research focus as needed to address the most critical—rather than simply the most tractable—question. An early awareness of the importance of soils led him to test—and reject—a hypothesis that mesoscale patterns could be explained by soil differences while later accepting the extent to which *land classification based on the land's crop production potential* would determine the fate of both wildlife and humans, particularly during drought. The early analyses summarized in the book foreshadowed the land and water use conflicts that are now well documented in other parts of Kenya (e.g., Campbell et al. 2000). The significance of understanding these dynamics was underscored by a recent analysis showing that the probability of civil war is associated with changes in arable land availability where increased access to arable land can reduce the probability of substate conflict (Black 2010).

MANAGEMENT IMPLICATIONS

Rangeland managers will benefit from a landscape science that is founded on an understanding of the potential of the land to support all possible ecosystem services and an acceptance that future generations may decide to optimize production of any one or all of these services (Millennium Ecosystem Assessment 2005). Western's management and policy recommendations were designed to support the survival of a culture and an ecosystem through a strategy that included the continued coexistence of wildlife and livestock and that excluded crop production. Each landscape will require a different management strategy. Specific strategies, like those in East Africa, will necessarily evolve. The continued relevance of rangeland science depends on our willingness to work with landscapes—as well as the people who depend on them and especially the managers who control them—regardless of current land cover or management objectives. The implication for managers is that they will benefit from a more synthetic science that supports all possible land management options.

While the focus of this article is on science in support of rangeland management, the arguments apply equally to most natural resource management disciplines, including forestry: as this article was being completed, the Brazilian Chamber of Deputies voted to ease restrictions on land use in the Amazon, including "allowing the use of previously excluded areas such as hilltops and slopes for some types of cultivation" (i.e., marginal lands; BBC News 2011). This example highlights the extent to which a single action can dramatically and rapidly shift research requirements for an entire region and provide new opportunities for rangeland to develop innovative management systems that can sustain the potential of marginal lands to continue to provide the ecosystem services on which future generations will depend. There is now an urgent need for research supporting the development of sustainable farming systems for these vulnerable parts of the landscape.

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