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Review

Multi-paddock grazing on rangelands: Why the perceptual dichotomy between research results and rancher experience?

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ABSTRACT

Maintaining or enhancing the productive capacity and resilience of rangeland ecosystems is critical for the continued support of people who depend on them for their livelihoods, especially in the face of climatic change. This is also necessary for the continued delivery of ecosystem services derived from rangelands for the broader benefit of societies around the world. Multi-paddock grazing management has been recommended since the mid-20th century as an important tool to adaptively manage rangelands ecosystems to sustain productivity and improve animal management. Moreover, there is much anecdotal evidence from producers that, if applied appropriately, multi-paddock grazing can improve forage and livestock production. By contrast, recent reviews of published rangeland-based grazing systems studies have concluded that, in general, field trials show no superiority of vegetation or animal production in multi-paddock grazing relative to continuous yearlong stocking of single-paddock livestock production systems. Our goal is to provide a framework for rangeland management decisions that support the productivity and resiliency of rangelands and then to identify why different perceptions exist among rangeland managers who have effectively used multi-paddock grazing systems and research scientists who have studied them. First, we discuss the ecology of grazed ecosystems under free-ranging herbivores and under single-paddock fenced conditions. Second, we identify five principles underpinning the adaptive management actions used by successful grazing managers and the ecological, physiological, and behavioral framework they use to achieve desired conservation, production, and financial goals. Third, we examine adaptive management principles needed to successfully manage rangelands subjected to varying environmental conditions. Fourth, we describe the differences between the interpretation of results of grazing systems research reported in the scientific literature and the results reported by successful grazing managers; we highlight the shortcomings of most of the previously conducted grazing systems research for providing information relevant for rangeland managers who aim to achieve desired environmental and economic goals. Finally, we outline knowledge gaps and present testable hypotheses to broaden our understanding of how planned multi-paddock grazing management can be used at the ranching enterprise scale to facilitate the adaptive management of rangelands under dynamic environmental conditions.

1. Introduction

Rangelands are diverse ecosystems and landforms that cover about half of the world's terrestrial area, excluding Antarctica and Greenland, and that are unsuited for intensive agriculture or forestry because of climatic, edaphic or topographic limitations (Holechek et al., 2004). People in many rural and urban populations depend on them for their livelihoods, often through livestock production, and for the ecosystem services that affect human well being. Such services include the maintenance of stable and productive soils, the delivery of clean water, the sustenance of plants, animals and other organisms that support human livelihoods, and other characteristics that support aesthetic and cultural values (Daily, 1997; Grice and Hodgkinson, 2002).

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Healthy rangelands are more productive, stable and resilient than those in poorer condition and they provide greater earnings and more abundant ecosystem services (Heitschmidt and Taylor, 1991; Oesterheld et al., 1992; Milchunas and Lauenroth, 1993; Wessels et al., 2007; Teague et al., 2009a, 2011). Therefore, to support their sustainability, anyone who manages rangelands should aim to enhance the health and socio-ecological resilience of these ecosystems (Walker et al., 2002). This requires adopting long-term planning horizons, conserving primary resources, choosing appropriate management goals, and continually adapting to dynamic ecological, social, and economic conditions.

Changes in environmental conditions often happen so gradually that most people are unaware of them until some threshold condition has been exceeded (Senge, 1994). Unless sufficiently sensitive indicators of change are continually monitored, landowners who focus on short-term profit maximization may not realize that the ecosystems upon which their production systems depend are being systematically degraded (Kothmann et al., 1971; Whitson et al., 1982; Knight et al., 1990; Teague et al., 2009a). As a result, *maximizing* livestock production from rangelands is inevitably an unsustainable goal both ecologically and economically (Workman, 1986). To remain economically viable, managers must maintain or improve the biophysical functions and processes necessary for sustaining ecosystem health and resilience, including soil organic matter accumulation, solar energy capture, water infiltration, and nutrient cycling while also maintaining ecosystem biodiversity. In the long term, this strategy provides the greatest cumulative production potential and economic profits without decreasing delivery of ecosystem services for society.

Ranchers with secure land tenure generally have a vested interest in managing their resources for sustained high yields and profitability. Achieving this goal requires ranchers to integrate knowledge from biological, economic and management disciplines and to continually adjust management actions in response to changing environmental and socio-economic conditions. In response, people have developed numerous grazing strategies for sustaining and improving rangeland health. However, applying any of them successfully requires the use of adaptive management based on relevant scientific information and, equally importantly, local knowledge and experience to respond to ever-changing circumstances (Walters, 1986; Holling and Meffe, 1996; Walker et al., 2002). The benefits of multi-paddock grazing for maintaining productivity and profitability and for adaptive management responses to changing conditions have been evident to ranchers for many years in many countries (Tainton et al., 1999; Teague et al., 2009b). However, recent reviews of published rangeland grazing studies suggest that multi-paddock rotational grazing improves neither vegetation nor animal production relative to single-paddock continuous stocking (Briske et al., 2008).

The goal of our paper is to provide a framework for rangeland management decisions to enhance ecosystem resilience and delivery of ecosystem services and to develop testable hypotheses that explain the differences in perspectives of ranchers' observations and scientific research results. In presenting the framework and hypotheses, we distinguish between principles and processes of adaptation and their local manifestations for plants, herbivores, and people. Many publications report the manifestations of particular responses unique to local conditions for plants, herbivores and researchers, and do not focus on principles and processes, which are required to increase broader understanding of responses to management actions. While principles and processes apply generally across time and space, the application of treatments varies from time-to-time and place-to-place, which makes their responses unique in space and time.

The reason for developing and implementing grazing management strategies as alternatives to continuous grazing is to prevent the degradation of rangeland ecosystems and to enhance ecological functions that increase primary and secondary production, and to provide other ecosystem services. Short-term field studies of grazing management have generally incorporated a minimal number of grazing system variables, notably plant and animal production, to obtain publishable results. In most cases, they have not investigated grazing management impacts on other system elements nor the interaction of these components. In addition, the spatial and temporal scales of such research are generally smaller and shorter, respectively, than those faced by ranchers. Therefore, the results of these grazing systems studies must be interpreted carefully to determine their value and applicability at a ranch-operation scale. When applied rigidly at these larger scales, they have often led to different and unsatisfactory outcomes. Accordingly, we concentrate our inquiry on determining the management principles, processes and approaches needed to maintain or improve the ecological function and biological resources upon which productivity is based, rather than on examining what management results in the highest productivity without examining long-term consequences on ecosystem function (see Van der Ploeg et al., 2006 for a discussion of these ideas regarding a grassland experiment).

The manuscript is based on five focal areas of inquiry. First, we outline the ecology of grazed ecosystems under free-ranging and single-paddock herbivory conditions. Second, we identify five principles underpinning the actions used by successful grazing managers and the ecological, physiological, and behavioral framework they use to achieve desired conservation, production, and financial goals. Third, we examine the adaptive management principles needed for sustainability in variable environments. While understanding ecological processes is critically important, such knowledge is insufficient for sustainable outcomes; to respond to ever-changing ecological, social, and economic conditions, people must combine knowledge of plant and animal ecology, physiology, and behavior with adaptive, goal-oriented decision-making. Fourth, we describe differences between the interpretation of results of grazing systems research reported in the scientific literature and the knowledge gained by successful grazing managers. In association with this we outline the shortcomings of grazing system research for providing information relevant for rangeland managers to meet their desired environmental and economic goals. Finally, we outline knowledge gaps and associated research needed to provide a clearer understanding of how grazing management can achieve desired socio-ecological goals. To facilitate future research, we develop testable hypotheses to explain why recent reviews of research have arrived at conclusions that differ from those obtained by many successful conservation award-winning ranchers. Given that the scientific procedure involves formulating testable hypotheses that aim to explain observations (Popper, 1959; Kuhn, 1970), we present well-founded observations from numerous sources to formulate testable hypotheses.

2. Ecology of grazed ecosystems

2.1. Grazing effects under free-ranging herbivory

From the late Mesozoic Era, grazing by large ungulates has been an integral part of most ecosystems. The co-evolution of plants and herbivores under changing environmental conditions has resulted in highly resilient grazed ecosystems that support more animal biomass and sustain considerably higher levels of herbivory than other terrestrial habitats (Stuart Hill and Mentis, 1982; Frank et al., 1998). Grazing, fire and fluctuating climatic regimes create the dynamic resilience of organisms that respond constantly to biophysical events. As a consequence, most ecosystems never reach a steady-state or climax seral stage (Pielou, 1991). Rather, periodic disturbances rejuvenate and transform landscapes including soil nutrients and structure, plant species composition, structure and biodiversity (Vogl, 1974; Rice and Parenti, 1978; Pickett and White, 1985; Hulbert, 1969, 1988).

The key elements characterizing grazed ecosystems are spatial and temporal variation in plant diversity, forage supply, and dominance by large migratory herds of herbivores. Vegetation heterogeneity is determined by spatial variation in topography and soils and temporal variation in precipitation (McNaughton et al., 1989; Frank et al., 1998). These vagaries cause grazers to move regularly for several reasons: satiation of water and nutrient requirements including both primary and secondary compounds, fouling sites with urine and feces, social organization, and the influences of fire, predation, herding and hunting (Provenza, 2003a, 2003b; Bailey and Provenza, 2008). Although grazing pressure can be intense at some sites, concentrated grazing seldom lasts long when the movement of herbivores is not restricted; instead grazed plants are typically afforded time for inter-defoliation recovery when herds move to new feeding grounds (Frank et al., 1998). Nomadic pastoralists who mimic the grazing patterns of unconstrained herbivores appear to have less detrimental effects on grasslands compared to sites where defoliation frequencies are increased when grazing animals are restricted to a single fenced paddock (Meuret, 2010).

Grazers and browsers affect many ecosystem processes. Through urination and defecation they can increase nutrient concentrations (Holland et al., 1992), and enhance mineral availability for soil microbes and plant roots. This positively influences plant nutrition, especially nitrogen, thereby increasing photosynthesis (Hamilton and Frank, 2001) and ultimately increasing plant production compared to ungrazed areas (Bryant et al., 1991; Frank et al., 1998). In addition, by creating concentrations of plant organic matter, nutrients and soil moisture, herbivores generate conditions that are more conducive for growth than for the development of chemical defences by plants, thereby enhancing the palatability of plants (Bryant et al., 1991; Coley et al., 1985; Provenza et al., 2003b). Such effects of grazers on carbon and nitrogen distribution are as important in determining landscape-scale ecological processes as topography, catenal position, and soil type (Frank and Groffman, 1998). However, the potentially positive feedbacks of grazers on ecosystems are mediated by low moisture or extreme temperature conditions that limit plant growth (Wallace et al., 1984; Coughenour et al., 1985; Louda et al., 1990).

2.2. Grazing effects under single-paddock fenced conditions

Unfortunately, the replacement of free-ranging wild herbivores with livestock managed by humans has frequently led to severe degradation of rangelands. Domesticated livestock have become sedentary as humans restricted their movements across landscapes, suppressed periodic fire, and eliminated large predators (Milchunas and Lauenroth, 1993). This has led to the removal of periodic animal use and positive impacts of animals on plants followed by the key revitalizing element of periodic rest from defoliation for plants and to decreased nutritional quality and health for herbivores (Provenza, 2008). In many instances, pressure on grazed plants has been further elevated through the use of supplementary feed to retain high animal numbers during less productive periods (Oesterheld et al., 1992).

Animals do not graze uniformly over the landscape but repeatedly consume preferred plants and patches of vegetation. This selectivity is affected most by vegetative heterogeneity at the landscape level and to a lesser degree by plant heterogeneity at the feeding-station scale and by distance of forage resources from water (Stuth, 1991; WallisDeVries et al., 1999). Overgrazing occurs when individual plants are subjected to multiple, severe defoliations without sufficient physiological recovery time (Briske, 1991; Roshier and Nicol, 1998). In turn, excessive herbivory removes threshold amounts of biomass and litter, causing soil exposure and degradation in heavily used areas (Thurow, 1991; Fuls, 1992; O'Connor, 1992; Derner et al., 1994; Ash and Stafford-Smith, 1996; Teague et al., 2004, 2011). The spatial arrangement and scale of vegetative patchiness are major determinants of patterns of grazing and site selection when livestock are stocked continuously in a given area. Grazing patterns are further influenced by topographic variation, the distribution of water, mineral licks and cover, and both intra- and inter-specific social interactions among herbivores (Coughenour, 1991; Provenza, 2003b). These factors combine to increase vegetative heterogeneity as the size of the grazing paddock increases (Stuth, 1991; Illius and O'Connor, 1999; WallisDeVries et al., 1999), which typically causes heavy, repeated impacts on preferred areas while other parts of the paddock receive light or no utilization (Coughenour, 1991; Fuls, 1992; Kellner and Bosch, 1992; Teague et al., 2004).

Droughts, which are common in many rangeland ecosystems, exacerbate the effects of chronic defoliation (McIvor, 2007) causing preferred plants to perish and enabling less desirable plants, which are more highly physically and chemically defended species of grass, forbs and shrubs, to expand (Bryant et al., 1983; Briske, 1991; Herms and Mattson, 1992). These degradation effects compound over time, decreasing the delivery of the ecosystem services that may be difficult or impossible to restore (Coughenour, 1991; Fuls, 1992; Kellner and Bosch, 1992; Teague et al., 2004).

Historically, high stocking rates have been identified as the leading cause of rangeland degradation (Heitschmidt and Taylor, 1991). Reducing stocking rates to low levels to reduce degradation often exacerbates uneven grazing impact because the most desirable areas and plants within them continue to be more frequently and intensively grazed while less desired areas and plants are frequented less often (Ash and Stafford-Smith, 1996; Earl and Jones, 1996; Teague et al., 2004, 2011). Therefore, while stocking according to forage supply is a crucial first step in sustainable rangeland management for livestock production, it must be applied in conjunction with other practices that increase animal distribution and movement, and that include periodic growing season recovery and short grazing periods to mitigate the damaging effects of repeated selective grazing (Morris and Tainton, 1991; O'Connor, 1992; Norton, 1998, 2003; Provenza, 2008; Teague et al., 2004, 2011).

3. Principles of successful grazing management

Ranching in rangeland ecosystems is characterized by ever-changing and unpredictable environmental conditions and circumstances due to low, variable and spatially and temporally heterogeneous precipitation and plant productivity, and to fluctuating economic conditions driven by market price fluctuations and shifting social values. Successful rangeland managers enhance the health of the ecosystems upon which they depend, their profitability and their life quality, while also providing ecosystems services desired by society, by using soil, water and plant resources efficiently and sustainably (Walters, 1986; Holling and Meffe, 1996; Walker et al., 2002). To do so, they combine scientific principles and local knowledge to adaptively manage animals to influence four ecosystem processes: efficient conversion of solar energy by plants; interception and retention of precipitation in the soil; optimal cycling of nutrients; and promotion of high ecosystem biodiversity with more complex mixtures and combinations of desirable plant species (Stinner et al., 1997; Reed et al., 1999; Savory and Butterfield, 1999; Sayre, 2001; Gerrish, 2004; Barnes et al., 2008;

Diaz-Solis et al., 2009; Teague et al., 2009b). To accomplish this, successful managers apply the following five principles:

1. Provide sufficient forage for animals to select a diet of adequate quantity and quality;
2. Manage grazing so animals eat a wide variety of plants and decrease impacts on desirable plants;
3. Leave enough leaf biomass on defoliated plants to facilitate interception and infiltration of precipitation and to maintain sufficient photosynthetic capacity for rapid plant recovery;
4. Allow adequate post-grazing recovery to maintain plant vigor and desired plant composition; and
5. Plan and create the means to control grazing pressure in time and space to facilitate the previous 4 principles.

These five management principles are implemented using an ecological, physiological, and behavioral framework to achieve the desired conservation, production, and financial goals. This framework comprises four operating actions including: 1) providing adequate plant recovery; 2) modifying livestock distribution; 3) regulating grazing intensity; and 4) modifying livestock nutrition and feeding behavior. The linkages of the five management principles with the four operating actions are depicted in Fig. 1 and each action category of emphasis is discussed in the following subsections:

3.1. Provide adequate post-grazing plant recovery

Long-term ranch-based research and theoretical analyses indicate that reducing livestock numbers when forage availability declines is insufficient to maintain rangeland health and productivity (Müller et al., 2007; Teague et al., 2004, 2011). Adequate post-grazing recovery during the growing season is also necessary to conserve rangelands and enhance their productivity. This requires excluding grazing animals from previously grazed areas for enough time to allow plants to regrow before they are again defoliated.

Post-defoliation plant recovery occurs, however, only if moisture and temperature regimes are suitable for plant growth during the grazing deferment period (Wallace et al., 1984; Coughenour et al., 1985; Louda et al., 1990). Suitable recovery periods are species- and even plant-specific (Caldwell, 1984). Recovery is slower or minimal during droughts; thus, drier rangeland ecosystems are affected more and require longer recovery periods (Heitschmidt and Taylor, 1991), often a year or more (Trlica et al., 1977; Cook and Stoddart, 1963). The length of time necessary for plant recovery during the growing season after moderate defoliation varies from approximately 30 days in mesic ecosystems to four or more months in xeric rangelands (Reece et al., 1996; Hendrickson et al., 2000). Many of the world's ecosystems, particularly in xeric areas, have been substantially degraded due to insufficient post-grazing recovery time (Tainton et al., 1999; Müller et al., 2007). Moreover, where such degradation has occurred, the recovery of plants after even moderate defoliation will be considerably slower than in healthy rangelands (Reece et al., 1996; Caldwell, 1984).

To overcome the effects of defoliation of preferred plants growing in preferred areas, periodic, adequate post-grazing recovery is critical to maintain or improve plant productivity, vigor, and diversity. That means moving livestock among separated locations (demarcated by paddocks or shepherding) within the grazing area in ways that enable light to moderate use of a variety of different plant species and sufficient plant recovery times within and between years.

3.2. Modifying livestock distribution

Using multiple paddocks per herd enables a manager to effectively increase the surface area utilized by grazing animals; subdividing a grazing unit into smaller paddocks facilitates placing livestock in parts of the landscape that they may have previously neglected or under-utilized. This creates a *de facto* increase in available forage that livestock actually seek, encounter and consume compared to that prior to subdivision (Teague et al., 2004). Even under continuous stocking more rangeland vegetation will be used by livestock that are restricted to smaller paddocks because landscape heterogeneity and forage patchiness increase as the size of grazing unit increases and stock density decreases (Senft et al., 1985; Hart et al., 1993a,b).

Because livestock develop preferences for some parts of the landscape over others (Senft, 1989; Provenza, 2003b), *de facto* stocking rates vary from high to low across a landscape that is, on average, stocked "modestly". The use of more numerous, smaller paddocks tends to spread out forage demand more equitably across the landscape by increasing the proportion of the landscape used by livestock, increasing the grazing pressure on previously unused or lightly used areas and decreasing the grazing pressure on preferred areas. The overall effect is to increase the livestock carrying capacity for the landscape.

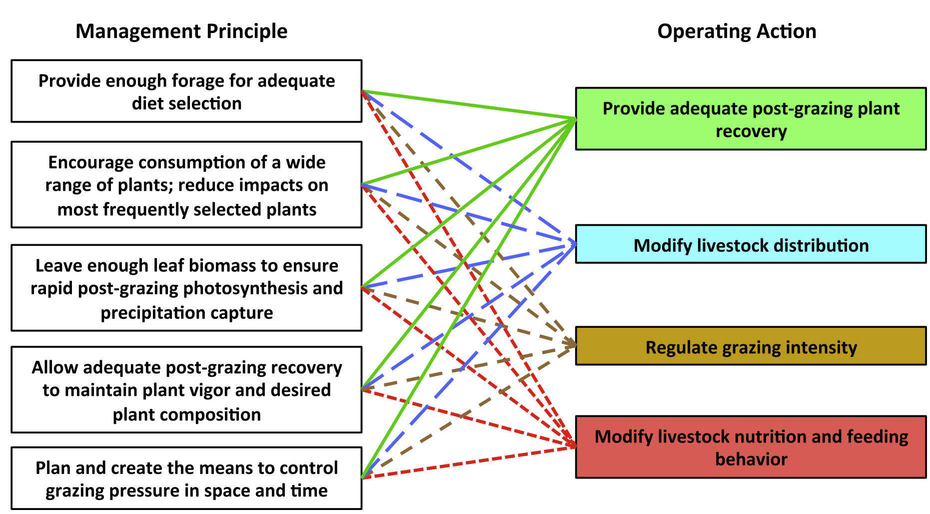

Fig. 1. Linkages between five principles of successful grazing management and four operational action categories used to apply these principles.

3.3. Regulating grazing intensity

Multi-paddock grazing can prevent or reverse rangeland degradation caused by area and patch-selective overgrazing that develops within single paddocks that are stocked continuously (Teague et al., 2004, 2011). While this applies to all grazed rangelands, livestock managers must be sensitive to the relative ability of plants to recover from grazing due to their unique co-evolutionary histories with herbivores, to differences in degree of defoliation among contemporaries, and to current environmental conditions (Caldwell et al., 1981; Milchunas and Lauenroth, 1993; Adler et al., 2004, 2005; De Bello et al., 2005). When plants must be grazed during the growing season, they persist best when defoliated moderately and when ample soil moisture and moderate air temperatures exist for regrowth following defoliation (Caldwell et al., 1981).

Using multiple paddocks per herd allows a manager to regulate the length of a grazing period and hence the average intensity of defoliation as well as the length of time before each paddock is grazed again (Teague et al., 2004; Barnes et al., 2008). When grazing period decreases proportionally more than stock density increases, the average defoliation intensity of preferred plants and the opportunity for repeated use of previously heavily used areas tend to decrease if graze periods are short enough (Steffens et al., 2009). When coupled with longer recovery between graze periods, shorter graze periods enable rapid perennial plant recovery and increase the possibility for germination and establishment of desirable species. The degree of control over timing of occupancy of a grazed area, and the potential for forage and animal production benefits, are both a function of the number of paddocks for an individual grazing rotation cycle (Norton, 1998; Teague et al., 2004) and the length of the grazing period in each paddock. Together they determine forage demand relative to forage available during the grazing period (Steffens et al., 2009).

Regulating the intensity of grazing is a major factor determining plant vigor and productivity. Maximum forage growth rate occurs when environmental conditions are optimum and plants are vegetative and have adequate (intermediate) leaf biomass (photosynthetic capacity) to regrow quickly following grazing; leaf growth rate is low when leaf biomass is low or when plants reach the reproductive phase (Booysen, 1966; Booysen and Tainton, 1978; Maeda and Yonetani, 1978). Season-long continuous stocking over the whole management unit results in over- and under-used plants, both of which exhibit low photosynthetic capacity and growth rates. By contrast, when quality differences between plants are relatively low, intensive multi-paddock grazing can enhance the photosynthetic capacity and growth rates of grazed plants for longer periods during the growing season and over a larger proportion of the grazing area by increasing the proportion of plants that are maintained in a vegetative, leafy state, assuming environmental conditions are optimum for growth (Teague et al., 2011). When these differences are high, increasing paddock numbers to provide extended post-defoliation recovery times provides a way to allow heavily defoliated very high quality plants to physiologically recover more fully between defoliations and, thereby, to better maintain their competitive position in the plant community.

In more mesic rangelands, such as tallgrass prairies where water and nutrients are less limiting for regrowth, well-managed multiple-paddock grazing can increase plant and animal production by maintaining plants in a vegetative state for a longer time (Gerrish, 2004; Teague et al., 2011). In such ecosystems, periods of growth are frequent and long enough that it is feasible to maintain large portions of the plants in the grazing unit in a leafy, non-reproductive phase using moderate levels of defoliation with grazing periods of 1–3 days followed by recovery periods as short as 45–90 days. Critically, achieving this outcome in highly variable environments means management must be flexible (Diaz-Solis et al., 2009).

In more xeric ecosystems that experience erratic precipitation and short and intermittent periods of plant growth, such as annual grasslands in California and perennial rangelands around the world where plant recovery is inherently slower, different grazing strategies are needed compared to those most suited for mesic areas (Tainton et al., 1999). Short and sporadic precipitation events favor plants that respond quickly, both in initiating and slowing growth in response to pulses of moisture. In xeric environments, the benefits of shorter grazing periods combined with longer growing season recovery periods are relatively small compared to more mesic areas. To maintain or improve range condition in drier environments, and those with a slower response to herbivory, managers should apply moderate use during the growing season along with *long growing season recovery* periods. Maintaining adequate vegetative cover and minimizing the adverse effects of bare ground on plants are paramount to retaining plant productivity and preventing soil erosion and deterioration (Thurow, 1991; Teague et al., 2011).

3.4. Modifying nutrition and feeding behavior

The nutritional regime of herbivores on rangelands is often highly variable. Animals cannot necessarily meet their nutritional needs during high demand periods, including conception, late pregnancy and lactation, especially if the processes of maintenance and reproduction are out of synchrony with seasonal vegetation growth and production (Provenza, 2008). Multi-paddock management can positively influence both forage productivity and quality and managers can plan stock movements to place animals in paddocks with the best chance of meeting higher nutritional requirements (Tainton et al., 1999). However, wet and dry rangelands require different management strategies to achieve this objective because forage quantity and quality and animal nutrition challenges are not the same.

Plant production is lower in drier than in wetter ecosystems, but the quality of forage declines more precipitously with plant maturity in wetter ecosystems. In more humid and sub-tropical rangelands, forage matures more quickly and taller grass species lignify as they mature. Animal performance increases as grazing period decreases if ample quantity and quality of green leaf is available. Conversely, animal performance decreases as the length of rest period increases beyond the time it takes grazed plants to recover as plants mature. Nutrient intake becomes more sensitive to grazing period length as paddock numbers increase because higher quality forage disappears more quickly with higher paddock numbers per herd (Steffens et al., 2009). Higher forage production also occurs at moderate utilization under short grazing periods (Gerrish, 2004). For optimum nutrient intake, rest periods should, therefore, be long enough for plant recovery but not so long that plants mature; the quality of grasses and forbs decreases markedly with maturity while shrubs maintain quality, especially protein, and can provide a complementary forage source when grasses mature (Provenza et al., 2003b). Grazing periods should be short and defoliation should be moderate to accomplish these goals but managers should also be flexible when determining grazing period and intensity as circumstances change (Voisin, 1959; Booysen, 1966; Booysen and Tainton, 1978; Teague et al., 2011).

Grazing management influences diet selection and animals optimize food intake based on how they have learned to use various combinations of plants and locations in a pasture (Provenza et al., 2003a; Provenza, 2003b). Under continuous, low density grazing livestock often learn to eat only a small subset of the more palatable foods that provide adequate nutrition, even though adequate quality may be available for them to use a greater proportion of the plants to meet dietary requirements if mixed over a short period of time (Steffens et al., 2009). Animals grazed in this way are unlikely to learn about the possible benefits of mixing different foods, especially those high in secondary compounds. Over time, such selective foraging will change the mix of plants on offer in a self-reinforcing cycle that further reduces opportunities to learn, and it will gradually degrade soils, plants, animal performance and landscapes (Provenza, 2008).

One of the primary advantages of high stock density, often overlooked in grazing studies, is to allow animals adequate opportunity to learn to select a high quality diet from a mixed sward or a landscape with diverse topographic, edaphic, and vegetation features. When they are introduced to multi-paddock grazing, they will rapidly deplete those preferred plants and can be encouraged to take a higher proportion of other plants (Provenza et al., 2003a). In the process, they learn to “mix the best with the rest” as opposed to “eat the best and leave the rest”, thereby spreading the grazing pressure to less palatable plants (Villalba et al., 2004; Shaw et al., 2006). That involves learning about complementarities among primary and secondary compounds in different plants (Villalba et al., 2011; Lyman et al., 2012; Owens et al., 2012). This process is accelerated if grazing periods are short and stock densities are high. Thus, the combination of more paddocks with high stock density for short periods can encourage livestock to eat a wider variety of plants and avoid regrazing only the most palatable plants (O’Connor, 1992; Provenza, 2003a, 2003b).

There are other ways for animals to learn to use new foods in combination with familiar foods as well. For instance, herders in France set up training paddocks for naïve animals and they move their livestock among different vegetation types in certain sequences to take advantage of synergisms that increase ingestion of certain foods after other specific forages have been consumed, thereby stimulating appetite and intake of a variety of forages, many of which animals ordinarily would not eat (Provenza, 2008; Meuret, 2010).

Although animals accustomed to selectively grazing plants under low-density, continuous stocking can perform poorly when beginning to graze under high-density grazing, as they learn to “mix the best with the rest” they acclimate to the new management within 3 years and resume previous performance levels as we discuss in the following sections and the same is true for learning to use new habitats, for instance uplands as opposed to riparian areas (Provenza et al., 2003a). Increasing the number of paddocks to shorten periods of occupation reduces the negative effects on animal performance, and depending on how they are used, they can also serve as training pastures (Meuret, 2010).

4. Adaptive management in variable environments

Management is relatively easy when resources for plant growth are abundant and predictable and when forage quality is reasonably high and consistent. Rangelands, by contrast, are difficult to manage because decisions must accommodate substantial change and uncertainty including inter- and intra-seasonal climatic variations with periodic droughts, low and variable forage quality, and variation in social preferences and economic factors that affect profitability (Tainton et al., 1999; Sayre, 2001). To manage resources sustainably in such variable and uncertain environments necessitates adaptive management that draws on both scientifically established principles and local knowledge. Adaptive management includes visioning to determine long-term goals, developing and implementing a plan of action to attain those goals, monitoring and analyzing the effects of the management actions, and continually adjusting to move in the direction of the stated goals (Savory and Butterfield, 1999). A fundamental principle of adaptive management is that, due to incomplete knowledge and invariably changing conditions, management decisions are imperfect and must be continually modified as conditions change and new knowledge is gained. Management must be flexible if the desired results are to be attained. Multiple paddocks provide the flexibility to facilitate adaptive management of grazing resources in heterogeneous and dynamic rangeland ecosystems (Norton, 1998).

In the following sub-sections we address the need for management flexibility in the context of climatic variability, periodic fire, and extensive versus intensive grazing management philosophies that promote the use of many or few paddocks. While we focus on fenced paddocks, at the outset we also emphasize that installing permanent fencing is not necessary for implementing alternatives to multi-paddock or high-density grazing strategies because the movement of animals can also be achieved effectively through the use of temporary electric fencing, herding (Bradford, 1998; Coughenour, 1991; Butler, 2000; Bailey et al., 2008 Meuret, 2010), prescribed burning (Archibald et al., 2005; Fuhlendorf et al., 2006), strategic supplementation (Bailey and Welling, 2007), control of water points, and other modifications of animal behavior (Provenza, 2003a,b; Launchbaugh and Howery, 2005). Any of these methods can be used to continually move grazing pressure across landscapes, thereby minimizing negative effects of plant and area selection, and enhancing biodiversity.

4.1. Strategic adaptive grazing management

Management protocols have been developed for few or many paddocks per herd in climatically variable rangelands. In more arid rangelands, the use of multiple paddocks to restrict grazing in one quarter to one half of the management unit during the growing season provides recovery for preferred plants. This approach also creates a forage reserve that may be carried over to the next year if it is not needed to offset forage shortages during a dry period or it may be used, for instance, to implement prescribed burning to suppress invading woody plants. Timing movement of animals to rested paddocks should coincide with peak nutritional requirements of the herd to ensure high animal performance. Such simple management strategies help ranchers maintain or improve the resource base while stabilizing animal numbers and cash flow (Danckwerts, 1984; Müller et al., 2007; Van de Pol and Jordaan, 2008). A low-intensity system with 2–4 paddocks per herd may provide adequate growing season recovery in each paddock every 2–4 years, but may require lower stocking rates to simultaneously achieve proper forage utilization and maintain individual livestock performance. For greater forage and animal production, a manager can implement more management-intensive grazing with 16 or more paddocks per herd (Norton, 1998; Savory and Butterfield, 1999; Beukes et al., 2002; Gerrish, 2004; Teague et al., 2011).

In more mesic rangelands, multi-paddock management provides added flexibility to facilitate effective decision-making in both wet and dry seasons. To achieve moderate defoliation in above-average rainfall years, animals are moved through paddocks that have not been assigned a rest period (Teague et al., 2011). When the first paddock grazed that season has had sufficient time for defoliated plants to fully recover, the herd is moved back to it regardless of the location of the herd in the grazing cycle. This approach leaves adequate residual plant biomass in grazed paddocks to maintain high growth rates for plants and high forage quality for animals. It also results in the last paddocks of the grazing sequence receiving little or no grazing in wet years, which allows palatable plants to grow and reproduce and the ungrazed area to be used as a forage buffer and a wildlife refuge, thereby creating diversity across landscapes. However, in mesic rangelands, interannual biomass carryover following wet seasons may be substantial. Excessive senescent standing crop can reduce nutrient cycling, light penetration, photosynthesis, and primary productivity, that produce undesirable changes in plant species composition, and diminish diet quality for grazing animals (Pieper, 1994; Olff and Ritchie, 1998). In multi-paddock systems, such senescent biomass can become litter that is incorporated into the soil during the dormant season through trampling by grazing animals that are concentrated in smaller areas due to the use of many paddocks per herd (Teague et al., 2011), burned to manage woody vegetation, or used as forage by animals during periods of lower nutrient requirements.

The same principles of moderate defoliation and recovery before regrazing also apply in dry years in mesic rangeland. However, because plant growth is slower, more paddocks will be grazed before plants in the first-grazed paddock have had time to regrow sufficiently (Tainton et al., 1999). In very dry years, that can be achieved only by utilizing areas scheduled for rest, which serve as a forage buffer during drought. If dry conditions persist, stocking rates must be reduced so that forage demand does not exceed supply. An underestimated value of multi-paddock grazing is that forage within a smaller paddock will be depleted more rapidly and thus noticeably than in a similarly stocked continuously grazed system, providing the manager a more immediate cue to preemptively adjust livestock numbers (Diaz-Solis et al., 2009).

4.2. Extensive versus intensive grazing management approaches

Due to substantial variability and uncertainty, rangelands are risky environments in which to conduct business. Keeping risk at an acceptable level is critical for most ranchers but they differ widely in their aversion to risk, resistance to change, and managerial capability (Teague et al., 2009b). Not all ranchers are comfortable with implementing intensive multi-paddock grazing strategies. Thus there is a need for a broad suite of strategies, each of which differ in grazing management complexity to provide suitable choices for diverse ranchers to obtain satisfactory productivity and to sustain or improve rangeland resources (Teague et al., 2009b).

For those wishing to use simpler less intensive management, strategies with less than 5 paddocks per herd can allow sufficient growing season rest at relatively low stocking rates (Teague et al., 2009b). For example, systems such as the 2 to 3 paddock Controlled-Fodder-Flow strategy (Van de Pol and Jordaan, 2008) and Merrill 4-paddock 3-herd system (Heitschmidt and Taylor, 1991; Taylor et al., 1993) can produce satisfactory results with less intensive management. Two or 4 paddocks per herd enable periodic full growing season recovery with or without multi-paddock grazing (Danckwerts, 1984; Tainton et al., 1999; Müller et al., 2007). However, while such systems do not require intensive management, they have minimal potential for inhibiting selective grazing by livestock not conditioned to “mix the best with the rest,” for providing meaningful post-grazing recovery, or for improving livestock distribution over the landscape (Teague et al., 2009b). When rangelands are in good condition these negative aspects may be difficult to notice in the short term but where they have been degraded, the desirable plants and vegetation patches will be low in vigor and abundance. The extended periods of grazing with fewer paddocks will maintain heavy negative pressure on these more valuable plants and they will require much longer periods of recovery if they are to maintain or increase plant vigor, abundance and productivity.

Intensive rotation through many paddocks per herd facilitates better planning and incurs lower ecological risk although management activities and decisions may be more intensive; hence the emphasis on “management” in “management-intensive” grazing (Gerrish, 2004; Howell, 2008; Teague et al., 2009b). More careful management to reduce animal numbers during periods of low plant productivity is facilitated, because forage shortfalls can be detected more quickly thus enabling a manager to avoid degrading the resource base and incurring economic losses (Diaz-Solis et al., 2009). Managers who use multiple paddocks per herd often experience less risk and usually have excess forage due to a combination of better grazing distribution over the landscape, shorter grazing periods, longer recovery periods and a greater proportion of the year when growth and recovery can occur on any particular area without the risk of repeated defoliation (Norton, 1998; Teague et al., 2009b). Moreover, management can be tailored to account for the relative defoliation responses of specific plant species to co-occurring species. Shorter defoliation periods reduce repeat defoliation impacts on desirable plants thereby supporting a competitive advantage for the more desirable species (Tainton et al., 1999).

4.3. Impacts of high density grazing

Rancher experience and scientific experiments indicate that the impacts of high stock densities on plants under intensive multi-paddock grazing can benefit plants due to the combination of three factors: animals include more species in their diets, preferred species experience fewer repeat defoliations, and post-grazing recovery periods are extended (Norton, 1998, 2003; Beukes et al., 2002; Teague et al., 2011). Because grazing impacts are spread over a larger portion of the ranch as the number of paddocks in the grazing sequence increases, the need for a long recovery period declines. If selectivity is reduced and more species experience a similar degree of defoliation, palatable species experience less of a competitive disadvantage relative to less preferred species during the regrowth period (Teague and Dowhower, 2001). Animal impacts at high stock densities can also alter the chemical characteristics of palatable and unpalatable species (Provenza et al., 2003a, 2003b). Palatable plants persist in grazed vegetation because they invest in fast-growing photosynthetic tissue rather than in energy-demanding physical and chemical defenses to resist herbivory (Bryant et al., 1983, 1991; Coley et al., 1985; Herms and Mattson, 1992).

Ranchers have used high intensity grazing successfully for decades in numerous countries and many regularly win prestigious conservation awards (Teague et al., 2009b). In addition, Norton (1998) listed 9 examples of grazing trials from Canada, United States, Zimbabwe, Australia and New Zealand that ran from 5 to 35 years. These trials reported no adverse ecological effects of either continuous or multi-paddock grazing treatments, probably as a direct result of using small paddocks in both cases, even though experimental stocking rates were maintained at 40–200% above those recommended for commercial properties. Norton (1998) hypothesizes that when small paddocks are used to contain grazing animals, forage availability is not limited by poor animal distribution that occurs in much more extensive, continuously stocked areas. This hypothesis is consistent with the published research relating to the process of uneven utilization in landscapes (Teague et al., 2004, 2010a,b, 2011).

When managed adaptively to conserve and restore resources and to provide ecosystem services, multi-paddock grazing can provide superior results relative to continuous stocking (Earl and Jones, 1996; Biondini and Manske, 1996; Jacobo et al., 2006; Sanjari et al., 2008; Teague et al., 2010a,b, 2011). In this context, multi-paddock grazing can increase perennial basal area as well as litter cover (Teague et al., 2004, 2010a,b, 2011), which, in turn enhances soil organic matter and soil-water content (Naeth et al., 1991; Snyman and du Preez, 2005; Weber and Gokhale, 2011). Over a 9 year period, the health of soil and plants in north Texas tallgrass prairie improved when ranchers used multi-paddock grazing with high stock densities for short durations, compared with light continuous or heavy continuous stocking on neighboring ranches (Teague et al., 2011). With multi-paddock grazing, the resultant vegetation was dominated by desirable high-seral grasses instead of the less desirable short grasses and forbs that occurred under both light and heavy continuous stocking. The dominance of high-seral grasses under multi-paddock grazing enhances hydrological functions (Pluhar et al., 1987; Thurow, 1991; Teague et al., 2011), which was demonstrated by the higher fungal to bacterial ratio with multi-paddock grazing, which indicates superior water holding capacity and nutrient availability. In addition, the amount of bare ground was less and soil aggregate stability was higher in areas subjected to multi-paddock grazing than in areas with heavy-continuous grazing at the same stocking rate, while soil organic matter and cation exchange capacity were higher with multi-paddock grazing than with light- or heavy-continuous stocking (Teague et al., 2011). Thus, higher stocking rates with management-intensive multi-paddock grazing can result in less impact on soil physical properties than continuous stocking at the same high stocking rate (Thurow, 1991). In contrast, increased stocking rates without intensified management can adversely affect soil properties and infiltration rates (Warren et al., 1986; Gerrish, 2004).

Although multi-paddock grazing can decrease landscape heterogeneity (Toombs and Roberts, 2009), the opposite result is also possible depending on management goals, operational execution, and the temporal and spatial scales that are evaluated. Smaller paddocks can improve distribution of animals across a landscape, which can increase or decrease diversity, depending on how animals were previously distributed. Increasing spatial and temporal heterogeneity of disturbance in grasslands is important for increasing biodiversity at higher trophic levels (Fuhlendorf et al., 2006; Isacch and Cardoni, 2011). Depending on management goals for vegetation structure and species diversity, the greater control with smaller paddocks allows managers more flexibility of animal placement and movement to create desired compositional and structural diversity of vegetation. This can be achieved by regrazing some paddocks sooner, or by allowing more regrowth and more structural similarity within a paddock. Thus small paddocks can be used to enhance patchiness with different vegetation structure in different paddocks if so desired. The manager can decide how to juxtapose these components to achieve specific plant, livestock and wildlife goals. Likewise, depending on placement of fences and diversity of topography, aspect, soils, and plant communities within paddocks, grazing can be more or less uniform within a paddock for a given graze period.

4.4. Limitations of multi-paddock grazing

A drawback of using multi-paddock grazing is that the intensity of management increases as the number of paddocks per herd increases. More intensive management requires higher levels of commitment, organizational skill, and knowledge, which may not always be readily available. However, this is not a reason to avoid grazing strategically, as strategies employing few paddocks per herd are easy to implement and can produce good animal performance, modest vegetation recovery, good wildlife habitat, and maintain the provision of ecosystem services. While less intensive management does little to ameliorate the extent of selective grazing or to improve distribution over the landscape, the less sophisticated management and effort needed to implement them must also be weighed against the higher infrastructural costs and greater management skills associated with potentially more effective and sustainable multi-paddock grazing management. Relative to continuous stocking, success has been achieved with both low and high levels of management intensity with multi-paddock management, or in the absence of fencing, by providing regular, adequate growing season recovery sequentially to the area under management. As no two ranch properties or managers are the same, every manager must choose the combination of investments, management strategies and tools that are most suited to their financial capacity, personality and social and biophysical environments where they live.

5. Limitations of experimental evidence

To be scientifically sound and meaningful for managers, a primary goal of any grazing experiment and the execution of any grazing treatment should be to enhance soil, vegetation, animal, and human performance over many years. Without this emphasis, and if the experimental design and implementation favors one outcome, it is inaccurate to claim that a given grazing treatment produced no better or inferior results than another treatment. When researchers conduct grazing trials, they become “managers” of the land on which the trials are placed, and by participating (through the questions they ask, the way they design and implement their experiments and the way they interpret the results) they influence the outcomes of their studies. There is no such thing as an “unbiased observer” in rangeland science or practice (Provenza, 2000; Van der Ploeg et al., 2006), and as researchers know from field studies that last more than 1 year, no two years, or months from year to year, are ever alike.

To be relevant to managers, research should provide fundamental information about principles and processes needed by ranch managers to achieve desired outcomes on the unique landscapes they manage (Provenza, 2000). Unless research results can be applied in the management of landscapes within a systems framework, they will likely be irrelevant or misleading for those managing commercial operations for long-term conservation and economic objectives at larger spatial and temporal scales (Provenza, 1991; Van der Ploeg et al., 2006). Rangeland managers operate at larger scales, so scientific studies of ecological processes should address landscape-scale and long-term consequences of alternative land management practices within a systems and adaptive management framework or specifically address how differences in spatial and temporal scales may affect the implications and implementation of their results for managers. Questions relevant to managers include: (1) What are the relative advantages of alternative management options; (2) What conditions are necessary for the greatest likelihood of successful application of the best management option; (3) How should the preferred option be implemented to make it most effective ecologically, economically and socially; and (4) What biophysical thresholds and indicators can provide guidance for adjusting to changing conditions or unanticipated outcomes?

We use the five management principles underpinning successful grazing management outlined in section 2 to evaluate how both the successes and failures observed in scientifically controlled experiments corroborate those guiding principles. We do this to understand how researchers have reached different conclusions about multi-paddock grazing than those reached by many successful ranchers who have used this grazing approach to achieve desired production and conservation goals.

5.1. Focus, implementation and scale of previous research

The manner in which researchers have implemented multi-paddock grazing treatments has rarely taken into account commonly recognized principles to maintain the health and vigor of plants and the nutrient intake by animals. Many studies have been conducted without stating in the methods how the research was conducted to achieve specific, desirable ecological or production goals and have ignored relevant ecological or practical knowledge, such as providing adequate recovery following grazing or adjusting stock numbers in times of drought, when choosing and implementing grazing treatments (e.g., Hart et al., 1993a,b; Derner and Hart, 2007a,b). As noted below these are accepted "best management practices" for managing to sustain resources and productive potential (Tainton et al., 1999). In cases where plant physiological needs were met through adequate recovery periods between defoliations, plant species composition shifted toward more productive and palatable species in some multi-paddock grazing cases, even when utilization levels were extremely high (e.g., Reardon and Merrill, 1976; HILF treatment of Taylor et al., 1993; Jacobo et al., 2006). Furthermore, when sufficient forage was available during each grazing period, animal performance was equal to or superior in multi-paddock grazing compared to continuous stocking (e.g., Reardon and Merrill, 1976; Denny and Barnes, 1977; Barnes and Denny, 1991; Biondini and Manske, 1996).

In grazing research, stocking rate and grazing treatment effects often have been confounded. For example Briske et al. (2008) summarizes results of 11 studies that compared the effects of continuous stocking at moderate stocking rates with multi-paddock grazing at much heavier stocking rates, as much as 1.5–2 times greater. Stocking rate, in any given circumstance, has greater effects on animal and vegetation responses than grazing system (Heitschmidt and Taylor, 1991; Manley et al., 1997; Gillen et al., 1998; McCollum et al., 1999). Nevertheless, in these 11 studies, plant productivity was generally equal to that of continuous stocking at lower stocking rates, indicating the benefits of physiological recovery following grazing especially when defoliation levels are more severe. In addition, in 3 of the 5 studies with different stocking rates among treatments where animal performance was measured, the performance of animals that were rotationally grazed was similar to that of the animals that were continuously grazed and stocked less heavily and animal production per hectare was higher in 4 of the 5 rotational grazing treatments. The relatively short duration of most grazing studies (Table 1) hides the fact that well managed ranches that improve species composition and soil health become much more productive over longer periods of time (Teague et al., 2011).

Confounding of different stocking rates between grazing strategies is exacerbated by variable weather in semi-arid ecosystems. Accepted good management practices during droughts commonly include reducing stock numbers early to minimize deleterious effects on vegetation, animal condition, and profitability (Diaz-Solis et al., 2009; Teague et al., 2009a,b). These management actions aim to mimic natural ecological responses in which animal populations decline during drought and then gradually increase as drought dissipates. Grazing experiments have rarely adjusted animal numbers in a similar way. If they did, the higher stocking rate treatments would be consistent with accepted good grazing practices and would likely not have incurred detrimental effects (Teague et al., 2011). As Briske et al. (2011) point out, management that adapts to changing conditions on the ground can be applied to either multi-paddock or continuous stocking and will outperform a lack of management using any grazing system. Unfortunately, research experiments have *almost never* been managed adaptively when addressing multi-paddock grazing questions, so it should come as no surprise that no differences among treatments were measured in the majority of instances.

Timely monitoring of and adaptation to changing conditions are fundamental for effectively managing ranching enterprises to achieve production and conservation goals (Danckwerts et al., 1993; Walker et al., 2002). However, the statistically "correct" design of grazing experiments and the implementation of such experiments have seldom incorporated treatment flexibility to adapt to ever-changing environmental and market conditions and, therefore, results do not reflect adaptive management at the ranch-scale (see for example fixed stocking management adopted by Heitschmidt et al., 1987a,b; Cassels et al., 1995; Gillen et al., 1998; McCollum et al., 1999). Therefore, most grazing experiments are merely unique inflections in time and space of biophysical processes that link soils, plants, herbivores and people, not generalizations that can be extrapolated across management systems and landscapes. If the same treatments were applied while managing for the best ecological, social and economic outcomes, it is likely the results would have differed as illustrated in several studies (Earl and Jones, 1996; Beukes and Cowling, 2003; Jacobo et al., 2006; Sanjari et al., 2008; Teague et al., 2011).

5.2. Underestimating the impact of selective grazing

Plant and patch selective over-grazing and resource deterioration have profound consequences for interpreting experimental results and for managing rangeland sustainably (Teague et al., 2004, 2011). Experimental paddocks in many grazing trials have been less than 25 ha and often less than 5 ha in size (Norton, 1998), and the size of paddocks in the research reviewed by Briske et al. (2008) were generally a small fraction of paddocks on commercial ranches (Table 1). The smaller experimental paddocks tend to diminish internal forage heterogeneity and, therefore, produce more uniform distribution of grazing pressure than in larger paddocks, thereby misrepresenting the way in which grazing animals at low stock densities use larger landscapes that are characteristic of continuous stocking (Barnes et al., 2008). As a result they ignore the documented heterogeneous patterns of forage selection and the associated vegetation impacts that occur in large paddocks where trans-generational foraging habits tend to lead to repeated preferential selection of specific microhabitats and plants species (Bissonette, 1997; Norton, 1998, 2003; Provenza, 2003b; Teague et al., 2004; Bailey and Provenza, 2008).

Gammon and Roberts (1978) and O'Reagain and Turner (1992) reported that defoliation is not always controlled more effectively and that forage quality and quantity are not consistently and substantially higher in multi-paddock than continuous stocking systems. However, based on published landscape research (Coughenour, 1991; Stuth, 1991; Fuls, 1992; Kellner and Bosch, 1992; Illius and O'Connor, 1999; WallisDeVries et al., 1999; Teague et al., 2004), these interpretations may have been different if pasture size had been equivalent to commercial-size pastures rather than a few hectares (Gammon and Roberts, 1978) or less than a hectare (O'Reagain and Turner, 1992). Similarly, other work reported no differences in performance of animals or vegetation between continuous stocking and a treatment including grazing deferment (Derner and Hart, 2007a,b; Hart et al., 1988). It is probable that their small-scale continuously grazed paddocks (24 ha) were more uniformly defoliated than would have been the case in commercial paddocks. A later publication (Hart et al., 1993a,b) illustrated that although grazing impacts in the 24 ha continuously stocked paddocks were not different from the rotationally grazed paddocks of the same size, they produced very different impacts compared with the continuously stocked paddock of 207 ha.

Notably, of the publications on rotational vs. continuous grazing reported by Briske et al. (2008), only 14% incorporated continuously stocked paddocks that were of similar size to those found in commercial ranches. The others were generally less than 1–10% of the size of commercial ranches (Table 1). Therefore, they are unlikely to accurately reflect the patch and area-selective grazing that causes the long-term deterioration within the large paddocks

Table 1
Experiments cited by Briske et al. (2008) to illustrate the extent that the methods used in each experiment limit their relevance to management at commercial ranch scale in each ecosystem.

Study	Location	Ecosystem	Grazing system	Study length (yrs)	# of paddocks	Size of paddocks RG (CG) (ha)	CG paddock size as % of commercial CG paddocks	Recovery period (days)	Graze period (days)	Adaptive or fixed management[a]
(A) Stocking rate equal for rotational and continuous stocking										
McCollum et al., 1999	Oklahoma	Tallgrass prairie	SDG	5	8	1.8–3.3 (26)	<10	32–38	3–6	F
Gillen et al., 1998	Oklahoma	Tallgrass prairie	SDG	5	8	1.8–3.3 (26)	<10	30–35	2–5	F
Cassels et al., 1995	Oklahoma	Tallgrass prairie	SDG	5	8	1.8–3.3 (26)	<10	21–49	3–7	F
Owensby et al., 1973	Kansas	Tallgrass prairie	Def-Rot	17	26	24 (24)	<10	60	300	F
Wood and Blackburn 1984		S. mixed prairie	HILF + Def-Rot	5	4	120 (240)	100	119	17	F
Kothmann et al., 1971	Texas	S. mixed prairie	Merrill	8	4	33 (240)	100	120	365	F
Merrill 1954	Texas	S. mixed prairie	Merrill	4	4	24 (24)	<10	120	365	F
Fisher and Marion 1951	Texas	S. mixed prairie	Rotation	8	5	4 (4)	<2	60	30	F
McIlvain and Savage 1951	Oklahoma	S. mixed prairie	Rotation	9	3	6.7–10 (20)	<5	60	30	F
Derner and Hart 2007a	Wyoming	N. mixed prairie	SDG	25	8	1–2 (81)	<15	16–49	2–7	F
Manley et al., 1997	Wyoming	N. mixed prairie	SDG+(Def-rot)	13	4–8	1–3 (81)	<15	21–49 (120)[b]	3–7 (365)[b]	F
Biondini and Manske 1996	N. Dakota	N. mixed prairie	SDG	6	6	32 (32)	<10	45	15–30	F
Hart et al., 1993a	Wyoming	N. mixed prairie	SDG	5	8	24 (207)	<30	21–49	3–7	F
Hepworth et al., 1991	Wyoming	N. mixed prairie	SDG + Def-rot	4	4–8	1–3 (24)	<1	21–49	3–7	F
Hart et al., 1988	Wyoming	N. mixed prairie	SDG + Def-rot	6	4–8	1–3 (81)	<15	21–49	3–7	F
Rogler 1951	N. Dakota	N. mixed prairie	Def-rot	25	3	9.4 (28)	<5	120	365	F
Derner and Hart 2007b	Colorado	Shortgrass prairie	SDG	9	7	65	–	–	–	F
Smoliak 1960	Alberta	Shortgrass prairie	Def-rot	9	2	61 (120)	<20	n	n	F
Hubbard 1951	Alberta	Shortgrass prairie	Def-rot	6	3	27–40	<10	n	n	F
Laycock and Conrad 1981	Utah	Sage grassland	Rest-Rotation	7	3	447–777	50–100	365	45	F
Hyder and Sawyer 1951	Oregon	Sage grassland	Rotation	11	3	850	100	n	n	F
Holechek et al., 1987	Oregon	Mountain range	Rest-rot + Def-rot	5	2	57–67	<10	n	90–365	F
Martin and Severson 1988	Idaho	Grass-shrub range	I herd-3 pasture	13	3	308–1979	50–100	120–365	n	A
Martin and Ward 1976	Arizona	Desert grassland	Alt. year rest	7	24	0.004	<<1	120–240	n	F
Ratliff 1986	California	Annual grassland	Rotation	8	3	30 (91)	<25	n	n	F
Heady 1961	California	Annual grassland	Def-rot	5	3	5.4	<1	n	n	F
Barnes and Denny 1991	Zimbabwe	Midgrass veld	SDG	6	4–8	<4	<1	30 (35)	10 (5)	F
Fourie and Engels 1986	South Africa	Shortgrass veld	SDG	4	6	30 (60)	<20	35	7	F
Fourie and Engels 1985	South Africa	Shortgrass veld	SDG	4	6	30 (60)	<20	35	7	F
Kreuter et al., 1984	South Africa	Tallgrass veld	SDG	8	6	0.6–1.2 (2.6–7.7)	<5	35	7	F
(B) Higher stocking rate for rotational grazing										
Jacobo et al., 2000	Argentina	Mesic C_3 grassland	SDG	3	10–12	45	50–100	25–90	3–15	A
Heitschmidt et al., 1987a,b	Texas	S. mixed prairie	SDG	4	16	33 (240)	100	30–65	2–4	A
Heitschmidt et al., 1982a	Texas	S. mixed prairie	SDG	2	10	4 (240)	100	35–42	3–7	F
Heitschmidt et al., 1982b	Texas	S. mixed prairie	Merrill	4	16	120 (240)	100	120	365	F
Reardon and Merrill 1976	Texas	S. mixed prairie	Def-rot	20	4	24 (32)	<20	120	365	F
Pitts and Bryant 1987	Texas	Shortgrass prairie	SDG	4	16	3 (32)	<10	30–60	2–7	F
Hirschfeld et al., 1996	N. Dakota	N. mixed prairie	SDG	2	8	16.25 (65)	<10	21–49	3–7	F
Kirby et al., 1986	N. Dakota	N. mixed prairie	SDG	2	8	16(130)	<5	35	5	F
Volesky et al., 1990	S. Dakota	N. mixed prairie	SDG	2	16	2.2	<1	15–45	1–3	F
White et al., 1991	New Mexico	Blue grama	SDG	6	9	45–210 (567)	100	n	n	F
Anderson 1988	New Mexico	Tobosa grassland	SDG	2	10	3.5 (33)	<5	19–40	1–9	F

HILF = High intensity, low frequency grazing; Merrill = Merrill 4-pasture, 3 herd grazing; SDG = Short duration grazing; Def-rot = Deferred rotation grazing; n = not available.
[a] Adaptive management = adjusting stock numbers or recovery periods according to prevailing weather conditions to achieve sustainable use of resources.
[b] Parentheses refer to the treatment in parentheses (column 4).

characteristic of continuous stocking in commercial ranch landscapes. Indeed, rather than representing continuous stocking at the ranch scale, small experimental paddocks more accurately represent individual paddocks of multi-paddock systems managed to reduce plant and grazing heterogeneity (albeit without rest from grazing).

Two small-plot studies of intensive grazing effects under rotational grazing (Warren et al., 1986; Savadogo et al., 2007) illustrate how studies on small-plots can produce results that, if implemented, would lead to poor animal performance and considerable damage to vegetation and soil in a ranch setting (Teague et al., 2010a,b). In the study by Warren et al. (1986), livestock did not even graze but were driven around at high densities in a small, barren pen to supposedly simulate the impact of high stock density. But this was done in a manner that closely resembles the overnight confinement of animals, such as overnight confinement to protect livestock from predators or to facilitate dehorning and castration. Such studies do not impact the land the way livestock do when managed by conservation-oriented ranchers and so have little relevance for ranchers managing to maintain resource and economic viability.

As an alternative to the preceding approaches, researchers can measure the impact of multi-paddock and continuous stocking on commercial ranches where the rangeland has been managed with a consistent strategy for many years. In the studies of Teague et al. (2011) in relatively mesic tallgrass prairie, multi-paddock grazing was applied for at least 9 years by defoliating moderately for short periods during the growing season, leaving relatively high biomass residues when livestock exited the paddocks, and adjusting the post-grazing recovery time for variations in growing conditions in order to allow sufficient plant regrowth before grazing resumed. Under this management animals moved in a controlled manner among paddocks, grazed for a few days only and the grazed plants recovered quickly and provided protective ground cover at all times. This allowed the most productive, high seral bunch grasses to maximize solar energy capture and to dominate the vegetation while a high rate of nutrient cycling was maintained. This adaptive grazing strategy also produced better soil, vegetation, and livestock performance than light or heavy continuous stocking management. In this investigation, the multi-paddock grazing was adaptively managed in accordance with prevailing conditions to achieve the best vegetation and animal responses by managers aiming to conserve resources. This was also the case with adaptively managed ranch-scale multi-paddock management in other ecosystems, including the arid Nama Karroo of South Africa (Beukes and Cowling (2003), semi-arid midgrass prairie of Texas (Teague et al., 2004, 2010a,b), semi-arid grassland in Australia (Earl and Jones, 1996; Sanjari et al., 2008) and relatively mesic pampas grassland in Argentina (Jacobo et al., 2006).

In summary, the results of the numerous small-scale experimental studies evaluated by Briske et al. (2008) (Table 1) bear little resemblance to the outcomes of ranch-scale management reported above. Most grazing trials have not represented operational scale soil–plant–animal interactions and the resulting effects of defoliation. Moreover, the management of small-plot, inflexible grazing studies have deviated significantly from how conservation-oriented ranchers manage multi-paddock grazing. Small-scale grazing experiments are unlikely to be relevant for ranchers attempting to maintain resource and economic sustainability, unless relevant temporal and spatial scales of heterogeneity, as well as the ability to adaptively respond to sporadic, event-driven soil and plant community changes are considered as part of the study and the interpretation of the results.

5.3. *Treatment lags and parameter measurements*

Outcomes of most business management actions are delayed in time and vary over the landscape (Senge, 1994), and that is certainly the case for grazing management on rangelands. When changing from continuous stocking at low stocking rates to multi-paddock grazing at the same or higher stocking rates, many ecosystem variables are affected simultaneously including soils, vegetation, and herbivores. These effects occur at different temporal and spatial scales and it usually takes 2–3 years after consistent and substantial management changes for the system to adapt to the new conditions (Provenza, 2003a, 2008; Pinchak et al., 2010), and decades for changes to be measurable at the landscape level (Burke et al., 1998). It is thus alarming to examine the number of grazing studies cited by Briske et al. (2008) that have not even been conducted for 4 years (Table 1). Rangelands are inherently variable climatically and spatially so to conduct grazing management experiments for less than 5 years in mesic or 10 years in drier rangelands ignores how ecosystems function and respond to climate and other perturbations as discussed by Burke et al. (1998). In essence, systems are continually responding to change, but those changes are discontinuous.

This is well illustrated by a relatively long-term cow-calf stocking rate experiment on rangeland conducted in north Texas mixed grass prairie over 20 years under continuous stocking. Heavily stocked treatments produced more saleable product per hectare but had greater annual fluctuations of production than moderately stocked treatments (Kothmann et al., 1971; Knight et al., 1990). For the first 10 years of the study heavy stocking produced higher net income per hectare than moderate stocking, but in the final 5 years of the study income stability was greater and supplementary feed inputs were lower on the moderately stocked treatment (Whitson et al., 1982). The reduced income stability was due primarily to a progressive decline in range condition with heavy stocking which resulted in changes in species domination from mid grasses to less productive short grasses (Heitschmidt et al., 1982b).

Animals accustomed to low-density continuous stocking can be trained to increase harvest speed and efficiency, but this takes 2–3 years and some individuals never adjust (Provenza, 2003a, 2008). When managed well, multi-paddock grazing programs improve after the livestock adaptation phase (Reardon and Merrill, 1976; Taylor et al., 1980, 1993; Provenza, 2003a; Pinchak et al., 2010). Grazing trials that run for short periods, or with new animals each year, likely capture the period of system adaptation only and underestimate the potential long-term benefits of multi-paddock grazing. For example Teague et al. (2004), working in southern mixed prairie in north Texas over a period of 5 years, recorded improvements in basal area, litter cover and amount of bare ground with multi-paddock grazing management relative to continuous stocking during wet years. In dry years, the improvements in these parameters declined but at a faster rate with continuous stocking. These impacts compound over time, such that in another study over 10 years multi-paddock grazing resulted in less bare ground, better species composition, higher primary productivity, soil carbon and soil water holding capacity relative to continuous stocking (Teague et al., 2011). Unless such time lags are addressed, grazing research results lead to spurious conclusions that have little relevance to long-term commercial ranch management.

In addition to treatment time-lags, it is difficult to determine treatment differences in rangeland ecosystems due to the slow and erratic response times triggered by reactions to stochastic events such as short-term weather and longer-term climatic fluctuations that interact with management actions (Walker, 1988; Danckwerts et al., 1993; Watson et al., 1996; Teague et al., 2004, 2010a). Nonetheless, these effects are critical to identifying grazing strategies that are sustainable (adaptable) and those that are not (inflexible). Adapting to climate-related effects on rangelands will become increasingly important in the face of projected climate changes. Nevertheless, Walker (1988) and Watson et al. (1996) emphasized that, although climate is the most important driver in rangeland ecosystems, adaptive management is critical to achieving sustainable use. Over-emphasizing climatic or other episodic drivers may erroneously de-emphasize the importance of management, which can take advantage of such events within a relatively stable plant community.

Finally, key parameters must be measured in ways that are most likely to detect differences if they occur. Under continuous stocking, heavily grazed herbaceous patches are impacted negatively compared to under-utilized patches (Bakker et al., 1983; Fuls, 1992; Kellner and Bosch, 1992). Thus, when assessing changes in grazing management, sampling across the continuum from over-utilized and under-utilized patches might mask actual differences. Consequently, in a landscape scale grazing study undertaken by Teague et al. (2004), sampling was stratified on adjacent over-utilized and under-utilized herbaceous patches separately rather than measuring across the continuum, as is the usual custom, to record changes at the pattern and scale they were hypothesized to occur. Had sampling been across and through different patches and a mean value calculated for the whole area under consideration, they would not have found differences where they existed (a type 2 error). Such considerations have not been included in other studies on grazing distribution.

5.4. Taking soil differences into account

Almost without exception soil differences between continuously stocked and multi-paddock grazing treatments have not been adequately reported or taken into account. Yet, the low productivity of rangelands means that management areas are large and consequently edaphic and topographic variability is also high. Substantially different primary and secondary productivity occur on different soils, so soil differences need to be taken into account when selecting sites for experiments and in analysing and reporting the results from any experiment (see also Van der Ploeg et al., 2006).

A case in point is the experiment examining the productivity and impacts of 3 grazing management treatments reported by Heitschmidt et al. (1985, 1990). They found significant differences among grazing treatments but the differences in soils among treatments were not taken into account. In a further analysis of this experiment using the SPUR rangeland simulation model, Teague and Foy (2004) found that the model predicted that differences in both primary and secondary productivity due to soil and slope composition in each treatment area were similar to the differences measured in the field, but ascribed to grazing treatment effects. Thus, the model simulated key parameters well enough to provide credible evidence that differences previously ascribed to grazing treatment were probably due to the differences in the soils and slopes rather than to grazing treatments. By not taking soil differences into account, it is likely that this experiment drew incorrect conclusions from this field experiment, as also discussed by van der Ploeg et al. (2006) for a grassland experiment.

Different soils also produce plants with substantially different kinds and concentrations of primary and secondary compounds (Bryant et al., 1983). From the standpoint of science or management, how pastures are subdivided is critical for maximizing opportunities for animals to mix their diets in ways that enhance nutrition and production. If a person fences for uniformity, and only moves animals occasionally, that can decrease nutrient intake and animal performance. On the other hand, fencing for uniformity, in combination with the daily moves becoming more common nowadays, can enable animals to meet nutritional needs. In Namibia, Botswana, and South Africa, many pastoralists are now fencing for heterogeneity, as opposed to homogeneity, due to the poor performance of livestock grazing in the latter relative to the former (Riaan Dames, personal communication).

5.5. Inadequate recovery time in experiments

The time plants require to recover after defoliation is strongly related to the intensity of defoliation during the grazing period (Trlica et al., 1977; Mencke and Trlica, 1981, 1983), the prior history of defoliation (Taylor et al., 1993), the stage of plant growth (Mullahey et al., 1990, 1991; Cullan et al., 1999), and the post-defoliation growing conditions (Thurow et al., 1988). Longer recovery periods that allow plants to re-establish a full complement of leaves tend to increase the proportion of taller, higher producing grasses (Trlica et al., 1977; Briske, 1991; Teague et al., 2011), and Sanjari et al. (2008) found that smaller paddock sizes along with longer recovery periods after grazing were major contributors to both physical and chemical recovery of the soil under time-controlled multi-paddock compared to continuous grazing.

In these studies, the optimum post-grazing recovery periods ranged from 84 to 126 days in areas with mean annual rainfall of around 600 mm to more than 2 years following heavy defoliation in areas with more xeric conditions such as western Colorado. In studies conducted in Sonora, Texas with mean annual rainfall of 570 mm, grazing treatments with longer recovery periods resulted in positive responses in midgrass abundance and productivity, even though the stocking rates applied during the grazing period and the resulting forage utilization were much higher than in the alternative treatments (Thurow et al., 1988; Taylor et al., 1980, 1993). By contrast, in wetter and tropical climates, rapid maturation and lignification of forages during extended growth periods may necessitate much shorter recovery periods, perhaps as little as 30 days, for sufficient recovery of edible plant material (Tainton et al., 1999).

In more arid environments, such as New Mexico, soil moisture greater than 30% at 100–300 mm soil depth required for rapid growth was experienced on only 28 non-continuous days in a 214-day growing season (Torell et al., 2008). In such instances, most of one or more growing seasons may be needed to achieve sufficient recovery between defoliations to sustain the resource. Cook and Stoddart (1963) found that in the northern Utah deserts, grazing plants was not sustainable with any growing season defoliation, regardless of intensity, and that only moderate dormant season defoliation was sustainable. Howell (2008) outlines how management has successfully accommodated such requirements near Van Horn, Texas (mean annual precipitation 300 mm) by stocking in the non-growing season only according to the forage available at the end of the short growing season and spreading grazing pressure over the whole ranch using many strategically placed smaller paddock subdivisions.

Advocates of multi-paddock grazing have long contended that timing of grazing and recovery periods based on plant growth rates are of central importance to their success (Booysen, 1969; Booysen and Tainton, 1978; Venter and Drewes, 1969; Savory, 1983; McCosker, 1994; Norton, 1998, 2003; Gerrish, 2004; Howell, 2008). The benefits of multi-paddock grazing treatments in field trials may have failed to manifest themselves owing to insufficient recovery during periods of slow or no plant growth (Savory and Butterfield, 1999), or owing to calendar-based, multiple-cycle rotations with insufficient recovery periods (e.g., Kirby et al., 1986; Gillen et al., 1998; Burboa-Cabrera et al., 2003; Derner and Hart, 2007a,b; Hart et al., 1988) even when the rotation was flexible (e.g., Bryant et al., 1989; Walker et al., 1989). Therefore, recommendations based on the assertion that there were no benefits from periodic recovery in such trials also must be questioned because the benefits occur only when environmental conditions are adequate for plant regrowth (e.g., Mullahey et al., 1990, 1991; Reece et al., 1996; Cullan et al., 1999).

The length of recovery periods used in multi-paddock experiments cited by Briske et al. (2008) are generally shorter than desirable (Table 1). In more mesic tallgrass prairie, recovery periods of 30–49 days are reported, but desirable results have been achieved at longer periods of 45–90 days (Teague et al., 2011). Similarly, in mixed prairie, recovery periods have been 16–49 days with Short Duration Grazing experiments (Table 1) whereas 50–120 days would usually be required (Thurow et al., 1988; Mullahey et al., 1990, 1991; Cullan et al., 1999), and even longer if defoliation had been heavy or the vegetation was in poor condition. Experiments involving deferred- or rest-rotations with 2–5 paddocks usually have periods of grazing from 30 to 365 days (Table 1) so periods of recovery less than 100 days can hardly be considered adequate considering the length of time preferred plants and areas have been exposed to grazing in mixed prairie. In drier rangelands, as noted above, moderate or light grazing needs to be followed by a full growing season's recovery.

Although Briske et al. (2008) did not discuss species composition differences, they found only 1 out of 26 studies that reported continuous stocking produced superior species composition and productivity relative to rotational grazing. This is remarkable because in 8 of the studies, stocking rates in the rotational grazing treatments were higher than in the continuous stocking treatment, and many studies did not provide adequate recovery periods following grazing. Even in the many studies that did not provide adequate recovery, the rate of plant community degradation was slowed by rotational grazing management. For example, in the research conducted by Thurow et al. (1988) at Sonora in Texas (mean annual rainfall 570 mm), multi-paddock camps decreased the rate of rangeland degradation compared to similarly stocked, continuously grazed paddocks, even with sub-optimal growing season recovery periods of as little as 50 days.

In summary, contrary to the conclusion of Briske et al. (2008), the evidence we provide above indicates that most researcher-designed and implemented rotational grazing treatments or "systems" differed little from, and thus are no better than, continuous stocking for improving plant community diversity, stability and productivity. However, when the interval between defoliations was increased using rotational grazing, beneficial effects were noted in plant community responses.

5.6. The roles of reductionist and systems approaches

Through the application of rigorous scientific methodology and reductionist research approaches, much knowledge has been gained about soils, water, plants, and herbivores and the interaction of these in biophysical processes that influence the health and resilience of rangeland ecosystems. However, the effective study of grazing management at the whole-ranch or landscape scale requires not only comparison of alternative management actions but also evaluation of the ways in which these actions and biophysical processes interact and evolve over time. The temporal and spatial variation inherent in biophysical processes and their interaction with management decisions precludes direct comparisons of grazing "systems" in classical, replicated grazing experiments, as noted by van der Ploeg et al. (2006), Briske et al. (2008), and Teague et al. (2011). All the biophysical variables in the various processes are in a state of constant flux that is influenced by history, prevailing conditions and chance and, therefore, their manifestations are unique in time and space as they are modified by ever-changing contexts and conditions (Provenza, 2000). Leading farmers and ranchers achieve superior results by the way they allocate resources, use different techniques, apply novel concepts and adaptively change these elements to achieve outcomes that exceed the sum of parts involved. This is the "art of farming", long acknowledged as the producer of superior results. Reductionist science is wholly inadequate for improving understanding of management as it simplifies and isolates inputs and treatments so as to preclude the discovery of emergent properties that are the signature achievement of leading managers as discussed in detail by the Dutch scientists van der Ploeg et al. (2006).

To be effective managers, ranchers must work within the dynamic constraints of biophysical processes that affect their landscapes. Optimally, this combines knowledge of the processes with the flexibility to respond to ever-changing environmental conditions. Therefore, "unbiased" studies of grazing management represent unique responses in space and time of more general processes regarding the interactive and adaptive behaviors of water, soil, plants, herbivores, and people within particular ecological, economic and social contexts. Science can illuminate fundamental principles and processes, but their manifestations represent unique case studies. Due to the necessity to replicate treatments with comparable measurable attributes in conventional scientific methodology, it is futile to attempt to compare various grazing "systems" using such methodology (Van der Ploeg et al., 2006). Indeed, scientists are not impartial observers. Rather, by interacting with a grazing management system, scientists become managers through the ways they design and implement their studies. In that sense, each study, replicated or not, is merely a case study. While, small plot research can be useful for parameterizing factors that occur at small sales, such as competitive relationships among plants or the length of time plants require to recover from defoliation under different circumstances (e.g., Mullahey et al., 1990, 1991; Reece et al., 1996; Cullan et al., 1999), the results of such research must be placed in appropriate temporal and spatial contexts for managers of landscapes and their implications should not be overextended.

Burke et al. (1998) argue that it is unreasonable to expect meaningful results from research conducted for less than 10-year periods as changes occur relatively slowly in more arid rangeland ecosystems. Moreover, given the dynamics of landscapes, it is reasonable to ask if soils, plants, and herbivores ever reach any sort of equilibrium (Pielou, 1991; Provenza, 2003b, 2008). If not, then on-going adaptation to ever-changing environments is the only option for "sustaining landscapes." Such challenges and opportunities are best addressed by monitoring biological processes related to soils, plants, herbivores, and people on ranches managed successfully for many years. Working with these ranchers and using systems-level simulation modeling has much potential to advance our understanding of what management is required to achieve desired goals. This dual approach can simultaneously evaluate ecological and managerial responses to changing conditions. It also allows researchers to evaluate entire ranch enterprises across different rangeland ecosystems within the constraints of respective grazing regimes, including the capacity of ranchers to adaptively manage for the best possible outcomes (Briske et al., 2011; Teague et al., 2011). Numerous ranchers world-wide have successfully managed their land for years, with some having operated successfully for over three decades, using various levels of sophistication (Earl and Jones, 1996; Jacobo et al., 2006; Teague et al., 2011). Data gathered from ranches with different histories of grazing management over decadal periods provide an essential adjunct to a systems modeling approach to grazing systems evaluations. This allows closer examination of a wider range of hypotheses to better understand the consequences of adopting alternative management strategies and practices.

Simulation modeling is an underutilized tool. Developing enhanced understanding of complex systems requires theory, and theory often requires models to test understanding (Starfield and Bleloch, 1985; Woodward, 2005). Simulation modeling at the systems level can complement both small-plot and ranch-based field research as treatments can be explored without the variability, space, time and cost limitations of traditional grazing research. Thus a systems simulation modeling approach could facilitate the development of a sound theoretical base for understanding biophysical processes and management hypotheses at the landscape scale and testing them against observed results, essential elements that have been lacking. So far, grazing systems modeling efforts have included attempts to better understand the outcomes of field experiments (Teague and Foy, 2004), spatial scale (Witten et al., 2005), relevance of adequate recovery in rangelands (Hui and Chen, 2006; Müller et al., 2007), stock number management strategies (Hahn et al., 1999; Cingolani et al., 2002; Diaz-Solis et al., 2003, 2009), and ecological economics (Beukes et al., 2002; Teague et al., 2008, 2009b).

The recent development of a number of computer-based tools provides another means to achieve more complete analyses of the impacts of different management and facilitate systems level investigation at the scale that rangeland ecosystems are managed. These technologies include geographic information systems, remote sensing, and global positioning system receivers to monitor livestock movements. Such technologies will assist in evaluating the impacts of different management strategies at the landscape and water-catchment scales over long periods to develop a better understanding of impacts. An example is the ability to conduct retrospective analyses of ranch landscapes under different management using the Landsat satellite data collected for 40 years (Wessels et al., 2007; Washington-Allen et al., 2010). These technologies provide a means of testing hypotheses we outline below to explain different results obtained by researchers working at small scales and ranchers working at landscape scales.

6. New theories and testable hypotheses

Although many disciplines have historically operated on the tenets of a single major paradigm, considering and comparing more than one paradigm often generates more complete knowledge than is possible with only one (Burrell and Morgan, 1979; Frost, 1980; Provenza, 2000). Different paradigms are based on fundamentally different assumptions and produce markedly different ways of approaching and building a theoretical foundation for any discipline (Gioia and Pitre, 1990). Moreover, according to the principle of consilience, the methods and assumptions of any field of study should be consistent with the known and accepted facts in other disciplines (Wilson, 1998; Gowdy and Carbonell, 1999). Accounting for different theoretical assumptions within a broader systems approach to research provides a more comprehensive understanding of the local responses of biophysical processes that affect managed ecosystems and their constantly changing manifestations (Van der Ploeg et al., 2006).

Numerous instances from research that we have cited together with substantial anecdotal evidence from ranchers around the world (Savory and Butterfield, 1999; Tainton et al., 1999; Howell, 2008) justify the modification and further testing of the hypothesis expressed by Briske et al. (2008) that there is no compelling evidence to demonstrate that rotational grazing enhances plant and animal production compared to continuous stocking on rangelands. We propose the following alternative testable hypothesis: at a ranch management scale, planned multi-paddock grazing, when managed to give best vegetation and animal performance, has the potential to produce superior conservation and restoration outcomes for rangeland resources, to provide superior ecosystem services for society, and to yield greater ranch profitability and greater socio-ecological resilience in the long run compared to season-long continuous stocking.

To evaluate this hypothesis and the observations we have documented, the following specific hypotheses need to be tested using spatially explicit simulation models over decadal timeframes and, to the fullest extent possible, verified with field investigations using case study comparisons at the landscape (ranch) scale. We specifically refer to comparisons between continuous, season-long grazing (CG) and multi-paddock grazing (MPG) that are adaptively managed to provide the best herbaceous vegetation and animal performance:

1. Due to selective use of plants and areas, continuous grazing by livestock for decades on a large single ranch paddock will increase bare ground and unpalatable plants. This will occur on preferred areas at light stocking rates and will degrade more and be more widespread as stocking rate increases. Periods of drought will cause heavily grazed plants and patches to have high mortality. Livestock performance will be high initially but will decrease as the amount of bare ground and proportion of unpalatable plants increases.
2. Plant species composition due to selective grazing will vary significantly according to the size of the grazed paddocks. In small paddocks, grazing will be more even, drought effects will be less severe and there will be reduced differences in species diversity between CG and MPG.
3. MPG that provides short periods of defoliation by grazers followed by adequate periods of recovery from grazing will allow heavily grazed plants to recover and survive droughts. Forage production and standing crop and animal condition (plant and animal buffers) will be greater and drought-related plant and livestock mortality will be less than with CG. Adaptively managed MPG will spread grazing pressure over a larger portion of the ranch and provide improved diet quality for livestock, which will increase livestock production and primary production.
4. In relatively mesic rangelands, MPG will benefit vegetation most with moderate use and long periods of growing season recovery, while animal performance will benefit most from shorter periods of moderate grazing during the growing season, and maintaining plants in a vegetative state.
5. In drier rangelands the benefits of shorter grazing periods with MPG are relatively small compared to the advantage of longer growing season recovery periods.
6. Plants growing in arid ecosystems may require no growing season defoliation and limited dormant season defoliation.
7. During average or above-average precipitation years, a full growing season of post-grazing recovery rotated annually throughout the paddocks in a management area will increase the proportion of desirable relative to undesirable forage species. This, in the long-term, will maintain or increase primary and secondary production, biodiversity and ecosystem services (Frank et al., 1998).
8. In transitions from CG with large paddocks to MPG with small paddocks, production per head and per hectare will increase with increasing numbers of paddocks because the extent to which MPG can ameliorate stocking rate effects on animal performance and vegetation condition is positively related to the number of paddocks in the grazing system (Norton, 1998).

7. Conclusions and recommendations

The benefits of effective multi-paddock grazing management, as well as the results of poor grazing management, have been observed and reported for many years and in many countries. Ironically, despite the observed and reported benefit to species composition and vegetation cover with planned grazing and adequate recovery, recent reviews of rangeland grazing studies suggest that multi-paddock grazing improves neither vegetation nor animal production relative to continuous stocking (Briske et al., 2008). Our paper developed hypotheses to explain why such different perceptions exist between many researchers and the experience of grazing managers around the world who have used multi-paddock grazing adaptively to achieve desired production, conservation and financial goals and enhance ecosystem resilience and delivery of ecosystem services. We have presented detailed comparisons of research methods and the practical experience of successful practitioners of multi-paddock grazing management to provide three overarching reasons for the existence of such different perceptions. To facilitate testing the validity of our observations, we outlined testable hypotheses to explain why much recent research has arrived at conclusions that differ from those obtained by ranchers who have used multi-paddock grazing to achieve conservation and economic goals.

First we postulate that the application of experimental treatments in controlled grazing experiments has, in general, not taken into account commonly recognized principles to maintain health and vigor of plants and nutrient intake of animals. In addition, the spatial limitations, short-term nature, and inflexible grazing treatments imposed in most experiments have prevented researchers from adequately accounting for the spatial heterogeneity of vegetation, temporal shifts in weather, plant composition, time lags in learning necessary for animals to perform to their potential with changes in management, and stocking rate adjustments that characterize most rangeland production systems. Such experimental limitations have frequently led to results that imply multi-paddock grazing treatments are no better than, or inferior to, lightly or moderately stocked continuous grazing treatments, when in each case the reaction of organisms of interest are at the mercy of these factors without management to adjust to these factors.

By contrast, many ranchers have achieved excellent animal production and soil and vegetation improvements using multi-paddock grazing and find that the flexibility and timeliness of feedback inherent in MPG facilitate improved management compared to CG. They have done so by pro-actively responding to changing environmental circumstances through the use of adaptive management practices including regular resource monitoring and timely adjustments in livestock placement and numbers. In complex ever-evolving ecosystems, components emerge, change, and then disappear and managers cope and then capitalize on changes they help to initiate. We typically long for a standard recipe to ensure that we sustain the status quo, despite knowing that we are awash with variability in social and biophysical environments whose changes are largely out of our control. Instead, good management of complex systems requires flexibility, and less of an attempt to *control* than an attempt to *understand* and *respond appropriately and continuously* to changes as they arise. In the context of productive landscapes, successes should be judged at the system level and based on whether it can support those who depend on it.

A second and related reason most grazing trials have not corroborated successful ranch-scale multi-paddock grazing experiences is that they have not adequately addressed animal–plant interactions at appropriate scales. Without management intervention, plant- and area-selective grazing increases with increasing paddock size and time. In general, small-scale and short-term grazing trials have not accounted for the uneven distribution of livestock in large continuously grazed paddocks which leads to localized pasture degradation over time. Neither has it accounted for the more even distribution of livestock in small continuously grazed research paddocks that leads to more even utilization. Nor have they generally adaptively managed recovery time to provide consistently adequate physiological recovery for defoliated plants. Either way, the conclusions are affected by the design and implementation of the study.

Associated with this oversight has been the assumption that forage availability and utilization are spatially homogeneous, which has been widely refuted by a large body of published research. Herbivores have entirely different impacts on large landscapes over long periods of time when continuously stocked than implied in the small temporal and spatial scale studies reviewed by Briske et al. (2008). While published research may accurately present the results of experiments, unless the results can be applied in the management of landscapes within a systems framework, they will likely be irrelevant and possibly misleading for those managing commercial operations for long-term conservation objectives (Provenza, 1991, 2003a). This is particularly the case if they have been conducted for short periods, on areas that are substantially smaller and more homogeneous than the size of continuously stocked paddocks on commercial ranches, and not adaptively managed in response to changing circumstances. In addition, many literature reviews are narrowly focused and draw categorical conclusions about grazing treatment effects without carefully evaluating the methodology and context of each grazing trial (e.g., Holechek et al., 1999, 2000, 2003; Briske et al., 2008; see also Van der Ploeg et al., 2006). Further, concentrating only on differences in productivity without meaningfully taking into account negative impacts on the environment can lead to extrapolations that are misleading. Such conclusions tend to cloud rather than enhance knowledge about sustainable grazing management and do not provide guidance relevant for practical grazing management applications.

A third reason for contradictory experimental and operational results is that most researchers have not designed their experiments to answer fundamentally important practical questions such as: 1) How good is a given management option ecologically, economically, and socially; 2) Within what context is it most likely to be successful; and 3) How can the results be contextualized to make them work as well as possible? For research results to be relevant, each experiment must be examined to determine how it was conducted and if the objective(s) allow the results to be extrapolated to ranch situations. When researchers conduct grazing trials, they too are "managers" of a piece of ground, and by participating through the questions they ask, the ways they design and implement the experiments, and ultimately interpret the results, they influence the outcomes of their studies. Unless grazing treatments are applied in a way that tries to produce the best possible integration of ecological, economic, and social contexts and conditions, researchers cannot accurately determine whether or not multi-paddock grazing can produce better results relative to continuous stocking treatments managed to provide the best results.

Successful ranchers modify their management as ecological, economic, and social conditions change to achieve the best possible outcomes in dynamic biophysical and economic environments. To attain the goal of sustainability on rangelands, thinking in terms of grazing systems is unimportant compared to understanding and applying management principles that support the proper functioning of ecological, economic, and social processes. To do so, managers achieve management goals through scientific understanding of processes combined with practical local experience.

To conduct research relevant at the operational scale, researchers have much to learn from working with successful conservation oriented ranch managers, as illustrated in comparisons of continuous and multi-paddock grazing on commercial ranches. Using this approach, many of the constraints that have characterized previous grazing systems research can be avoided. Specifically, monitoring ranches that have successfully operated multi-paddock grazing management, in some cases for decades, may be the best way for rangeland scientists to appreciate the on-going dynamics as rangeland ecosystems respond to changes in grazing management. In addition, combining on-ranch research with simulation modeling can provide information relevant to managers. Computer-based tools such as geographic information systems, remote sensing and global positioning system receivers complement and facilitate research at the landscape scale. These approaches are well suited to evaluating both the managerial and ecological components of grazing systems and can facilitate developing a sound theoretical base for understanding the ecology and management of grazed ecosystems.

Science can help us understand biological processes, including the interrelationships among biophysical processes that link soils, plants, herbivores, and people (Provenza, 2000). Science can help us appreciate the workings of the processes of nature, which enable creatures to adapt, but there is no absolute truth in science. All concepts and theories are limited and approximate. Science is a quest for understanding, an attempt to account for observable phenomena. Moreover, nature does not show us any "isolated building blocks" but rather appears as a web of relations among various parts of the whole and that always includes the human observer and participant. While other disciplines have come to accept this phenomenon, we still cling to the notion of scientists as impartial observers who do not influence the outcomes of their experiments.

Grazing studies have focused least on the most important feature of the management system, the human element. Understanding biophysical processes is of little value in the absence of flexibility needed to manipulate those processes toward desired human goals in uncertain environments. What matters most to achieve sustainable outcomes on grazed rangelands is continually obtaining feedback through monitoring and adjusting *herbivore numbers and movements* to ensure the health of herbivores, plants, soils and ultimately people. Achieving sustainability on rangelands depends upon animals frequently moving across landscapes, whether driven by their nutrient needs, predators, herders, fire, or fenced paddocks (Provenza, 2003a, 2003b). Intelligent, goal-directed management is required to achieve sustainable goals. To understand how to do so, we must understand biophysical processes and how the best managers manipulate and adjust them (Provenza, 2003a).

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References

Adler, P.B., Milchunas, D.G., Lauenroth, W.K., Sala, O.E., Burke, I.C., 2004. Functional traits of graminoids in semi-arid steppes: a test of grazing histories. Journal of Applied Ecology 41, 653–663.
Adler, P.B., Milchunas, D.G., Sala, O.E., Burke, I.C., Lauenroth, W.K., 2005. Plant traits and ecosystem grazing effects: comparison of U.S. sagebrush steppe and Patagonian steppe. Ecological Applications 15, 774–792.
Anderson, D.M., 1988. Seasonal stocking of tobosa managed under continuous and rotation grazing. Journal of Range Management 41, 78–83.
Archibald, S., Bond, W.J., Stock, W.D., Fairbanks, D.H.K., 2005. Shaping the landscape, fire-grazer interactions in an African savanna. Ecological Applications 15, 96–109.
Ash, A.J., Stafford-Smith, D.M., 1996. Evaluating stocking rate impacts in rangelands, animals don't practice what we preach. Rangeland Journal 18, 216–243.
Bailey, D.W., Welling, G.R., 2007. Evaluation of low-moisture blocks and conventional dry mixes for supplementing minerals and modifying cattle grazing patterns. Rangeland Ecology and Management 60, 54–64.
Bailey, D.W., Provenza, F.D., 2008. Mechanisms determining large-herbivore distribution. In: Prins, H.T.T., van Langevelde, F. (Eds.), Resource Ecology, Spatial and Temporal Dynamics of Foraging. Springer, Dordrecht, Netherlands, pp. 7–28.
Bailey, D.W., VanWagoner, H.C., Weinmeister, R., Jensen, D., 2008. Evaluation of low-stress herding and supplement placement for managing cattle grazing in riparian and upland areas. Rangeland Ecology and Management 61, 26–37.
Bakker, J.P., de Leeuw, J.F., Von Weiren, S.E., 1983. Micro-patterns in grassland vegetation created and sustained by sheep. Vegetatio 55, 153–161.
Barnes, D.L., Denny, R.P., 1991. A comparison of continuous and rotational grazing on veld at two stocking rates. Journal of the Grassland Society of South Africa 8, 168–173.
Barnes, M.K., Norton, B.E., Maeno, M., Malechek, J.C., 2008. Paddock size and stocking density affect spatial heterogeneity of grazing. Rangeland Ecology and Management 61, 380–388.
Beukes, P.C., Cowling, R.M., Higgins, S.I., 2002. An ecological economic simulation model of a non-selective grazing system in the Nama Karoo, South Africa. Ecological Economics 42, 221–242.
Beukes, P.C., Cowling, R.M., 2003. Non-selective grazing impacts on soil properties of the Nama Karoo. Journal of Range Management 56, 547–552.
Biondini, M.E., Manske, L.L., 1996. Grazing frequency and ecosystem processes in a northern mixed prairie, USA. Ecological Applications 5, 239–256.
Bissonette, J.A., 1997. Scale-sensitive ecological properties. In: Bissonette, J.A. (Ed.), Wildlife and Landscape Ecology. Springer, New York, pp. 3–31.
Booysen, P. deV., 1966. A physiological approach to research in pasture management. Proceedings of the Grassland Society of Southern Africa 4, 77–96.
Booysen, P. deV., 1969. An evaluation of the fundamentals of grazing systems. Proceedings of the Grassland Society of Southern Africa 4, 84–91.
Booysen, P. de V., Tainton, N.M., 1978. Grassland management, principles and practice in South Africa. In: Proceedings 1st International Rangeland Congress, Denver Colorado, pp. 551–554.
Bradford, D., 1998. Holistic resource management in the West Elks – why it works. Rangelands 20, 6–9.
Briske, D.D., 1991. Developmental morphology and physiology of grasses. In: Heitschmidt, R.K., Stuth, J.W. (Eds.), Grazing Management: an Ecological Perspective. Timber Press, Portland, Oregon, pp. 85–108.
Briske, D., Derner, J., Brown, J., Fuhlendorf, S., Teague, R., Gillen, B., Ash, A., Havstad, K., Willms, W., 2008. Benefits of rotational grazing on rangelands: an evaluation of the experimental evidence. Rangeland Ecology and Management 61, 3–17.
Briske, D.D., Sayre, N.F., Huntsinger, L., Fernandez-Gimenez, M., Budd, B., Derner, J.D., 2011. Origin, persistence, and resolution of the rotational grazing debate: integrating human dimensions into rangeland research. Rangeland Ecology and Management 64, 325–334.
Bryant, J.P., Chapin III, F.S., Kline, D.R., 1983. Carbon/nutrient balance of boreal plants in relation to vertebrate herbivory. Oikos 40, 357–368.
Bryant, F.C., Dahl, B.E., Pettit, R.D., Britton, C.M., 1989. Does short-duration grazing work in arid and semiarid regions? Journal of Soil and Water Conservation 44, 290–296.
Bryant, J.P., Provenza, F.D., Pastor, J., Reichardt, P.B., Clausen, T.P., DuToit, J.T., 1991. Interactions between woody plants and browsing mammals mediated by secondary metabolites. Annual Review of Ecological Systems 22, 431–446.
Butler, P.J., 2000. Cattle distribution under intensive herded management. Rangelands 22, 21–23.
Burboa-Cabrera, F.R., Schacht, W.H., Anderson, B.E., 2003. Utilization and grazing distribution of cattle at 4 stocking densities. Journal of Range Management 56, 328–333.
Burke, I.C., Lauenroth, W.K., Vinton, M.A., Hook, P.B., Kelly, R.H., Epstein, H.E., Aguiar, M.R., Robles, M.D., Aguilera, M.O., Murphy, K.L., Gill, R.A., 1998. Plant-soil interactions in temperate grasslands. Biogeochemistry 42, 121–143.
Burrell, G., Morgan, G., 1979. Sociological Paradigms and Organizational Analysis. Helnemann, London.
Caldwell, M.M., Richards, J.H., Johnson, D.A., Nowak, R.S., Dzurec, R.S., 1981. Coping with herbivory, photosynthetic capacity and resource allocation in two semi-arid Agropyron bunchgrasses. Oecologia 50, 14–24.
Caldwell, M.M., 1984. Plant requirements for prudent grazing. In: Developing Strategies for Rangeland Management. Westview, Boulder, pp. 117–152.
Cassels, D.M., Gillen, R.L., McCollum, F.T., Tate, K.W., Hodges, M.E., 1995. Effects of grazing management on standing crop dynamics in tallgrass prairie. Journal of Range Management 48, 81–84.
Cingolani, A.M., Anchorena, J., Stoffella, S.L., Collantes, M.B., 2002. A landscape-scale model for optimal management of sheep grazing in the Magellanic steppe. Applied Vegetation Science 5, 159–166.
Coley, P.D., Bryant, J.P., Chapin, F.S., 1985. Resource availability and plant anti-herbivore defense. Science 230, 895–899.
Coughenour, M.B., McNaughton, S.J., Wallace, L.L., 1985. Responses of an African graminoid (*Themeda triandra* Forsk.) to frequent defoliation, nitrogen and water: a limit of the adaptation to herbivory. Oecologia 68, 105–111.
Cook, C.W., Stoddart, L.A., 1963. Effect of intensity and season of use on the vigor of desert range. Journal of Rangeland Management 16, 315–317.
Coughenour, M.B., 1991. Spatial components of plant-herbivore interactions in pastoral, ranching, and native ungulate ecosystems. Journal of Range Management 44, 530–542.
Cullan, A.P., Reece, P.E., Schacht, W.H., 1999. Early summer grazing effects on defoliation and tiller demography of prairie sandreed. Journal of Range Management 52, 447–453.
Daily, G.C., 1997. Natures services: societal dependence on natural ecosystems. In: Daily, G.C. (Ed.), Introduction: What Are Ecosystem Services? Island Press, Washington, pp. 1–10.
Danckwerts, J.E., 1984. Towards Improving Livestock Production off Sweet Grassveld. PhD. thesis. University of Natal, Pietermaritzburg, South Africa.
Danckwerts, J.E., O'Reagain, P.J., O'Connor, T.G., 1993. Range management in a changing environment, a southern African perspective. Rangeland Journal 15, 133–144.
De Bello, F., Leps, J., Sebastià, M.-T., 2005. Predictive value of plant traits to grazing along a climatic gradient in the Mediterranean. Journal of Applied Ecology 42, 824–833.
Denny, R.P., Barnes, D.L., 1977. Trials of multi-paddock grazing systems on veld 3. A comparison of six grazing procedures at two stocking rates. Rhodesian Journal of Agricultural Research 15, 129–143.
Derner, J.D., Hart, R.H., 2007a. Grazing-induced modifications to peak standing crop in northern mixed grass prairie. Rangeland Ecology and Management 60, 270–276.
Derner, J.D., Hart, R.H., 2007b. Livestock and vegetation responses to rotational grazing in shortgrass steppe. Western North American Naturalist 67, 359–367.

Derner, J.D., Gillen, R.L., McCollum, F.T., Tate, K.W., 1994. Little bluestem tiller defoliation patterns under continuous and rotational grazing. Journal of Range Management 47, 220–225.

Diaz-Solis, H., Kothmann, M.M., Hamilton, W.T., Grant, W.E., 2003. A simple ecological sustainability simulator (SESS) for stocking rate management on semi-arid grazinglands. Agricultural Systems 76, 655–680.

Diaz-Solis, H., Grant, W.E., Kothmann, M.M., Teague, W.R., Díaz-García, J.A., 2009. Adaptive management of stocking rates to reduce effects of drought on cow-calf production systems in semi-arid grazinglands. Agricultural Systems 100, 43–50.

Earl, J.M., Jones, C.E., 1996. The need for a new approach to grazing management – is cell grazing the answer? Rangeland Journal 18, 327–350.

Fisher, C.E., Marion, P.T., 1951. Continuous and rotation grazing on buffalo and tobosa grassland. Journal of Range Management 4, 48–51.

Fourie, J.H., Engels, E.A.N., 1985. Influence of stocking rate and grazing systems on available grazing in the northern Cape. Journal of the Grassland Society of South Africa 2, 24–26.

Fourie, J.H., Engels, E.A.N., 1986. Herbage intake by cattle on *Tarchonanthus* veld in the northern Cape as affected by stocking rate and grazing system. Journal of the Grassland Society of South Africa 3, 85–89.

Frank, D.A., Groffman, P.A., 1998. Ungulate vs. landscape control of soil C and N processes in grasslands of Yellowstone National Park. Ecology 79, 2229–2241.

Frank, D.A., McNaughton, S.J., Tracy, B.F., 1998. The ecology of the Earth's grazing ecosystems. BioScience 48, 513–521.

Frost, P., 1980. Toward a radical framework for practicing organizational science. Academy of Management Review 5, 501–507.

Fuhlendorf, S.D., Harrell, W.C., Engle, D.M., Hamilton, R.G., Davis, C.A., Leslie Jr., D.M., 2006. Should heterogeneity be the basis for conservation? Grassland bird response to fire and grazing. Ecological Applications 16, 1706–1716.

Fuls, E.R., 1992. Ecosystem modification created by patch-overgrazing in semi-arid grassland. Journal of Arid Environments 23, 59–69.

Gammon, D.M., Roberts, B.R., 1978. Patterns of defoliation during continuous and rotational grazing of the Matopos Sandveld of Rhodesia. 1. Selectivity of grazing. Rhodesia Journal of Agricultural Research 16, 117–131.

Gerrish, J., 2004. Management-intensive Grazing, the Grassroots of Grass Farming. Green Park Press, Ridgeland, Missouri.

Gillen, R.L., McCollum, F.T., Tate, K.W., Hodges, M.E., 1998. Tallgrass prairie response to grazing system and stocking rate. Journal of Range Management 51, 139–146.

Gioia, D.A., Pitre, E., 1990. Multiparadigm perspectives on theory building. The Academy of Management Review 15, 584–602.

Gowdy, J.M., Carbonell, F.A., 1999. Toward consilience between biology and economics: the contribution of Ecological Economics. Ecological Economics 29, 337–348.

Grice, A.C., Hodgkinson, K.C., 2002. Challenges for rangeland people. In: Grice, A.C., Hodgkinson, K.C. (Eds.), Global Rangelands: Progress and Prospects. CABI Publishing, New York, pp. 1–11.

Hahn, B.D., Richardson, F.D., Starfield, A.M., 1999. Frame-based modeling as a method of simulating rangeland production systems in the long term. Agricultural Systems 62, 29–49.

Hamilton, E.W., Frank, D.A., 2001. Can plants stimulate soil microbes and their own nutrient supply? Evidence from a grazing tolerant grass. Ecology 82, 2397–2402.

Hart, R.H., Clapp, S., Test, P.S., 1993a. Grazing Strategies, stocking rates, and frequency and intensity of grazing on western wheatgrass and blue grama. Journal of Range Management 46, 122–126.

Hart, R.H., Bissio, J., Samuel, M.J., Waggoner Jr., J.W., 1993b. Grazing systems, pasture size, and cattle grazing behavior, distribution and gains. Journal of Range Management 46, 81–87.

Hart, R.H., Samuel, M.J., Test, P.S., Smith, M.A., 1988. Cattle, vegetation, and economic responses to grazing systems and grazing pressure. Journal of Range Management 41, 282–286.

Heady, H.F., 1961. Continuous vs. specialized grazing systems: a review and application to California annual type. Journal of Range Management 14, 182–193.

Heitschmidt, R.K., Conner, J.R., Canon, S.K., Pinchak, W.E., Walker, J.W., Dowhower, S.L., 1990. Cow-calf production and economic returns from yearlong continuous, deferred rotation and rotational grazing treatments. Journal of Production Agriculture 3, 92–99.

Heitschmidt, R.K., Dowhower, S.L., Walker, J.W., 1987a. 14- vs. 42-paddock rotational grazing: aboveground biomass dynamics, forage production, and harvest efficiency. Journal of Range Management 40, 216–223.

Heitschmidt, R.K., Dowhower, S.L., Gordon, R.A., Price, D.L., 1985. Response of vegetation to livestock grazing at the Texas Experimental Ranch. Journal of Range Management 35, 204–210.

Heitschmidt, R.K., Dowhower, S.L., Walker, J.W., 1987b. Some effects of a rotational grazing treatment on quantity and quality of available forage and amount of ground litter. Journal of Range Management 40, 318–321.

Heitschmidt, R.K., Frasure, J.R., Price, D.L., Rittenhouse, L.R., 1982a. Short duration grazing at the Texas Experimental Ranch: weight gains of growing heifers. Journal of Range Management 35, 375–379.

Heitschmidt, R.K., Kothmann, M.M., Rawlins, W.J., 1982b. Cow-calf response to stocking rates, grazing systems, and winter supplementation at the Texas Experimental Ranch. Journal of Range Management 35, 204–210.

Heitschmidt, R.K., Taylor, C.A., 1991. Livestock production. In: Heitschmidt, R.K., Stuth, J.W. (Eds.), Grazing Management: an Ecological Perspective. Timber Press, Portland, Oregon, pp. 161–177.

Hendrickson, J.R., Moser, L.E., Reece, P.E., 2000. Tiller recruitment patterns and biennial tiller production in prairie sandreed. Journal of Range Management 53, 537–543.

Hepworth, K.W., Test, P.S., Hart, R.H., Waggoner Jr., J.W., Smith, M.A., 1991. Grazing systems, stocking rates, and cattle behavior in southeastern Wyoming. Journal of Range Management 44, 259–262.

Herms, D.A., Mattson, W.J., 1992. The dilemma of plants: to grow or defend. Quarterly Review of Biology 67, 283–335.

Hirschfeld, D.J., Kirby, D.R., Caton, J.S., Silcox, S.S., Olson, K.C., 1996. Influence of grazing management on intake and composition of cattle diets. Journal of Range Management 49, 257–263.

Holechek, J.L., Gomez, H., Molinar, F., Galt, D., 1999. Grazing studies, what we've learned. Rangelands 21, 12–16.

Holechek, J.L., Gomes, H., Molinar, F., Galt, D., Valdez, R., 2000. Short duration grazing, the facts in 1999. Rangelands 22, 18–22.

Holechek, J.L., Berry, T.J., Vavra, M., 1987. Grazing system influences on cattle performance on mountain range. Journal of Range Management 40, 55–59.

Holechek, J.L., Pieper, R.D., Herbel, C.H., 2004. Range Management, Principles and Practices, fifth ed. Prentice Hall, Upper Saddle River, New Jersey, p. 624.

Holland, E.A., Parton, W.J., Detling, J.K., Coppock, D.L., 1992. Physiological responses of plant populations to herbivory and other consequences of ecosystem nutrient flow. American Naturalist 140, 685–706.

Holling, C.S., Meffe, G.K., 1996. Command and control and the pathology of natural resource management. Conservation Biology 10, 328–337.

Howell, J., 2008. For the Love of Land, Global Case Studies of Grazing in Nature's Image. BookSurge Publishing,, Charleston, South Carolina.

Hulbert, L.C., 1969. Fire and litter effects in an undisturbed bluestem prairie in Kansas. Ecology 50, 874–877.

Hulbert, L.C., 1988. Causes of fire effects in tallgrass prairie. Ecology 69, 46–58.

Hubbard, W.A., 1951. Rotational grazing studies in western Canada. Journal of Range Management 4, 25–29.

Hui, J., Chen, L., 2006. A piecewise smooth rangeland grazing model shows that setting recovery period of plant is beneficial to prevent overgrazing. Journal of Biological Systems 14, 231–242.

Hyder, D.N., Sawyer, W.A., 1951. Rotation-deferred grazing as compared to season-long grazing on sagebrush-bunchgrass ranges in Oregon. Journal of Range Management 4, 30–34.

Illius, A.W., O'Connor, T.G., 1999. On the relevance of non-equilibrium concepts to arid and semi-arid grazing systems. Ecological Applications 9, 798–813.

Isacch, J.P., Cardoni, D.A., 2011. Different grazing strategies are necessary to conserve endangered grassland birds in short and tall salty grasslands of the flooding pampas. The Condor 113, 724–734.

Jacobo, E.J., Rodríguez, A.M., Bartoloni, N., Deregibus, V.A., 2006. Rotational grazing effects on rangeland vegetation at a farm scale. Rangeland Ecology and Management 59, 249–257.

Kellner, K., Bosch, O.J.H., 1992. Influence of patch formation in determining stocking rate for southern African grasslands. Journal of Arid Environments 22, 99–105.

Kirby, D.R., Pessin, M.F., Clambey, G.K., 1986. Disappearance of forage under short duration and season long grazing. Journal of Range Management 39, 496–500.

Knight, Jan C., Kothmann, M.M., Mathis, G.W., Hinnant, R.T., 1990. Cow-calf production with alternative grazing systems. Journal of Production Agriculture 3, 407–414.

Kothmann, M.M., Mathis, G.W., Waldrip, W.J., 1971. Cow-calf response to stocking rate and grazing systems on native range. Journal of Range Management 24, 100–105.

Kreuter, U.P., Brockett, G.M., Lyle, A.D., Tainton, N.M., Bransby, D.I., 1984. Evaluation of veld potential in east Griqualand using beef cattle under two grazing management systems. Journal of the Grassland Society of South Africa 1, 5–10.

Kuhn, T.S., 1970. The Structure of Scientific Revolutions. University of Chicago Press, Chicago.

Launchbaugh, K.L., Howery, L.D., 2005. Understanding landscape use patterns of livestock as a consequence of foraging behavior. Rangeland Ecology and Management 58, 99–108.

Laycock, W.A., Conrad, P.W., 1981. Responses of vegetation and cattle to various systems of grazing on seeded and native mountain rangelands in Eastern Utah. Journal of Range Management 34, 52–58.

Louda, S.M., Keeler, K.H., Holt, R.D., 1990. Herbivore influences on plant performance and competitive interactions. In: Grace, J.B., Tilman, D. (Eds.), Perspectives in Plant Competition. Academic Press, New York, USA, pp. 414–444.

Lyman, T.D., Provenza, F.D., Villalba, J.J., Wiedmeier, R.D., 2012. Phytochemical complementarities among endophyte-infected tall fescue, reed canarygrass, birdsfoot trefoil and alfalfa affect cattle foraging. Journal of Animal Science 6, 676–682.

Maeda, S., Yonetani, T., 1978. Optimum cutting stage of forage plants, II. Seasonal changes in CGR and average productivity in Italian ryegrass populations. Journal of Japan Grassland Science 24, 10–16.

Manley, W.A., Hart, R.H., Samuel, M.J., Smith, M.A., Waggoner Jr., J.W., Manley, J.T., 1997. Vegetation, cattle, and economic responses to grazing strategies and pressures. Journal of Range Management 50, 638–646.

Martin, S.C., Severson, K.E., 1988. Vegetation response to the Santa Rita grazing system. Journal of Range Management 41, 291–295.

Martin, S.C., Ward, D.E., 1976. Perennial grasses respond inconsistently to alternate year seasonal rest. Journal of Range Management 29, 346.

McCollum, F.T., Gillen, R.L., Karges, B.R., Hodges, M.E., 1999. Stocker cattle response to grazing management in tallgrass prairie. Journal of Range Management 52, 120–126.

McCosker, T., 1994. The dichotomy between research results and practical experience with time control grazing. Australian Rural Science Annual, 26–31.
McIlvain, E.H., Savage, D.A., 1951. Eight-year comparisons of continuous and rotational grazing on the Southern Plains Experimental Range. Journal of Range Management 4, 42–47.
McIvor, J.G., 2007. Pasture management in semi-tropical woodlands, dynamics of perennial grasses. Rangeland Journal 29, 87–100.
McNaughton, S.J., Oesterheld, M., Frank, D.A., Williams, K.J., 1989. Ecosystem-level patterns of primary productivity and herbivory in terrestrial habitats. Nature 341, 142–144.
Mencke, J.W., Trlica, M.J., 1981. Carbohydrate reserve, phenology, and growth cycles of nine Colorado range species. Journal of Range Management 34, 269–277.
Mencke, J.W., Trlica, M.J., 1983. Effects of single and sequential defoliations on the carbohydrate reserves of four range species. Journal of Range Management 36, 70–74.
Merrill, L.B., 1954. A variation of deferred rotation grazing for use under southwest range conditions. Journal of Range Management 7, 152–154.
Meuret, M., 2010. Un Savoir-faire de Bergers. Versailles and Dijon, France.
Milchunas, D.G., Lauenroth, W.K., 1993. Quantitative effects of grazing on vegetation and soils over a global range of environments. Ecological Monographs 63, 327–366.
Morris, C.D., Tainton, N.M., 1991. Long-term effects of different rotational grazing schedules on the productivity and floristic composition of Tall Grassveld in KwaZulu-Natal. African Journal of Range and Forage Science 13, 24–28.
Mullahey, J.J., Waller, S.S., Moser, L.E., 1990. Defoliation effects on production and morphological development of little bluestem. Journal of Range Management 43, 497–500.
Mullahey, J.J., Waller, S.S., Reece, P.E., 1991. Defoliation effects on yield and bud and tiller numbers of two sandhills grasses. Journal of Range Management 44, 241–245.
Müller, B., Frank, K., Wissel, C., 2007. Relevance of rest periods in non-equilibrium rangeland systems – a modeling analysis. Agricultural Systems 92, 295–317.
Naeth, N.A., Bailey, A.W., Pluth, D.J., Chanasyk, D.S., Hardin, R.T., 1991. Grazing impacts on litter and soil organic matter is mixed prairie and fescue grassland ecosystems of Alberta. Journal of Range Management 44, 7–12.
Norton, B.E., 1998. The application of grazing management to increase sustainable livestock production. Animal Production in Australia 22, 15–26.
Norton, B.E., 2003. Spatial management of grazing to enhance both livestock production and resource condition: a scientific argument. In: Allsopp, N., Palmer, A.R., Milton, S.J., Kirkman, K.P., Kerley, G.I.H., Hurt, C.R., Brown, C.J. (Eds.), Proc. VII International Rangeland Congress, Durban, South Africa, pp. 810–820.
O'Connor, T.G., 1992. Patterns of plant selection by grazing cattle in two savanna grasslands: a plant's eye view. Journal of the Grassland Society of South Africa 9, 97–104.
Oesterheld, M., Sala, O.E., McNaughton, S.J., 1992. Effect of animal husbandry on herbivore carrying capacity at the regional scale. Nature 356, 234–236.
Olff, H., Ritchie, M.E., 1998. Effects of herbivores on grassland diversity. Trends in Ecology and Evolution 13, 261–265.
O'Reagain, P.J., Turner, J.R., 1992. An evaluation of the empirical basis for grazing management recommendations for rangeland in South Africa. Journal of the Grassland Society of South Africa 9, 38–49.
Owens, J., Provenza, F.D., Wiedmeier, R.D., Villalba, J.J., 2012. Supplementing endophyte-infected tall fescue or reed canarygrass with alfalfa or birdsfoot trefoil increases forage intake and digestibility by sheep. Journal of the Science of Food and Agriculture 92, 676–682.
Owensby, C.E., Smith, E.F., Anderson, K.L., 1973. Deferred-rotation grazing with steers in the Kansas Flint Hills. Journal of Range Management 26, 393–395.
Pickett, S.T.A., White, P.S., 1985. The Ecology of Natural Disturbance and Patch Dynamics. Academic Press, Boston.
Pielou, E.C., 1991. After the Ice Age: the Return of Life to Glaciated North America. The Univ. Chicago Press, Chicago, Illinois.
Pieper, R.D., 1994. Ecological implications of livestock grazing. In: Vavra, M., Laycock, W.A., Pieper, R.D. (Eds.), Ecological Implications of Livestock Herbivory in the West. Society for Range Management, Denver, Colorado, pp. 177–211.
Pinchak, W.E., Teague, W.R., Ansley, R.J., Waggoner, J.A., Dowhower, S.L., 2010. Integrated grazing and prescribed fire restoration strategies in a mesquite Savanna: III. Cow-calf production responses. Rangeland Ecology and Management 63, 298–307.
Pitts, J.S., Bryant, F.C., 1987. Steer and vegetation response to short duration and continuous grazing. Journal of Range Management 40, 386–389.
Pluhar, J.J., Knight, R.W., Heitschmidt, R.K., 1987. Infiltration rates and sediment production as influenced by grazing systems in the Texas rolling plains. Journal of Range Management 40, 240–243.
Popper, K.R., 1959. The Logic of Scientific Discovery, First English ed. Routledge, London.
Provenza, F.D., 1991. Viewpoint, range science and range management are complementary but distinct endeavors. Journal of Range Management 44, 181–183.
Provenza, F.D., 2000. Science, myth, and the management of natural resources. Rangelands 22, 33–36.
Provenza, F.D., 2008. What does it mean to be locally adapted and who cares anyway? Journal of Animal Science 86, 271–284.
Provenza, F.D., 2003a. Foraging Behavior: Managing to Survive in a World of Change. Utah Agricultural Experiment Station, p. 63. <http://behave.net/products/booklet.html>.
Provenza, F.D., 2003b. Twenty-five years of paradox in plant-herbivore interactions and "sustainable" grazing management. Rangelands 25, 4–15.
Provenza, F.D., Villalba, J.J., Dziba, L.E., Atwood, S.B., Banner, R.E., 2003a. Linking herbivore experience, varied diets, and plant biochemical diversity. Small Ruminant Research 49, 257–274.
Provenza, F.D., Villalba, J.J., Bryant, J.P., 2003b. Foraging by herbivores, linking the biochemical diversity of plants with herbivore culture and landscape diversity. In: Bissonette, J.A., Storch, I. (Eds.), Landscape Ecology and Resource Management, Linking Theory with Practice. Island Press, New York, pp. 387–421.
Ratliff, R.D., 1986. Cattle responses to continuous and seasonal grazing of California annual grassland. Journal of Range Management 39, 482–485.
Reardon, P.O., Merrill, L.B., 1976. Vegetative response under various grazing management systems in the Edwards Plateau of Texas. Journal of Range Management 29, 195–198.
Reece, P.E., Brummer, J.E., Engel, R.K., Northrup, B.K., Nichols, J.T., 1996. Grazing date and frequency effects on prairie sandreed and sand bluestem. Journal of Range Management 49, 112–116.
Reed, F., Roath, R., Bradford, D., 1999. The grazing response index, a simple and effective method to evaluate grazing impacts. Rangelands 4, 3–6.
Rice, E.L., Parenti, R.L., 1978. Causes of decreases in productivity in undisturbed tall grass prairie. American Journal of Botany 65, 1091–1097.
Rogler, G.A., 1951. A twenty-five year comparison of continuous and rotation grazing in the northern plains. Journal of Range Management 4, 35–41.
Roshier, D.A., Nicol, H.I., 1998. Implications of spatio-temporal variation in forage production and utilization for animal productivity in extensive grazing systems. Rangeland Journal 20, 3–25.
Sanjari, G., Ghadiri, H., Ciesiolka, C.A.A., Yu, B., 2008. Comparing the effects of continuous and time-controlled grazing systems on soil characteristics in Southeast Queensland. Australian Journal of Soil Research 46, 348–358.
Savadogo, P., Savadogo, L., Tiveau, D., 2007. Effects of grazing intensity and prescribed fire on soil physical properties and pasture yield in the savanna woodlands of Burkina Faso. Agriculture Ecosystems and Environment 118, 80–92.
Savory, A., 1983. The savory grazing method or holistic resource management. Rangelands 5, 155–159.
Savory, A., Butterfield, J., 1999. Holistic Management, a New Framework for Decision Making, second ed. Island Press, Washington, D.C, p. 616.
Sayre, N.F., 2001. The New Ranch Handbook: a Guide to Restoring Western Rangelands. Quivira Coalition, Santa Fe, New Mexico.
Senft, R.L., Rittenhouse, L.R., Woodmansee, R.G., 1985. Factors influencing patterns of cattle behavior on shortgrass steppe. Journal of Range Management 38, 82–87.
Senft, R.L., 1989. Hierarchical foraging models: effects of stocking and landscape composition on simulated resource use by cattle. Ecological Modelling 46, 283–303.
Senge, P.M., 1994. The Fifth Discipline: the Art and Practice of the Learning Organization. Currency Doubleday, New York, p. 445.
Shaw, R.A., Villalba, J.J., Provenza, F.D., 2006. Resource availability and quality influence patterns of diet mixing by sheep. Journal of Chemical Ecology 32, 1267–1278.
Smoliak, S., 1960. Effects of deferred-rotation and continuous grazing on yearling steer gains and shortgrass prairie vegetation of southeastern Alberta. Journal of Range Management 3, 239–243.
Snyman, H.A., du Preez, C.C., 2005. Rangeland degradation in a semi-arid South Africa-II. Influence on soil quality. Journal of Arid Environments 60, 483–507.
Starfield, A.M., Bleloch, A.L., 1985. Building Models for Conservation and Wildlife Management. MacMillan, New York.
Steffens, T.R., Barnes, M.K., Rittenhouse, L.R., 2009. Graze period and stocking rate, not stock density determines livestock nutrient intake. Proceedings of the 4th National Conference on Grazinglands, December 13–16th 2009, Reno Nevada.
Stinner, D.H., Stinner, B.R., Martsolf, E., 1997. Biodiversity as an organizing principle in agroecosystem management, case studies of holistic resource management practitioners in the USA. Agriculture Ecosystems and Environment 62, 199–213.
Stuart Hill, G., Mentis, M., 1982. Co-evolution of African grasses. Proceedings of the Grassland Society of Southern Africa 17, 122–128.
Stuth, J.W., 1991. Foraging behavior. In: Heitschmidt, R.K., Stuth, J.W. (Eds.), Grazing Management: an Ecological Perspective. Timberland Press, Portland, Oregon, pp. 65–83.
Tainton, N.M., Aucamp, A.J., Danckwerts, J.E., 1999. Principles of managing veld. In: Tainton, N.M. (Ed.), Veld Management in South Africa. University of Natal Press, Pietermaritzburg, South Africa, pp. 169–193.
Taylor, C.A., Kothmann, M.M., Merrill, L.B., Elledge, D., 1980. Diet selection by cattle under high-intensity low-frequency, short duration, and Merrill grazing systems. Journal of Range Management 33, 428–434.
Taylor Jr., C.A., Brooks, T.D., Garza, N.E., 1993. Effects of short duration and high-intensity, low-frequency grazing systems on forage production and composition. Journal of Range Management 46, 118–121.
Teague, W.R., Dowhower, S.L., 2001. Do life history traits predict responses to defoliation in co-occurring prairie grasses. Applied Vegetation Science 4, 267–276.
Teague, W.R., Dowhower, S.L., Waggoner, J.A., 2004. Drought and grazing patch dynamics under different grazing management. Journal of Arid Environments 58, 97–117.
Teague, W.R., Foy, J.K., 2004. Can the SPUR rangeland simulation model enhance understanding of field experiments? Arid Land Research and Management 18, 217–228.
Teague, W.R., Grant, W.E., Kreuter, U.P., Diaz-Solis, H., Dube, S., Kothmann, M.M., Pinchak, W.E., Ansley, R.J., 2008. An ecological economic simulation model for

assessing fire and grazing management effects on mesquite rangelands in Texas. Ecological Economics 64, 612–625.
Teague, W.R., Kreuter, U.P., Grant, W.E., Diaz-Solis, H., Kothmann, M.M., 2009a. Economic implications of maintaining rangeland ecosystem health in a semi-arid savanna. Ecological Economics 68, 1417–1429.
Teague, W.R., Provenza, F.D., Norton, B.E., Steffens, T., Barnes, M.K., Kothmann, M.M., Roath, R.L., 2009b. Benefits of multi-paddock grazing management on rangelands: limitations of experimental grazing research and knowledge gaps. In: Schroder, H.G. (Ed.), Grasslands: Ecology, Management and Restoration. Nova Science, New York, pp. 41–80.
Teague, W.R., Dowhower, S.L., Baker, S.A., Ansley, R.J., Kreuter, U.P., Conover, D.M., Waggoner, J.A., 2010b. Soil and herbaceous plant responses to summer patch burns under continuous and rotational grazing. Agriculture Ecosystems and Environment 137, 113–123.
Teague, W.R., Dowhower, S.L., Ansley, R.J., Pinchak, W.E., Waggoner, J.A., 2010a. Integrated grazing and prescribed fire restoration strategies in a mesquite Savanna: I. Vegetation responses. Rangeland Ecology and Management 63, 275–285.
Teague, W.R., Dowhower, S.L., Baker, S.A., Haile, N., DeLaune, P.B., Conover, D.M., 2011. Grazing management impacts on vegetation, soil biota and soil chemical, physical and hydrological properties in tall grass prairie. Agriculture Ecosystems and Environment 141, 310–322.
Thurow, T.L., Blackburn, W.H., Taylor, C.A., 1988. Some vegetation responses to selected livestock grazing strategies, Edwards Plateau, Texas. Journal of Range Management 41, 108–113.
Thurow, T., 1991. Hydrology and erosion. In: Heitschmidt, R.K., Stuth, J.W. (Eds.), Grazing Management: an Ecological Perspective. Timberland Press, Portland, Oregon, pp. 141–159.
Toombs, T.P., Roberts, M.G., 2009. Are natural resources conservation service range management investments working at cross-purposes with wildlife habitat goals on western United States Rangelands? Rangeland Ecology and Management 62, 351–355.
Torell, L.A., McDaniel, K.C., Hurd, B.H., Cox, S., 2008. Using soil moisture to estimate the economic value of rainfall events for range forage production. In: Conference Proceedings, Corona Range and Livestock Research Center – 2008 Field Day. New Mexico State University, Dept. of Animal and Range Sciences, Corona, NM, pp. 34–37. Available at: <http://aces.nmsu.edu/aes/corona/field-day-proceedings.html> (accessed 24.01.11.).
Trlica, M.J., Buwai, M., Menke, J.W., 1977. Effects of rest following defoliations on the recovery of several range species. Journal of Range Management 30, 21–27.
Van der Ploeg, J.D., Verschuren, P., Verhoeven, F., Pepels, J., 2006. Dealing with novelties: a grassland experiment reconsidered. Journal of Environmental Policy and Planning 8, 199–218.
Venter, A.D., Drewes, R.H., 1969. A flexible system of management for sourveld in Natal. Proceedings of the Grassland Society of Southern Africa 4, 104–107.
Villalba, J.J., Provenza, F.D., GouDong, H., 2004. Experience influences diet mixing by herbivores, implications for plant biochemical diversity. Oikos 107, 100–109.
Villalba, J.J., Provenza, F.D., Clemensen, A.K., Larsen, R., Junke, J., 2011. Preference for diverse pastures by sheep in response to intraruminal administrations of tannins, saponins, and alkaloids. Grass and Forage Science 66, 224–236.
Van de Pol, R., Jordaan, J.J., 2008. The fodder bank system: its current place in veld management. Grassroots: Newsletter of the Grassland Society of Southern Africa 8, 36–44.
Vogl, R.J., 1974. Effects of fire on grasslands. In: Kozlowski, T.T., Ahlgren, C.E. (Eds.), Fire and Ecosystems. Academic Press, New York.
Voisin, A., 1959. Grass Productivity. Philosophical Library, New York. pp. 353.
Volesky, J.D., Lewis, J.K., Butterfield, C.H., 1990. High-performance short duration and repeated-seasonal grazing systems: effect on diets and performance of calves and lambs. Journal of Range Management 43, 310–315.
Wallace, L.L., McNaughton, S.J., Coughenour, M.B., 1984. Compensatory photosynthetic responses of three African graminoids to different fertilization, watering and clipping regimes. Botanical Gazette 145, 151–156.
WallisDeVries, M.F., Laca, E.A., Demment, M.W., 1999. The importance of scale of patchiness for selectivity in grazing herbivores. Oecologia 121, 355–363.
Walker, B.H., 1988. Autecology, synecology, climate and livestock as agents of rangeland dynamics. Australian Rangeland Journal 10, 69–75.
Walker, B.H., Carpenter, S., Anderies, J., Abel, N., Cumming, G., Janssen, M., Lebel, L., Norberg, J., Peterson, G.D., Pritchard, R., 2002. Resilience management in social-ecological systems: a working hypothesis for a participatory approach. Conservation Ecology 6 (1), 14. URL: <http://www.consecol.org/vol6/iss1/art14>.
Walker, J.W., Heitschmidt, R.K., Dowhower, S.L., 1989. Some effects of a rotational grazing treatment on cattle preference for plant communities. Journal of Range Management 42, 143–148.
Walters, C.J., 1986. Adaptive Management of Renewable Resources. MacMillan, New York.
Warren, S.D., Thurow, T.L., Blackburn, W.H., Garza, N.E., 1986. The influence of livestock trampling under intensive rotation grazing on soil hydrologic characteristics. Journal of Range Management 39, 491–495.
Washington-Allen, R.A., West, N.E., Ramsey, R.D., Phillips, D.H., Shugart, H.H., 2010. Retrospective assessment of dryland soil stability in relation to grazing and climate change. Environmental Monitoring and Assessment 160, 101–121.
Watson, I.W., Burnside, D.G., Holm, A.McR., 1996. Event-driven or continuous; which is the better model. Rangeland Journal 18, 351–369.
Weber, K.T., Gokhale, B.S., 2011. Effect of grazing on soil-water content in semiarid rangelands of southeast Idaho. Journal of Arid Environments 75, 464–470.
Wessels, K.J., Prince, S.D., Carroll, M., Malherbe, J., 2007. Relevance of rangeland degradation in semiarid northeastern South Africa to the nonequilibrium theory. Ecological Applications 17, 815–827.
White, M.R., Pieper, R.D., Donart, G.B., Trifaro, L.W., 1991. Vegetational response to short-duration and continuous grazing in southcentral New Mexico. Journal of Range Management 44, 399–403.
Whitson, R.E., Heitschmidt, R.K., Kothmann, M.M., Lundgren, G.K., 1982. The impact of grazing systems on the magnitude and stability of ranch income in the Rolling Plains of Texas. Journal of Range Management 35, 526–532.
Wilson, E.O., 1998. Consilience. Alfred Knopf, New York.
Witten, G.Q., Richardson, F.D., Shenker, N., 2005. A spatial-temporal analysis on pattern formation around water points in a semi-arid rangeland system. Journal of Biological Systems 13, 1–23.
Wood, M.K., Blackburn, W.H., 1984. Vegetation and soil responses to cattle grazing systems in the Texas rolling plains. Journal of Range Management 37, 303–308.
Woodward, I., 2005. Modelling and theory. New Phytologist 165, 337–338.
Workman, J., 1986. Range Economics. Macmillan Publ. Co., New York, NY, p. 217.