Is rangeland agriculture sustainable?[1,2]

R. K. Heitschmidt[3], L. T. Vermeire, and E. E. Grings

USDA-ARS, Fort Keogh Livestock and Range Research Laboratory, Miles City, MT 59301

ABSTRACT: The objective of this paper is to examine the sustainability of rangeland agriculture (i.e., managed grazing) on a world-wide basis, with a focus on North America. Sustainability is addressed on three fronts: 1) ecological, 2) economic, and 3) social acceptance. Based on previous and on-going research, we suggest that employment of science-based rangeland grazing management strategies and tactics can ensure ecological sustainability. The formidable challenge in employing such technology centers around the need to balance efficiency of solar energy capture and subsequent harvest efficiencies across an array of highly spatially and temporally variable vegetation growing conditions using animals that graze selectively. Failure to meet this fundamental challenge often accelerates rangeland desertification processes, and in some instances, enhances rate and extent of the invasion of noxious weeds. We also suggest that the fundamental reason that ecologically sound grazing management technologies are often not employed in the management of grazed ecological systems is because social values drive management decisions more so than ecological science issues. This is true in both well-developed societies with substantial economic resources and in less-developed societies with few economic resources. However, the social issues driving management are often entirely different, ranging from multiple-use issues in developed countries to human day-to-day survival issues in poorly developed countries. We conclude that the long-term sustainability of rangeland agriculture in 1) developed societies depends on the ability of rangeland agriculturalists to continually respond in a dynamic, positive, proactive manner to ever-changing social values and 2) less-developed societies on their ability to address the ecological and social consequences arising from unsustainable human populations before the adoption of science-based sustainable rangeland management technologies.

Key Words: Ecology, Economy, Grazing, Management, Social Acceptance, Sustainability

 J. Anim. Sci. 2004. 82(E. Suppl.):E138–E146

Introduction

The long-term sustainability of agriculture is a subject of great interest and lively debate in many segments of the world. This debate goes on in part because sustainable agriculture is often viewed more as a management philosophy rather than a method of operation (MacRae et al., 1993), and as such, acceptance or rejection of any definition is linked to one's value system (Clark and Weise, 1993). Still, most agriculturalists agree that the concept of sustainable agriculture is of paramount importance to the sustainability of our biosphere and its ever-increasing human population.

The objective of this paper is to examine the fundamental role that livestock grazing plays in the development of sustainable agriculture systems. Our focus is on the sustainability of rangeland agriculture (i.e., grazing) as it relates to ecological processes, economic viability, and social acceptance. We address these three components because they generally encompass the broadly accepted components defining sustainable agriculture. For example, the Food and Agricultural Organization (FAO, 1991) defines sustainable agriculture as the management and conservation of the resource base and the orientation of technological and institutional changes in such a manner as to ensure the attainment and continued satisfaction of human needs for present and future generations. Such sustainable development is environmentally nondegrading, technically appropriate, economically viable, and socially acceptable. This definition follows closely the

[1]This article was presented at the 2003 ADSA-ASAS-AMPA meeting as part of the International Animal Agriculture symposium "Sustainable Animal Agriculture: National and International Prospective."

[2]This research was conducted under a cooperative agreement between USDA-ARS and the Montana Agric. Exp. Stn. Mention of a proprietary product does not constitute a guarantee or warranty of the product by USDA, Montana Agric. Exp. Stn., or the authors and does not imply its approval to the exclusion of other products that may be also suitable.

[3]Correspondence: 243 Fort Keogh Road (phone: 406-232-8200; fax: 406-232-8209; e-mail: rod@larrl.ars.usda.gov).

Received July 22, 2003.
Accepted September 27, 2003.

definition of others, including the legal definition as incorporated into the 1990 Farm Bill (U.S. Congress, 1990). It also reflects the essence of Aldo Leopold's writings of 65 yr ago (Leopold, 1938), when he suggested that the challenge to humans is to live on a piece of land without spoiling it.

Ecological Sustainability

Agriculture as an Ecological Process

Agriculture is formally defined as the science, art, or practice of cultivating the soil, producing crops, and raising livestock and in varying degrees the preparation and marketing of the resulting products, or in lay terms as the production of food and fiber. But from an ecological perspective, agriculture can be defined or viewed as the business of managing resources to capture solar energy and transfer it to people for their use (Heitschmidt et al., 1996). As such, agricultural production is an integrated measure of the amount of solar energy captured and the efficiency whereby that energy is transferred across trophic levels within various agricultural food chains.

Based on this fundamental ecological understanding, we can broadly redefine sustainable agriculture as ecologically sound agriculture or more narrowly define it as eternal agriculture, that is, agriculture that can be practiced for eternity. It follows then that eternal agriculture must be fully natural in that no finite, exogenous inputs (e.g., fossil fuels) are necessary for it to function. It is from this definition that we propose that grazing of indigenous rangelands is one of the most sustainable forms of agriculture known. This is because no other form of agriculture is less dependent on external, finite resources, such as fossil fuels, and/or external, potentially environmentally disruptive resources, such as fertilizers or pesticides, than grazing of native grasslands.

Fundamental Impacts of Rangeland Agriculture on Ecological Processes

Assessing the sustainability of rangeland agriculture requires a fundamental understanding of its potential impacts on critical ecological processes (Hobbs, 1996). The four most direct avenues of impact are 1) defoliation of plants, 2) treading, 3) fecal and urine depositions, and 4) atmospheric gas exchanges.

Response of individual plants to defoliation varies depending upon a wide array of biotic (e.g., plant morphological and physiological traits, phenological growth stage) and abiotic (e.g., availability of water and nutrients, temperature) factors. Regardless of the modifying effects of these factors, repeated intensive defoliations generally reduce plant growth and productivity, whereas light-to-moderate levels only marginally suppress growth with occasional instances of growth enhancement noted (Briske and Richards, 1995). As such, selective defoliation processes alter competitive relationships and can cause shifts in plant species composition toward less productive and less desirable mixes (Dyksterhuis, 1949; Ellison, 1960; Friedel, 1991; Pieper, 1994).

Trampling and treading of vegetation and soil surfaces generally increases surface water runoff and sediment production as a result of decreasing vegetation cover and increasing soil bulk densities (Blackburn, 1984). These effects, in turn, cause soil organic matter content, aggregate stability, and water infiltration rates to decline (Thurow, 1991).

Defecation and urination on soil surfaces and in situ vegetation alter nutrient cycles over both time and space (Pieper, 1977; Floate, 1981). This is because of the direct addition of nutrients (Woodmansee, 1978; Heady and Childs, 1994) and their subsequent effects on soil biotic and vegetation growth patterns (Schimel et al., 1986; Detling, 1988; Jaramillo and Detling, 1992a,b).

Increased awareness of the potpourri of abiotic and biotic factors affecting the gaseous composition of the earth's atmosphere has resulted in increasing interest in the regulatory role animals, particularly ruminants, might play. The potential impacts are substantial considering that it is estimated that domestic livestock may contribute up to 15% of the world's methane (CH_4) output (Crutzen et al., 1986). McCauley et al. (1997) reported methane production rates for 356-kg steers grazing summer pastures in Canada averaged 0.69 $L \cdot kg\ BW^{-1} \cdot d^{-1}$ over a 140-d grazing season. Work by Pol-van Dasselaar et al. (1998, 1999) has shown that pastures in the Netherlands serve as sinks for methane at the rate of about 1.1 $kg \cdot ha^{-1} \cdot yr^{-1}$. Converting liters to kilograms (i.e., 0.7168 g/L) reveals 1 ha of pasture in the Netherlands could consume about 625 d of methane emissions by 356-kg steers grazing summer pasture in Canada! Although we recognize combining these two data sets provides very limited insight into the grazing/atmospheric gas interface, it does serve to emphasize the very dynamics of that interface. Moreover, the ecological significance of this interface is difficult to assess without knowledge of the historical contributions of ruminants to CH_4 and other gaseous compounds. Still, it is a potentially important avenue of grazing impact on ecological systems.

Although the above effects are singular in context, the effects of rangeland agriculture on rangeland ecosystems represent an integrated measure of the four avenues of impact and there is an abundance of scientific literature documenting these effects. Specifically, these studies show that 1) rangeland agriculture alters both the structure and function of ecological systems (Sims and Singh, 1978a,b,c), including rates of energy flow and nutrient cycling (Briske and Heitschmidt, 1991); 2) defoliation intensity has greater impact than trampling and treading (Curll and Wilkins, 1983); and 3) that impacts vary depending upon the evolutionary history of the rangeland of interest. For example, historical monitoring of the impacts of large ungulates on the structure and function of rangelands in regions with long evolutionary grazing histories, such as the grasslands of the Great Plains of North America (Lauenroth et al., 1994), suggests grazing at moderate intensities is ecologically fully sustainable (Milchunas et. al., 1988; Milchunas and Lauenroth, 1993). However, the response in regions with limited evolutionary grazing histories, such as the Desert Southwest and Great Basin regions of the United States, are quite different. Still, there is considerable evidence that indicates well-managed, light-to-moderate grazing intensities are ecologically sustainable (Laycock, 1994; Pieper, 1994) although alternative interpretations of the published literature exist (Fleischner, 1994; Heitschmidt et al., 2001).

Management Challenges

Obviously, ecological sustainability is closely linked to the abilities of rangeland agriculturalists to manage the impacts of grazing animals on rangeland resources. These challenges are of considerable magnitude in extensive rangeland environments because limited economic returns prohibit employing high-cost, ecologically ameliorating management tactics. For example, in intensively managed grazing environments, such as tame or planted pasture systems, such exogenous energy inputs as insecticides, herbicides, fertilizers, and water can be used to affect fundamental ecological processes. But under extensive rangeland conditions, management is largely limited to how grazing animals are managed over both time and space.

The concept of proper grazing is a product of extensive rangeland management strategies. Proper grazing is defined as the act of continuously obtaining proper use, with proper use being defined as a degree of utilization of current year's growth which, if continued, will achieve management objectives and maintain or improve the long-term productivity of the site (SRM, 1989). In other words, proper grazing is sustainable grazing.

Driving proper grazing are three, over-whelming, broad-based challenges. The first challenge is the need to balance efficiency of solar energy capture (i.e., forage production) and subsequent harvest efficiency (i.e., consumption by the grazing animal). This concept has been clearly demonstrated by Parsons et al. (1983) and discussed in detail by Briske and Heitschmidt (1991). Results from this experiment clearly reveal that as harvest efficiency increases beyond some optimum, forage production declines (Figure 1).

The second challenge stems from the inherent range in abiotic growing conditions over both time and space (Friedel et al., 1990; Stafford Smith and Morton, 1990). For example, seasonal and annual droughts are common in rangeland environments, which ensures

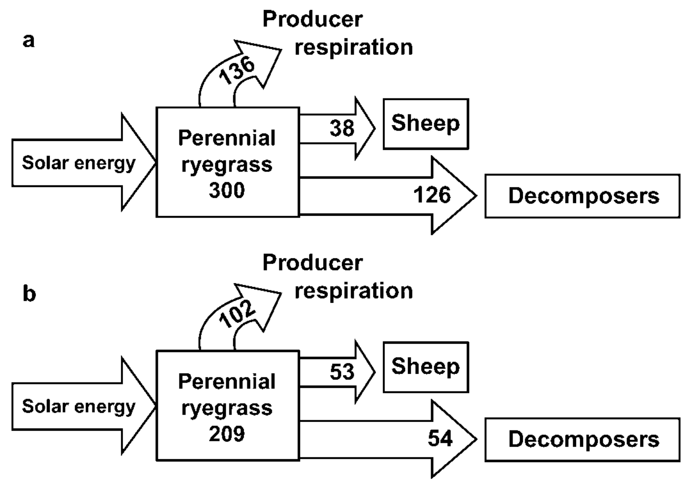

Figure 1. Energy capture and flow (kg carbon·ha^{-1}·d^{-1}) within (a) leniently and (b) severely grazed perennial ryegrass pasture (data taken from Briske and Heitschmidt, 1991, after Parsons et al., 1983).

primary productivity will vary considerably over both time and space. Likewise, primary productivity capacity will vary spatially because of inherent differences in soil quality and topography among spatially distributed ecological sites.

The third challenge is managing the impacts of selective grazing. This challenge is particularly robust in rangeland agriculture environments because of the short-term interaction effects of selective grazing on both herbage production and harvest efficiencies and the long-term effects on potential herbage production arising from alterations in plant species composition. In the short term, selective grazing ensures rates of growth will vary among plants and plant species because of variations in frequency and severity of defoliation. In the long term, differences in frequency and severity of defoliation alter competitive interactions, which in turn impact rate, direction, and magnitude of ecological succession in species-rich rangeland environments (Archer and Smeins, 1991).

In light of these three challenges, managers have implemented a number of tactics to ensure rangelands are properly grazed over both time and area. The most obvious of these tactics are proper stocking rates, strategic herding, fencing, water development, and the use of various grazing systems (Vallentine, 1990; Heady and Childs, 1994). But there are a great many other livestock management tactics that can affect ecological sustainability across a landscape. For example, location of supplemental feeds/feeding grounds (Bailey and Welling, 1999), early life experiences (Provenza and Balph, 1988), and kinds and breeds of animals (Winder et al., 1996; Simm et al., 1996; Bailey et al., 2001) can all affect the intensity of utilization of various ecological sites, communities, and individual plants within a landscape. And because landscape composition relative to ecological sites, communities, and individual plants varies, grazing impacts vary across a landscape in direct proportion to grazing intensities. Animal management tactics can also affect such specific variables as gaseous emissions, such as methane. For example, Moe and Tyrrell (1979) have shown differing sources of carbohydrates alter quantity and mix of gaseous emissions, whereas Martin and Seeland (1999) have shown similar results when a production system was changed from dual purpose to separate milk and meat systems.

The resulting effect is that averages, such as average forage production, average diet quality, and average weaning weight, are often of only limited value to managers. Rather, the challenge lies in capturing opportunities and avoiding pitfalls arising from deviations from the average (Danckwerts and King, 1984; Fouche et al., 1985; Foran and Stafford Smith, 1991; Dankwerts and Tainton, 1993; Pickup and Stafford Smith, 1993; Heitschmidt and Walker, 1996) because management for the average will often result in financial ruin.

Ecological Threats to Sustaining Rangelands

There are three major threats to the ecological sustainability of rangelands and rangeland agriculture. One threat is the unabated invasion and spread of noxious plants that alter the ecological integrity of rangeland ecosystems. Infestations by a wide array of noxious plants continue to diminish the functionality of rangelands. For example, about 750 invader plant species have either been intentionally or accidentally introduced into the northwest United States over the past 100 yr (Rice, 2003). Two of the most notorious rangeland species are Russian knapweed (*Centaurea scabiosa* L.) and leafy spurge (*Euphorbia esula* L.), both of which have increased over the past 75 yr, from minimal infestations to current occupations of about 560,000 (Whitson, 1999) and 1.1 m ha (Lajeunesse et al., 1999) of western and north central U.S. lands, respectively. Combating this threat is difficult as both environmental concerns and treatment costs limit management options.

A second major threat is the continued conversion of rangelands to other uses, such as cropland and homesteads in the form of ranchettes and housing subdivisions. For example, the U.S. Natural Resource Conservation Service reported a 3% decline in privately owned rangelands from 1982 to 1997 (Mitchell, 2000), with greatest loss being conversion to cropland (USDA Forest Service, 2001). But the impacts of such losses on the ecological sustainability of rangeland agriculture extend beyond the direct impacts of losses in grazing capacity. This is because the spatial pattern of varying types and/or land uses can affect the ability of keystone plants and animals to maintain viable populations. As such, limiting fragmentation is important, at least in some instances, to sustaining rangeland ecosystems (De Prietri, 1995; de Soyza et al., 2000; Flather and Seig, 2000; Washington-Allen, 2003).

The third major threat is loss of rangelands via desertification processes, of which soil erosion is key (Figure 2). Although deserts are classified as rangelands, their level of productivity is considerably less than that for more traditional grassland-dominated rangelands. Thus, management practices, such as improper grazing, and natural phenomena, such as shifts in climate, can enhance rate and extent of desertification of rangelands (Thurow, 1991).

Economic Sustainability

Economics is defined as a social science concerned with the description and analysis of the production, distribution, and consumption of goods and services. However, in its simplest form, economics can be viewed as measures of human beliefs that form value systems, which in turn drive economic choices. People, businesses, and governments buy and sell goods and services based upon their beliefs as to the value of available goods and services. That is why economics is deemed a social science and why it is so closely tied to social acceptance. That is also the reason why it is difficult to independently address the roles that economic sustainability and social acceptance play in sustaining any enterprise.

Despite surveys that show ranchers tend to value their lifestyle over economic well-being (Torell et al., 2001), their economic sustainability is ultimately dependent upon profit margins if their livelihood is dependent strictly upon the ranching enterprise. Potential threats to profit margins may be either from reduced income or increased costs or both. Potential threats to loss of income include loss of productive capacity and reduced selling prices. Examples of potential forces that might reduce productivity capacity would include recurring drought and/or deleterious invasion of noxious weeds. Drought, almost without exception, reduces ranch income with impacts greatest at high grazing intensities (Hart et al., 1988; Valentine, 1990; Conner, 1991). Likewise, it is well known that invasive weeds continue to spread (Figure 3) and that their economic impacts can be devastating. For example, it is estimated that the annual economic impact on the Montana economy of just three species of knapweed is $42 million (Hirsch and Leitch, 1996). These costs are in terms of both loss of income, because of reduced productivity, and increased management costs.

Although there is an array of factors that can cause selling prices to decline, most are related to fundamental supply and demand relationships. It is reasonable to assume that the production of rangeland agricultural products is probably near maximum, at least in North America, as essentially all available rangeland is currently stocked to capacity. On the other hand, worldwide demand for red meat is increasing dramati-

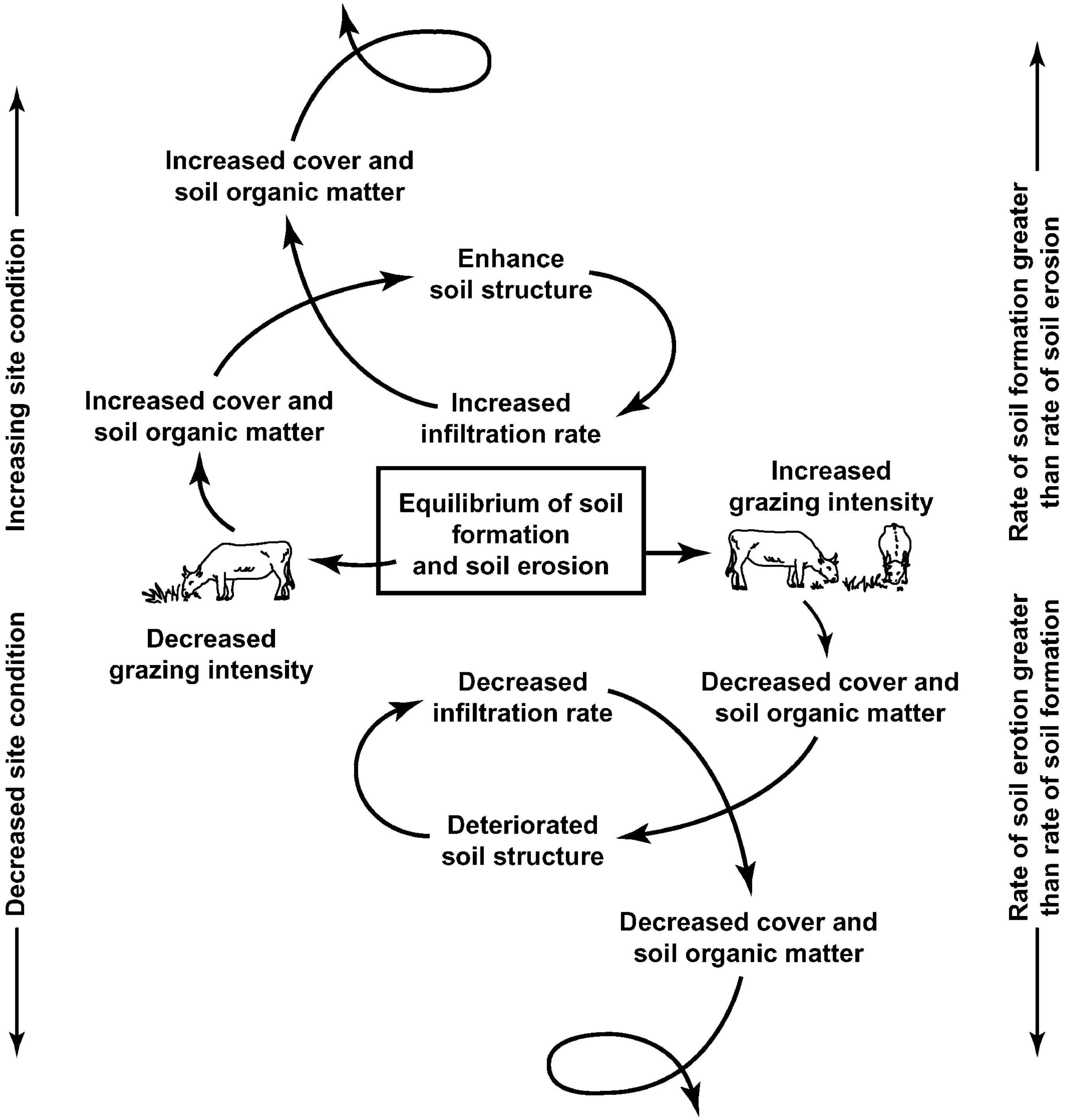

Figure 2. Conceptual pathway of rangeland desertification process (from Thurow, 1991).

cally, as Rosegrant et al. (1995) estimated demand would increase 100% by 2020. Thus, the potential for the price of red meat to increase in the future is substantial.

In addition to the increased management costs associated with the management of invasive weeds, there is an array of other forces that may increase production costs dramatically in the future. One potential factor is ever-increasing land purchase prices. Rangeland purchase prices continue to increase and, in many instances, beyond the economic potential of agriculture production. But in a free-enterprise system, such increases simply reflect what the market will bear and intrusive controls of those prices would be unwelcome. An additional threat is substantial increases in fossil fuel costs. As Heitschmidt et al. (1996) have shown, most U.S. beef cattle production systems are highly dependent on fossil fuel, and as such, substantial increases in fossil fuel prices will severely cripple profit margins unless product selling prices

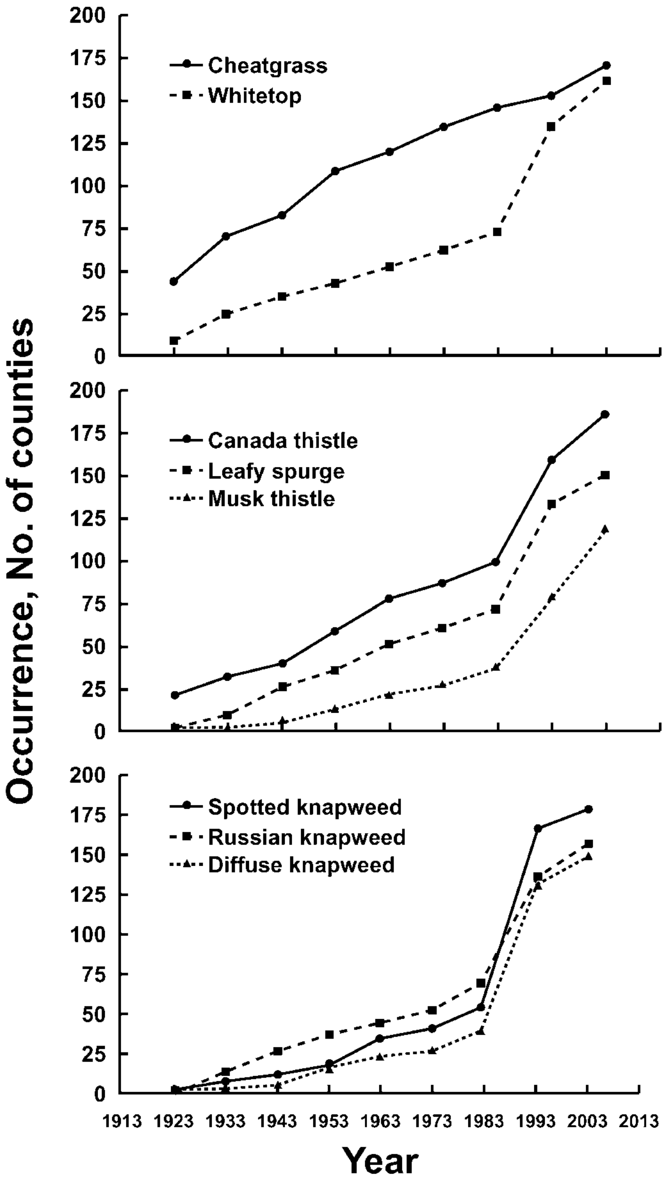

Figure 3. Number of counties in Oregon, Washington, Idaho, Montana, and Wyoming reporting presence of eight invasive weeds from 1923 to 2003. Total number of counties in five states is 198.

rise at a similar rate. Still, rangeland agriculture per se will continue because its existence is not dependent upon fossil fuels as is evident in other parts of the world besides North America. The incorporation of fossil fuel-dependent technologies into North American rangeland agriculture production systems is a luxury that stems from relatively cheap fossil fuel, but it is not a requirement for rangeland agriculture to function.

Economic Sustainability/Social Acceptance Interface

Obviously, there is a close linkage between economic sustainability and social acceptance in that both are value driven. Values are a reflection of beliefs, and unfortunately, there is no requirement that beliefs be based on either sound knowledge or absolute truths. Thus, social acceptance or rejection of any social process, event, or phenomenon is based upon perceived truths, all of which are subject to emotional and political manipulation. We forward these ideas because it is imperative that rangeland agriculturalists understand that economic sustainability and social acceptance are both closely tied to social perceptions and beliefs, whereas ecological sustainability is dependent on the biological and physical laws of nature. If a resource management scheme does not ensure ecological sustainability, its long-term economic sustainability is questionable. That is so because economic viability at any instant is strictly dependent upon current social perceptions and values, whereas long-term sustainability is dependent upon absolute truths. And because humans lack perfect ecological knowledge, a portion of our natural resource management strategies and tactics have failed and will probably continue to fail although they are at some point considered economically sustainable.

There are several closely related social acceptance threats to rangeland agriculture. One of considerable concern is the perception that rangeland agriculture is environmentally inappropriate. This is somewhat surprising when one considers that grazing is the oldest and most natural form of agriculture known. That does not mean, however, that all past, current, or future rangeland agriculture management schemes are deemed ecologically sustainable and therefore, socially acceptable. Still, there is considerable debate among knowledgeable scientists as to the ecological sustainability of rangeland agriculture in the arid western United States (Fleishner, 1994; Laycock, 1994; Pieper, 1994; Donahue, 1999). In a review of this debate, Heitschmidt et al. (2001) concluded that creditable scientific support can be generated for a wide array of land uses, including conflicting uses, because author interpretations (including ours) of similar scientific information can vary depending upon personal experiences and values. This, in turn, means society's information base may be filled with conflicting information that makes good land management decisions more difficult.

The perception that rangeland agriculture is environmentally inappropriate appears to be a driving force behind society's changing value system as it relates to alternative uses of rangeland resources. Greater social value is being placed on nonlivestock-oriented products, such as water, recreation, biodiversity, and ecosystem integrity. For example, a recent Shields et al. (2002) survey of over 80 focus groups and 7,000 individual citizens showed there is wide public support for adopting management tactics and strategies for U.S. forests and grasslands that 1) enhance the ecological health, 2) preserve the opportunity for wilderness experiences, 3) incorporate sound science in development of management plans, and 4) favor less consumptive uses over more consumptive uses. Alternatively, the survey results showed only limited support for 1) increasing motorized recreational opportunities, 2) providing resources to dependent communities and traditional cultural uses, and 3) continuation of subsidies for development and leasing of public lands. In addition, livestock grazing of public rangelands continues to be closely scrutinized with strong advocacy for its removal (Wuerthner and Matteson, 2002). These calls for action to remove livestock grazing from public lands seem to disregard any and all reports that proper livestock grazing may be a greater positive force in maintaining the integrity of rangeland ecosystems than either ranchettes or preserves (Maestas et al., 2002). Still, it is imperative that rangeland agriculturalists understand that societal values are not necessarily based on knowledge and truth, but rather on perceptions. Thus, failure to adjust to changing societal values in a timely manner may place many rangeland agricultural enterprises at grave risk.

An International Perspective

Although the focus of this paper has been on the sustainability of rangeland agriculture in North America, the concepts presented are equally applicable to other continents and countries, and social and ecological systems. For example, the avenues of impact of rangeland agriculture on ecological systems (e.g., defoliation, treading) are constant regardless of the ecological system of interest. Granted, relative impacts will vary among ecological systems depending on such factors as evolutionary history, soil type, climate, and grazing animal, but avenues of impact will remain the same. But because of differences in social values and understandings, animal management tactics and strategies do vary among social entities, thereby creating the perception that the ecological impacts of grazing vary. Consider, for example, that in a certain setting animals are quite concentrated, with one of the resulting impacts being nutrient overloading of soils and water (de Hann, 2003; Orskov, 2003). Although one might initially surmise that this phenomenon is because of a fundamental change in the functional aspect of grazing, the truth is that the nutrient overloading resulted from the concentrated deposition of animal feces and urine, a fundamental ecological impact stemming from all animal production systems. Regardless of setting, social values are often the underlying variable either hindering or driving the development of sustainable rangeland agriculture systems. For example, in countries with substantial economic resources, exogenous energy can be purchased to support agriculture production systems, including animal agriculture (Heitschmidt et al., 1996), thereby providing the perception that such systems are fully sustainable. But in reality their long-term sustainability is dependent, at least in part, on the continued availability of affordable exogenous sources of energy. This is because observed levels of productivity are closely linked to the amount of fossil fuels used in the production process (Pimentel, 1984). And although it may be argued that there is substantial risk in assuming that affordable exogenous sources of energy will always be available, social levels of concern appear to be negligible as evidenced by the ever-increasing use of fossil fuels in agricultural production systems.

Social issues tend to also drive the management of rangeland agricultural systems in societies with limited economic resources, particularly in those instances where the human ecological carrying capacity has been surpassed (i.e., overpopulation). In such situations, management strategies and tactics required for day-to-day survival severely limit the development and adoption of strategies and tactics necessary to ensure long-term ecological sustainability. The fundamental challenge in these situations centers on the alteration of social values that encourage rampant expansion of human populations.

Implications

Properly managed grazing is ecologically sustainable. But because long-term sustainability is linked closely to social values, the greatest challenges to the development and implementation of fully sustainable rangeland agriculture systems are social rather than ecological. As such, rangeland agriculture in the United States and other economically developed countries will continue to be threatened if rangeland agriculturalists do not respond to changing social values in a positive, proactive, and understanding manner. This is in contrast to those regions of the world where economic development is severely limited and current human population is at or in excess of ecological carrying capacity. In those situations, we suggest that it is folly to attempt to develop sustainable agriculture systems, including rangeland agriculture systems, before addressing and rectifying the ecological and social challenges arising from unsustainable human populations.

Literature Cited

Archer, S., and F. E. Smeins. 1991. Ecosystem-level processes. Pages 109–140 in Grazing Management: An Ecological Perspective. R. K. Heitschmidt and J. W. Stuth, ed. Timber Press, Portland, OR.

Bailey, D. W., and G. R. Welling. 1999. Modification of cattle grazing distribution with dehydrated molasses supplement. J. Range Manag. 52:575–582.

Bailey, D. W., D. D. Kress, D. C. Anderson, D. L. Boss, and K. C. Davis. 2001. Relationship between terrain use and performance of beef cows grazing foothill rangeland. J. Anim. Sci. 79:1883–1891.

Blackburn, W. H. 1984. Impacts of grazing intensity and specialized grazing systems on watershed characteristics and responses.

Pages 927–984 in Developing Strategies for Rangeland Management, National Research Council/National Academy of Sciences. Westview Press, Boulder, CO.

Briske, D. D., and R. K. Heitschmidt. 1991. An ecological perspective. Pages 11–26 in Grazing Management: An Ecological Perspective. R. K. Heitschmidt and J. W. Stuth, ed. Timber Press, Portland, OR.

Briske, D. D., and J. H. Richards. 1995. Plant responses to defoliation: a physiologic, morphologic and demographic evaluation. Pages 635–710 in Wildland Plants: Physiological Ecology and Development Morphology. Soc. Range Manag., Denver, CO.

Clark, E. A., and S. F. Weise. 1993. A forage-based vision of sustainable agriculture. Pages 95–110 in Proc. 92nd Symp. NE Branch, Am. Soc. Agron., Madison, WI.

Conner, J. R. 1991. Social and economic influences on grazing management. Pages 191–200 in Grazing Management: An Ecological Perspective. R. K. Heitschmidt and J. W. Stuth, ed. Timber Press, Inc., Portland, OR.

Crutzen, P. J., I. Aselmann, and W. Seiler. 1986. Methane production by domestic animals, wild ruminants, and other herbivory fauna and humans. Tellus Ser. B Chem. Phys. Meteorol. 38:271–284.

Curll, M. L., and R. J. Wilkins. 1983. The comparative effects of defoliation, treading and excreta on a Lolium perenne-Trifolium repens pasture grazed by sheep. J. Agric. Sci. (Camb.) 100:451–460.

Danckwerts, J. E., and P. G. King. 1984. Conservation stocking or maximum profit: A grazing management dilemma. J. Grassl. Soc. S. Afr. 1:25–28.

Danckwerts, J. E., and N. M. Tainton. 1993. Range management: optimizing forage production and quality. Pages 843–850 in Proc. XVII Int. Grassl. Congr., Keeling and Mundy Ltd., Palmerston North, New Zealand.

de Haan, C. 2003. A global overview of sustainability in animal agriculture systems. J. Anim. Sci. 86(Suppl. 1):30. (Abstr.)

De Pietri, D. E. 1995. The spatial configuration of vegetation as an indicator of landscape degradation due to livestock enterprises in Argentina. J. Appl. Ecol. 32:857–865.

de Soyza, A. G., J. W. Van Zee, W. G. Whitford, A. Neale, N. Tallent Hallsel, J. E. Herrick, and K. M. Havstad. 2000. Indicators of Great Basin rangeland health. J. Arid Environ. 45:289–304.

Detling, J. K. 1988. Grasslands and savannas: Regulation of energy flow and nutrient cycling by herbivores. Pages 131–148 in Concepts of Ecosystem Ecology. Springer-Verlag, New York.

Donahue, D. L. 1999. The Western Range Revisited: Removing Livestock from Public Lands to Conserve Native Biodiversity. Univ. Oklahoma Press, Norman.

Dyksterhuis, E. J. 1949. Condition and management of rangeland based on quantitative ecology. J. Range Manag. 2:104–105.

Ellison, L. 1960. Influence of grazing by large herbivores on nitrogen cycling in agricultural ecosystems. Bot. Rev. 26:1–78.

Flather, C. H., and C. H. Sieg. 2000. Applicability of Montreal Process Criterion 1—conservation of biological diversity—to rangeland sustainability. Int. J. Sustain. Dev. World Ecol. 7:81–96.

Fleischner, T. L. 1994. Ecological costs of livestock grazing in western North America. Conserv. Biol. 8:629–644.

Floate, M. J. S. 1981. Effects of grazing by large herbivores on nitrogen cycling in agricultural ecosystems. Pages 585–602 in Terrestrial Nitrogen Cycles. Swed. Nat. Sci. Res. Counc. Stockholm.

FAO. 1991. Sustainable agriculture and rural development in Asia and Pacific. The Netherlands: Regional Document No. 2. FAO/Netherlands Conf. Agric. Envir.

Foran, B. D., and D. M. Stafford Smith. 1991. Risk, biology and drought management strategies for cattle stations in Central Australia. J. Environ. Manag. 33:17–33.

Fouche, J. H., J. M. De Jager, and D. P. J. Opperrman. 1985. A mathematical model for assessing the influence of stocking rate on the incidence of droughts for estimating the optimal stocking rates. J. Grassl. Soc. S. Afr. 2:4–6.

Friedel, M. H., Foran, B. D., and D. M. Stafford Smith. 1990. Where the creeks run dry or ten feet high: Pastoral management in arid Australia. Proc. Ecol. Soc. Aust. 16:185–194.

Friedel, M. H. 1991. A viewpoint on range condition assessment and the concept of thresholds. J. Range Manag. 44:422–426.

Hart, R. H., M. J. Samuel, P. S. Test, and M. A. Smith. 1988. Cattle, vegetation, and economic responses to grazing systems and grazing pressure. J. Range Manag. 41:282–288.

Heady, H. F., and R. D. Childs. 1994. Energy flow and nutrient cycling. Pages 72–87 in Rangeland Ecology and Management. Westview Press, Boulder, CO.

Heitschmidt, R. K., J. D. Johnson, and K. D. Klement. 2001. Social values in the assessment of livestock grazing in the Great Plains. Gt. Plains Res. 11:361–374.

Heitschmidt, R. K., R. E. Short, and E. E. Grings. 1996. Ecosystems, sustainability, and animal agriculture. J. Anim. Sci. 74:1395–1405.

Heitschmidt, R. K., and J. W. Walker. 1996. Grazing management: Technology for sustaining rangeland ecosystems? Rangel. J. 18:194–215.

Hirsch, S. A., and J. A. Leitch. 1996. The impact of knapweed on Montana's economy. Agric. Econ. Rep. No. 355. Dep. Agric. Econ., Agric. Exper. Sta., North Dakota State Univ., Fargo.

Hobbs, N. T. 1996. Modification of ecosystems by ungulates. J. Wildl. Manag. 60:695–713.

Jaramillo, V. J., and J. K. Detling. 1992a. Small-scale heterogeneity in a semi-arid North American grassland. I. Tillering, N uptake and retranslocation in simulated urine patches. J. Appl. Ecol. 29:1–8.

Jaramillo, V. J., and J. K. Detling. 1992b. Small-scale heterogeneity in a semi-arid North American grassland. II. Cattle grazing of simulated urine patches. J. Appl. Ecol. 29:9–13.

Lajeunesse, S., R. Sheley, C. Duncan, and R. Lym. 1999. Leafy Spurge. Pages 249–260 in Biology and Management of Noxious Rangeland Weeds. Oregon State Univ. Press, Corvallis.

Laurenroth, W. K., D. G. Milchunas, J. L. Dodd, R. H. Hart, R. K. Heitschmidt, and L. R. Rittenhouse. 1994. Effects of grazing on ecosystems of the Great Plains. Pages 69–100 in Ecological Implications of Livestock Herbivory in the West. Soc. Range Manag., Denver, CO.

Laycock, W. A. 1994. Implications of grazing vs. no grazing on today's rangelands. Pages 251–280 in Ecological Implications of Livestock Herbivory in the West. Soc. Range Manag., Denver, CO.

Leopold, A. 1938. The River of the Mother of God and Other Essays by Aldo Leopold. Univ. Wisconsin Press, Madison.

MacRae, R. J., J. Henning, and S. B. Hill. 1993. Strategies to overcome barriers to the development of sustainable agriculture in Canada: The role of agribusiness. J. Agric. Environ. Ethics 6:21–51.

Maestas, J. D., R. L. Knight, and W. C. Gilgert. 2002. Cows, condos, or neither: What's best for rangeland ecosystems? Rangelands 24:36–42.

Martin, S., and G. Seeland. 1999. Effects of specialization in cattle production on ecologically harmful emissions. Livest. Prod. Sci. 61:171–178.

McCauley, W. P., K. Wittenberg, and D. Corrigan. 1997. Methane production by steers on pasture. Can. J. Anim. Sci. 77:519–524.

Milchunas, D. G., and W. K. Lauenroth. 1993. Quantitative effects of grazing on vegetation and soils over a global range of environments. Ecol. Monogr. 63:327–366.

Milchunas, D. G., O. E. Sala, and W. K. Lauenroth. 1988. A generalized model of the effects of grazing by large herbivores on grassland community structure. Am. Nat. 132:87–106.

Mitchell, J. 2000. Rangeland resource trends in the United States. GTR RMRS-GTR-68. USDA Forest Service Rocky Mountain Res. Stn. Fort Collins, CO.

Moe, P. W., and H. F. Tyrell. 1979. Methane production in dairy cows. J. Dairy Sci. 62:1583–1586.

Orskov, E. R. 2003. Contribution of animal agriculture to sustainable systems. J. Anim. Sci. 86(Suppl. 1):30. (Abstr.)

Parsons, A. J., E. L. Leafe, B. Collett, P. D. Penning, and J. Lewis. 1983. The physiology of grass production under grazing. II. Photosynthesis, crop growth and animal intake of continuously grazed swards. J. Appl. Ecol. 20:127–139.

Pickup, G., and D. M. Stafford Smith. 1993. Problems, prospects and procedures for assessing the sustainability of pastoral land management in arid Australia. J. Biogeogr. 20:471–487.

Pieper, R. D. 1994. Ecological implications of livestock grazing. Pages 177–211 in Ecological Implications of Livestock Herbivory in the West. Soc. Range Manag., Denver, CO.

Pieper, R. D. 1977. Effects of herbivores on nutrient cycling and distribution. Pages 249–275 in The Impact of Herbivores on Arid and Semi-Arid Rangelands. Proc. 2nd U.S./Austr. Rangel. Panel 1972. Adelaide, South Australia.

Pimentel, D. 1984. Energy flow in agroecosystems. Pages 121–132 in Agricultural Ecosystems. Wiley & Sons, New York.

Pol-van Dasselaar, A. V. 1998. Methane emissions from grasslands. Thesis. Wageningen Agric. Univ., the Netherlands.

Pol-van Dasselaar, A. V., M. L. van Beusichem, and O. Oenema. 1999. Effects of nitrogen input and grazing on methane fluxes of extensively and intensively managed grasslands in The Netherlands. Biol. Fertil. Soils 29:24–30.

Provenza, F. D., and D. F. Balph. 1988. Development of dietary choice in livestock on rangelands and its implications for management. J. Anim. Sci. 66:2356–2368.

Rice, P. M. 2003. INVADERS Database System. Available: http://invader.dbs.umt.edu. Division of Biological Sciences, Univ. Montana, Missoula. Accessed March 1, 2003.

Rosegrant, M. W., M. Agcaoili-Sombilla, and N. D. Perez. 1995. Global food projections to 2020: Implications for investment. Inter. Food Policy Res. Inst., Washington, DC.

Schimel, D. S., W. J. Parton, F. J. Adamsen, R. G. Woodmansee, R. L. Senft, and M. A. Stillwell. 1986. The role of cattle in the volatile loss of nitrogen from a shortgrass steppe. Biogeochem. 2:39–52.

Shields, D. J., I. M. Martin, W. E. Martin, and M. A. Haefele. 2002. Survey results of the American public's values, objectives, beliefs, and attitudes regarding forests and grasslands: A technical document supporting the 2000 USDA Forest Service RPA Assessment. Gen. Tech. Rep. RMRS-GTR-95, USDA, Forest Service, Rocky Mountain Res. Stn. Fort Collins, CO.

Simm, G., J. Conington, S. C. Bishop, C. M. Dwyer, and S. Pattinson. 1996. Genetic selection for extensive conditions. Appl. Anim. Behav. Sci. 49:47–59.

Sims, P. L., and J. S. Singh. 1978a. The structure and function of ten western North American grasslands. II. Intra-seasonal dynamics in primary producer compartments. J. Ecol. 66:547–572.

Sims, P. L., and J. S. Singh. 1978b. The structure and function of ten western North American grassland III. Net primary production, turnover and efficiencies of energy capture and water use. J. Ecol. 66:573–597.

Sims, P. L., and J. S. Singh. 1978c. The structure and function of ten western North American grasslands. IV. Compartmental transfers and energy flow within the ecosystem. J. Ecol. 66:983–1009.

SRM. 1989. A Glossary of Terms Used in Range Management. 3rd ed. Society of Range Management, Denver, CO.

Stafford Smith, D. M., and S. R. Morton. 1990. A framework for the ecology of arid Austr. J. Arid Environ. 18:255–278.

Thurow, T. L. 1991. Hydrology and erosion. Pages 141–150 in Grazing Management: An Ecological Perspective. R. K. Heitschmidt and J. W. Stuth, ed. Timber Press, Portland, OR.

Torell, L. A., N. R. Rimbey, J. A. Tanaka, and S. A. Bailey. 2001. The lack of a profit motive for ranching: implications for policy analysis. Pages 47–58 in Current Issues in Rangeland Resource Economics. Western Coordinating Committee (WCC-55), New Mexico State Univ. Agric. Exper. Stn. Res. Rep. 737. Las Cruces.

USDA Forest Service. 2001. RPA Assessment of Forest and Range Lands. FS-687. USDA Forest Service, Washington, DC.

U.S. Congress. 1990. Public Law 101-624. 101st Cong., 2830 ses., 28 November 1990. Food, Agriculture, Conservation, and Trade Act of 1990. Title XVI, subtitle A, section 1603.

Vallentine, J. F. 1990. Grazing Management. Academic Press, Inc., San Diego, CA.

Washington-Allen, R. A. 2003. Retrospective Ecological Risk Assessment of Commercially-Grazed Rangelands using Multitemporal Satellite Imagery. Ph.D. Diss. Utah State Univ., Logan.

Whitson, T. D. 1999. Russian knapweed. Pages 315–322 in Biology and Management of Noxious Rangeland Weeds. Oregon State Univ. Press, Corvallis.

Winder, J. A., D. A. Walker, and C. C. Bailey. 1996. Effect of breed on botanical composition of cattle on Chihuahuan desert range. J. Range Manag. 49:209–214.

Woodmansee, R. G. 1978. Additions and losses of N in grassland ecosystems. Bioscience 28:448–453.

Wuerthner, G., and M. Matteson. 2002. The Subsidized Destruction of the American West. Island/Palace Press, San Rafael, CA.