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Environmental Impacts of Livestock on U. S. Grazing Lands

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Summary

Grazing lands are the single largest land type in the United States. Thus, the environmental quality and the sustainability of these lands are important to all citizens. Properly managed grazing lands provide positive environmental benefits, including the provision of clean water supplies, the capacity to sequester atmospheric carbon (C), and the potential to maintain biodiversity. The key issues of concern regarding the environmental impacts of livestock on both public and private grazing lands are their effects on soil, water quality, riparian areas, and biodiversity (including invasive plant species).

Livestock can affect soil quality through compaction, erosion, and changes in the plant community. Water quality impacts of livestock on grazing lands include manure and urine deposited directly into water or on land near surface waters where leaching and surface runoff can transport potential contaminants to streams, ponds, and lakes. Inappropriate grazing practices may accelerate erosion and sediment transport to water, alter stream flow, and disrupt aquatic habitats. Mismanagement of grazing lands can impair the capacity of riparian vegetation to filter contaminants, shade aquatic habitats, and stabilize stream banks and shorelines.

Invasive species threaten the productivity, stability, and ecological functioning of some grazing lands. Controlling the spread of invasive species requires the development and application of low-maintenance strategies that are site-specific and focused on the management of plant succession. An important question is the societal commitment to weed management in terms of herbicide use, revegetation with nonnative species, introduction of biological controls, and use of domestic livestock to direct and to maintain a level of plant succession.

Livestock grazing on public lands has become a major issue in states with significant areas of public lands. Many rural families depend on federal grazing permits for production of forage used by private livestock herds. Increased use of public lands in the West has resulted in a number of conflicts between environmentalist groups and live-

stock permittees. Livestock grazing, however, is one of the few tools available to natural resource managers for developing and maintaining desirable plant community structure, decreasing fuel loads to decrease wildfire risks, and regulating nutrient cycling in the ecosystem.

Biodiversity is a key feature of properly functioning ecosystems, and long-term studies on grazing lands indicate that appropriate grazing management can support a relatively high level of plant species diversity. Although increased biological diversity is often a goal stated by natural resource managers, it must be considered in the context of ecosystem stability, sustainability, and the production of goods and services for humans. Increased diversity may result in decreases in certain of these other characteristics. Managers must, therefore, consider trade-offs before policies are implemented and management is changed to increase biodiversity.

Much of the grazing land in the East and irrigated pastureland in the West integrates grazing land uses with confined animal feeding. In certain areas, heavy fertilization of grazing lands results in runoff of nutrients or leaching of nutrients into groundwater. Intensifying animal production on grazing lands as an alternative to concentrating confined animal production and feeding operations may not solve certain nutrient management problems. Primary management techniques for decreasing or preventing nonpoint source pollution in grazed watersheds include management of vegetation, grazing, and nutrient application.

The environmental impacts of livestock on grazing lands can be prevented, minimized, or ameliorated by control of when, where, how long, and how intensively livestock graze on forages growing within the landscape. In the same way, proper grazing management can result in positive environmental impacts, such as control of fuel to decrease wildfires, sequestration of carbon, and maintenance of biodiversity. The key to sustainability of grazing lands is managing vegetative cover, not only to provide feed for grazing livestock but also to hold soil in place, to filter water, and to recycle nutrients.

Introduction

Constituting more than 350 million hectares (ha), grazing lands are the most widely distributed lands in the United States (Figure 1; USDA–NRCS 1997a). Livestock and forage production on grazing lands is the foundation for an agricultural industry that generates $40 billion in agricultural income from 100 million domestic ruminants annually (USDA–NASS 2001). These lands also support large populations of wildlife, supply much of the nation's water, and provide a wide array of recreational opportunities. Most rangelands, both federal and private, are west of the ninety-eighth meridian where, generally, elevation increases and annual precipitation decreases. Pasturelands in the higher-precipitation regions of the country are concentrated where soils generally are unsuited for crop production. In arid parts of the country, pasturelands often are irrigated.

Some people view livestock use of public and private grazing lands as harmful. Key issues of concern include alteration of wildlife habitat and degradation of soil, water, and environmental quality. Ecological changes on the land often are slow to appear and may take years of effective management to correct. Some current concerns about grazing lands may have their sources in the land-use practices of several decades to more than a century ago, and active management practices often are needed to restore ecosystem health. Issues are varied and complex, resulting from a myriad of interactions among land-use practices and a specific site's potential to meet the multiple goals of land managers.

This paper summarizes key scientific concepts that explain the environmental impacts and the multiple roles of livestock on grazing lands. It begins with a history of grazing lands management in the United States and discusses the role of livestock in grazing lands ecosystems. These first two sections set the stage for understanding the key issues relative to the environmental effects of livestock on grazing lands; then each key issue is discussed separately. The paper concludes with a consideration of how these issues influence decision making at the farm and ranch level.

History of Grazing Lands Management in the United States

Land-use history has a powerful influence on many ecosystem properties (Schimel et al. 2001). Thus, current issues relating to the effect of livestock on grazing lands must be viewed within a historical context of grazing lands management. *Grazing lands* are "any vegetated land that is grazed or has the potential to be grazed by animals" (Forage and Grazing Terminology Committee 1991). These lands include rangelands that incorporate livestock use into a natural system, natural meadows and rangelands planted to forage species, croplands incorporating livestock use, pastures planted to native or introduced grasses and legumes, and forestland with the potential to be grazed.

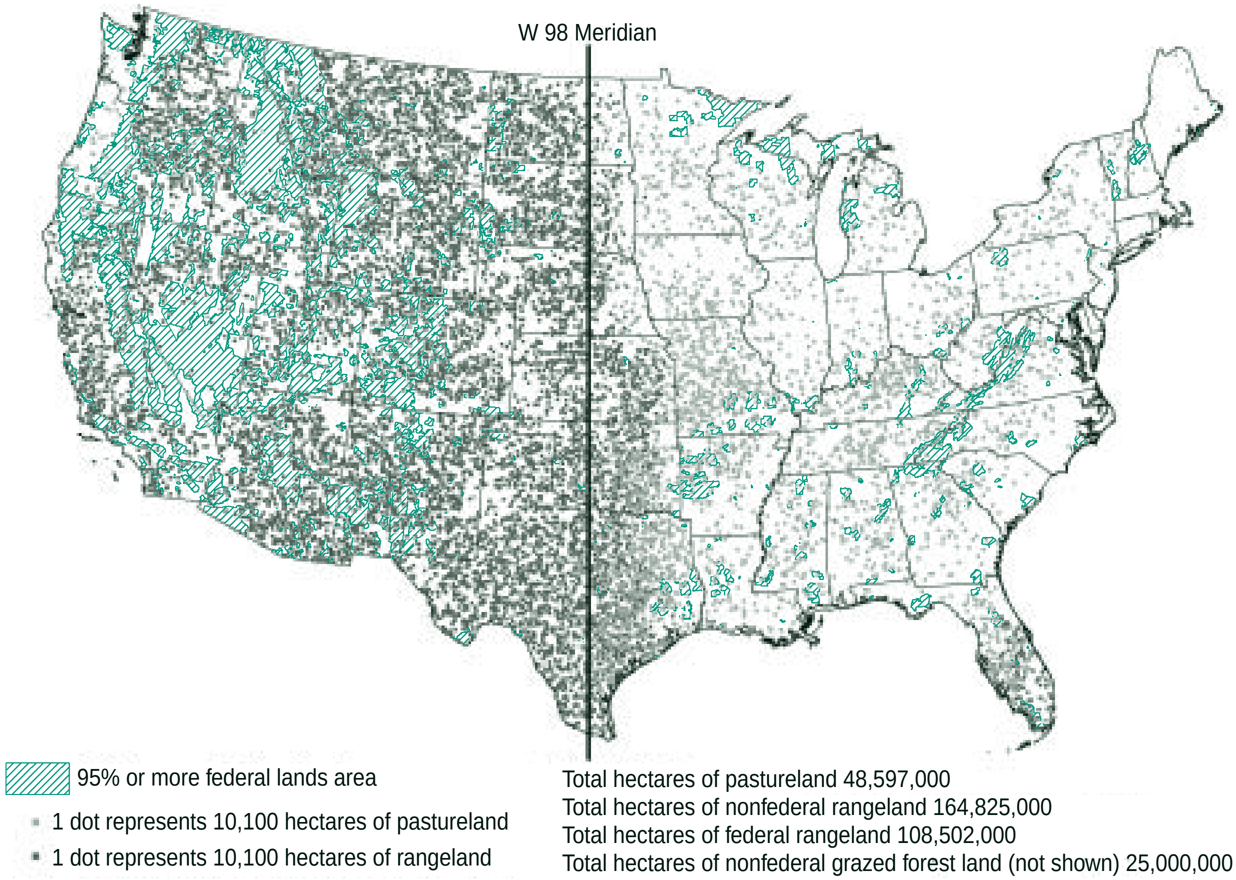

Figure 1. Hectares of pastureland and rangeland 1997. Totals include all states and possessions except Alaska. Based on USDA–NRCS 1997a.

Livestock were introduced into different parts of the United States as early as the fifteenth century and as late as the eighteenth century. Since the eighteenth century, cattle have been the dominant domestic grazing animal in the United States (Holechek, Pieper, and Herbel 1989; Maly and Wilcox 2000).

In the southeastern United States, cattle were introduced by early Spanish explorers and European settlers (Blevins 1998). By the 1800s, cattle grazing in large herds, which was a dominant land use of the piney woods from Florida to Texas (Grelen and Duvall 1966), was displaced by row-crop farming in most of the southern states, leaving the only large herds of cattle in Florida and Texas (Taylor 1995). In recent years, however, smaller livestock operations have increased in number in the southeastern states on land that was in row-crop production. From 1982 to 1992, the amount of pastureland in the Southeast increased by 100,000 ha (Conant, Paustian, and Elliott 2002). In the rangeland areas of the West and the Great Plains after the Civil War, the grazing of cattle became the dominant land use. In the north central states, dairy agriculture replaced crop production on highly erodible lands, whereas level areas with deep soils remained in crop production. Steep lands or bottom lands that could not be tilled were maintained as pastures; the steepest land reverted to forest. In the Northeast, land conversions from meadows or forests produced most grazing lands (Bromley 1935; Foster 1993).

In the western rangeland states, government policies focused on settling the land and converting vast holdings of public lands to private ownership; this practice resulted in conversion of the most productive land (usually with all its water supplies) to private ownership. These areas then became headquarters for many western ranches. Arid rangelands that surrounded the fertile watered areas remained in public ownership. Buildup of livestock and privatization of the best lands occurred, accompanied by lack of regulated grazing management in public rangelands and forests. These circumstances limited the opportunity to apply grazing management to public lands, because any forage not grazed by one operator's livestock eventually was grazed by another's. No grazing regulations on public lands existed until the Forest Reserves were formed, mostly in the early 1900s, followed by the delineation of public lands, now overseen by the Bureau of Land Management (BLM), that were managed initially under the Taylor Grazing Act of 1934.

Because of widespread overstocking during the late nineteenth and early twentieth centuries and severe drought during the 1930s, damage to the rangelands of the West caused severe deterioration of the health of western rangelands and grazed forests. Beginning in the early 1900s, experiment stations were developed to help livestock owners understand the deterioration of grazing lands and to learn how to use those lands sustainably. Grazing lands research became a part of the mission at most federal and state experiment stations in the United States throughout the twentieth century. This ecologically based research developed both the modern principles that define ecological sites and the livestock grazing practices that address specific characteristics of each type of grazing land. Research and outreach programs helped land managers improve their grazing lands management. Improved management led Box and Malechek (1987) to assert that U.S. grazing lands are in the best condition they have been in since the late nineteenth century and are continuing to improve.

Throughout the twentieth century, grazing lands were used and developed in different ways as the Industrial Age changed U.S. society. Issues relating to environmental regulations, high production costs, and competing land uses influenced historical production practices. Today, while many urbanites view pastures as a desirable use of open space (CAST 2002), grazing lands issues increasingly are interacting with urban land uses all across populated regions of the United States.

In the 1970s, significant environmental legislation affecting grazing lands was passed. Two primary laws, the Clean Water Act of 1972 and the Endangered Species Act of 1972, focused on the protection of water and endangered species, respectively. As understanding and implementation of this federal legislation increased during the 1980s and the 1990s, it has become a major influence on management strategies for both public and private grazing lands. A vast complex of land-use regulations is now in place across the United States to monitor land use and to ensure compliance with regulations protecting endangered species and water quality. Currently, state and federal agencies regulate land use across the country by an evolving blend of measures, from voluntary compliance with outcome-based requirements to enforcement of strict regulations.

Grazing as an Ecological Process

Grazing animals are a natural and integral component of most grassland ecosystems (Frank, McNaughton, and Tracy 1998). Grazing animals, known as *herbivores*, depend on plants such as grasses, *forbs* (broadleaf herbs), and shrubs for sources of energy and nutrients. Native grazers range from large herbivores such as bison, elk, deer, and antelope to small herbivores such as prairie dogs, mice, grasshoppers, and aphids. As domestic livestock (e.g., cattle, horses, sheep, and goats) have displaced certain native grazers on U.S. grazing lands, humans have assumed the role of land and forage managers, often deciding which grazers should use the forage and to what extent vegetation should be grazed.

Effects of Grazing on Plants

In many grazing lands ecosystems, more grazing occurs below the soil surface than above (Evans and Seastedt 1995). Little or no direct control is exerted on these subterranean grazers, which include soil insects, nematodes, and other organisms that may graze roots or simply suck juices from root cells (Byers and Barker 2000). Through feeding on roots, below-ground grazers also may introduce soilborne diseases into plants. Grazing effects on plants occur above ground and below ground, and often simultaneously. These effects range from the almost nondetectable to the quite severe, and the effect depends on frequency, intensity, and season of use of the plants being grazed.

At the level of an individual plant, grazing may increase, decrease, or not affect plant growth (Trlica and Rittenhouse 1992). For example, grazing may stimulate basal shoot production in grasses and lateral branching in shrubs. On the other hand, production of seed may decline while vegetative reproduction actually may increase. Certain plants have evolved defense mechanisms—such as thorns, toxic chemicals, fibrous and less nutritious tissue, altered morphology to protect growing points, and rapid regrowth after defoliation—either to avoid or to tolerate the effects of grazing (Briske and Richards 1995).

Grazing affects ecosystem development and succession, as well as plant communities within the ecosystem (Joern and Keeler 1995). Grazing land ecosystems alter in response to factors such as climatic changes over long periods, soil development, and plant and animal interactions within the system. Selective grazing can lead to changes in plant species composition, which in its turn affects the structure and function of the plant community. Effects are widespread, influencing everything from competing herbivores to microflora and microfauna. When grasses are the species preferred by herbivores, shrubs may be more competitive and eventually may dominate the system. If herbivores prefer to browse on shrubs rather than to consume herbaceous grasses and forbs, then herbaceous species may come to dominate the system. Thus, the course of change or succession often can be directed by the type of grazing animals present. When management is applied appropriately, in the correct season, and with suitable intensity, grazing can be used to manipulate vegetation to attain desired management objectives such as decreasing herbaceous plant growth and encouraging shrub growth. If conducted improperly, or when natural herbivore populations are excessive, grazing can affect ecosystem structure adversely.

There also are differences among grazing lands ecosystems in terms of their responses to grazing animals. Plant communities in grazing lands that have a long history of grazing, such as grasslands of the central Great Plains, are affected little by livestock grazing (Milchunas, Lauenroth, and Burke 1998; Sims, Singh, and Laurenroth 1978). On the other hand, ecosystems that historically have not had a grazer component may show significant changes in ecosystem structure and function in response to grazing animals (Mack and Thomas 1982).

Effects of Grazing on Water and Runoff

Grazing also influences water, nutrient cycles, and energy flow in the ecosystem. Grazing can have a negative, neutral, or positive benefit, depending on the ecosystem, environmental conditions, and grazing season and intensity. When grazing land is poorly managed, grazing can affect the hydrologic cycle by decreasing plant and litter cover, which can increase raindrop impact on the soil surface, decrease soil organic matter, and accelerate soil erosion. But grazing also can decrease the amount of water lost through transpiration by plants and thus prolong the availability of soil water for plant growth.

Treading by large herbivores may increase soil compaction, which decreases water infiltration and increases surface water runoff. Consequently, the amount of soil water available for plant use is lessened, erosion increased, and stream water quality decreased. But if grazing is well managed, negative effects are minimal and increases in soil organic matter may be greater in grazed land than in ungrazed land (Franzleubbers, Steudemann, and Wilkinson 2001). Decreased amounts of certain vegetation and litter cover may result in less rainfall interception and more available soil water for plant uses later in the growing season. In short, a number of factors interact to determine the role that grazing will play in ecosystems.

Effects of Grazing on Distribution of Nutrients

Grazing animal behavior influences the distribution of nutrients to various landscape positions. Animals may graze in one area but move to another area to rest or to drink. Dung and urine may thus be more plentiful in the resting area and around a watering place than in the grazing area, a fact affecting the soil fertility of both areas, resulting in a net transfer of nutrients from the grazed area to the resting and watering areas. Grazing promotes nutrient cycling through rapid breakdown of organic matter into smaller particles in the system, so organic matter is available more readily for soil microorganisms such as soil bacteria and fungi. Microorganisms use the organic matter as an energy source and can release nutrients back into the soil for plant uptake. Thus, grazing may increase the rate at which nutrients cycle through an ecosystem. It may be argued that if nutrients are not bound up in soil or plant matter, then they are more vulnerable to being lost from the ecosystem in runoff or erosion or through removal in animal products from the system. Management is important for ensuring that nutrient resources within the ecosystems are not depleted and that nutrients lost from the system are replenished through natural processes or by fertilizer additions.

Effects of Grazing on Carbon Sequestration

The large areas occupied by grazing lands, the diversity of their climates and soils, and the potential to improve their use and productivity all contribute to the great importance of grazing lands in sequestering C and mitigating the greenhouse effect and other aspects of global climate change (Follett, Kimble, and Lal 2001). Productive, sustainable grazing lands provide high-quality vegetation and soils, which lead to high rates of C sequestration and low levels of carbon dioxide (CO_2) emissions. The total soil C sequestration potential for U.S. grazing lands is approximately 70 million metric tons (MMT) of C/year (yr). This figure represents a store of C about 1.6 times the size of the CO_2-C emission from all other U.S. agriculture (Lal et al. 1998) and about 4.4 times the CO_2-C emission for all grazing lands agriculture. Conversion of marginal agricultural lands to grazing lands has the potential to sequester approximately 10 MMT of C/yr, which would be stored as soil organic C.

Increased soil C due to sequestration would have a positive effect on soil quality and enhance plant production. Grazing lands may be used in the future to influence the global C cycle and to take up more CO_2 from the atmosphere. With careful, appropriate management of these soils and vegetation, biomass productivity on grazing lands can be enhanced, and a significant contribution to offsetting U.S. emissions of CO_2 can be made (Conant, Paustian, and Elliott 2002; Schuman, Janzen, and Herrick 2002).

The general principles describing how grazing affects the structure of plant and animal communities in the ecosystem have been understood for many years, but now a much greater appreciation exists of how grazing can influence important processes such as the C, water, and nutrient cycles, as well as the energy flow from plants to animals to soil microbes. How livestock and wildlife on grazing lands are managed has consequences beyond those associated with certain pieces of land. Management can affect downstream water users, air quality, and even atmospheric CO_2 levels. These important lands must be managed sustainably so that natural resources remain available in perpetuity.

Key Issues

The key issues regarding the environmental effects of livestock on grazing lands include the effects on (1) soil quality, (2) water quality, (3) riparian and wetland communities, (4) invasive plant species, (5) public lands, (6) grazing and fire, (7) biological diversity, and (8) high-density livestock areas. Each issue is discussed separately in the following sections.

(1) Soil Quality

The concept of soil quality addresses the crucial role that soil processes play in any ecosystem. *Soil quality* is defined as the capacity of a specific kind of soil to function (Karlen et al. 1997). Vital soil functions include the capacities (1) to sustain biological activity, diversity, and productivity; (2) to regulate and partition water and solute flow; (3) to filter, buffer, degrade, immobilize, and detoxify organic and inorganic materials, including industrial and municipal by-products and atmospheric depositions; (4) to store and to recycle nutrients and other elements within the biosphere; and (5) to support socioeconomic structures and to protect archeological treasures associated with human habitation (Karlen et al. 1997).

Soil quality assessment is based on the evaluation of specific biological, physical, and chemical functions in soil and the change in these functions in response to natural or introduced stresses or management practices. Several soil functions related to soil quality of grazing lands are directly or indirectly affected by livestock activities, especially the level and frequency of forage plant defoliation. These soil functions include soil respiration, *infiltration* (the process of rainfall entering the soil), *bulk density* (the ratio of soil mass to bulk volume, an indicator of compaction), and *aggregate stability* (the resistance of soil aggregates to external destructive forces) (Franzleubbers, Stuedemann, and Wilkinson 2001; Franzluebbers, Wright, and Stuedemann 2000).

An appropriate level, timing, and frequency of *defoliation* (the removal of vegetation, as by herbivore consumption, clipping, and trampling) by grazing animals is a sustainable practice for grazing lands. Grazing management to achieve appropriate and sustainable levels of defoliation is necessarily site-specific and depends on climate, soil, water, nutrients, and many other considerations. Repeated grazing by both domestic and wild grazers that exceeds the ability of vegetation to tolerate such use initiates a chain of events that results in damage to the quality of vegetation, soil, and water in a grazed landscape.

Differences in soil and vegetative cover often confound comparisons of infiltration capacities among different grazing conditions. Certain grazing lands managed under light grazing can have infiltration capacities at least twice those of lands under heavy grazing (Brooks et al. 1997). Spaeth and colleagues (1996) concluded that many other qualitative soil variables (e.g., structure, texture modifiers, or pore characteristics) and plant variables (e.g., root structural characteristics, plant growth form, or plant leaf form) may be crucial to a complete understanding of these relations.

Compaction

Soil compaction is the packing together of soil particles by forces exerted at the soil surface that results in an increase in specific gravity or bulk density by decreasing pore space (Heady and Child 1994). Soil compaction by livestock is most severe in the surface 5 centimeters (cm) of soil but can extend as deep as 30 cm (Greenwood and McKenzie 2001). As grazing animals walk, their weight falls on restricted areas of their hooves, and weight per contact area can exceed *soil strength* (resistance to penetration). The amount of weight per contact area varies with livestock species. For example, the static pressure of livestock hooves on soil is greater for cattle than for sheep or horses (Greenwood and McKenzie 2001).

Animal treading may chip dry soil surfaces and compact or deform wet soils. Maximum compaction occurs at soil moisture levels of between 20 to 30% moisture-holding capacity (depending on soil type) and field capacity, as well as at high stocking densities. Wetter soils give way or deform with less compaction than those with intermediate moisture content; the depth of compaction may be greater, however, on wet soils. *Puddling* (loss of soil structure) and compaction may occur with repeated animal traffic on heavy soils. Consequently, excessive soil compaction in grazed pastures can decrease plant growth (Heady and Child 1994).

Grazing increases bulk density or decreases porosity of soil (Blackburn 1984; Heady and Child 1994; Warren, Blackburn, and Taylor 1986). But even though soil changes can result from excessive compaction during grazing, studies also have shown that natural processes such as soil wetting and drying cycles and grazing recovery periods can restore the physical condition of soil (Greenwood and McKenzie 2001; Heady and Child 1994; Weltz and Wood 1986; Wheeler et al. 2002).

Erosion

Soil erosion is the detachment and movement of soil or rock by wind, water, ice, or gravity (SSSA 1997). A vegetative cover decreased by inappropriately heavy grazing is less able to protect soil from such erosive forces. Moreover, decreased cover does not make efficient use of moisture or nutrients entering the soil through infiltration, including nutrients returned to the soil in manure. Because of the close association between surface runoff and water erosion, any grazing management practice that decreases surface runoff will decrease erosion, conserve soil moisture and nutrients for vegetation growth, and restore underground water supplies (Thurow 1991).

Streambank or Shoreline Erosion

Where livestock are allowed uncontrolled access to the tops and sides of banks, streambank and shoreline erosion increases. Streambanks often are naturally unstable because of undercutting, which results in very steep walls on the verge of collapse. The sharpness and the pressure load of livestock hooves cause banks to shear and to slough into the water (Vallentine 1990). This sloughed-off soil is eroded away by water currents or wave action, and an encroaching front of repetitive undercutting and sloughing is created. Depending on the extent of removal, receding shorelines may become mud flats. Slow-moving streams may end up in a similar condition, leading to water contamination by suspended sediment and elevated bacterial counts and nutrient levels.

The overwidening of streams and shallow areas in ponds also results in elevated water temperature (Vallentine 1990). These changes, along with increased nutrient loading, can cause algae bloom and can accelerate growth of other aquatic weeds. If blue-green algae blooms occur in stock ponds and drift into drinking areas, animals may be poisoned by the toxins produced by the blooms and may even die (Cheeke 1998).

Livestock-accelerated streambank and shoreline erosion can be prevented by provision of (1) alternative watering sites (Sheffield et al. 1997); (2) improved stream fording areas; (3) abundant forage outside the immediate banks, by control of grazing duration, timing, and forage use; (4) shade elsewhere; (5) cattle ramps to the water's edge; or (6) fences around key areas, to control or to prohibit access. Often, some combination of these techniques is used to slow erosive processes.

Fencing streams to exclude livestock can have unanticipated consequences. Fencing programs should take into consideration that wildlife may need to move through fences for migration and for access to food, water, and habitat. Streams that flood frequently can damage fences and increase repair and maintenance costs. Total exclusion will allow tree and shrub growth that eventually may result in a streamside hedgerow if not prevented actively. The hedgerow will produce shade within a few feet of the stream, inviting livestock to lounge and to concentrate urine and feces near open water. Streams in which these hedgerows have occurred also may have their channels clogged by vegetation and may change their course. Even if this does not occur, winding streams tend to move laterally, with or without livestock on their banks. As streambanks move laterally at outside curves, adjacent fences are eventually undercut and drop into the moving stream. Thus, consideration of stream dynamics is a necessary factor in managing riparian areas and livestock grazing.

Sheet and Rill Erosion

Sheet erosion is caused by the impact of raindrops on bare soil, which dislodges soil particles and keeps the finer particles suspended in a thin sheet of runoff water when the soil surface seals over (Stallings 1957). Rill erosion occurs when water becomes concentrated into small parallel flow paths created by irregularities in the soil surface. In pastures, rill erosion seldom occurs except at areas where the surface is nearly bare and steep. Sheet and rill erosion on grazing lands can be minimized or prevented by maintaining a vegetative ground cover of at least 75% (Borst, McCall, and Bell 1945; Dickerson and Rogers 1941; Smith et al. 1945).

Gully Erosion

The erosive process of gullying creates deep (> 0.5 meters [m]), incised steep-walled channels by means of the scouring action of concentrated but intermittent flows of water during or immediately after a heavy rain or rapid snowmelt (SSSA 1997; Stallings 1957). Such erosion typically occurs in concentrated flow channels or has its beginnings in heavily used livestock trails (on highly erodible soils) in pastures (Howard and Higgins 1987; USDA–SSDS 1993). Frequent, heavy cattle use of raw banks and streambeds tends to maintain gullies on hillsides. Livestock tend to graze steep (>30%) slopes by moving across the hillside (perpendicular to the slope). This grazing behavior may result in a series of narrow terraces (grazing-step terracettes) that run across the slope, creating a stairstep appearance (Howard and Higgins 1987). Terracettes also are formed by natural processes other than grazing (Buckhouse and Krueger 1981). These formations are prone to *landslip erosion* (whereby the soil slides along a shear plane).

Wind Erosion

Soil loss to wind erosion is a concern on both arid and semiarid grazing lands. Exposed or unstable soil surfaces are especially vulnerable to wind erosion. In certain semiarid grasslands, mismanagement of grazing (repeated heavy grazing) has decreased the cover of grasses, increased the cover of shrubs and the amount of bare ground, and resulted in “islands of fertility” where soil nutrients are concentrated beneath shrubs. The bare ground between shrubs is susceptible to wind erosion, further exacerbating degradation (Schlesinger et al. 1990). Factors stabilizing the soil surface include vegetative cover, plant litter, and biological crusts.

A *biological crust* is a community of living organisms formed by a large number of microorganisms and nonvascular plant species (algae, bacteria, fungi, lichens, and moss). Biological crusts have been recognized recently as important components of the soil surface flora in arid and semiarid rangelands (Harper and Marble 1988; Jones, Wicklow-Howard, and Pellent 1999). The importance of these organisms has been related to soil surface stabilization (Belnap and Gillette 1998), water infiltration (Brotherson and Rushforth 1983), and nitrogen (N) fixation (Evans 1996; Evans and Ehleringer 1993). Grazing *ungulates* (hoofed mammals) may disturb these crusts, and their restoration can take several years depending on the extent of disturbance (Harper and Marble 1988). Currently, most knowledge pertains to localized areas or situations; general principles to predict the broader importance and value of biological crusts are under development.

(2) Water Quality

Water quality involves many individual components and chemical constituents. A *water quality standard* refers to the physical, chemical, or biological characteristics of water in relation to a specific use (Brooks et al. 1997). For example, water quality standards for irrigation are different from those for drinking water. The term *polluted* indicates that water has been degraded in some way by human actions or inactions. Water quality degradation also can result from natural events such as large rainstorms (Brooks et al. 1997).

Most water quality degradation that occurs on grazing lands is characterized as “nonpoint source” rather than “point source” pollution. *Point source pollution* is associated with industries and municipalities and refers to the discharge of pollutants to natural waters through a pipe or ditch. *Nonpoint source pollution* refers to pollution that occurs over a wide area and usually is associated with land-use activities. *Best management practices* (BMP) often are selected as an approach to controlling nonpoint source pollution on managed land. The BMP approach involves identification and implementation of land-use practices that prevent or decrease nonpoint source pollution (Brooks et al. 1997; Brown, Brown, and Binkley 1993).

Surface Water and Groundwater

Except where prolonged heavy grazing occurs, grazing generally does not have a significant effect on the sediment or dissolved chemical constituents in surface water. But when grazing animals become concentrated near water bodies, or when they have unrestricted long-term access to streams for watering, sediment and nutrient loading can be high and the bacteriological quality of surface water can be affected adversely (Brooks et al. 1997; Thurow 1991).

Groundwater occurs in saturated zones beneath the soil surface and is generally of higher quality than surface water (Brooks et al. 1997). There is, however, a heightened likelihood of N and phosphorus (P) losses from overfertilized pastures through surface water runoff or percolation past the root zone (Schmidt and Sturgul 1989; Stout et al. 2000). But landscape position and depth to a shallow water table determine whether surface runoff or subsurface flow carries N and P to the receiving water body (Gburek and Sharpley 1998). If manure or sludge is applied to pastures only as something to discard or to meet crop N requirements, then other nutrients often are applied that are not needed. This excessive fertilization can elevate levels of soil nutrients such as N and P, which in excess can escape to surface water or leach into groundwater.

Soil nutrient distribution in grazing lands can be highly heterogeneous. Grazing animals return ingested nutrients to the land in highly concentrated patches through the natural processes of defecation and urination. Nutrient concentration also depends on how skewed the distribution of urine patches and dung pats is relative to shade, feeding areas, watering sites, and comfort zones closest to natural water courses or groundwater tables (West et al. 1989). Livestock concentrated in areas near permanent shade, watering areas, and feeding stations can enrich the soil within a 30-m radius (Franzluebbers, Stuedemann, and Schomberg 2000). Grazing management, however, can result in better distribution of nutrients throughout the pasture.

Microbial pathogens and organics are components of animal waste as well (Pell 1997) and can become contaminants of surface waters present in or downstream of pastures, especially when livestock are allowed to congregate in areas adjacent to water courses (Trlica et al. 2000). Manure and urine spots are more frequent, the soil surface more compacted, and vegetation thinner or more likely to be absent in such areas. This combination of concentrated animal waste and ideal runoff conditions can lead to significant downstream loadings at the initiation of runoff. Animal concentration areas can be avoided by providing more-frequent watering facilities and feeding areas away from water bodies. If shade or shelter is provided, it should be located away from drainage courses so that an intervening vegetative filter can remove most contaminants or absorb runoff before it reaches a water body (Franzluebbers, Stuedemann, and Schomberg 2000).

(3) Riparian and Wetland Plant Communities

Riparian and wetland systems are biologically diverse and hydrologically important features of watersheds. *Riparian communities* consist of plants growing adjacent to streams or lakes and often have root systems in or near the water table; these communities occur in both wet and dry climates. Riparian vegetation is valuable for the protection of streambanks and shorelines, the preservation of wildlife habitat, and the protection of adjacent aquatic ecosystems (Brooks et al. 1997).

Because riparian and wetland systems are biologically diverse and hydrologically important features of watersheds, heavy grazing in riparian and other wetland communities can have a significant effect on surface-water and groundwater quality (Brooks et al. 1997). Additionally, management solutions for protection of riparian and wetland systems must include consideration of the interdependence between hydrologic processes operating both on uplands and in stream channels (Heady and Child 1994).

Alteration of riparian vegetation by mismanaged grazing animals can have significant effects on aquatic life. Riparian zone vegetation can influence water quality in small tributary streams by creating shade that extends during midday over most of the channel. Shading may moderate water temperature, which may be important in maintaining a salmonid fishery on streams capable of supporting those species. Shade also is important for warm-water game species such as smallmouth bass. High water temperatures in streams favor the survival of rough fish such as suckers and carp at the expense of game fish (Palone 1990).

Degraded riparian areas in grazing lands can result in elevated sediment loads in streams. Excessive sediment in the streambed can damage spawning grounds by smothering incubating fish eggs and newly hatched juveniles. Excessive sediment also affects habitat for many beneficial aquatic insects that are food sources for game fish. As little as 200 parts per million (ppm) of suspended sediment can abrade fish gills, decreasing their ability to absorb oxygen and weakening affected fish. At 20,000 ppm, sediment can clog gill filaments, prevent water circulation through the gills, and suffocate fish (Welsch 1992). Much of this sediment can come from bank erosion along streams in which substantial amounts of riparian vegetation have been lost (Colman 1953; Wohl and Carline 1996).

(4) Invasive Plant Species

Invasive plant species threaten the productivity, stability, and ecological functioning of many grazing lands in the western United States (CAST 2000). Weeds invading U.S. grazing lands originated primarily in Europe and Asia (Sheley, Petroff, and Borman

1999). Most were accidentally introduced into western grazing lands during the nineteenth century and, after various periods of initial colonization, are now spreading rapidly to occupy available habitat. These weeds include annual grasses such as cheatgrass (*Bromus tectorum*) and Medusahead (*Taeniatherum caput-medusae*), as well as several species of thistle (*Carduus* and *Cirsium* spp.), the knapweed complex (*Centaurea* spp.), leafy spurge (*Euphorbia esula*), rush skeletonweed (*Chondrilla juncea*), sulfur cinquefoil (*Potentilla recta*), perennial whitetop (*Lepidium latifolium*), and hoary cress (*Cardaria draba*).

Some plant species classified as invasive in certain ecosystems (e.g., Kentucky bluegrass in native grasslands) are actually desired forage species in other grazing lands. For example, introduced forage species grow on most of the grazing lands of the eastern United States and irrigated pastures in the western states. These introduced, highly productive forage species are key to sustained use of grazing lands in these regions. But certain introduced species, such as common bermudagrass (*Cynodon dactylon*), johnsongrass (*Sorghum halapense*), and quackgrass (*Elytrigia repens*), have become invasive weeds on croplands and other nongrazed areas. Proper grazing management contributes to the persistence of desired forages whereas poor management (heavy grazing and poor timing) hastens the demise of preferred forages and promotes their replacement by invasive species (Archer and Smeins 1991).

Successful weed management on grazing lands requires the development and application of low-maintenance strategies that are site-specific and focused on the management of plant succession (Larson, McInnis, and Kiemnec 1997; Sheley, Svejcar, and Maxwell 1996). Strategies include the use of traditional weed management tools (herbicide and mechanical treatments), as well as the integration of biocontrol, revegetation, and grazing techniques to achieve long-term management goals.

A number of social issues must be addressed before long-term management goals can be set and management strategies developed to control invasive species on grazing lands. What is the degree to which weed invasion can occur on grazing lands before it compromises production and aesthetic goals? If the current rate of weed invasion is unacceptable, what is the societal commitment to weed management in terms of herbicide use, revegetation with nonnative species, introduction of biological controls, and use of domestic livestock to direct and to maintain a level of plant succession? Weed invasion on grazing lands will continue unabated if these questions cannot be answered in a manner that facilitates effective management.

(5) Public Lands

Livestock grazing on public lands has become a major environmental quality concern and a political issue in states with significant areas devoted to public lands. These issues were discussed in depth in a previous Council for Agricultural Science and Technology report (1996). In most western states, public lands managed by federal agencies such as the BLM, the U. S. Department of Agriculture's Forest Service, the U.S. Fish and Wildlife Service, and the National Park Service account for a large part of the total land area. These agencies often have different policies regarding livestock grazing, from exclusion to managed grazing allotments whereby grazing is permitted to individuals for extended periods.

Although much less extensive than in the West, public grazing lands in the eastern United States face similar pressures. Many rural families depend on federal grazing permits for production of forage used by private livestock herds. The arid and semiarid grazing lands in the West have been identified as vulnerable to degradation if grazing is excessive or poorly timed. Damaged arid and semiarid grazing lands require many years to recover or may never return to previous vegetative states (Cook and Child 1971; Westoby, Walker, and Noy-Meir 1989). Consequently, public land managers and private ranchers have developed a high level of cooperation to sustain the production of public lands.

Increased use of public lands in the West has resulted in many conflicts between environmentalist groups and livestock permittees. Certain groups consider livestock grazing a destructive use of public lands and request that livestock be removed. Yet any use of public lands, including recreational, can cause resource damage if uncontrolled. Livestock grazing is one of the few tools available to natural resource managers for vegetation manipulation, which can be important for (1) production of a desirable plant community structure, (2) decreased fuel loads to decrease wildfire risks, and (3) regulation of nutrient cycling in the ecosystem. In certain instances, livestock grazing also can aid control of weedy species.

(6) Grazing and Fire

Grazing of domestic livestock is a valuable tool when dealing with both planned burning for land management and wildfires. Planning the timing and intensity of grazing to influence the *fuel loads* (weight of fuel per unit area) of an area is a valuable consideration in planning for the use of prescribed burning (USDA–NRCS 1997b, 2000, 2002). In most rangeland and pastureland situations, a minimum of 670 to 1,120 kilograms (kg)/ha of *continuous fine fuel* (fuel that ignites readily and is consumed rapidly by fire) is needed to conduct a prescribed burn. A fuel load of 3,370 to 4,500 kg/ha usually is optimal and provides the greatest flexibility in planning the burn (Wright and Bailey 1982). Livestock grazing can be managed to achieve these fuel loads by applying the grazing based on a plan that balances the need for animal forage with an optimal fuel load.

Grazing also can be managed to decrease the damage done by wildfires. A minimum of 340 kg/ha of continuous fine fuel generally is needed for a wildfire to carry on most grazing lands (Wright and Bailey 1982). Planning the grazing treatment to decrease fuel loads or to cause discontinuities in the fuel bed, thus limiting the spread of unplanned fires during the wildfire season, can be an effective tool in decreasing wildfire frequency and severity (USDA–NRCS 2000).

(7) Biological Diversity

The mix of species in an area, their abundance, and their population interactions determine biological diversity (West 1993). In the past, grazing lands managers often did not consider biological diversity when livestock production was the primary objective. Often, diversity was decreased by means of mechanical and chemical control of shrubby species followed by the planting of introduced grasses such as crested wheatgrass (*Agropyron desertorum*) and Russian wildrye (*Psathyrostachys juncea*). Such methods sometimes resulted in stands of a single grass species over large areas. Certain crested wheatgrass stands have existed in the intermountain area for more than 50 yr, with little invasion by native plant species. These monotypic stands of grass often have been useful for spring-fall grazing by domestic livestock but have low value for wildlife and other uses. Because seed for many native species now is available that was unavailable 20 yr ago, revegetation efforts today often involve the use of native species.

Biodiversity is recognized as a key attribute of properly functioning ecosystems (Tilman 1999), and long-term studies on western and eastern grazing lands indicate that appropriate grazing management can support a relatively high level of plant species diversity (Hart 2001; Milchunas, Lauenroth, and Burke 1998; Sanderson et al. 2001; Tracy and Sanderson 2000). Excluding grazing animals from ecosystems that evolved with grazing may decrease biodiversity through competitive exclusion of certain plant species. But where drought and uncontrolled heavy grazing have caused degradation, allowing the ecosystem to recover from grazing may increase plant species diversity (Anderson and Inouye 2001).

Although increased biological diversity often is a goal stated by natural resource managers, it must be considered in the contexts of ecosystem stability and sustainability and of the production of goods and services for humans. Increased diversity may result in decreases in certain of these other characteristics. Managers must, therefore, consider trade-offs before policies are implemented and management is changed to increase diversity. Increased diversity may not be desirable if invasive species increase or if a habitat is modified so as to decrease a service such as the yield of water to fill a reservoir or to replenish an aquifer.

(8) High-Density Livestock Areas

Much of the grazing land in the East and irrigated pastureland in the West integrates grazing land uses with confined animal feeding. In areas such as the northcentral United States, animal waste is placed on croplands as fertilizer, but in areas such as the Southeast there is insufficient cropland to use all the animal waste, so it also is spread on pastures. In certain areas, heavy fertilization of grazing lands results in runoff of nutrients or leaching of nutrients into groundwater. These situations are site-specific and soil-specific and need careful consideration to prevent impairment of water quality when management strategies are developed.

Because a living animal instead of a machine harvests the forage, nutrient management in grazing systems may be more complex than in forage-livestock operations where the forage is mechanically harvested and stored. With the stored forage system, there is the potential for efficient control of nutrients moving from the field to the barn, and back to the field. Forage nutrients are packaged in a bale or silo and fed in a barn or corral, and waste nutrients are collected for spreading on a field (where some control over nutrients is again lost). But with grazing animals, there is less control of where and when waste nutrients from feces and urine are deposited in the pasture, a condition that results in a very heterogenous distribution of nutrients (Afzal and Adams 1992; West et al. 1989).

As much as 75 to 95% of the nutrients that the grazing animal eats as herbage and supplement may be returned to the pasture in feces and urine, deposited in highly concentrated patches (Whitehead 1995). Because the solubility and concentration of N in urine are much greater than in feces, N leaching beneath urine patches is potentially much greater than leaching beneath fecal patches. Depending on the quality of the forage and the size of the animal, an effective N application rate beneath a urine patch is approximately 700 to 1,000 kg N per ha (kg ha^{-1}). The forage plants within the area affected by urine are unable to use the concentrated N fully. Plant use efficiencies are only 16 to 30% for N deposited in urine (Stout et al. 2000). Thus, a large portion of the N in urine is susceptible to leaching or gaseous losses.

Nitrogen losses from intensively managed grazing systems are related to stocking density and N inputs. As N input (regardless of source) and stocking density of the system increase, N losses also increase (Cuttle, Scurlock, and Davis 1998; Jarvis, Wilkins, and Pain 1996). The ultimate method of controlling N loss is to decrease N inputs into the system; however, this strategy also may limit the economic returns of the operations.

Cattle-grazing on pastures managed at low intensity (continuous stocking, no fertilizer input, low stocking rates) has little effect on surface water quality (Owens, Edwards, and Van Keuren 1989). More-intensive management (increased N fertilizer, higher stocking rates) on improved cool-season grass pastures may increase nitrate-N (NO_3-N) levels in groundwater, depending on the soil (Owens, Edwards, and Van Keuren 1992, 1994). Because of low P inputs, P losses through surface runoff are relatively small (1 to 1.5 kg ha^{-1} yr^{-1}) from pastures managed at a low intensity (Owens, Van Keuren, and Edwards 1998). Fertilizer P application contributes much more P to surface runoff water than P from grazing cattle (Nash et al. 2000). Dissolved forms of P generally dominate P export from well-managed pastures. Vegetative cover limits soil erosion and P export associated with particulates and sediments. The amount of P exported therefore depends on the desorption-dissolution reactions governing P release from soil, litter, herbage, fertilizer, and excreta (Nash et al. 2000).

Intensifying animal production on grazing lands as an alternative to concentrating confined animal production and feeding operations may not solve certain nutrient management problems. Primary management techniques for decreasing or preventing nonpoint source pollution in grazed watersheds include management of vegetation, grazing, and nutrient application (Nelson, Cotsaris, and Oades 1996). Decreasing grazing pressure and increasing vegetative cover on pastures can decrease nutrient export. Grazing management should encourage uniform grazing and minimize loafing or idling time by limiting the congregating of animals in areas where wastes can affect water quality adversely. In this way, manure nutrient distribution and nutrient cycling in pastures will be improved through a decrease in the transfer of nutrients from pastures to either unproductive areas or receiving waters.

Incorporating Environmental Impact Criteria into Management Decisions

In discussions of the potential environmental effects of livestock on grazing lands, it is clear that management is the key to preventing, minimizing, or ameliorating the effects. Land managers increasingly are required to consider the environmental effects of grazing lands management in their decision-making processes.

Grazing lands managers make decisions daily that affect lands’ long-term and short-term ability to meet both ecological and business goals. The factors that managers use to make these decisions have been the subject of several studies (e.g., Hanselka et al. 1990). New tools have been developed to aid land managers in monitoring the health or condition of grazing lands. Agencies within the U.S. Departments of Interior and Agriculture have developed a guide to monitoring and interpreting indicators of rangeland health (USDI–BLM 2000). This tool is designed to help land managers identify areas that are potentially at risk of degradation and to provide early warnings of potential problems. Similarly, the U.S. Department of Agriculture–Natural Resources Conservation Service has developed a tool for monitoring the condition of pasturelands for the purposes of (1) evaluating current pasture productivity and the stability of its plant community, soil, and water resources and (2) identifying what treatment needs, if any, are required to improve a pasture’s productivity and to protect soil, water, and air quality (Cosgrove, Undersander, and Cropper 2001).

Grazing lands managers must learn to recognize and to integrate ecological relations to achieve short- and long-term objectives. The availability of information and data is an important part of the decision-making process. Decisions seem to be based frequently on perceptions of current or past resource conditions (Rowan, Ladewig, and White 1994) and seldom on quantifiable monitoring data (Hanselka et al. 1990). Modern management requires an integration of experiential or professional resource knowledge with science as a foundation and with monitoring to provide a sound base for improvement in management practices.

To assist managers in the proper use and integration of the different types of knowledge, Krueger and Kelley (2000) have proposed a classification system for literature in the natural resources disciplines. The proposed system does not imply anything about the quality of information used in the classification process, but it does point to the need to distinguish scientific from experiential reports so that each can be used under appropriate circumstances. The researchers suggest classification criteria to reference published reports as examples of either professional resource knowledge or science.

Rowan, White, and Conner (1994) noted that rangeland operators consider improved livestock performance the most important benefit associated with initiating a grazing program. These researchers also found that ranchers considered forage issues the most important influence on annual stocking rate. This finding suggests that livestock performance goals and objectives must be incorporated into a forage supply inventory to enable decision makers to develop management alternatives and to make decisions regarding land management.

Conclusion

Domestic livestock have been an important component of grazing lands in the United States throughout its 200-yr history. As society changed over the last two centuries, livestock production on grazing lands has changed likewise. In the late twentieth century, society as a whole became increasingly concerned with environmental quality. Grazing lands management evolved substantially throughout the twentieth century and, by its end, the overall condition of grazing lands was much better than it had been when the 1900s began. Modern grazing lands management is based on effective tools that allow economical production of livestock in a myriad of sustainable land management systems. The general principles describing how grazing affects the structure of plant and animal communities in the ecosystem have been understood for many years. But now a much greater appreciation exists of how grazing can influence important processes such as the C cycle, water, and nutrient cycles, as well as energy flow from plants to animals to soil microbes.

As a new century of grazing lands management begins, there is an urgent need for new tools and technology that synthesize existing knowledge to aid land managers in assessing and monitoring the status of grazing lands. New knowledge is needed to identify lands at risk of degradation, to forecast and to communicate early warnings of potential problems, and to prescribe treatments or management practices needed to protect the natural resources while maintaining an economically viable operation. These tools will require new knowledge of the extensive natural variation in soils, plants, animals, and weather across both time and space in grazing lands ecosystems and a greater understanding of how these components interact in relation to the multiple roles of grazing livestock.

The overall trend of land improvement and the modern land manager's emphasis on a sustainable land ethic is encouraging. The continuing development of science and experience in managing grazing lands should enable producers to maintain or to enhance environmental quality while feeding the nation.

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