GRAZING SYSTEMS ECOLOGY: A PHILOSOPHICAL FRAMEWORK

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ABSTRACT

Grazed ecosystems are generally complex, and the human decision-making process is an integral part of ecosystem function and structure. Establishing a vision of what the landscape should look like and understanding which ecological processes can be controlled by the human decision process are critical to the success of grazing systems. We define grazing systems as planned grazing programs which address strategic issues of stocking levels and animal types, tactical responses to accommodate variability, and monitoring of impact on resources. These grazing programs should be based on our understanding of animal and vegetation ecology, hydrology and animal nutrition/husbandry. Such systems must be evaluated in the context of hierarchical relationships embodied in the concept of SWAPAH (soil, water, atmosphere, plant, animal, human). Recent developments in decision support systems mean that we can account for selective grazing and vegetation response at several scales. However, we need an integrated ecological framework for identifying situations where grazing, or other processes, are driving vegetation change. The role of information technologies linked with properly targeted ecological research must enter the dialogue of the agricultural community. Issues of packaging, delivery and connectivity must be addressed in a manner that is conducive to addressing relevant grazing land issues that are valued by society.

KEYWORDS

grazing, decision-making, monitoring, ecosystems, hydrology, information technology

INTRODUCTION

Grazing systems serve multiple goals to meet management objectives. Once a proper stocking rate has been established relative to the desired mix of domestic and wild herbivores, a grazing regime can be designed which facilitates desired effects. Too often we get the cart before the horse and debate grazing systems without paying attention to management goals, resource capacity, proper stocking rates and the financial state of the individual animal. Grazing systems allow for fine-tuning of management practices, matching the skills of the manager with the nature of the resource and enterprise selected.

We define grazing systems as those planned grazing programs which address goals and skills of management, consider strategic stocking levels of the ecosystem in question, allow for tactical manipulation to meet management goals, and allow for monitoring and timely operational adjustments due to changes in weather, markets, laws, disease and personal conditions. Grazing systems should be viewed more in the light of grazing strategies designed to meet long-term goals of management. There is much to be gained by moving the analytical process to visioning of landscapes, assessing ecological processes critical to meeting a landscape goal, integrating management practices and adjusting livestock timing and stocking levels as environmental and market conditions warrant. Each property is unique in terms of resources, land form, economic stability, and managerial skills (Danckwerts et al., 1993). Grazing management must be flexible enough to accommodate a high degree of complexity. The challenge for scientists and land managers is to develop a greater understanding of ecological processes to better design effective grazing regimes.

Over the past 50 years, a wide variety of grazing systems have been devised for grazing lands worldwide (Heitschmidt and Taylor, 1991). Rotational grazing regimes first emerged from planted pastures exhibiting a high degree of stability in parts of the world with high and reliable rainfall, good soil fertility and water holding capacity and good demand for the animal products (milk, meat, fibre) produced from those lands, e.g. ryegrass-clover pastures of the United Kingdom and New Zealand. Rotational grazing strategies were devised to improve efficiency of harvest, limit patch grazing, enhance nutrient acquisition and utilization and improve management's ability to control frequency and intensity of grazing in a relatively simple vegetation matrix on small landscapes. The primary goal was to manage inputs into the system in a cost-efficient manner given the level of market demand and price subsidies.

During this same period, rangeland scientists in the USA, South Africa and Zimbabwe began a series of grazing studies designed to convert plant communities from a low ecological state to one possessing more productive and palatable species of a higher ecological state (as reviewed by Heitschmidt and Taylor, 1991; Heady and Childs, 1994). The goal was not initially to improve harvest efficiency, but to change the composition of vegetation on offer to the animal, eg. induce upward trend in ecological condition. A basic tenet of these studies was that regular resting of rangeland is essential to maintain or improve range condition. Regular resting via some form of rotational grazing has become a standard part of the rangeland discipline in South Africa and North America. Recent reviews reveal the lack of evidence behind some of the dogma associated with such grazing systems and have shifted the emphasis to the overriding impact of stocking rate, spatial distribution of grazing, animal type, fire and tactical resting (Pieper and Heitschmidt, 1988).

In recent times, much attention has been given to the feasibility of using high stocking rates on rangelands in conjunction with intensive rotational grazing systems commonly referred to as "short-duration" or "time-controlled" grazing systems (Pieper and Heitschmidt, 1988). Evidence to support these systems is equivocal, although several authors have contended that modest increases in stocking rate can be attained over moderate stocking levels in years with average or above-average rainfall due to improved harvest efficiency of leaf turnover and improved livestock distribution. However, these management-intensive grazing systems require good skills in judging graze:rest sequences, given the higher stock density or animal effect within the paddock. Greater control and flexibility is provided by these multi-pasture systems but greater risk of management errors is also incurred (Roberts, 1993). Therefore, managerial ability is as much a part of grazing system design as biology, husbandry and economics.

This paper attempts to address some of the critical ecological concepts driving "outcome" from grazing systems. The framework used to address these concepts will be in the context of hierarchical relationships embodied in the concept SWAPAH (Soil, Water, Atmosphere, Plants, Animals, Humans) (Stuth et al., 1993). Figure 1 provides a generalized view of the SWAPAH, depicting a hierarchical representation of various driving forces affecting structure and function of grazed ecosystems managed by humans.

HUMAN ACTIONS IN GRAZING SYSTEMS ECOLOGY

Grazing systems are a product of human thoughts, decisions and actions and therefore, humans must be considered an integral part of ecosystem function. Management implies control, whether informed or ignorant of ecological processes. Decisions are based on the goals and objectives of management relative to a hierarchy of needs, either for the individual or the firm, and on the perception of external and internal processes (ecological, weather, market) which shape those decisions (Stuth et al., 1991).

We believe that the process of "landscape visioning" is critical to the success of any grazing system, i.e. developing a perspective of the desired future landscape relative to current conditions and placing a timeline on the emergence of the envisioned landscape. How quickly desired landscapes emerge is dependent on the amount of effort (energy, money) and time that management is willing to allocate to the process which will reflect, in turn, the perceived importance of vegetation/soil conditions to meeting the hierarchy of needs for the firm or individual.

Hierarchy of needs can be classed into need for 1) survival (staying alive in the case of the individual or staying in business in the case of the firm), 2) establishing a minimum standard of living, 3) avoidance of catastrophic losses (taking actions that have short-term inefficiencies (time and money) to protect the long-term survival of the individual or firm, eg. haymaking, insurance, predator control), and 4) in the case of the individual, seeking a higher meaning in life (learning, improving quality of life, giving to others, inventing) or in the case of firms, improving operations, investing in advanced technologies, and/or diversifying. Within this decision framework, decision-making is driven by perception of current conditions, likely outcomes and needed actions to meet an individual's or firm's "view" of the world. Perception is shaped by personal experiences throughout life, the level and kind of knowledge acquired, social and cultural values and constraints, the life stage of the individual and needs for intergenerational transfer of wealth and knowledge. Regardless of the state of knowledge concerning ecological processes and their impact on grazing systems, we must accept that the human who owns and/or controls use of the land ultimately impacts ecosystem processes, on and off site. **How we transfer ecological knowledge to the decision maker and get that knowledge internalized to influence their actions is still a major ecological issue, just as much as understanding how the grazing animal impacts the system and subsequent reaction of plants, soils and hydrological processes.**

Worldwide, there is large variation in the potential degree of human interference in the diet selection process among the large array of livestock production systems (Table 1). Animals set-stocked within large paddocks are constrained more by spatial configuration of land types relative to water locations, patterns of vegetation and configurations of shelter rather than by diet preference per se. With increasing intensity of use comes greater sub-division of land into smaller paddocks, providing opportunities for controlling access of livestock to plant communities or land systems. Grazing impacts of animals are controlled even more through herding and tethered grazing practices. The ultimate control over the diet selection process comes from zero-based or confined feeding of animals where the human essentially selects the animals diets. As population density of humans increases, there is increasing pressure on grazing lands, and therefore greater needs for ecologically-based planning of grazing management.

Most grazing research has focused on manipulating spatial and temporal use of subdivided landscapes and manipulating competitive interactions between plant species through managing the diet selection process. However, as the amount of land area available for livestock diminishes and the degree of human intervention in the diet process increases, smaller scale processes such as patch grazing and nutrient cycling/availability increase in importance within the research agenda.

MANAGEMENT MUST SET GOALS

Traditional emphasis on the design of grazing systems has focused on manipulating rest and grazing intensity for maximum livestock production per unit of land area. However, we find little acceptance and application of the narrow set of grazing "systems" that have been developed in the research community. The very act of conducting research on grazing systems makes the assumption that all landscapes are the same (no significant replication effect), and that motivation for grazing systems are essentially the same across landholdings. Our experience with most planning environments indicate that land resources are unique to each landholder and motivation for manipulating grazing varies with human need and goals (see also Danckwerts et al., 1993). Each property or landholding offers such a complex decision making environment, that "fixed" grazing strategies often employed in research systems have limited extension to livestock producers. The list below outlines common motivations for designing and implementing grazing systems. In many cases, all of the reasons listed below are driving the decision process, and many are interdependent:

- Improve Profitability
- Sustain Operations
- Drive Successional Change in a Desired Direction
- Facilitate Implementation of Other Management Practices
- Facilitate Other Enterprises (Profit Centers)
- Enhance Wildlife Habitat or Recreational Experience
- Respond to Environmental Issues (water quality and quantity, biodiversity)

We believe that grazing systems represent the interface between grazing management planning and our understanding of grazing behavior, vegetation ecology, ecophysiology, hydrology, animal nutrition, and range economics. Therefore, the land manager must consider all elements of the planning process, of which the issue of grazing method (continuous, rotational, or tactical spelling) is only one consideration (Table 2).

Not all resource managers are interested in just livestock production. Recently, environmental organizations, such as the Texas Nature Conservancy, have expressed interest in using livestock grazing to manage biodiversity. In some areas, grazing can alter competitive relationships to enhance diversity through differential disturbance of preferred species (Milchunas et al., 1988). Production- oriented managers usually want to maximize distribution of livestock across the landscape, while managers who focus on plant diversity may want livestock grazing to have a heterogeneous distribution creating a variety of patches from heavily grazed to ungrazed (Fuhlendorf, 1996).

Thus, planned grazing management operates in a range of production systems and with a diversity of management goals. In all cases, however, there are only a limited number of means of controlling the grazing process.

CONTROL AND INFLUENCE OF THE GRAZING PROCESS

Set base stocking rate. Establishing a base stocking rate or carrying capacity is the most critical decision affecting the success of a grazing system and its subsequent impact on ecological processes. The importance of overall grazing pressure far exceeds that of grazing method (eg. continuous vs. rotational). As most enterprises have only limited ability to adjust seasonal or annual stock numbers to match forage supply, the base stocking rate represents the expectation of the number of animals that can be safely carried in most years. As such, the base stocking rate integrates the manager's understanding of climate, land capability, land condition, animal distribution and animal demand with his/her attitude to risk. Risk, in this context, should refer to the degree of security desired with respect to both (1) adequacy of forage supply to meet nutrient demand (a feed-budgeting perspective), and (2) maintenance of the land's capability to grow useful forage (an ecological perspective). Although these aspects of risk are interdependent, the more immediate urgency of the former in relation to short-term economic performance tends to result in the latter aspect of risk being overlooked or ignored, often leading to overstocking and, subsequently, to land degradation in the medium to longer term.

An example of this scenario is the mulga (*Acacia aneura*) lands of south-west Queensland. Widespread land degradation, combined with depressed commodity prices, have motivated a government-sponsored reconstruction scheme that seeks buildup in property size and, hopefully, lower overall grazing pressure. As part of this scheme, a carrying capacity calculator, integrating climate, plant growth and land condition knowledge, has been developed and validated on properties with a history of safe stocking levels (Johnston et al., in press). It is hoped that this information will form the basis of revamped grazing management plans.

As scale of paddocks increases and/or vegetation diversity (within and between landscapes) increases, the inherent level of secondary productivity may increase and the sensitivity of production to grazing pressure may decrease. Thus, steer growth rates measured on commercial paddocks appear to exceed expectations based on small-scale experiments (Quirk et al., 1996). Also, the decline in animal performance with increasing stocking pressure of rangelands at commercial scales of operation may be somewhat less than expected from stocking rate trials conducted at small scales or with planted pastures (Ash and Stafford Smith, in press). If management is focussed on animal condition, then this lack of sensitivity may contribute to choice of stocking levels that are not ecologically sustainable in the medium to longer term.

Match animals with the environment. Productivity from a given grazing environment, and consequences for ecological processes, are strongly influenced by the degree of matching of animal species to the vegetation structure and composition, to the climate, and to the array of endemic predators, parasites, and diseases. Animal scientists have often emphasized the selection of species, breeds and genotypes that require minimal husbandry input while still satisfying product specifications. However, this has not always been matched with concern for effects on the environment. For example, land condition in tropical eucalypt woodlands in north-east Australia has declined dramatically over the past 20 years, associated with replacement of less adapted *Bos taurus* cattle with *Bos indicus* breeds and greater usage of molasses-urea supplements. The lower basal metabolic rate and more efficient nitrogen recycling of *Bos indicus* animals (Frisch and Vercoe, 1977), together with ready availability of supplement, resulted in better dry-season performance and ability to survive long dry periods, i.e. animal productivity could be sustained, at least in the short-term, with much higher utilization levels of forage. This effectively removed the traditional husbandry incentives for conservative stocking and, together with depressed markets, led to increases (up to double) in base stocking rates and widespread land degradation following a series of dry years (Gardener et al., 1990).

How does one determine the optimal mix of different animal species for a given landscape? Animal species have an evolutionary predisposition to particular foraging strategies and diet preferences. The functional nature of diet selectivity, its ultimate consequences for genetic fitness, and its proximate causes are well documented (eg, Provenza, 1995). However, the impact of this knowledge on natural resource management is equivocal. There exists a hierarchy of physical and vegetative factors that interact with the foraging strategies of different herbivores to determine forage demand at the species level. Recent development of decision support systems has provided planners with the capability to characterize landscape configurations and the composition of plant communities, and compute appropriate stocking rates for various combinations of wildlife and livestock species (Ranching Systems Group, 1994). A preference-based stocking calculator was recently enhanced by Quirk and Stuth (1995), providing the capability to assess impact of selective grazing on complex landscapes. The Ranching Systems Group has linked equations of Quirk (1995) with the PHYGROW hydrologic-based plant growth model, along with a physiologically based landscape use model, to create a spatially-explicit analytical environment which allows depiction of temporal and spatial processes in grazed landscapes.

The preference-based stocking system is unique in that emphasis is shifted to understanding the diet-selection process (diet selection is defined as preference modified by availability) and establishment of desired levels of utilization on target plant species. Quirk and Stuth (1995) categorized plant species within plant communities into six major selection classes, depending upon the animal species of interest. These include:

Preferred -	species "sought" out by animals such that proportions in animal diets are greater than those found in the field regardless of level of standing crop of the species.
Undesirable-	species which are "avoided" by animals such that proportions in animal diets are lower than those found in the field regardless of level of standing crop of the species.
Variable or Desirable -	dietary selection is dependent on the relative availabilities of preferred and undesirable species.
Emergency -	species not included as food plants unless forage resources are severely depleted.
Non-consumed -	species that will not contribute to an animal's diet.
Toxic -	species that when consumed result in death or severe health problems.

Management regimes that include small ruminants, such as sheep and goats, are heavily influenced by the presence or absence of predators and parasites, requiring mediating structures and drugs to minimize negative effects. Avoidance of predators and parasites can sometimes be achieved by temporal and spatial control of the livestock distribution that accommodates behavior of predators or the life-cycle of parasites.

Develop a grazing plan. Implicit in control of the grazing process is development of planned strategies for meeting management objectives. Land managers must:

(a) determine which and how many paddocks/pastures are allocated to each class of livestock, eg, cows vs young steers,

(b) decide on a grazing method, eg, continuous +/- tactical resting vs rotational resting,

(c) plan the use of fire,

(d) assess the need for conserved fodder or other energy supplement, and

(e) control forage demand via timing of parturition and purchase/ sale policies.

Modify spatial distribution of grazing pressure. Control of grazing pressure occurs spatially and temporally. The degree of spatial control depends on the arrangement of water, terrain, cover and forage across a landscape relative to the hierarchy of needs of the animal. Because water is essential for life processes, location of water and its distribution across the landscape dictates the frequency of grazing and occupancy by animals in a gradient from water sources (Stuth, 1991). Animals with greater water use efficiency have more effective grazing capacity per water source. Other animal species vary with respect to mobility across terrains varying in obstacles (dense brush), roughness, and slope which, in turn, affect accessibility to forage resources. The density and distribution of woody plants, pattern of openings in woodlands and degree of human landscape modifications (roads, clearing) all influence how animals use wooded landscapes with woody species. Man also impacts spatial patterns through the creation of fences and pattern of fencing relative to water locations. Anecdotal evidence suggests that as the angle of two or more fences leading away from water decreases, distance grazed from water increases but intensity of animal impact on soil stability also increases through the development of trails.

Location of water sources relative to thermal regulation sites create differential domains of attraction (Stuth, 1991). A recent study on landscape use patterns of cattle by Erickson et al. (1996) noted greater use of landscapes that were in line between multiple watering sources and where roads or trails connected watering points with adequate shade to accommodate multiple social groups of 25-35 head each. When water and thermal foci are highly associated with each other, spatial inefficiencies of grazing increase, especially when grazing capacity of the land is low, and results in a small number of social groups in the livestock population grazing that pasture.

The linkages between evolution, maternal-based learning, influence of peers and post-ingestive feedback on diet selection behavior (spatial, temporal, species specific) allow internalized experiences (learning) by the animal to link multiple spatial scales and temporal variations across landscapes (Provenza, 1995). When organized into social groups, animals combine a collective knowledge base of their environment which helps reduce risk during infrequent, resource-limited conditions. Therefore, experiential memory and social structure of animal populations should be considered along with genetics when exploring management options to impact ecological process through grazing systems.

Accommodate temporal variability. Tactical adjustment of stocking number and distribution to accommodate seasonal and annual fluctuations in forage supply is essential in all grazing environments, but is especially important in rangeland environments with highly variable rainfall. Tactical management requires key decision points and contingency plans so that stocking, resting, and burning decisions reflect forage supply, condition and trend. Monitoring of range condition and standing crop is required. In north-east Australia, seasonal forecasts based on the El Nino-southern oscillation may contribute to a better tactical assessment of risk and opportunities (McKeon et al., 1990). In more intensive grazing environments, feed budgeting and regulation of rest/graze periods help accommodate temporal variability. Monitoring of pastures and animals is required to optimize harvest efficiency across the whole production cycle (McCall and Sheath, 1993). The greater the degree of match between intake profiles of animals and growth cycles of forages grazed, the greater harvest efficiency of annual production. However, the greater the mismatch between dietary preferences of the animal and species on offer, the lower the efficiency of harvest by the grazing animal. The critical issue is to understand what drives intake in livestock, what species they like to eat and the growth patterns of vegetation on offer relative to weather events. The advent of decision support systems is helping managers to deal with this complexity (Stuth, 1996).

MANAGING COMPETITIVE INTERACTIONS WITHIN PLANT COMMUNITIES

Changes in rangeland vegetation have been associated with many factors, including grazing by livestock, variable weather patterns, and altered fire regimes. These changes occur at multiple spatial and temporal scales and are often interactive with feedback mechanisms that confound the identification of specific driving-processes. Traditionally, rangeland management and ecological theory have been based on the climax community concept, where grazing pressure dictates the movement toward or away from a single stable state (climax) through fairly linear dynamics (Dyksterhuis, 1949). This theory is based on the view that succession on rangelands can be largely driven and controlled by grazing, and range condition can be manipulated by domestic livestock to direct succession toward or away from climax. Recently, several alternatives have been proposed including state and transition models (Westoby et al., 1989; Laycock, 1991) and the concept of ecological thresholds (Archer, 1989; Archer and Smeins, 1991). These approaches argue that up to a certain threshold, vegetation can be relatively stable and resistant to changes in fire or grazing regimes. Past the threshold, changes may become more rapid and possibly irreversible over management time frames as the system moves into a new domain of attraction. Identification of possible states and thresholds, as well as understanding the processes that cause transitions between states, is essential to improving land management practices.

The success of grazing management regimes depends on the ability to recognize those vegetation conditions where grazing processes can move vegetation structure and function in a direction desired by management, either directly or through facilitation of other practices. Early researchers in rangeland grazing systems recognized the need for proper stocking and strategic rest periods to enhance the positive influences and limit the negative influence of grazing on the competitive relationships between desirable and undesirable plant species. Significant improvements in rangeland ecological condition and livestock production were noted for grazing systems which were properly stocked at their initiation. These successes were recorded in grasslands and open grassland savannas (Pieper and Heitschmidt, 1988). However, where the plant community has shifted to a dense shrubland composed of undesirable species for the targeted herbivore, grazing management alone cannot drive successional response back to a grassland or open savanna state using the traditional management strategies (Stuth and Scifres, 1982; Scifres et al., 1987; Archer, 1989).

To understand rangeland processes, vegetation should be viewed as a hierarchy of spatio-temporal scales or levels of organization, such as individuals, patches, communities and landscapes (Archer and Smeins, 1991). Interpretation of vegetation dynamics and identification of stable states, as well as the influence of grazing, is dependent upon the level or scale of observation (Fuhlendorf and Smeins, 1996). Temporal patterns observed at small scales can be different from large scale patterns and driven by different processes. Grazing animals make decisions at each of these levels and the influence of grazing is different at each scale. Management must decide on the appropriate scale(s) for monitoring condition and trend (eg., plant community, paddock, or catchment), and develop management strategies that recognize the primary driving mechanisms at each scale (eg., grazing, fire, drought).

For example, on the western edge of the Edwards Plateau of Texas over the past 100-150 years, the vegetation has changed from a relatively open grassland or savanna dominated by mid-grasses to a community where the dominant species are short grasses, and evergreen shrubs (Fuhlendorf, 1996; Fuhlendorf et al., 1996). These changes have been influenced by grazing, episodic weather patterns and elimination of natural fire regimes where importance of each factor is dependent upon scale of observation. Studies at the TAES field station, Sonora, showed that until 1948, heavy grazing caused shifts in the herbaceous component from a mid-grass-dominated community to a short-grass-dominated community (Smeins and Merrill, 1988). From 1948, three grazing intensity treatments (heavy, moderate, and ungrazed) were established and annual measurements were taken to determine the response of the herbaceous communities (Fuhlendorf, 1996). Response of individual grasses and populations to decreasing grazing intensity was reduced plant density, and an increase in individual grass basal area, reflecting a change from many small tussocks to fewer larger tussocks. Episodic weather events influenced basal area of individuals and communities but had less of an influence on plant density. At the community level, the primary influence of grazing was on species composition with no influence on collective total basal area of grasses within each treatment. Periodic weather events, such as drought and extreme freezes, had little direct influence on herbaceous composition but did interact with grazing intensity. For example, a severe drought (1951-1956) and an extreme freeze event (10 days in 1983) both resulted in a dramatic decrease in the total basal area of grasses within the community which essentially increased grazing intensity by reducing forage availability. These weather events were associated with compositional shifts under heavy stocking rates but little or no change in moderate and ungrazed treatments. For this system, therefore, plant density and composition were the best indicators of range condition.

When analysis of vegetation change includes an increasing woody component, the direct influence of grazing is more difficult to determine. Grazing has been reported to increase, decrease, or not affect the abundance of woody plants on rangelands, depending upon the kind/class of animal and the plant community. Since 1948, the increase in woody plants on the Edwards Plateau has not been significantly different between grazing treatments except for a decreased rate of increase under heavy stocking rates of domestic browsers (goats) (Smeins et al., 1994). Also, a simulation model parameterized for the same area predicted that, without grazing or fires, a change would occur from an open grassland to a closed-canopy juniper woodland after 70-80 years (Fuhlendorf et al., 1996). The maintenance of a grassland or savanna would require cool-season fires with a return interval of at least 20 years or periodic hot fires that would potentially kill large trees. The primary influence of grazing is reduction of fuel loads which reduces both the probability of natural occurring fires and the potential use of prescribed fire for control of woody plants.

Grazing may reduce the competitive ability of grasses and allow woody plants to invade at faster rates. However, the alternative has also been demonstrated, where increase in woody plant density was slower under grazing because of harsher environmental conditions at the soil surface when less vegetation is present (O'Connor, 1985,1995). Thus, there is no universal agreement concerning the influence of grazing on the rate of increase of woody plants, but apparently woody plant density can increase under all grazing conditions, suggesting that grazing is not the primary driving variable. Altered fire regimes appear to be the primary factor in this example and grazing systems must incorporate prescribed burning to maintain a herbaceous-dominated system.

Management of changes in vegetation, therefore, require a multi-scale approach and an understanding of the influence of several processes that can be interactive (Figure 2). The traditional method for analysis of range condition and trend was developed in grassland communities and best describes the grazing-induced changes that occur in herbaceous-dominated communities and in the herbaceous interspaces of shrublands and woodlands. Population structure and morphology of individuals are directly influenced by differential grazing within the herbaceous plant community. These structural changes in populations result in competitive interactions between species that are highly preferred by grazing animals and those that are less preferred (Briske and Richards, 1995). For the herbaceous component of this system, weather patterns and/or altered fire regimes should be considered as an interactive force with grazing intensity where the greatest influences would occur under heavy stocking rates. These changes could be considered linear and frequently reversible over reasonable management time frames. This suggests that traditional range condition theory is reasonable for many herbaceous populations, patches or communities within a landscape.

However, when a landscape perspective is taken, primary change in many rangelands involves the interaction between woody and herbaceous layers. At this larger scale, grazing is less important and variables such as altered fire regimes and long-term directional shifts in climate become more important. As woody plants increase they can cause positive feedbacks through increased seed availability, nutrient redistribution, and reduction in herbaceous vegetation necessary for fires, resulting in an ecological threshold where increases are exponential and often irreversible (Archer, 1989; Fuhlendorf et al., 1996). These changes occur at a decade to century time scale and can result in major decreases in livestock carrying capacities. As these large-scale changes continue, stocking rates must be reduced because of relative increases in less palatable woody species and eventually a threshold could be crossed where return to a grassland dominated state is not likely under typical management conditions. Grazing systems ecology requires integration of management strategies that focus on changes driven by processes other than grazing with more traditional grazing management practices. Ecological frameworks should combine elements of Clementsian-style concepts with those of State-and-Transition.

ESTABLISHING GRAZING SYSTEMS

Given that each landscape is unique and the needs of managers vary, can a given set of management principles emerge to help guide the decision process and impact ecological processes in a desired manner? We have ordered what we feel to be critical managerial considerations in a hierarchical manner below.

- Landscape visioning
- Objectives of animal production
- Understanding climate and land capability for determining base stocking rate
- Understanding weather and market patterns and risk to determine required flexibility in decision making and enterprise mix
- Understanding interactions with other enterprises (wildlife, recreation, mixed livestock)
- Matching management skills and capability with complexity of the decision environment
- Identifying relevant spatial and temporal scales for monitoring
- Targeting plant species, forage residue levels, soil surface conditions and nutritional parameters for monitoring
- Understanding critical growth periods of the target plant species
- Understanding how to give competitive advantage to the target species and limit impact of unwanted plant species
- Establishing analytical capability to make strategic and tactical decisions and interpret monitoring information for operational adjustment.

It is essential for individuals to have a realistic vision of what they would like the landscape to look like in terms of species, their distribution and stature. It is crucial for land managers to give landscape condition as much attention as this traditional focus on animal condition. The "landscape visioning" process helps link perception with reality because objectives of management can be met through either manipulation of processes for slow, incremental change, or by high-energy inputs to accelerate change. This is essentially an economic and legal decision process, relative to the needs of the individual land manager.

An understanding of risk in terms of climate, future weather (precipitation) and market conditions is critical for design of grazing strategies in terms of base stocking rate, flexibility in animal numbers and destock/restock decisions. The greater the coefficient of variation in annual rainfall, the greater the need for flexibility in the decision making process, and the less predictable the outcome of the plan. Monitoring of conditions is essential for timely decision making.

Diversity of enterprises creates opportunities for risk aversion in terms of market and weather flux, but also creates higher order complexity in decision making. Landscape diversity (spatial and temporal events) adds to the complexity when more than one enterprise is utilizing the area, but it creates more options for management which may, in turn, lessen risk of adverse ecological change. The key is provision of analytical tools to help comprehend this diversity and the complexity of the dynamics involved.

Decision-making in complex environments is often limited by managerial skill levels and understanding of the management environment. Outcome can be enhanced both ecologically and economically when grazing systems are designed to match skill levels of the landholder/decision maker. The outcome can be greater in many cases with less complex systems simply because the human factor is considered an integral part of the grazed ecosystem. Greater intervention does not always equal more benefits.

A key to the success of grazing strategies is the establishment of proper monitoring systems at the appropriate scale and temporal frequency relative to landscape size and complexity. Much debate exists as to the appropriate parameters to measure, where the measurements should take place in the landscape and how often information should be gathered (Danckwerts et al., 1993; Friedel, 1994; Stafford Smith and Pickup, 1990; Stuart Hill, 1989; Brown and Howard, 1995). The challenge for scientists, agency personnel and technical advisors is to identify the appropriate variables to measure to best serve the decision-making process in terms of timeliness, accuracy and perceived value to the land manager. Building the appropriate information infrastructures to best serve the sustainability of grazinglands is the challenge facing all agricultural professions as we approach the 21st century (Stuth, 1996).

Successful monitoring of rangeland dynamics requires identification of spatial and temporal scales relevant to the objectives of the landholder (Fuhlendorf and Smeins, 1996). Selection of key forage species for monitoring requires an understanding of their forage value, landscape position, competitiveness, growth patterns, phenology and temporal response potential. Competitive advantage can be manipulated directly through the grazing process and indirectly through the management of deferment or non-grazing periods. Stocking pressure is the overall driving force. Tactical resting should be based on the ecology of the target species, eg., sensitivity to defoliation in early grazing season, seed-set, etc. Resting/spelling should be integrated with overall control of grazing pressure.

CONCLUSION

Throughout this discussion, we have stressed that grazed ecosystems are generally complex, and the human decision-making process is an integral part of the ecosystem function and structure. We have redefined grazing systems to direct primary attention away from grazing methods, enabling us to focus on all elements of planned grazing management. We have also integrated grazing systems in the context of new ecological frameworks. Monitoring of processes was stressed as essential for rational decision making and realization of the manager's landscape vision. We submit that sustainability of grazed ecosystems into the future will require greater linkages between the human decision-making process, ecological processes, economic systems and political systems across several temporal and spatial scales. The only way we can hope to achieve this goal is to begin development of information infrastructures that link the knowledge generator with the knowledge purveyor and knowledge seeker. Our contention is best summarized by Stuth (1996):

The success of these new technologies will depend on managing information complexity rather than focusing on simplification of ecological, economic and social dynamics. The heart of the matter is whether we hide complexity from livestock producers to build awareness of the impact of their management on the environment or whether we build information systems that package complexity in an understandable manner. The former keeps the decision maker in the dark while the latter leads to a forum for continued life-long learning, an essential ingredient to meeting the goals of sustainability of grazing lands.

The role of information technologies linked with properly targeted ecological research must come into the dialogue of the agricultural community. Issues of packaging, delivery and connectivity must be addressed in a manner that is conducive to addressing relevant grazing land issues that are valued by society.

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Figure 1
Spatio-temporal complexity of the grazing systems decision environment which encompasses a hierarchical view of the SWAPAH concept of Soil, Water, Atmosphere, Plants, Animals and Humans.

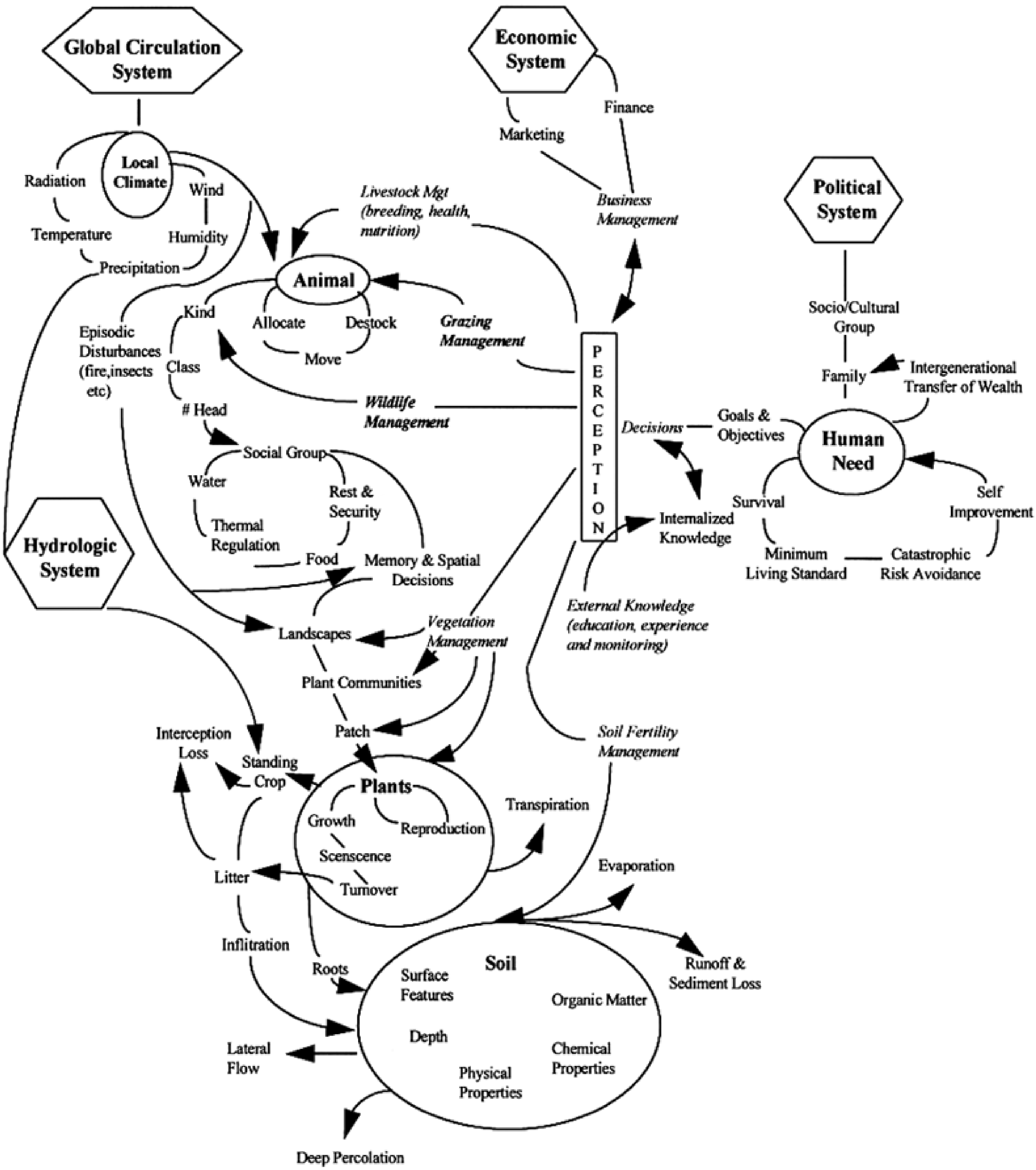

Figure 2
Interactions of grazing, fire and episodic weather events driving successional change within grassland/savanna and woodland/shrubland domains and across thresholds in a oak-dominated savanna ecosystem in the Edwards Plateau of Central Texas (adapted from Fuhlendorf et al. 1996).

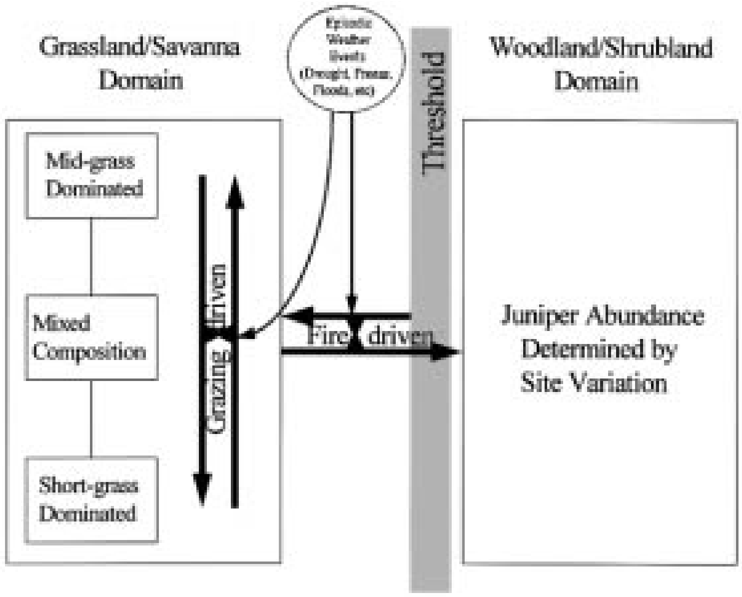

Table 1
Six broad categories of managed grazing environments. The degree of human interference in the diet selection process increases from the top of the list to the bottom.

grazing production system	example
Free ranging within a static set of landscape conditions	Set stocking of paddocks
Free ranging across multiple landscape conditions extensive herding	Rotation among several paddocks
Across multiple landscapes	Transhumance herding practices
Intensive herding within a static set of landscapes conditions	Village agriculture
Tethered grazing, rotated among patches	High density cropping systems
Confined feeding/zero-based grazing/cut and carry	All land in crops and human shelter or feedlots

Table 2.
The elements of effective grazing management planning

time dimension	period of influence	typical decisions	decision profile
Strategic	for next few years	* animal type(s) * production system * base stocking rate (carrying capacity) * grazing plan * brush management plan * wildlife management plan * specific * measurable	* longer term reassessment of goals and strategies
Tactical	for next 6-18 months	* stocking decisions - adjust numbers for whole property - adjust numbers across paddocks - spelling * burning * feeding * brush and habitat treatments	* tailoring management to accommodate variability * key decision points and contingency plans
Operational	for next month or so	* work plan - applying tactical decisions * respond to unforseen circumstances	* focussed * flexible