# ENVIRONMENTAL DRIVERS AND MONITORING OF RANGELANDS

**J. R. Brown[1] and K.M. Havstad[2]**

[1]USDA- Natural Resource Conservation Service and [2]USDA- Agricultural Research Service,
Jornada Experimental Range, Las Cruces, NM, 88003, U.S.A.
E-mail: joelbrow@nmsu.edu and khavstad@nmsu.edu

## 1. INTRODUCTION

Environmental drivers are factors that cause measurable changes in properties of biological communities. Drivers affecting rangeland ecosystems can be divided into: physical, social, and economic/policy. Examples of physical drivers are factors such as variability in rainfall and available soil nitrogen, and management factors such as livestock grazing practices and prescribed burning. Examples of economic/policy drivers are domestic and global actions such as tax laws, environmental policies, and trade agreements. Examples of social drivers are trends such as attitudes regarding property rights, prevailing public values about land management, and changes in land occupation.

While there is ample evidence that changes in ecosystem properties can be linked to environmental drivers, it is difficult to identify the impact of specific drivers on specific properties at specific times since drivers seldom operate independently or singularly and time-lags are common (Aber et al 2001). Rangeland monitoring approaches of the past have been based on the intent to detect relatively subtle changes in response variables and initiate a management change prior to undesirable ecosystem change. This approach relies on two assumptions that may not be valid for the majority of rangeland ecosystems. First, there is scant evidence that many of the indicator variables adequately reflect changes in important system processes, especially in a relevant timeframe. Detecting subtle changes in soil and/or vegetation properties indicative of impending change requires spatial and temporal resolution unachievable by most monitoring strategies. Second, the assumption that raw data from monitoring will somehow be transformed into a management decision is seldom warranted by action, either at the individual property or larger-scale policy level. Few, if any, monitoring systems are packaged with site specific guidance on what levels of indicator attributes should trigger explicit management responses. Although there have been notable improvements in monitoring systems to integrate improved understanding of a wider range of indicators, the problem of linking generic attributes to site-specific decisions remains (see Pyke et al 2002).

In this paper, we 1) contrast two distinctly different approaches to the design of monitoring systems, data collection and management response, 2) demonstrate the need for greater refinement in both the data collection and interpretation phases of a monitoring system and 3) propose another category of variables that may be relevant in improving the design and implementation of monitoring rangeland ecosystems.

## 2. BASIS FOR MONITORING

There are two reasons for monitoring rangeland ecosystems: compliance and management. Compliance monitoring involves collection of information to ensure that land users are extracting services via the implementation of best practice. The implicit assumption is that extraction rules and guidelines are sufficient to protect resources if these rules and guidelines are followed. Perhaps the best example of this approach on rangelands is the monitoring of stocking rates and forage utilization levels on publicly held lands in the United States grazed by permitees. In most cases, stocking rates are developed based on models that integrate average growing conditions (primarily driven by average precipitation), inherent soil properties, generic livestock consumption rates and implicit assumptions regarding ecosystem stability. In some cases, there may be seasonal data collected to link stocking rates to ‘utilization’, but these are seldom the basis for decision-making. In compliance monitoring, the emphasis is on activities rather than outcomes and compliance is often the basis for certification programs.

Monitoring for management, on the other hand, does not rely on such close assumed links between activities and outcomes, but focuses more on making continual adjustments to management inputs in response to assumed effects of changes in driving variables. In this case, monitoring is an essential step to evaluate progress towards meeting management objectives. A major challenge for adaptive management is implementation of a monitoring program that can identify rangeland structure and dynamics in an objective, efficient, and widely-understood fashion (NRC 1994). There are a number of site-specific, field-based protocols to monitor rangeland structural characteristics (e.g. NRCS 1997, Elzinga et al 1998). These monitoring approaches are effective for detailing vegetation status at site-specific locations (ground-based), and can be used to guide short-term management decisions.

Given that values and knowledge change over time it is important to design monitoring programs to detect a system's potential to 1) function in support of a spectrum of societal values rather than a single interest, 2) resist degradation (the property of resistance), and 3) recover following disturbance or degradation (the property of resilience). Building a monitoring program around these purposes should lead to a core set of measurements that have direct utility for management (Havstad and Herrick 2003).

Monitoring for decision-making involves a different set of assumptions compared to compliance monitoring. In this case, an explicit management model is the basis for decisions. In North American rangelands, the range condition model (uni-equilibrial states) served as an unstated basis for decisions and monitoring for many years. Today, the concept that rangeland vegetation is better characterized as multi-equilibrial has been increasingly recognized and accepted (Westoby et al 1989, Laycock 1991, Friedel 1991, Bestelmeyer et al 2003). Monitoring within a uni-equilibrial model is very different than monitoring based on a multi-equilibrial model. Under the range condition concept monitoring could be structured to compare an existing state to a single desired state, even if that state was unattainable in a practical sense. However, monitoring within a multi-equilibrial model can include both a need to compare current conditions to a desired state, as well as monitoring to recognize a transition to another state. This means that monitoring must include indicators that can reflect transitional changes in soils and vegetation properties and processes related to transitional dynamics.

## 3. ENVIRONMENTAL DRIVERS

There are three key classes of environmental drivers that initiate change on rangelands –physical, social and economic/policy. Currently, most monitoring schemes rely on tracking indicators that may have little or no sensitivity to changes in environmental drivers. In this paper we propose to shift the focus to monitoring environmental drivers as the framework for selecting indicator variables.

### 3.1 Physical Drivers

Climatic changes, particularly in the amount and distribution of precipitation, are the major driver of change in rangelands. Although rangeland managers currently tend to think of climate change as a future driver of change on rangelands, there is strong evidence that many of the guiding principles of rangeland management have been developed based on unstated (and perhaps invalid) assumptions about climate stability and rates of change. Swetnam and Betancourt (1998) demonstrated how shifts in precipitation patterns over the past 500 y have driven change and interacted with other drivers to result in change. In particular, although drought has been a common phenomenon in the American southwest over the past millennium, the mid-century drought (1951-1956) was one of the most severe and initiated processes that directly or indirectly resulted in dramatic vegetation change. During that period, even drought tolerant grasses and arborescent shrubs suffered massive die-offs. Post-drought return to higher precipitation levels combined with increased availability of safe-sites for establishment likely increased shrub recruitment and contributed to the dramatic shrub dominance observed over the past sixty years. In examining vegetation x climate interactions over longer periods, they concluded that although management may have somewhat exacerbated vegetation change, the primary and overwhelming driver was climate.

Other physical drivers apart from climate may have an influence on rangeland ecosystems both in the past and in the future. For example, increased levels of $CO_2$ are almost certain to occur globally regardless of changes in local climatic patterns. The effects of this change in atmospheric chemistry could have dramatic effects on rangeland ecosystems depending on individual species responses. Polley et al (2002) have suggested that elevated $CO_2$ levels (350 ppm currently to 700 ppm by 2100) may favor C3 shrubs over C4 grasses in the southern tallgrass prairie of North America. Conversely, Huxman et al (1999) demonstrated that elevated $CO_2$ decreased seed size and mass of *Bromus madritensis,* an invasive species, reducing reproductive success compared to other exotic and native species.

Even when climate is stable over a time period that encompasses management decisions (>50y), short-term climate variability may interact with changes in management to initiate vegetation change. In the Mitchell grass plains of central Australia, populations of *Acacia nilotica*, an exotic arborescent shrub, were stable throughout the first 50 years after introduction (Brown and Carter 1998), but changes in the species of dominant domestic herbivore initiated an increase in shrubs within a short period. The original domestic herbivore, sheep, was a poor dispersal vector for *Acni* due to their complete mastication of seeds, and shrub populations were stable through two cycles (3-5 y) of higher than average precipitation. Cattle replaced sheep as the dominant grazer in the 1960s and provided a highly efficient means of dispersal within paddocks. This change in grazer interacted with a series of above average precipitation years in the early 1980s to initiate a recruitment event that increased *Acni* populations dramatically.

## 3.2 Social Drivers

We know that human activities and attitudes can have significant direct and indirect affects on ecosystems. This occurs both at high and low population densities and in developed and developing regions. Human activities are recognized as primary drivers of biological invasions in all environments (Vila and Pujadas 2001). It is important to recognize that drivers are often socioeconomic and demographic, and may operate independently to the landscape being managed. For example, areas within China have experienced degradation to giant panda habitats due to the harvest of fuelwood from these habitats. An et al (2001) have linked fuelwood use to both the age structure and family income in communities surrounding the Wolong Nature Reserve in China. Households with seniors (persons over the age of 60) consumed 19% more fuelwood in order to maintain interior temperatures at a higher level for longer periods during the year. In addition, households with higher incomes produced more crops that led to purchasing more pigs as a cash commodity. More pigs required more fuelwood to prepare fodder for feeding to the pigs. These drivers are operating outside the Nature Reserve but are having significant effects on the conditions of giant panda habitats within the Nature Reserve. Protection of areas does not quarantine those areas from effects of external drivers (Vila and Pujadas 2001).

In western North America, human occupation patterns are changing dramatically (Knight et al 2002). Improved transportation (corridors and vehicles) and communication networks (landline and satellite) have facilitated access and increased attractiveness of regions and landscapes historically occupied at low human densities. While the direct impact of these new human occupants on rangeland landscapes can be substantial, their attitudes and beliefs may also have dramatic impacts on land use and management decisions (Brunson and Wallace 2002). Fragmentation of rangeland landscapes is an unintended consequence of a series of unrelated decisions about property size, homestead location and viewscape selection. As population density increases in arid rangelands, the tolerance of new residents for previously widely accepted practices usually declines and conflicts between landowners are common. Many of the practices integral to good management, such as prescribed fire, may be challenged legally and implementation criteria may become so onerous that wise use is no longer an option.

## 3.3 Economic/Policy Drivers

Globally, rangelands have been valued primarily for the capacity to produce food and fiber. As societies have gained more control over factors that drive net primary production and developed technologies to appropriate that production (Vitousek 1994), rangelands gained value as sources of water, wildlife habitat, pharmaceuticals etc. The concept of ecosystem services (Daily 1997) includes a much broader perspective on value and has emerged as a more robust means of allocating scarce goods and services associated with rangelands, and ultimately how they are managed. Butler (2002) presented a complex array of potential income-producing enterprises based on extractive and nonextractive practices for rangelands. Some of the alternative revenue producing activities are mutually exclusive, but many are compatible and a few are even complimentary. However, much the same as traditional extraction technologies, the early analysis of impacts on rangeland ecosystem behavior has been done at the property level. The nonlinear and interactive effects at larger spatial scales and longer timeframes have not been considered.

Government land use and management policies may also have direct impacts on rangeland use and management objectives. The United States Congress recently passed the 2002 Farm Security and Rural Development Act; a key component of which was the Conservation Security Program (CSP). The CSP defines locally acceptable conservation practices and authorizes incentive payments for their adoption. In effect, the public is paying farmers and ranchers to implement and maintain conservation practices over long time periods. While there have been efforts to provide incentives for land use change, this is the first to provide a long-term reward for applying socially acceptable management practices on private land. A key element of the program on grazed rangelands will be proper grazing use, which includes moderate stocking rates and invasive species control on all rangelands.

These examples are merely to demonstrate that there are many diverse factors that drive change, desirable or undesirable, on rangelands. It should also be apparent that none of the drivers described above are explicitly described in any extant monitoring scheme. In each of these cases, it is highly unlikely that monitoring soil or vegetation indicators, regardless of how sensitive the indicator or how much effort went into monitoring, would have triggered a management response. This is not to say that monitoring would not have detected a change in the vegetation or soil properties of interest. But because monitoring systems have typically lacked a basis in management models, there would have been no specific link between the driving variable and a realistic management model with explicitly stated management responses.

# 4. MONITORING BASED ON ECOSYSTEM MODELS, MANAGEMENT OBJECTIVES AND KEY DECISION POINTS

One of the implications of replacing a uni-equilibrium model with a multi-equilibrium model to describe the behavior of rangeland ecosystems is that changes in assumptions about system behavior should be reflected in the design and implementation of monitoring schemes and subsequent management decisions. Multi-equilibrium systems have several characteristics that should govern the selection of management models to represent their behavior. First and foremost is the existence of multiple stable 'states' that have unique attributes (values) and are characterized by ecological processes that function within a defined range (Stringham et al 2001). These stable states represent alternative management objectives (see Westoby et al 1989 and Jackson et al 2002 for description and critique of state and transition models). Characterizing or classifying rangeland into states is an inventory challenge that we will not address here (see Bestelmeyer et al 2003).

A second important characteristic of multi-equilibrium systems is that states have differing levels of inertia and differing requirements for overcoming that inertia to initiate a change in state. Walker et al (2002) defined this inertia as resilience (the ability of a system to remain in its present configuration and to reorganize following a disturbance or degradation) and proposed 'resilience management' as a key element of sustainable resource use in complex ecological systems. They outlined 4 steps required to manage natural resources for resilience: 1) development by stakeholders of a conceptual model of the system, 2) identifying unpredictable drivers of the system, 3) identifying factors that affect resilience, and 4) stakeholder analysis of possible management actions. Imbedded in this analysis is the implicit need to be able to monitor resilience (loss, creation, or maintenance) of the managed resources. Environmental drivers are those factors that can overcome the inherent resilience and induce a change of state. Thus, environmental drivers are those factors that can initiate a state change and, as such, should be the focus of an effective monitoring system.

A third key characteristic of multi-equilibrium systems is the presence of thresholds. Thresholds are critical regions that delineate between two distinct states. Archer (1989) presented a graphical model of the change from grass dominance to shrub dominance in South Texas rangelands. The threshold was defined as the point at which the environmental drivers grazing pressure and drought overcame the resilience of grassland dominance and allowed for the widespread establishment of shrubs. Subsequent shrub survival and growth ultimately resulted in the majority of resources within the system (water, nutrients, light) being controlled by shrubs rather than grasses. At the time the threshold was being crossed (1940s-1950s), the prevailing model of rangeland ecosystem behavior suggested that removal of adult shrubs via chemical or mechanical methods was sufficient to restore grass dominance. The model (and policies, programs and management recommendations based on it) failed to recognize that the threshold was not the presence of adult shrubs, but the persistence of juveniles, and once adult shrubs were present, return to a grassland dominant state was a very low probability.

Brown et al (1999) presented a similar analysis of exotic shrub increase in an Australian tropical grassland. They defined the ecological threshold as a series of events leading to shrub establishment and survival. Shrub dominance did not occur until 15-20 y after a threshold has actually been crossed. By the time conventional monitoring (species composition, soil properties) detected the change in dominance, the threshold had long since been crossed. On the other hand, monitoring environmental drivers such as presence of exotic shrub propagules and dispersal vectors, annual precipitation patterns adequate for establishment and survival patterns of juveniles could have been the basis for implementing any of several effective management responses.

The threshold concept is useful for other elements of land management as well, such as for integrated pest management, (Kogan 1998, Hoffman et al 1999), landscape stability and soil erosion (Davenport et al 1998, Weltz et al 1998. These models are based on an assumption that relationships between different properties and processes become increasingly non-linear as a threshold is approached. This increasing non-linearity in process-property relationships nearing thresholds means that linear combinations of indicators which effectively reflect changes in ecosystem function may become completely ineffective at these critical periods.

There are a number of studies in the literature that demonstrate the importance of thresholds, and the most effective early-warning indicators are not necessarily the most obvious. For example, herbaceous species composition and productivity are commonly considered to be good indicators of condition. However, Northrup et al (1999) illustrated that while a tussock-grass dominated community appeared to be stable based on these indicators, loss of biological integrity in response to overgrazing was occurring via the fine-scale redistribution of soil resources. In another example, Brown and Ash (1996) showed that monitoring species composition and plant production data to detect shrub invasion can result in delaying important management decisions until well after woody invaders have become established. Instead, indicators that quantify susceptibility to invasion need to be identified. Davenport et al (1998) clearly demonstrated the role of erosion thresholds in defining different states for grasslands invaded by pinon and juniper in the southwest, and documented that the probability of crossing different thresholds is strongly dependent on specific site characteristics.

Bestelmeyer et al (2003) has presented the state and transition diagram illustrated in Figure 1. This model is based on current understanding of the ecological dynamics on a northern Chihuahuan Desert site with sandy soils. The figure is relatively simple where community pathways branch within states, but there are at most two potential transitions for each state. The number of potential states can change in response to climate change, or to species invasions. The key points illustrated by this example are that transitions are defined by non-linear changes in the function of the system, and that mean values of a suite of indicators may provide relatively little information about the status of the system when it is near threshold. The precise definition, quantification and recognition of site-specific thresholds are some of the most important and difficult tasks faced by the range management community.

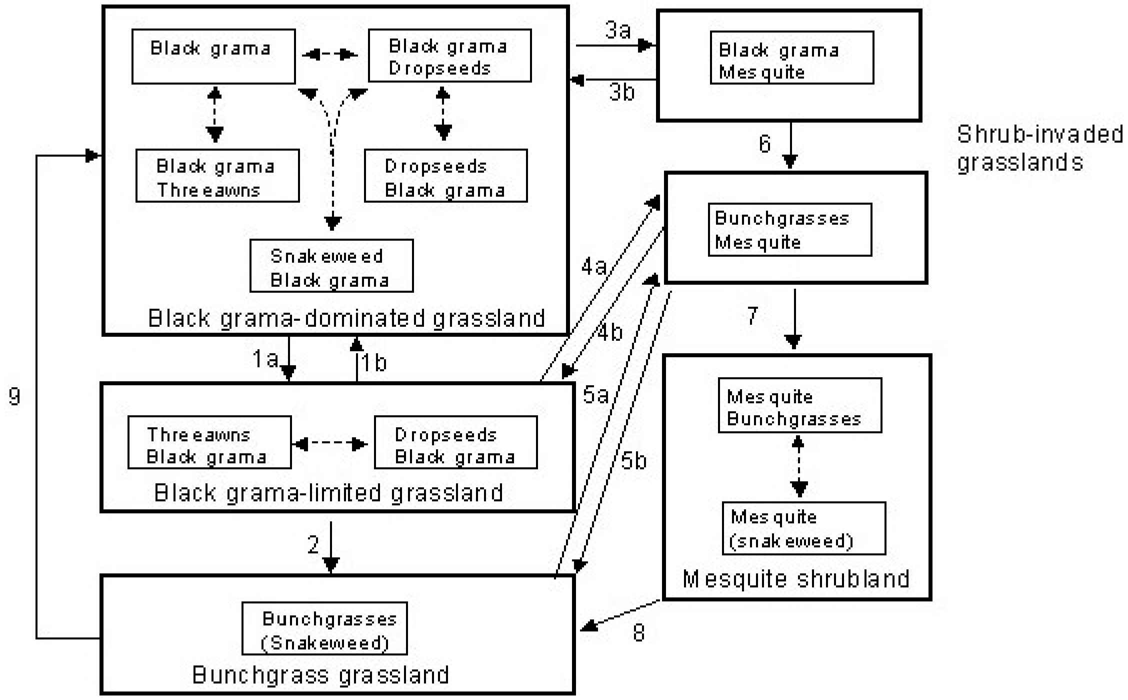


Figure 1. State and transition model for a sandy range site in the northern Chihuahuan Desert (from Bestelmeyer et al 2003).

Typically, once a threshold is crossed, a different set of environmental drivers is responsible for stabilizing the system or further change in the ecosystem. Thus, monitoring should be focused on different environmental drivers. There are several research topics that need to be addressed: 1) cost effective measurements that accurately reflect processes related to transitions between states, 2) integration of remote sensing and ground-based measurements which detect change at management-relevant scales, and 3) development of effective landscape scale models for monitoring to support adaptive management.

Although the acceptance of multi-equilibrium models as a basis for rangeland management is near universal and the importance of thresholds in managing sustainably is increasingly recognized, there is a very poor quantitative understanding and elucidation of thresholds, especially in a predictive capacity. In lieu of possessing critical knowledge about ecosystem behavior and an ability to communicate in detail what local fine scale indicators of change are, we propose that the concept of monitoring rangeland ecosystems be expanded to include environmental drivers that can initiate change, either desirable or undesirable. The elucidation of environmental drivers should be a distinct component of ecosystem management models, regardless of the scientific basis for the model or the spatial and temporal scales at which the models are intended to function. It should be apparent from the foregoing discussion that extensive, complex systems need not be constructed to collect data linked to environmental drivers. In most cases, sufficient information is available. The key is to organize and synthesize the available information and then to integrate it into models that describe system behavior. Finally, and most importantly, key points must be identified and critical regions of change must be linked to management decisions and actions.

## 5. SUMMARY

By 2050, earth's population may be over 9 billion and may be wealthier than today. The demand for food and a host of other ecosystem services by this global population will be a major driver of environmental change (Tilman et al 2001). In conjunction with a less predictable climate system (whether human induced or natural) these demands will require adapting management of natural resource systems in response to a constant flow of new information and changes in objectives. Providing a framework for these decisions is the most daunting challenge rangeland management professionals will face in the new millennium. Though our abilities to generate accurate predictions are currently limited, conceptual models of system responses to drivers are improving. Continued incorporation and refinement of our understanding and monitoring effects and interactions of different drivers will contribute to improvements in these predictive capacities.

Environmental drivers have typically not been incorporated into monitoring schemes. Yet, analysis of major changes in rangeland ecosystem function in both the distant and immediate past clearly demonstrates that even a less-than-complete understanding of environmental drivers and incorporation of that information into decision making could dramatically improve outcomes and lead to enhanced sustainability.

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