PROJECT PLAN
NP 215 – Rangeland, Pasture and Forages
Panel Review: September – November 2007

Old Project Number
6235-11210-005-00D

Research Management Unit
Range Management Research Unit

Location
Las Cruces, New Mexico

Project Title
Management Technologies for Arid Rangelands

Investigator(s)
D.C. Peters, Lead........................1.0
D.M. Anderson 1.0
J.R. Barrow 1.0
B. Bestelmeyer............................1.0
R.E. Estell 1.0
E.L. Fredrickson 1.0
K.M. Havstad...............................1.0
J.E. Herrick..................................1.0
M.E. Lucero 1.0
A. Rango 1.0
S. Tartowski 1.0

Scientific Staff Years
11.00

Planned Duration
60 months

Post-Peer Review

D.C. Peters, 6235-11210-005-00D
Management Technologies for Arid Rangelands

This project plan was revised, as appropriate, according to the peer review recommendations and/or other insights developed while considering the peer review recommendations. A response to each peer review recommendation is attached. If recommendations were not adopted, a rationale is provided. This final version of the project plan reflects the best efforts of the research team to consider the recommendations provided by peer reviewers. The responses to the peer review recommendations are satisfactory.

____________________________________ 12 / 11 / 2007
RL or CD/LD Date

The attached plan for the project identified above was created by a team of credible researchers and internally reviewed and recognized by the team's management and National Program Leader to establish the project's relevance and dedication to the Agricultural Research Service's mission and Congressional mandates. It reflects the best efforts of the research team to consider the recommendations provided by peer reviewers. The responses to the peer review recommendations are satisfactory. The project plan has completed a scientific merit peer review in accordance with the Research Title of the 1998 Farm Bill (PL105-185) and was deemed feasible for implementation. Reasonable consideration was given to each recommendation for improvement provided by the peer reviewers.

____________________________________ ____________________
Area Director (original signature required) Date

Table of Contents

X. FIGURES

XII. PAST ACCOMPLISHMENTS OF INVESTIGATORS

I. Project Summary

The goal of the research unit based at the Jornada Experimental Range (JER) is to develop ecologically based technologies for monitoring, remediation, and grazing management in desert environments. To achieve this goal, our overall research objective is to determine how biological, soil, and geomorphological processes interact across multiple spatial and temporal scales to affect soil development, soil stability, nutrient and water retention and acquisition, plant establishment and survival, and animal foraging behavior. Within this overall goal are four specific objectives designed to achieve ecologically based technologies with application to rangeland management:

1. Develop an integrated assessment and monitoring approach for vegetation structure and composition, soil stability, watershed function, and biotic integrity of spatially and temporally heterogeneous rangelands at landscape, watershed, and regional scales.

2. Identify key plant and soil processes, and environmental factors, such as landscape position, land use history, and climate, that influence the potential for remediation success.

3. Develop adaptive strategies for livestock management across multiple scales based on animal foraging behavior.

4. Predict responses of ecosystem dynamics and livestock distribution across time and space to changes in climate and other management-dependent and -independent drivers, and develop an integrated management, monitoring, and knowledge toolbox that can be easily applied by individuals with a range of management experience, from minimal to extensive.

We will build upon information collected since 1912, complemented with ongoing and new research, to address our objectives. We will integrate short- and long-term data sets with simulation modeling, geographic information systems, and remote sensing tools. Our approach will combine short-term experiments to test specific hypotheses with synthetic experiments requiring a more complex integration of ecosystem components and drivers. Although this is an ambitious proposal, it reflects the singular efforts of a collaborative, interdisciplinary group of 11 ARS scientists at the JER working towards a common goal.

II. Objectives

The goal of the research unit based at the Jornada Experimental Range (JER) is to develop ecologically based technologies for monitoring, remediation, and grazing management in desert environments. In order to achieve this goal, our overall research objective is to determine how biological (plant, animal, microbial), soil, and geomorphological processes interact across multiple spatial and temporal scales to affect soil development, soil stability, nutrient and water retention and acquisition, plant establishment and survival, and animal foraging behavior. Our ecologically based management technologies will be built from a knowledge of these processes. We will accomplish this objective by integrating short- and long-term experiments with a suite of tools (simulation modeling, geographic information systems [GIS], and remote sensing) to extrapolate information across spatial scales from individual plants to landscapes (Fig. 1) (Pg. 44). Such an approach will enable us to accomplish four specific objectives and associated products (Fig. 2) (Pg. 45):

1. Develop an integrated assessment and monitoring approach for vegetation structure and composition, soil stability, watershed function, and biotic integrity of spatially and temporally heterogeneous rangelands at landscape, watershed, and regional scales.

2. Identify key plant and soil processes, and environmental factors, such as landscape position, land use history, and climate, that influence the potential for remediation success.

3. Develop adaptive strategies for livestock management across multiple scales based on animal foraging behavior.

4. Predict responses of ecosystem dynamics and livestock distribution across time and space to changes in climate and other management-dependent and -independent drivers, and develop an integrated management, monitoring, and knowledge toolbox that can be easily applied by individuals with a range of management experience, from minimal to extensive.

III. Need for Research

Problem Description. One-half of the Earth's land surface has arid or semiarid climate, with drylands occurring on all continents. Human populations and the intensity of development are increasing rapidly in many of these regions, placing increasing demands on goods and services, and changing the way people interact with the unique diversity of desert systems. Past management actions and climatic fluctuations have caused degradation or desertification of many of these rangelands. One-sixth of the world's population is affected by desertification, and 73% of drylands in North America are degraded (UNEP 1992). Degraded drylands have significant and negative global impacts (Schlesinger et al. 1990). The potential exists for future dramatic shifts under directional changes in climate and as a result of shifts in land use and management practices (Havstad et al. 2007; Seager et al. 2007). These changes may result in further desertification of some sites and remediation of others (Schlesinger et al. 1990; Herrick et al. 1997; Havstad et al. 2006). Because desert systems are among the most temporally and spatially heterogeneous systems in the world, achieving management goals and predicting future conditions and dynamics is challenging. Desert systems are characterized by extreme temporal variability for short time scales (within and between years), as well as for longer time periods (20y and 50y drought cycles). The stability of arid rangeland ecosystems is poorly buffered against changing drivers, and changes typically exhibit significant time lags and ‘pulse-reserve’ responses (Noy-Meir 1973). Short, intense rain and wind events combined with high topographic and edaphic variation result in heterogeneous patches and landscape units that are spatially connected through redistribution of soil, water, seeds, and nutrients across the landscape. Interactions between grazing animals and landscape dynamics provide further challenges to management decisions and predictions about future dynamics.

In the U.S., arid rangelands of the desert Southwest provide forage for livestock production, habitat for native flora and fauna, watersheds for rural agriculture and urban uses, invasion sites for exotic species, sources of oil, gas, coal, and minerals, and open areas for recreation. These rangelands are in a variety of conditions, from degraded to fully functional, and are managed by a number of different individuals, agencies, and institutions with different objectives. Significant changes in these landscapes have occurred over the past 100 to 150 years that are related to, but not completely dependent upon, excessive grazing pressure by domestic herbivores, in particular cattle (Humphrey 1958; Buffington and Herbel 1965; Grover and Musick 1990; Gibbens et al. 2005). Large-scale conversion of perennial grasslands to shrublands has resulted in rangelands with lower quality and quantity of forage and greater susceptibility to wind and water erosion (Schlesinger et al. 1990). The JER has a long history of research dating to 1912, and the program has developed management tools with application for historical uses and prior conditions. However, we currently do not have sufficient ecologically based tools to sustainably and cost-effectively manage, monitor, or restore these lands, given current and future demands and conditions. In the next 5 years, we will continue to build upon the experience gained from this long history of research in order to develop these tools. Because of high spatial variation and inherent time lags in these rangelands, many interesting and important insights from experiments initiated in the mid-1900’s are now becoming apparent. Analysis of new and long-term experimental manipulations over a broad range of environmental conditions, combined with active use of these data sets, will continue to be strengths of JER research.

Relevance to National Program Action Plan. This project falls entirely within National Program 215, Component I, Rangeland Management Systems to Enhance the Environment and Economic Viability. The project focuses on Problem A, the need for economically viable rangeland management practices, germplasm technologies, and strategies to conserve and enhance rangeland ecosystems, and Problem B, the need for improved production for rangelands that provide and use forages in ways that are economically viable and enhance the environment. Our research addresses Objective A.1, to develop management and monitoring strategies that conserve natural resources, Objective A.3, to identify factors that can be used to predict and minimize rangeland degradation, Objective B.1, to develop monitoring tools and management strategies for managers, and Objective B.4, to assess animal productivity under alternative management strategies.

Benefits of achieving our objectives will be gained by rangeland livestock producers, public land managers, scientists, and the public. Achieving our objectives will result in maintained or improved conditions of desert rangeland resources. Specifically, identification of monitoring methods will provide quantitative, science-based information for resource management decisions. Remediation techniques that are ecologically and economically valid will result in sustainable practices for improving resource conditions. Development of livestock practices based on knowledge of animal behaviors will result in grazing management practices better suited to arid southwestern environments. Synthesis and integration of short- and long-term experiments with monitoring, remediation, and livestock management technologies using quantitative techniques (simulation modeling, GIS, aircraft and remotely sensed images) will provide general predictive tools that can be applied to many arid rangelands in the U.S. and abroad.

Key products include (1) indicator-based methods that integrate field and remotely sensed data for rangeland assessment and monitoring, (2) ecologically based techniques for remediating desertified lands, (3) behavior-based livestock practices for grazing management, and (4) a synthetic simulation model of ecosystem processes integrated with the most current GIS, GPS, and remote sensing technologies (Fig. 2).

Customers include technical field staff with land stewardship agencies, especially staff with the Natural Resources Conservation Service (NRCS) and the Bureau of Land Management (BLM). These customers and partners are technical staff who work at local scales, dealing with range management on both public and private lands; regional staff working in the western U.S. dealing with implementation of policies, especially related to ecological site descriptions, inventory, assessment and monitoring; and headquarters staff working at a national scale dealing with development of policies for western rangelands. This research program has specific collaborations with all of these customers at these different scales of interest (Appendix 14). Other customers include public land ranchers interested in assessing management impacts and evaluating long-term changes on their rangelands. A specific example of these customers is the Malpai Borderlands Group, an association of public land ranchers along the border region with Mexico in both Arizona and New Mexico. This customer group is linked to our research program through a specific cooperative agreement (see collaboration letter). An additional customer is K-12 educators in the region devoted to improving science education curricula. A specific link to this customer is through our collaborations with the National Science Foundation Long Term Ecological Research Program Schoolyard program (http://www.cdnp.org) that is directly tied to our research through an easement for access to the Jornada Experimental Range. This easement provides access for over 12,000 students (each year), teachers, and the general public to research information from this Unit. This information has been used to develop science education curricula for use in dozens of schools in this region. Other customers, partners and stakeholders are identified in the letters of collaboration included in Appendix 14.

IV. Scientific Background

The mission of the research unit at the JER is to develop new knowledge of ecosystem processes as a basis for monitoring, remediation, and management of desert rangelands (Fig. 1). The USDA-ARS has nearly a century of research at the JER on managing desert rangelands. Research during the first 80 years was extremely effective in identifying grazing management guidelines, principles of proper utilization, supplemental nutrition practices for livestock, strategies for avoiding poisonous plants, and mechanical and chemical techniques for improving rangelands. Results from these studies still have tremendous utility. However, they are limited by an incomplete understanding of the key processes and multi-scale interactions that control plant and animal production, by a failure to address non-grazing ecosystem services, and because they do not take advantage of new and emerging tools and technologies, including state-and-transition conceptual models, process-based simulation models, and remote sensing imagery. Although we have made significant progress in addressing these limitations during the past five years (as described below under the objectives section, Pg. 10-19), challenges remain that guide the research to be conducted over the next five years.

First, we need technologies founded on a more thorough, process-based understanding of the complexity of Southwestern desert rangelands. Previous technologies failed in part because they were not based on an understating of interactions between management actions and ecological processes. Our understanding of how these systems function has changed dramatically over time and remains incomplete. A number of studies have revealed that landscape-scale patterns in vegetation are determined by subtle differences in soils and hydrology (e.g., Wondzell et al. 1996) and spatial differences in the consequences of drought (Herbel et al. 1972) and livestock use (Holechek et al. 1994). These studies provide insight into the large-scale drivers (e.g., climate, fire, herbivory) influencing conversion of grasslands into shrublands (Humphrey 1958; Buffington and Herbel 1965). These studies have also been very effective in establishing general grazing guidelines for arid rangelands. However, insights associated with controls of vegetation dynamics for different ecological sites are emerging after more than 50 years of monitoring–insights not predictable from short-term observations (Havstad et al. 1999; Peters et al. 2006b; Yao et al. 2006). Thus, process-based research is needed to understand and predict how systems change through time, the constraints associated with those changes, and how to more effectively integrate livestock behaviors into adaptive process-based grazing management strategies.

Second, we need to consider a greater range of spatial and temporal scales in our research program and its application to rangeland management. Most process-based research in arid rangelands has historically focused on individual grasses or shrubs and their associated interspaces (Schlesinger et al. 1990). Feedbacks between individual plants and soil properties are well documented, while microbial influences are increasingly being understood. All of these feedbacks are important components of shrub invasion into perennial grasslands. However, the impacts of management decisions made at small scales often cascade into unintended consequences at broader scales and vice versa (Van de Koppel et al. 2002; Peters et al. 2004a; 2007b) or are constrained by processes operating at broad scales, such as climate (Fuhlendorf and Smeins 1999). In general, we have a limited understanding of these hierarchical relationships. Because arid rangelands exhibit a high degree of temporal variation and spatial heterogeneity (Bestelmeyer et al. 2004), there is extensive but sporadic redistribution of resources (water, soil, nutrients) across landscapes. Historic patterns of grazing by domestic livestock constitute another spatial component interacting with other factors to accentuate spatial and temporal heterogeneity (Bahre and Shelton 1993). Nonetheless, this heterogeneity and its causes can be organized according to different scales, ranging from individual plants and associated microflora to groups of plants (patches) and groups of patches (landscape unit or range site = ecological site in current terminology). Pastures or landscapes can be conceptualized as a mosaic of ecological sites, each composed of a hierarchy of patches.

Because of connections within and among scales, a linear extrapolation of process-based information collected at one scale is often insufficient to explain or predict larger scale patterns and dynamics (Peters et al. 2004b). Insufficient information is known about the key processes constraining rangeland response at each spatial scale. Furthermore, it is unknown which processes must be considered in order to extrapolate or interpolate across scales. Studies in other systems show that variability in fine-scale within patch processes (such as nutrient cycling) becomes less important and fluxes of materials among spatial units become increasingly important as spatial scale increases from patches to landscapes (Mazerolle and Villard 1999). In arid landscapes, seed dispersal can connect different parts of a landscape to influence shrub invasion dynamics (Yao et al. 2006).

Very little attention has been devoted to connecting within- and between-patch processes, yet we expect this information is critical in explaining patterns and dynamics at the scale of landscapes. For example, trigger sites have been identified as important elements in remediation (Herrick et al. 1997; Whisenant 1999), but establishing the identity and function of such patches in an interconnected landscape has not been fully addressed. We contend that patches are a critical, intermediate scale needed to extrapolate fine-scale, process-based information gathered in experiments to landscape patterns and dynamics. We need to understand how to monitor, remediate, and manage rangelands at broad scales relevant to the needs of our customers. Furthermore, we need to understand how processes measured at one scale translate into patterns at smaller or larger scales, and the relative importance of processes at different scales.

Third, we need to integrate a suite of technologies (ground-based indicators, simulation models, GIS, aircraft and remotely sensed images) with our short- and long-term experiments in order to develop predictive models and management tools applicable to a variety of issues facing managers of arid rangelands. These technical approaches must reflect the range of spatial and temporal scales across which key processes interact to generate pattern and dynamics.

We have four specific objectives needed to meet our overall goal. We will build upon past and ongoing research to address our objectives. We will provide a synthetic framework for our research that will allow us to predict responses of ecosystem dynamics and livestock distribution across spatial and temporal scales as climate and other management-independent drivers change (Fig. 1). Our approach will be to combine short-term experiments to test specific hypotheses with synthetic objectives requiring more complex integration of ecosystem components and drivers.

Objective 1. Develop an integrated assessment and monitoring approach for vegetation structure and composition, soil stability, watershed function, and biotic integrity of spatially and temporally heterogeneous rangelands at watershed, landscape, and regional scales.

Literature Relevant to Objective 1.

A major challenge facing resource managers is how to assess and monitor rangeland structure and dynamics in a scientifically rigorous, but cost-effective and widely understood fashion (NRC 1994). Currently, a large number of site-specific, field-based protocols are available to monitor structural characteristics of rangelands (e.g., Elzinga et al. 1998; USDA-NRCS 2003). These monitoring approaches are effective for determining vegetation status at specific locations at fine scales, and are often used to guide short-term management decisions. The capacity of remote sensing tools to detect broad-scale compositional and structural changes is increasing, particularly in relatively homogeneous, mesic systems (Muchoney and Unnasch 2001); high resolution photography shows promise for quantifying fine-scale patterns and identifying individual plant species (Booth et al. 2006; Rango et al. 2006). Adopting currently available tools to assess and monitor rangelands is limited by a combination of high costs, high training requirements, and low repeatability. In addition, there is often a poor correlation between measured indicators and the properties and processes of interest; in particular, an explicit consideration of rangeland function is often ignored (Herrick 2000; Herrick et al. 2002). Because existing approaches rely almost exclusively on point estimates of a limited number of vegetation indicators, they are relatively insensitive to ecological thresholds that, if crossed, can limit the ability of rangelands to recover from perturbations (Friedel 1991; Archer 1994; Davenport et al. 1998; Bestelmeyer et al. 2006a). Indicators of soil (NRC 1994; West et al. 1994) and landscape processes (Rango et al. 2006) are also needed to detect thresholds. Current approaches to rangeland evaluation are only beginning to be linked to conceptual models that incorporate nonlinear, threshold behavior (Scheffer and Carpenter 2003). Existing linkages between indicators and conceptual models tend to describe the consequences of changes in ecosystem function, but not the underlying causes (Bestelmeyer 2006).

Our research unit has been instrumental in developing indicators to monitor fundamental changes in ecosystem function associated with threshold and non-threshold type behaviors (Herrick et al. 2005). At broader scales required by state and federal agencies, we have developed methods for use of hyperspectral digital data at 5 cm resolution obtained by Unmanned Aerial Vehicles (UAVs) to extend rangeland health approaches to landscapes (Rango et al. 2006). We have also developed conceptual frameworks to aid in interpretation of measurements (Bestelmeyer et al. 2003). Although we have been successful in using these techniques to address specific questions in arid rangelands, there is a critical need for assessment and monitoring approaches that are better connected to conceptual frameworks of ecosystem dynamics, and more explicitly linked to policy and management at landscape, regional, and continental scales. Thus, a multi-scale, integrated approach is needed to allow public and private individuals to cost-effectively use a set of information-rich indicators to measure current and potential status of rangelands (Fig. 1). There are three critical areas of research needed to develop this general monitoring approach:

> a) Conceptual models need to be developed and integrated with remote sensing and ground-based measures in order to evaluate the sensitivity of different parts of a landscape to both new and existing threats (such as invasive species or exurban development) and changes in management (such as altered grazing practices or implementation of prescribed burning). This information can then be used to prioritize monitoring and management efforts as part of an adaptive management strategy. In particular, we need conceptual models that predict the conditions under which different kinds of thresholds are likely to be crossed and management solutions no longer yield expected results. In arid rangelands, increasing bare ground connectivity via grass loss and shrub dominance leads to increased erosion by both wind and water (Tongway and Ludwig 1997; Okin and Gillette 2001). The point at which perennial grass loss initiates processes producing erosion has been referred to as either a soil erosion (Davenport et al. 1998) or pattern threshold (Bestelmeyer 2006). This threshold is the strategic point at which management interventions must be implemented to prevent persistent degradation and to promote grass recovery. In contrast, a degradation threshold (Bestelmeyer 2006) or resource threshold (Aguiar and Sala 1999) is the point at which environmental change precludes recovery in response to the same management actions.
>
> State-and-transition models are one type of conceptual model of particular importance in understanding rangeland dynamics and threshold behavior (Appendix 1a). We have been instrumental in developing state-and-transition models connected to state and federal agency objectives (Bestelmeyer et al. 2003, Bestelmeyer et al. 2004, Briske et al. 2005, Briske et al. in review). These models are part of recent national efforts to improve the scientific basis of rangeland and forestland management in the BLM (USDI Bureau of Land Management 2004), United States Forest Service (USFS) (Winthers et al. 2005), National Park Service (Miller 2004), and US Geological Survey Gap Analysis Program (Comer and Schulz 2007). Although these models have great utility in predicting ecological sites distinguished by soil and climate properties, a specific understanding of the effects of soils and climate across ecological sites within a landscape, and especially soil-climate interactions, on rangeland dynamics is missing. Multi-scale studies from plots to landscapes and regions are needed across a broad

range of soil, climatic, and land management settings. In addition, ground-based and remote sensing measures need to be better linked to state-and-transition models. Knowledge of ecological sites and their dynamics across spatial scales is critical, but we also need to be able to monitor these dynamics effectively for this knowledge to have application.

b) Cost-effective vegetation and soil measures are needed that accurately reflect the status of underlying ecological processes (NRC1994). We have been successful in achieving elements of this goal: a soil stability kit and gap intercept approaches to estimate soil resistance and resilience to disturbance are key methods developed at the Jornada Experimental Range (JER) and described in our monitoring manual (Appendix 2) (Herrick et al. 2001; Havstad and Herrick 2003; Herrick et al. 2005). Key components of this manual have been implemented in a number of programs, including the NRCS National Resource Inventory (Spaeth et al. 2003, 2006) and the USGS post-fire monitoring protocol (Wirth and Pyke 2006), which is being adopted by the BLM. We also participated in developing and revising a qualitative assessment protocol emphasizing rapidly executed measurements based on the same principles (Pyke et al. 2002; Pellant et al. 2000, 2005). This protocol has been nationally adopted by the BLM and NRCS, and has been independently translated into Chinese, Mongolian, and Spanish. The effective application of these ground-based protocols to using state and transition models is limited by three factors. The first is that the relationship between spatial distribution of plants and soil and water loss and redistribution is poorly defined. The second is that there is little guidance available on how to apply these protocols to increasingly common linear disturbances (such as off-road vehicle tracks). The third is that there is little guidance on the level of replication required to describe and detect changes in critical vegetation and especially dynamic soil properties at multiple spatial scales (Tugel et al. 2005).

c) Remote sensing tools must be integrated with ground-based measurements to detect change at management-relevant scales. Remote sensing is the most efficient and effective way to stratify the landscape into relatively homogeneous assessment and monitoring units; the Range Management Research Unit has been a leader in collecting, collating, and making images from the site easily accessible to researchers (Appendix 3). However, the ability of remotely sensed images to detect ecologically significant change has been limited by several factors.

First, the resolution is often too coarse to detect fine-scale changes in bare soil gaps, patches, and vegetation types.

Second, these data are often insensitive to changes in soil properties and processes.

Third, remote sensing approaches are sensitive to variables that fluctuate in response to short-term weather (e.g., plant greenness) that may not indicate changes in ecosystem function. However, remote sensing capabilities can be important in identifying spatial patterns that indicate areas susceptible to remediation treatments. By contrast, ground-based measurements are effective in detecting critical changes in ecosystem function in relatively small areas, but it is difficult, if not impossible, to extrapolate these results to larger areas. Rango and colleagues (Martinec and Rango 1981; Brubaker et al. 1996) exploited this complementarity using remotely sensed images to define the spatial extent of snow cover and using ground-based data to quantify the amount of snowmelt in each monitoring unit. The integration of ground-based and remotely sensed indicators is essential to cost-effectively increase the sensitivity of assessment and monitoring systems to changes in ecosystem properties and processes, and to test model predictions. Such approaches are critical where degradation and recovery are associated with resource redistribution, and where the scale and location at which changes are first detectable cannot be anticipated (Peters et al. 2004a). Integrating ground-based and remotely sensed indicators using new, high resolution imagery will require two types of research. The first is careful calibration of indicators that can be detected using both ground measurements and imagery. The results of this research will allow remote sensing to dramatically increase the area sampled. This approach can be used where the indicators scale linearly with spatial extent, and to increase the cost-effectiveness of national sampling programs (e.g., National Resource Inventory; Herrick et al. 2006a). The second type of research will develop new imagery-based and integrated ground-imagery indicators that cannot be detected using ground-based measurements alone. The results of this research will increase our ability to detect more subtle and broad-scale changes in the landscape than obtained by only sampling individual plots.

Objective 2. Identify key plant and soil processes, and environmental factors, such as landscape position, land use history, and climate, that influence the potential for remediation success.

<u>Literature Relevant to Objective 2.</u>

In arid lands globally, vast areas previously dominated by perennial grasslands have been invaded by woody plants (McPherson 1997; Scholes and Archer 1997). These vegetation shifts have also occurred at the JER (Appendix 4) (Gibbens et al. 2005). A number of causes of woody plant expansion have been identified, including livestock overgrazing, drought, changes in fire regime and small animal populations, directional changes in climate, and introduction of exotic plants and animals (Archer 1994; Archer et al. 1995; Bahre and Shelton 1993; Grover and Musick 1990; Weltzin et al. 1997). While the causes of shrub invasion are variable and often poorly understood, the consequences are clear and relatively consistent. Shrub invasion leads to increased soil heterogeneity at the plant-interspace scale as resources become concentrated near the base of shrubs due to self-reinforcing feedbacks with soil properties (Schlesinger et al. 1990). Loss of plant cover in interspaces results in a net loss of soil and water resources from the system through wind and water erosion (Schlesinger et al. 1990; Okin and Gillette 2001, Wainwright et al. 2002). Shrub invasion can promote the spread of exotic herbaceous species (Masters and Sheley 2001), and result in a forage base that is typically less palatable and higher in secondary compounds (Bryant et al. 1991).

Because shrub-dominated systems have less usable forage and higher erosion potential, it is often desirable to return the system to a state dominated by perennial grasses. At the JER, numerous remediation approaches have been attempted since 1912 either to control shrub invasion or to return perennial grasses to dominance (Appendix 5; Herrick et al. 2006b). Although most attempts were unsuccessful, there have been sufficient successes to indicate the system can, in some fashion, be managed (e.g., Cassady and Glendening 1940). In some cases, it has taken decades for positive effects to become apparent, and these responses are not uniformly distributed across the landscape (Rango et al. 2002; Peters et al. 2006b). Because many treatments are well documented, we have been able either to continue long-term measurements or to recover archived experiments for resampling. Availability of these long-term data provides convincing evidence that remediation of these systems is possible. For example, long-term experiments from the Jornada show that perennial grasses can recover following animal exclusion and periodic shrub removal (Havstad et al. 1999). Small-scale redistribution of water by small (15-cm high) ponding dikes results in a dramatic increase in shrub and perennial grass cover after 18 years (Walton 2005). Observations from west Texas also show perennial grasses are recovering following the removal of large herbivores (Wondzell and Ludwig 1995). Evidence from the paleo-record shows transitions from shrub- to grass-dominated systems have occurred several times over the past 10,000 years (Van Devender 1995; Monger et al. 1998).

We believe most attempts promoting grass remediation in arid rangelands have had limited success for three major reasons: (1) the key processes limiting perennial grass recovery at different spatial and temporal scales have not been identified, (2) the spatial context of experiments and (3) the importance of linkages among spatial units within a landscape have been ignored. Although the high spatial and temporal heterogeneity inherent in arid rangelands has created difficulties in the past and led to the failure of many remediation attempts, we see this heterogeneity as an opportunity we can use to our advantage. Recognizing the potentials, limits, and connections among different parts of the landscape and extrapolating our process-based information across spatial and temporal scales will be essential to our approach in the next 5 years for addressing three main areas of research (Fig. 1):

a) Understanding key processes limiting grass recovery or persistence is needed. For example, seeds can be added artificially to sites without grasses; however, this approach is often not cost-effective (Ethridge et al. 1997). Understanding controls on spatial and temporal variation in seed availability is critical to determine the key processes limiting grass response and to guide remediation efforts. This information is also needed to predict site sensitivities or probabilities that perennial grasses will be successful for different parts of the landscape. Seed availability depends on a number of processes (i.e., seed production, presence of viable seeds in the soil, and dispersal of seeds), each with a low probability of occurrence at any given place or time, especially for perennial grasses in arid rangelands (Peters 2002a). Seed presence in the soil is a measure of availability that integrates across these processes (Peters 2002a). Information is needed concerning the abiotic (soils, landscape position) and biotic (vegetation and microbial community type) controls on seeds stored in the soil, and the variability in seed storage through time as precipitation (timing and amount) and temperature vary. Information is also needed on the effectiveness of different dispersal agents (wind, water, animals) for perennial grass species. The importance of animals in dispersal of mesquite seeds is well documented; however, little is known about dispersal of grass seeds other than by wind and water (Fraleigh 1999), although it is known that many seeds survive passage through ruminant digestive tracts (Harmon and Klein 1934; Fredrickson et al. 1997).

After seeds are available to a site, then constraints on seedling establishment and growth become operative. Recent evidence shows that fungi associated with seeds can assist establishment under laboratory conditions (Lucero et al. 2006). These responses need to be tested in the field, and the mechanisms for improved remediation success, such as improved water and nutrient uptake, increased seed and stolon production, and improved plant defenses against herbivory, need to be examined. In addition, genetic evidence of endophyte transfer needs to be documented, and the endophytes useful for revegetating arid lands need to be identified. The ability to separate genetic markers with exceptionally high resolution via denaturing gradient gel electrophoresis (DGGE) (van Elsas et al. 2000; Dent et al. 2004) combined with the ability to transfer obligate endophytes, including fungi, to novel host plants (Redman et al. 2002; Barrow and Lucero 2005) has provided a powerful mechanism by which unculturable microbes that enhance plant establishment in arid lands can be identified.

b) Landscape context, or the location and composition of a spatial unit of interest relative to its broader-scale surroundings, is increasingly recognized as a critical element in management and remediation research (Whisenant 1999). Characteristics such as location, adjacency, connectedness, and spatial configuration of spatial units must be accounted for when managing landscapes (Beeson et al. 2001). In arid ecosystems, landscape context can be used as a surrogate for landscape processes that are difficult to measure, such as seed dispersal, meso-scale weather variability, or the anisotropic spread of disturbance and resources (Turner et al. 2001). Effects of landscape context can be examined using multi-scale surveys of plant, patch, and landscape scale properties to explain variation in vegetation patterns at different scales (Legendre and Legendre 1998, Lichstein et al. 2002, Borcard et al. 2004). We have employed similar approaches to produce novel explanations about the drivers of grassland degradation from long-term permanent quadrats (Yao et al. 2006) and changes in grassland spatial structure (Bestelmeyer et al. 2006b). However, data do not exist with suitable extent and intensity to dissect the spatial structure of ecosystem processes throughout the Jornada.

c) The role of connections among spatial units in limiting remediation efforts needs to be better understood. Failure to account for connections among spatial units when flows of water, soil, nutrients, or seeds are important often results in unexplained variation in responses (Mazerolle and Villard 1999; Peters et al. 2006a). Furthermore, time lags and indirect effects often occur over longer time periods and at broader spatial scales that are not apparent in short-term observations of small plots (Wiens 1984; Havstad et al. 1999). At the JER, many remediation studies initiated in the mid-1900's did not account for these temporal and spatial characteristics of landscapes. Thus, a number of studies termed “failures” in the short term have shown positive results in the long term (Rango et al. 2002; Herrick et al. 2006b). We are particularly interested in the dynamics of “run-on” sites that receive additional water inputs. Recent analyses of long-term JER data show that aboveground net primary production (ANPP) is higher than expected in lowlands based on rainfall amounts only; flooding events are required to understand patterns in ANPP at these run-on sites (Peters et al. 2006a). Understanding connections among landscape units (patches, ecological sites) is needed to fully understand and use the results from remediation studies previously conducted at the JER.

Objective 3. Develop adaptive strategies for livestock management across multiple scales based on animal foraging behavior.

<u>Literature Relevant to Objective 3.</u>

Approximately 70% of the world’s land surfaces are rangelands primarily managed for livestock production (Holechek et al. 2000), much of which occurs in arid and semiarid regions. Livestock exert major effects on ecosystem dynamics (e.g., nutrient cycling, vegetation biomass, and associated faunal populations) through foraging, trampling, urination, and defecation. Livestock can also be important integrators by connecting spatially distant landscape units through the redistribution of nutrients and seeds. Livestock effects on ecosystem dynamics feed back on animal behavior and productivity through altered composition, productivity, and distribution of plant resources (Duncan and Gordon 1999). The response of livestock to their environment depends on spatial and temporal variation in forage quality and quantity, as well as abiotic features, such as topography, soil properties, and sources of water. Livestock production, as well as the stability of grass-shrub interactions, depends on the manner in which animals respond to heterogeneous environments (Van de Koppel et al. 2002). Animal interactions with their environment occur across a range of scales, from individual plants and feeding stations to patches and large spatial units such as that of the animal's 'home range' (Fig. 1); these scales can be based either on plant community or animal behavioral attributes (Senft et al. 1987; Bailey et al. 1996). Understanding and manipulating foraging patterns and animal distribution at multiple scales is particularly important in spatially and temporally heterogeneous arid rangelands. Grazing intensity and frequency can vary within each pasture due to patterns in animal distribution that reflect variation in forage and water availability. Thus, there is a critical need to understand how animals respond to, as well as affect, variable environments across a range of scales in order to develop adaptive strategies for managing livestock and promoting ecosystem stability over time. A variety of factors influence foraging behavior, including plant and animal characteristics as well as abiotic features (Fig. 1). Three critical areas of research are needed to develop these adaptive strategies and account for many of these factors:

a) Information is needed regarding the biochemical principles of diet selection. If factors influencing decisionmaking of livestock at small scales (individual plants, feeding stations) are understood, then they can be used to modify feeding behavior and influence larger-scale patterns in animal distribution and productivity. Shrubs on arid rangelands are typically highly defended by chemical compounds, and avoided by livestock. Selection for plants and plant parts is affected by a number of parameters related to diet quality and nutrient acquisition rates; however, the role of secondary metabolites in foraging behavior is not well understood (Foley et al. 1999). Although the involvement of secondary compounds in diet selection and animal preference is increasingly being studied, there is still much to be learned about plant-chemical-animal interactions.

First, both pre- and post-ingestive processes affect diet selection (Provenza 1995; Pass and Foley 2000), with both odor and taste serving as sensory cues that affect feeding behavior (Elliott and Loudon 1987; Narjisse et al. 1996). At the JER, we are examining interactions between desert shrubs and herbivory using tarbush (*Flourensia cernua* DC) as a model for understanding and modifying diet selection of other unpalatable shrubs. While much progress has been made toward understanding the effects of volatile compounds on diet selection (Appendix 6), a better understanding of the synergistic and cumulative effects of multiple compounds on animal selection of plants and plant parts is needed in order to develop mechanisms to increase intake of unpalatable shrubs.

Second, serious limitations exist regarding our knowledge of the metabolic fate of secondary compounds once consumed. It has generally been accepted that intake of secondary metabolites by herbivores is limited by an animal's ability to detoxify them because of pathway saturation and depletion of required enzymes and co-substrates (Freeland and Janzen 1974). However, evidence to support this assumption is based primarily on modified intake and feeding behavior when secondary compounds are consumed rather than on metabolic evidence (Marsh et al. 2006). Blood levels and clearance of secondary metabolites play a major role in limiting intake (Foley et al. 1999; Dziba et al. 2006). Thus, rates and extents of absorption and elimination of phytochemicals likely have major implications in terms of the ability of an animal to safely consume shrubs. However, these shrubs can be highly nutritious under certain conditions (Estell et al. 1996). Learning to capitalize on the positive attributes of shrub compounds, developing methods to minimize their negative effects, and developing dietary combinations and additives to ameliorate their negative effects depend on an understanding of how shrub compounds affect intake and metabolism. It is possible that modifying animal preference for these shrubs may provide a method of biological control, improve animal nutrition, and allow the broader use of pastures containing a mixture of grasses and shrubs. More importantly, understanding the biochemical principles of animal foraging will allow us to better predict foraging patterns at multiple scales, and will ultimately enhance our ability to manage animal productivity from shrublands.

b) Understanding and successfully manipulating animal distribution continues to be one of the most complex processes facing resource managers (Anderson et al. 2003; Bailey 2004, 2005; Thrift et al. 2007). Ground-based conventional fences combined with various grazing strategies (rotational, continuous) have been used to confine animals to different pastures or parts of pastures for different periods of time. Because fences have been constructed primarily in locations accessible to humans (Duffy et al. 1999), they seldom provide the complete solution for managing domestic livestock (Arnold and Dudzinski 1978; Hosokawa 1989). Furthermore, construction and maintenance of conventional fences make rotational grazing cost-prohibitive for many land managers (USDI, Bureau of Land Management (BLM) 1988; Duran and Kaiser 1972). Virtual fences provide an alternative to conventional fences for controlling animal location in space and time. Until recently, virtual fencing systems required ground-based wires or transmitters to emit a continuous, coded signal (DelCurto et al. 1999). At the JER, we developed, patented, and tested prototypes of a virtual fencing methodology termed Directional Virtual Fencing (DVF™) that has the ability to autonomously alter the direction as well as the location of free-ranging cattle on large landscapes (Anderson and Hale 2001; Anderson 2007). The method uses invisible, electronically generated radio frequency (RF) signals emanating from Global Positioning Satellites (GPS; Hurn 1993; Herring 1996; Enge 2004; Kaplan and Hegarty 2005). The RF signals activate a suite of bilateral cues in the DVF™ device to direct animal movement. Recent results show that individual animals can be successfully controlled (Appendix 7). However, optimizing an animal's response within groups as well as the electronic factors that make virtual fencing possible are needed, as well as determining when and where "virtual" boundaries are acceptable in resource management (Anderson 2007).

c) Arid land-adapted livestock traits need to be identified to determine economically viable beef cattle biological types that effectively forage within arid environments. Few studies have examined variation between cattle breeds in how animals perceive their nutritional environment and, subsequently, how they interact with their environment. Identifying these within-species differences would allow managers to select for traits or animals that are better adapted to arid rangelands. Most breeds currently in use in the U.S. deserts are of temperate and tropical descent that are not well-suited to hot, dry conditions. Foraging dynamics of livestock breeds with different evolutionary histories need to be examined at multiple spatial scales since diets selected at smaller scales (plants) may not reflect diet selection at larger scales (patches). This differential selection appears to be dynamic, complex, and poorly understood. There is also a critical need to identify the animal and ecosystem attributes affecting distribution of different breeds of cattle (Appendix 8). For example, Hernandez et al. (1999) reported that feral Mexican cattle, probably of criollo influence, had a mean annual home range of 47 ± 3 km^2, while domestic beef cattle had home ranges of 14 ± 2 km^2. Feral cattle traveled 20 ± 2 km/day while domestic animals traveled 7 ± 1 km/day. Although differences in how livestock use landscapes can vary significantly among cattle breeds, these differences are largely ignored in current foraging models. Yet, this aspect of animal behavior could significantly improve model predictions. There is a need to conduct long-term studies of movement of different breeds of cattle, including non-conventional breeds, over a range of vegetation, soil, and climatic conditions.

Objective 4. Predict responses of ecosystem dynamics and livestock distribution across time and space to changes in climate and other management-dependent and-independent drivers, and develop an integrated management, monitoring and knowledge toolbox that can be easily applied by individuals with a range of management experience, from minimal to extensive.

Literature Relevant to Objective 4.

Arid rangeland dynamics are complicated by multiple biotic (plant, microbial, animal) and abiotic (soils, elevation, topography, climate) factors and processes interacting across a range of spatial and temporal scales (Fig. 1). These interactions are further complicated by extreme variability in abiotic conditions characterizing these systems. It is critical to understand how these factors and processes interact in order to manage these systems and to predict changes in system dynamics as climate and other drivers change. Addressing our overall goal depends on a synthetic approach that integrates these multiple factors and processes across temporal and spatial scales. A number of tools are available for this synthesis that will improve our understanding and prediction of complex rangeland dynamics; each tool has its own strengths and weaknesses. Short-term experiments are most useful for isolating and quantifying processes occurring over short time periods and small spatial extents. Long-term experiments are critical in determining the response of these processes to a broad range of environmental conditions. Conceptual models provide the framework for improved understanding. Simulation modeling, used in combination with short- and long-term databases, is a commonly used approach to synthesize and integrate ecosystem process interactions and to predict responses to environmental drivers and changes in management (Appendix 9). Geographic information systems are critical to cataloguing and analyzing large amounts of spatially resolved data and, when used in combination with GPS, can integrate ground-based estimates with aircraft and remotely sensed images.

In most cases, these various tools are used singly or, at most, with one to two other tools (Peters and Herrick 2002). However, to meet our overall goal of effectively addressing the multifaceted problems facing land managers today and in the future, a more synthetic approach is required (Fig. 1). There are three critical areas of research needed to meet our goal:

a) Understanding historical dynamics is needed to understand how biotic and abiotic processes, climatic conditions, and historic management decisions resulted in current landscape patterns, and predictions are needed as to future vegetation and ecosystem dynamics under alternative climate and management scenarios. Although shrub invasion is a well-observed process, it remains one of the most pervasive and least understood problems in arid rangelands throughout the world. A number of factors have been implicated in promoting shrub invasion, yet the separate and interactive effects of each factor have not been determined (Humphrey 1987). A synthetic approach integrating effects of multiple interacting factors is needed to determine how interactions among plant, animal, and soil processes, climatic and edaphic conditions, and management decisions influenced dynamics of shrub invasion and grass loss in the past to result in current patterns.

There is a critical need to predict long-term consequences of short-term decisions. A synthetic approach combining multiple technologies is needed to predict future ecosystem dynamics for the complexity of interactions involved. Predictions are needed for a broad range of vegetation and soil conditions under variable climatic conditions and management scenarios. Effects of drought at multiple frequencies (1-2y, 20y, and 50y) as well as directional changes in climate on ecosystem dynamics are needed. Furthermore, feedbacks between plants, microbes, soils, and animals as well as threshold behavior need to be investigated in the context of variable microbial, vegetation, soil, and climatic conditions. Plant-microbe combinations with an ability to establish on different soil and vegetation conditions need to be identified. Effects of plant chemistry on foraging behavior with feedbacks to plant distribution need to be examined across multiple spatial and temporal scales. Interactions among different types of cattle and their environment need to be examined in terms of their effects on landscape structure (e.g., species composition, patch structure and configuration, soil properties, topography) and dynamics, and how dynamic landscape properties affect behavior and performance of different breeds. Effects of alternative management decisions, including location and timing of grazing, on landscape structure and dynamics need to be examined along with the feedbacks to future management decisions. In order to extrapolate information across scales, the relative importance of fluxes of water, soil, seeds, and nutrients within spatial units compared to fluxes between spatial units needs to be determined.

b) The term ‘science-based management’ represents more of a dream than a reality. Large bodies of existing knowledge are ignored not because they are irrelevant, but because they are not easily available. Assessment and monitoring data are often irrelevant and unavailable to land managers (Herrick et al. 2006a). Web portals are needed to improve data accessibility. Many managers are unaware of new state-and - transition models, and new and existing assessment and monitoring protocols, or do not understand where and how they can be applied. An obvious answer would seem to be a comprehensive, computerized ‘decision support system’ (e.g., Yakowitz et al. 1993). However, a one-size-fits-all system would take too long to develop and is unlikely to generate useful recommendations for specific management challenges at the local level. In place of a comprehensive decision support system, decision trees developed for specific applications are needed to help guide users addressing specific management challenges in specific regions. This adaptive and adaptable approach would allow users to choose assessment, monitoring, and management tools from a general toolbox that are most relevant to their region, and to the educational background and experience of the various individuals involved in management. In this fashion, ‘science-informed management’ may be a realistic outcome.

CSREES-CRIS Search. A search of current CRIS projects revealed 46 other projects addressing rangeland management objectives. Approximately a third of these are ARS projects, and the remainder are a mixture of Hatch, McIntire-Stennis, State-supported, National Research Initiative supported, or other funding sources. The projects are based in the 17 western states and Florida. Of these 46 projects, 18 address ecological or management principles, 6 are focused on livestock management or nutritional objectives, 7 emphasize inventory, assessment and/or monitoring techniques, 2 address hydrologic responses of the environment to management or environmental dynamics, and 6 concern controlling weeds (and often focused on a species or genera). The 7 remaining projects are a diverse unrelated group addressing economic, public education, or sociological objectives. Many of these 46 projects involve 4 investigators or fewer. A few projects are focused on identifying ecological principles with application to land management, and none of these are in hot, arid environments. There are no other range management projects that involve 10 or more scientists, and there are no projects that integrate ecological principle objectives with livestock management objectives and objectives to develop technologies suitable for land management.

V. Approach and Research Procedures

Site Description. The primary research site is the Jornada Experimental Range (ca. 783 km^2; see Section VI for further description) located 37 km northeast of Las Cruces in southern New Mexico. The site is characteristic of the northern Chihuahuan Desert. Long-term (80y) mean annual precipitation is 247 mm/y with 53% of annual rainfall occurring between July 1 and September 30. Mean maximum monthly temperatures over the same time period range from 13.3 ^{o}C in January to 36 ^{o}C in June. Topography is characteristic of the Basin and Range Physiographic Province; basin elevation averages 1650 m asl. Five major plant communities typically occur that are in general related to surface soil texture and subsurface geomorphology: black grama grasslands on loamy uplands with some remnant areas on sandy basin soils; tobosa grasslands in fine-textured playas; creosotebush shrublands on bajadas with thin, rocky soils; mesquite dunelands on sandy basin soils, and tarbush on clay lowlands (Appendix 4). Although 25% of the area was dominated by perennial grasses in 1915, much of this area has converted to shrublands such that < 7% of the JER is now dominated by herbaceous species (Appendix 4). To ensure that our research has regional, national, and international relevance, we have established collaborative research projects at a number of other locations throughout the western U.S., Latin America, and Asia. As these projects are not absolutely essential to the success of our research program, they are not discussed in this project plan. Similarly, we omitted some of the noncore experiments on the Jornada, and focus on the long-term studies, some dating to the 1930s (Appendix 10).

Objective 1. Develop an integrated assessment and monitoring approach for vegetation structure and composition, soil stability, watershed function, and biotic integrity of spatially and temporally heterogeneous rangelands at landscape, watershed, and regional scales.

Sub-objective 1.A. Develop data-supported conceptual models and general methods to describe the states and transitions of rangelands in response to variation in climate and soils. (Bestelmeyer, Herrick, Havstad)

Hypothesis 1.A. Soil and climate gradients condition threshold and feedback behavior of rangelands such that relatively small differences in climate and soil properties can have large affects on ecosystem resilience.

Experimental Design. The structure of state-and-transition models is expected to vary with differences in climate and soil properties (Bestelmeyer et al. 2003, 2004, 2006c). Although these models are increasingly used by the NRCS and BLM to guide management decisions, these relationships have not been rigorously examined. We will sample vegetation and soil properties over a range of vegetation states within different ecological sites across these two environmental gradients in the Chihuahuan Desert of southern New Mexico (including the Jornada), western Texas, and eastern Arizona. Methods follow previously established procedures (see Herrick et al. 2002; Bestelmeyer et al. 2006a). Statistical analyses based on a completed pilot study indicate that ca. 800 plots will be needed for the Chihuahuan Desert. Plots will be selected based on three levels of stratification: 1) climate gradients (precipitation, temperature), 2) geomorphological regions, and 3) geomorphic gradients. Climate gradients will be based on E-W differences in the proportion of annual rainfall that falls in winter and N-S differences in minimum winter temperatures. Geomorphological regions are land areas that feature similar geomorphic histories and similar combinations of soil map units. Geomorphic gradients are sequences of soil types connected by erosion/deposition processes that often have a common lithic inheritance. Within 400 m^2 plots, vegetation cover and composition as well as surface soil properties will be used to identify rangeland states. Subsoil properties (to 75-100 cm depth) will be used to characterize inherent soil variation that can affect plant rooting depth, soil chemistry, and water dynamics; this variation is also linked to ecological site concepts (e.g., Bestelmeyer 2006c). Plots will be linked to spatially referenced data in a GIS, including climate (from digital climate models based on weather data), land-use history (when available), topography (digital elevation models), and historical records of vegetation (e.g., aerial and ground photography). Vegetation will be sampled at several locations along each geomorphic gradient using either ocular estimates in plots with sparse vegetation (< 15% canopy cover) or line-point intercept measurements (5, 20 m lines) in higher cover plots. One soil pit will be characterized per plot following standard National Cooperative Soil Survey (Soil Survey Staff 1993) protocols.

Statistical analyses will be used to evaluate how the occurrence of states, changes from historical conditions, and plant species composition are related to soil and climate gradients, and land-use history using Bayesian procedures and classification and regression trees. Results of these analyses will be used to indicate the ecological sites to be recognized, how vulnerable these sites have been to transitions (i.e., resilience), and whether there is evidence that particular ecological sites routinely undergo transitions to alternative states. We will also determine the conditions under which different ecological sites exhibit threshold behavior via large changes in vegetation with small changes in climate or soil properties. This work will eventually be extended into the Sonoran, Mojave, and Great Basin deserts, and at locations in Argentina, Australia, China, and Mongolia to test the generality of the approach.

Contingencies. Some relationships may not be generalizable to other arid rangelands, which will limit the number of sites used. Funding opportunities and constraints may determine number and location of sample plots outside of the Chihuahuan Desert.

Collaborations. Tucson ARS (Phil Heilman); DoD (Dallas Bash); (sampling and model development); NRCS (George Peacock; Jeff Repp; William Puckett) (assist in method development, house models nationally), BLM (Jim McCormick) (provide data and feedback about model performance); USGS (David Pyke), NPS (Hildy Reiser), NMSU (Curtis Monger; Rhonda Skaggs), University of Arizona (Mitch McClaran), Texas A&M (David Briske) (provide data and conceptual development for linking models and ecological site concepts to other evaluation systems); University of California-Berkeley (Nathan Sayre); Agricultural University of Inner Mongolia (China) (President Changyou) , Agricultural Research University of Mongolia (Dr. Tserendash) , CSIRO Sustainable Ecosystems, Australia, Instituto Argentino de Investigaciones de las Zonas Áridas (develop international protocols for parallel research).

Sub-objective 1.B. Develop and calibrate ground-based indicators of ecosystem processes, including resource redistribution, at scales that are relevant to threshold changes in ecosystem function. (Herrick, Havstad)

Research Goal 1.B. Develop tools that increase the ability of managers to detect and anticipate critical changes in ecosystem function.

Experimental Design. We will initiate three new studies to address current weaknesses in interpretation of changes in the spatial pattern of vegetation, the application of ground-based protocols to linear impacts, and sampling requirements for dynamic soil properties (e.g., soil organic matter).

First, we will compare indicators calculated from basal gap, canopy gap, ***soil aggregate stability, and soil water infiltration methods*** (Herrick et al. 2005) to measures of ecosystem function (soil and water loss and horizontal redistribution) in experimentally manipulated plant communities at the Jornada and in adjacent areas in the Chihuahuan desert. We will use two existing manipulative experiments from which different plant species have been removed in different densities to examine ***(a) the effects of increasing the amount and spatial connectivity of bare soil patches (i.e., gaps) on soil and water redistribution***, and (b) the ability of indicators to characterize these changes. Redistribution rates will be measured with mini-flumes that capture soil and water, and compared with control plots without mini-flumes. ***Indicator measurements will be stratified by current and pre-treatment plant cover.***

Second, we will develop and test a set of protocols for applying the Interpreting Indicators of Rangeland Health assessment protocol and a suite of four soil and vegetation measurements to linear disturbances, including dirt roads and off-road vehicle tracks, in cooperation with BLM offices in southern New Mexico, southeast Utah and northeast Wyoming. ***The four measurements include line-point intercept, canopy gap intercept, soil aggregate stability and soil penetrometer resistance. The first three were selected because they generate most of the information required to evaluate the three attributes addressed by Interpreting Indicators of Rangeland Health. Furthermore, they are more likely to be applied in the future because they already being nationally applied by NRCS and regionally applied by the BLM to address other resource management issues. Penetrometer resistance is a rapid indicator of compaction that can be used to compare treatment and control areas on similar soils with similar moisture content.*** Areas adjacent to linear disturbances will be stratified based on level of impact detectable with high resolution aerial photography. ***Measurements and qualitative evaluations will be completed in the potentially impacted area associated with the linear disturbance, and in a nearby control area.*** The consistency of the relationships between the air photo-based stratification and ground-based qualitative and quantitative indicators in each strata will be evaluated using non-parametric tests.

Third, we will re-analyze existing datasets to determine the number of measurements required to define the range of variability in a core set of dynamic soil properties (selected in consultation with the NRCS) for ***benchmark soils*** in a minimum of three different Major Land Resource Areas ***encompassing the majority*** of the Southwestern U.S. We will use variance partitioning (as previously applied in Herrick et al. 2005) and geostatistics (where sufficient data are available) to determine the optimal scales at which sampling should be completed. We will use two datasets from the Jornada and a minimum of eight datasets described in the literature in cooperation with individuals responsible for these datasets.

Contingencies. Determination of water and fluvial sediment fluxes is contingent on the modification of distributed systems (mini-flumes) to compare with connectivity indicators.

Collaborations. ARS Locations: Boise (Fred Pierson) and, Tucson (Mary Nichols) (assistance with methods development for indicator calibration). Other Cooperators: USGS (Jayne Belnap, Dave Pyke) will collaborate on development and testing of linear impacts methods. NRCS (William Puckett) and NPS (Hildy Reiser) (prioritization of dynamic soil properties).

Sub-objective 1.C. Improve the accessibility and utility of different remote sensing technologies, and integrate them with ground-based measurements to increase assessment and monitoring sensitivity and cost-effectiveness. (Rango, Herrick, Bestelmeyer)

Research Goal 1.C. Evaluate remote platform, sensors, and image-analysis for their potential as effective sensing technologies for monitoring patterns in soil and vegetation across a range of spatial and temporal scales, and integrate these remote sensors with ground-based measurements for application at landscape, regional, and continental scales.

Experimental Design. Combinations of different remote sensing platforms and sensors will be used to monitor spatial and temporal variability in vegetation type and distribution ***of patches and gaps in relation to bare soil amount***. We will fly remote sensors ranging from simple, single band hyperspatial digital cameras on Unmanned Aerial Vehicles (UAVs) (Rango et al. 2006) to more complex hyperspectral, multiangle, and Light Detection And Ranging (LIDAR) instruments on piloted aircraft and satellites. ***Each of the acquired data sets and platforms will be analyzed and evaluated for suitability for measuring rangeland health indicators (percent bare soil and vegetation patches and gap sizes), vegetation type, and vegetation change. Each sensor measurement will be compared against conventional line-point intercept surveys, belt transects, and ground-based, millimeter resolution vertical photography using standard statistical methods (Laliberte et al. 2007)*** Finally, combined sensor approaches will be evaluated to identify the easiest and most cost-effective approaches for inventorying, assessing, and monitoring plant community composition and spatial structure in Southwestern rangelands using representative vegetation areas located on the Jornada ***and other selected sites in the western US.*** Since the final solutions are a trade-off between information content and cost, this comparison will give us a firm basis for selecting solutions to current problems as well as for future, more complex applications. Testing of different platforms and sensors will be conducted using ***standardized data processing*** and methods adapted from an ongoing research project (see the JORNEX project at: http://hydrolab.arsusda.gov/jornex/jornada1.html). Patterns will be examined using the same suite of platforms and sensors for ***all ARS locations***; different seasons of the year will be used to examine effects of temporal variation in vegetation structure and cover on image quality. ***The same set of variables (i.e., percent bare soil and vegetation patches and gap sizes, vegetation type, and vegetation change) obtained from a suite of platforms, including UAVs, ultralight aircraft, piloted research aircraft and high, moderate, and low resolution satellites, will be acquired concurrently when possible to determine the degree of resolution.*** Data and analysis products will be compared with ground measurements of vegetation and soils from all locations and time periods for Sub-objective 1.A to evaluate accuracy and precision.

Contingencies. Sensor development may be required (e.g., miniaturized hyperspectral instrumentation may need to be developed or modified to fly on UAVs) if different sensors are needed on a particular platform. Although we will co-locate remote images with ongoing ground-based sampling when possible, in some locations new ground sampling may be needed to provide comparable data to remote sensing capabilities.

Collaborations. ARS Locations: Beltsville (Jerry Ritchie), Tucson (Mary Nichols), Cheyenne (Justin Derner), Boise (Fred Pierson) DoD (Dallas Bash). Other Cooperators: NRCS (Jeff Repp); BLM (Jim McCormick); USGS (Dave Pyke); NSF (Hildy Reiser); NMSU (John "J." Wright); NASA (James Foster). In all cases, collaborators will assist in deployment of sensors at their location.

Objective 2. Identify key plant and soil processes, and environmental factors, such as landscape position, land use history, and climate, that influence the potential for remediation success.

Sub-objective 2.A. Quantify key biotic processes that limit remediation and affect arid land ecosystem dynamics under different climate and soil conditions. (Lucero. Barrow, Peters)

Hypothesis 2.A. Transfer of bacterial and fungal endophytes from desert shrubs to native grasses will increase establishment and survival success of these grasses.

Experimental Design. Previous results show that co-cultivation of dominant perennial grasses *Sporobolus cryptandrus* (sand dropseed) and *Bouteloua eriopoda* (black grama) with endophyte-laden callus tissues of the shrub, *Atriplex canescens* (fourwing saltbush*),* results in increased grass biomass and reproductive potential, putatively attributed to endophyte transfer (Barrow and Lucero 2005; Lucero et al. in review). Identification of transferred endophytes has been hindered by the genetic complexity of recipient plant-endophyte consortia. Thus, we will use several tools to verify endophtye transfer and to select grass-endophyte combinations with traits expected to increase remediation success:

<u>Polymerase Chain Reaction (PCR) and Denaturing Gradient Gel Electrophoresis (DGGE):</u> Despite limitations (Appendix 11c), ribosomal RNA gene (rDNA) sequences serve as the standard for initial identification of novel microbes. Several unique rDNA gene sequences have been isolated from micropropagated *A. canescens*, *B. eriopoda* and associated endophytes (Appendix 11a). Higher resolution DGGE gels have permitted isolation of rare sequences that typically escape detection in mixed PCR products. Sequence data permit design of specific PCR primers and molecular probes for detecting targeted, cryptic microbes in plants.

<u>Microbial isolates:</u> We have preserved a collection of bacteria and fungi isolated from *A. canescens* in frozen glycerol stocks. These culturable specimens likely represent only a fraction of the microbial population present in the host plant. However, because they can be isolated and cultured, these specimens can be used as inoculum for *B. eriopoda*. Bioassays comparing callus inoculated plants with non-inoculated plants will be used to determine whether one or more of the isolate strains are responsible for inducing grass biomass increases following co-cultivation with *A. canescens* callus.

<u>Monoclonal lines of *B. eriopoda* and *S. cryptandrus*:</u> We have previously encountered difficulty detecting transferred endophytes due to genetic variability within *in vitro* grass cultures (Appendix 11a, c). DNA profile variations among untreated control plants can mask variability due to novel, transferred endophytes. To minimize this variability, we have developed monoclonal populations of micropropagated *B. eriopoda* and *S. cryptandrus.* Comparison of genomic, ribosomal DNA profiles obtained from a single genotype of *B. eriopoda* before and after co-cultivation with *B. eriopoda* callus (of the same genotype) and *A. canescens* callus will

increase probability that bacterial and fungal rDNA sequences that appear in grass tissues represent *A. canescens* endophytes.

Rapid Bioassay Protocols: Plate bioassays permit rapid screening of plant responses to endophyte isolates. Grass seeds germinated *in vitro* can be inoculated with microbes or co-cultivated with callus and examined after 7 days to select plant-endophyte combinations with establishment potential. Image analysis of black and white photographs of these plates provides assessment of early growth responses. The ability to control the nutrient composition of the growth media, the temperature and light regime of the growth chambers as well as the endophyte or callus genotype to which the seedlings are exposed, facilitates examination of multiple combinations of endophytes and environmental stressors in minimal time, and allows selection of plant-endophyte combinations with positive traits for establishment success that can be evaluated under field conditions.

General approach. Grasses inoculated with *A. canescens* endophytes will be screened with plate bioassays to identify plant-endophyte combinations exhibiting rapid early growth. Selected plants will be transferred to soil in a greenhouse, and propagated to evaluate performance throughout the season. Monoclonal grasses co-cultured with *Atriplex* callus will be evaluated as described in Appendix 11b to identify endophyte-specific molecular markers. Plant-endophyte combinations that perform well in both plate and greenhouse bioassays and ***contain endophyte species which pose minimal risk to forage quality*** will be asexually propagated to generate sufficient material for field trials. Greenhouse-cultivated plants and their progeny will be assayed using PCR targeting known endophyte sequences to evaluate temporal and cross-generational persistence of transferred endophytes. We will also use the SOILWAT simulation model (Appendix 14) to simulate the influence of endophytes on the probability of seedling establishment of *B. eriopoda* and *S. cryptandrus* under a variety of climate and soil conditions. We have used SOILWAT previously to simulate the probability of *B. eriopoda* establishment under historic vegetation, soil, and climate conditions as well as to predict probabilities under changes in surface soil properties, shifts in dominant species, and directional changes in climate (Peters et al. 2006c, 2007a). We will parameterize SOILWAT for *S. cryptandrus* without endophytes based on information in the literature. We will then use data from our endophyte studies to parameterize and test the influence of endophytes on establishment for both species under current climate and soil conditions. ***SOILWAT integrates daily precipitation and temperature with monthly climate variables (wind speed, cloud cover, relative humidity) and soil properties by depth to determine available soil water by depth. Criteria for germination and establishment based on greenhouse experiments are then compared with simulated water availability to determine if conditions for sufficient for germination and establishment in any given year. We assume that a seedling becomes established after the development of adventitious roots, a well-accepted definition for survival of grasses. We will compare seedling establishment probabilities with and without endophytes to determine the value-added by the presence of endophytes. In general, probabilities of establishment are expected to increase with endophyte associations: based on our greenhouse studies, endophytes appear to both increase the probability of establishment under lower water availability and to also increase the robustness of seedlings.***

Contingencies. Detection of uncharacterized, unculturable endophytes relies heavily on PCR methods, the weaknesses of which are described in Appendix 11c. Use of degenerate primers and other PCR modifications will maximize numbers of endophtyes that are successfully characterized. Some data may not be available in the literature to parameterize SOILWAT for *S. cryptandrus*; data from other species of the same genera will be used, if necessary.

Collaborations. ARS Locations: Beltsville (Catherine Aime), Cheyenne (Justin Derner) (assist in model parameterization for *S. cryptandrus*).

Sub-objective 2.B. Quantify the importance of landscape context to ecosystem dynamics and biotic patterns associated with remediation success. (Bestelmeyer, Herrick, Peters)

Hypothesis 2.B. Importance of biotic processes and soil properties to the rate and pattern of rangeland degradation and remediation depends on climatic conditions, landscape position, and spatial context.

Experimental Design. We will conduct two experiments to test this hypothesis.

<u>First</u>, we will take advantage of above-average rainfall in 2006 (in some cases, 100% above average) followed by a wet spring in 2007 to determine if unusual weather conditions can catalyze significant, long-term changes in the trajectory of arid ecosystems. We will employ a rapid landscape-wide inventory to document the occurrence of perennial grass-dominated areas and establishment patterns of grasses and shrubs across the JER through time. We will use a variety of geospatial data (landform, soils, geographic spread, and road proximity) to select 200 400-m^2 plots located across the JER. Samples will be stratified according to soils, geomorphology, and climate (estimated via changes in the Normalized Difference Vegetation Index based on MODIS imagery from September 2005 and 2006). Soil type, landform, and vegetation type maps will also be used to identify strata for sampling; locations will then be selected within each strata with either high or low aboveground production. Vegetation cover and recruitment of perennial grasses will be photographed and estimated using standardized ocular procedures or using line-point intercept procedures. Soils will be characterized using a soil auger and field estimates (following National Cooperative Soil Survey protocols) of the A horizon texture, B horizon texture, carbonate accumulation, and calcic horizon development in lower B horizons. A horizon samples and samples with maximum clay accumulation will be further subjected to particle size analysis in the laboratory. Aerial photography from the JORNEX project will be classified to vegetated and non-vegetated classes in ERDAS Imagine, and used to extract landscape variables for each plot, including bare ground connectivity, directional connectivity with respect to prevailing winds, and area of vegetation around each plot at several scales, from 10 to 1000 m^2. In addition, seed availability through time will be estimated by collecting surface soil samples (0-5 cm) under dominant plants and in adjoining bare interspaces from each plot in April (pre-growing season) and October (post-growing season) in 2008 and 2009, and counting emerging seedlings under greenhouse conditions (methods follow Peters 2002a). Seed dispersal by livestock in these areas will be examined in Sub-objective 3.C. Logistic regression and classification trees will be used to statistically evaluate the effects of plant and landscape variables on recruitment patterns and vegetation structure. A subset of plots will be monitored through time to examine the conditions where recruitment results in either maintained or transient change in vegetation or no change in vegetation. This rapid assessment of a large number of plots will be used to quantify the contributions of landscape variables to the characteristics and occurrence of vegetation states, and will serve as a basis for additional experiments.

<u>Second</u>, an experiment initiated in 1997 will be continued to better understand the long-term effects of soil type on vegetation and soil responses to different types of disturbance. Three types of soil surface disturbance (horse traffic, foot traffic and jeep traffic) were applied to each of 5 soil types in southern New Mexico in 1997, and repeated on ½ of each of the 6 plots assigned to each treatment in 2001. Measurements include plant cover by species, soil

aggregate stability, infiltration capacity, penetrometer resistance, bulk density, and soil surface shear strength, chlorophyll content (for cyanobacteria) and nitrogen fixation capacity (by some lichens). Analysis of variance of data through 2005 showed that resistance to different types of degradation varied among the five soils, and that the responses may be modified by drought. Continued long-term monitoring of these plots in 2008 and 2012 will allow us to evaluate the persistence of these effects. ***Livestock grazing is very light in this plant community due to very low forage availability (<50 pounds/acre). In order to maintain the integrity of the treatments (including trampling) and measurement systems, the study has been excluded from livestock grazing since 1997.***

***C*ontingencies.** Access to all points in the survey may be precluded in the first year as a result of road conditions. Points not sampled in year 1 will be sampled in the second year.

Collaborations. USGS (Jayne Belnap) will analyze soil chlorophyll content and nitrogen fixation potential for the soil surface disturbance experiment. DoD (Dallas Bash) will collaborate on disturbance experiment design, implementation and interpretation.

Sub-objective 2.C. Quantify the importance of connections among spatial units to rangeland dynamics and biotic patterns associated with remediation success. (Herrick, Tartowski, Bestelmeyer)

Hypothesis 2.C. The success of rangeland remediation practices can be increased and the rate of degradation reduced by controlling the location and timing of management actions that alter soil resources by modifying connectivity at multiple spatial scales.

Experimental Design. We will conduct three experiments to test this hypothesis.

First, we will work with Las Cruces and Socorro Field Offices of the BLM to use planned shrub control applications as a means to test the success of commonly-applied remediation practices as part of the "Restore New Mexico" program initiated by BLM. Specifically, the treatments will involve herbicides used for woody plant control, primarily *Larrea tridentata* (creosotebush), on gravelly ecological sites, the spatial dominant in southern NM. Tests of remediation success will provide tests of assertions in existing state-and-transition models (Sub-objective 1.A). Specifically, we will work with BLM to establish paired treatment and control plots within these ecological sites and in three additional states within these site that represent: 1) persistent shrublands with biophysical properties suggesting a low likelihood of grass recovery, 2) recently invaded shrublands with degraded soils ***based on aggregate stability of < 3, and A horizon Munsel values >5, and small patches of grass isolated by bare ground that suggest high bare ground connectivity***, and 3) recently invaded shrublands with slightly degraded soils, ***aggregate stabilities > 3, Munsel values suggesting A horizons darkened by organic matter, and interconnected grass patches with lower bare ground connectivity that suggest recovery is possible.*** The state classes will be evaluated using rangeland health procedures, soil characterization (specifically A horizon depth and organic matter content), and connectivity measurements and recent invasion history derived from classified aerial photography from the 1930s and 2005/2006. ***Our previous work in this region shows that these states can be consistently distinguished from each other by different observers.*** We will replicate these studies in as many blocks as possible, subject to BLM resources and resource management priorities. ***These conditions tend to occur as relatively discrete areas of several ha or more in this study area. Thus, discrete blocks will be easily defined.*** Monitoring will involve line-point intercept transects distributed to capture within-plot variability, and soils will be characterized at each transect following National Cooperative Soil Survey protocols. ***Initial soil/vegetation parameters will be treated as continuous variables in the analyses; the blocking simply ensures that there is some degree of control in treatment-nontreatment pairs and that a range of conditions are represented between pairs.***

Second, we will use a retrospective analysis of long-term manipulations to identify those parts of the landscape in which ecosystem recovery can be promoted by slowing runoff and increasing water availability through the installation of 15-cm high ponding dikes. We will continue an intensive study of dike effects on soils and vegetation on four sites with different soils located on the Jornada. We will compare changes in vegetation cover over time on dikes to adjacent areas using a series of aerial photos and expansion of detailed ground-based measurements initiated in 2004 (modified from Walton 2005). Cover and composition will be measured using point intercept along three transects arrayed perpendicular to each dike. Soil measurements, including aggregate stability, infiltration capacity, bulk density, and carbon content, will be measured at fixed distances upslope and downslope from each dike along the vegetation transects. Historical air photo analyses will be used to compare changes in cover through time. Surface soil samples (0-5 cm) will be collected through time and analyzed for the presence of germinable seeds. The generality of our results will be tested with a regional comparison of dike effects across a range of ecological sites and states using field estimates (vegetation cover and composition, aggregate stability) and historical aerial photo analysis of previously identified areas that were treated between the 1930's and 1970's. We will measure at least 10 sets of dikes in the Chihuahuan Desert. Verification of treatment date and type will be completed using historical documents as described in Rango et al. (2005). ***Due to the presence of multiple confounding factors, we expect this study to generate only very general guidance on the effects of dikes (e.g. low vs. high slopes and fine vs. coarse textured soils) on system properties.***

Third, we will implement a new study designed to generate predictions about the minimum level of connectivity among obstructions to wind and water necessary to promote grass recovery in shrub-dominated plant communities. Arrays of artificial barriers will be placed at five different densities (0, 25, 50, 100 and 200% of existing plant cover) in three different ecological sites to simulate the effects of reducing gap size and increasing fine-scale spatial connectivity among grass plants. Each array will cover a relatively uniform vegetation patch a minimum of 400 m^2 in area. Fifty-cm wide x 20-cm tall 1 cm mesh barriers will be placed in bare interspaces between shrubs, and oriented perpendicular to water flow in shrub-dominated communities on a stable and on an active (eroding) alluvial fan, and perpendicular to the dominant wind direction in a shrub-invaded grassland on a wind-erodible soil. A second piece of hardware cloth will be installed perpendicular to the first to create four quadrants with different exposure to water and wind vectors. At the simulated plant scale, we will measure sediment and litter accumulation ***adjacent to (1cm from each side of) the hardware cloth barriers*** using digital soil surface height bridges, and will count number of seedlings in each quadrant of the barriers. At the patch scale, we will measure plant cover and composition across each patch using point intercept, and changes in connectivity based on size of gaps between obstructions using gap intercept methods (Herrick et al. 2005). ***We will also use point intercept at both plant and patch scales to measure changes in soil cover (litter, coarse fragment, plant bases and microbiotic crusts).*** Wind and water flux measurements will be based on existing studies being conducted by the Jornada LTER (http://jornada-www.nmsu.edu/). Eolian soil flux (movement by wind) will be measured using BSNE (Big Spring Number Eight) sediment collectors located upwind and downwind of the plots, and water and fluvial soil flux will be measured using arrays of modified miniflumes located upslope and downslope of the plots. Measurements will be compared with and without barriers of similar size, plant composition, soils, and topographic position. We will use quantile regression to identify threshold barrier densities and connectivities required to reduce resource redistribution and result in an increase in grass cover at plant (barrier) and patch scales. Interpretation of these two sets of regressions will be used to generate hypotheses about the relative importance of decreasing physical connectivity and increasing conneactivity of grasses for restoration in diverse ecological sites. ***Additional measurements of soil water and nutrient availability, and of the biological and physical processes associated with their dynamics, will be completed as resources permit. Once established, we expect this experiment to lead to additional collaborations and applications for outside funding that could support this work on mechanisms. The sites currently have very low forage productivity and will not be grazed for at least the first five years of the experiment. We will then evaluate the degree of recovery and determine whether or not to initiate grazing.***

Contingencies. Seed additions may be required to initiate perennial grass establishment in the field experiment. Interpretation of historic dike impacts may be compromised by site selection protocols, which necessarily involve air photo identification due to the geographic imprecision of references in historical documents. The number of ecological sites that can be analyzed will depend on where dikes were installed.

Collaborations. BLM (Jim McCormick) has agreed to provide logistical support and available GIS layers for the shrub removal and dike studies. Greg Okin (UCLA) and Tony Parsons (University of Sheffield) will collaborate to measure wind and water fluxes for the connectivity study.

Objective 3. Develop adaptive strategies for livestock management across multiple scales based on animal foraging behavior.

Sub-objective 3.A. Identify biochemical principles of diet selection on individual shrubs to modify livestock foraging strategies. (Estell, Fredrickson)

Hypothesis 3.A. Mixtures of specific mono- and sesquiterpenes affect intake by ruminants.

Experimental Design. Because individual terpenes tested previously had minimal effects on intake, we will examine effects of mixtures of volatile phytochemicals on intake by browsing livestock. Effects of mono- and sesquiterpene mixtures on intake of alfalfa pellets by growing lambs will be measured using existing protocols developed at the Jornada (Estell et al. 2000; 2002), ***with intake during a 20-minute interval serving as the response variable***. In each experiment, a mixture of chemicals will be examined at five different concentrations [0X, .5X, 1X, 2X, and 10X; multiples of the concentration of each chemical in tarbush (our shrub model)]. ***Mixtures will initially consist of approximately 10 compounds that are dominant in our shrub model (e.g., alpha-pinene, limonene, 1,8-cineole) and the number will be reduced in subsequent experiments to isolate important synergisms in the event of significant effects.*** Forty-five ewe lambs will be individually fed treated pellets each morning for 5 days after a 10-day adaptation period to familiarize lambs with protocols and to establish baseline intake of untreated alfalfa pellets. Lambs without prior experience on tarbush will be used to avoid the impact of prior learning and feedback. Lambs will be maintained outdoors and fed untreated alfalfa pellets (4.7% of body weight) between trials. Chemical treatments will be suspended in ethanol and applied as described previously with controls receiving only ethanol (0X level). Treatments will be applied to diets in a separate room to minimize exposure to aromas. A randomized complete block design (nine lambs per treatment; 15 lambs per feed group) will be used, and data will be analyzed using the ***MIXED procedure of SAS with fixed***

effects of block, treatment, day, and day x treatment interaction, with a first order autoregressive AR(1) covariance structure for repeated measurements of individual animals across days. Mixtures of volatiles that impact herbivory will be identified. This information will provide insight into biochemical mechanisms that affect foraging behaviors in shrub-dominated landscapes.

Experiments will also be conducted to examine the metabolic fate of terpenes ingested while consuming shrubs high in essential oils (e.g., *Flourensia cernua*). Twelve ewe lambs will be individually fed terpene-laden shrubs during active summer plant growth. Branches will be harvested immediately before studies and stored in a walk-in cooler prior to feeding. Lambs will be adapted to diets for 10 days, followed by 5 days of sample collection. Lambs will have access to shrubs *ad libitum* for 3 hours each morning and a basal diet of alfalfa pellets will be fed after the last sample collection each day. Daily shrub intake will be measured and rumen samples (via stomach tube) and plasma samples (jugular venipuncture) will be collected at 0, 3, 6, 9, and 12 hours postfeeding. Forage, rumen fluid, and plasma terpene profiles and concentrations will be determined, and disappearance of terpenes from the rumen and plasma will be measured over time. This information will improve our understanding of the routes and timeframe of clearance of secondary metabolites from the animal as well as their role in the regulation of intake by ruminants.

Contingencies. Experiments and hypotheses will be modified to accommodate unexpected results (e.g., extreme intake reduction). Chemicals used in mixtures may be adjusted based on availability and cost.

Collaborations. ARS Locations: Boise (Fred Pierson) (conceptual advice). Other Cooperators: New Mexico State University (Andres Cibils) (data collection and interpretation), University of Zadar, Croatia (Dr. Jozo Rogosic) (conceptual advice).

Sub-objective 3.B. Control livestock distribution to optimize management of resources. (Anderson, Havstad, Fredrickson)

Hypothesis 3.B. Directional Virtual Fencing (DVF™) can be used to manage the spatial and temporal distribution of cattle on landscapes with or without tree cover in various geographical regions including deserts.

Experimental Design. In prior research, the proof-of-concept was established that DVF™ is a viable methodology to hold and move small groups of cattle across arid landscapes. Our current focus is to test if DVF™ is an effective management tool for larger groups of cattle (n = 30 to 50) and different landscapes including arid deserts. We have developed a series of experiments at several geographic locations, including New Mexico, Kansas, Texas, and Scotland. In each environment, the minimum number of instrumented animals necessary to consistently achieve 80 to 90% spatial and temporal control in herds of 30 to 50 animals will be determined. Complete control is unrealistic because virtual fencing is based on modifying animal behavior that is never absolutely predictable. Therefore, this methodology will be evaluated in ecosystems and under situations for which a virtual boundary is practical and ecologically acceptable. To determine the percentage of a herd needing instrumentation in order for the entire herd to be controlled requires consideration of both animal and environmental factors. Key animal factors to be evaluated include breed, age, temperament, physiological status, and prior and current training (husbandry). Environmental characteristics will include topography, weather, presence and extent of woody canopy cover, geographic location, and grazing management practices. The specific experimental designs used at each field test site will be optimized to account for the features unique to that location's ecological needs and managerial goals. An emphasis will be placed on providing the maximum number of consecutive days of animal control commensurate with resources, with a minimum of 14 consecutive days of control as the goal for each study.

We will use a four-step approach to testing our hypothesis that DVF™) can positively impact animal distribution and ultimately standing crop utilization by melding electronics with animal behavior.

(1) We will first determine if there is a "utilization" problem resulting from the distribution of animals and their subsequent use of the standing crop. Field sampling of the vegetation in small plots will be combined with remotely sensed images to increase the spatial extent of coverage.

(2) We will then determine how livestock without DVF™ cues being activated use the landscape. Only Global Positioning System (GPS) data together with observations will be taken during this phase.

(3) We will alter the spatial and temporal location of cattle on the landscape using DVF™. Evaluation of the GPS data from the DVF™ system, with cues now activated, will show if DVF™ was effective in altering animal distribution.

(4) Finally, we will conduct post-livestock manipulation vegetation sampling to confirm if utilization was changed. If utilization was positively changed and livestock were controlled with DVF™ then DVF™ was a useful tool. If animals were controlled using DVF™ but utilization was not improved then livestock were not the cause of the improper standing crop utilization and an alternative hypothesis will be considered.

Contingencies. The experiments and hypotheses will be modified to accommodate new or improved hardware and software or unexpected results. In the event of occasional electronic equipment failure of the DVF™ components, GPS data alone can provide intra- as well as inter-spatial distribution pattern data among cattle necessary to develop models that explain the dynamic nature of free-ranging animal distribution.

Collaborations. ARS Locations: None. Other Cooperators involved in engineering, hardware and software development include AgriTech Electronics LC (Robert Marsh), Commonwealth Scientific Industrial Research Organization (CSIRO) (Dave Swain), Massachusetts Institute of Technology (MIT) (Daniela Rus), New Mexico State University (NMSU) (Andres Cibils), Routescene, Edinburgh, Scottish Agricultural College, Edinburgh (SAC) (Michael Smith), The UK Grazing Animals Project (GAP) (Jim Swanson).

Sub-objective 3.C. Identify aridland-adapted traits associated with different breeds of cattle that influence multiscale interactions with their environment. (Fredrickson, Estell)

Hypothesis 3.C. Cattle breeds with different evolutionary histories will respond differently to landscape heterogeneity with differential effects on the redistribution of nutrients and propagules.

Experimental Design. Based on our previous research, a criollo breed of beef cattle from the Chinapas region of the Sierra Tarahumara in southwestern Chihuahua, Mexico, that evolved in North American hot deserts uses heterogeneous landscapes at the JER more evenly than temperate breeds (Angus x Hereford) currently used in the southwestern U.S. These cattle are descendants of the first cattle imported into the New World by Columbus in 1493 and have co-evolved with the region's drylands from the mid to late 1500's (Rouse 1977). We will test our hypothesis that differences in animal movement patterns influence seed and nutrient redistribution by monitoring livestock spatial patterns of forage intake and fecal excretion across a range of spatial scales for each breed of cattle. Plant-scale herbivory will be used to categorize patterns of plant tissue removal with time and the probability of seed ingestion using arena studies. Animals will then be equipped with GPS collars containing sensors that measure lateral and perpendicular head movements to estimate grazing time and bite rate. Ruminally fistulated cows will be fitted with the same GPS collars and used to estimate bite size, from which a spatial estimate of forage intake will be estimated. Three areas differing in vegetation type and topography will be used for each breed during two seasons (fall and spring). Using head angle and GPS locations, grazing behaviors at multiple spatial scales will be determined and mapped (Bailey et al. 1996). Distance traveled and patterns of movement will be analyzed statistically between treatment groups (breeds) for each area and period of sampling. Across landscapes, we will examine the effects of topography and broad-scale vegetation patterns (using techniques described by Laliberte et al. 2007 on animal movement, foraging, and seed dispersal patterns. An animal movement simulation model will be developed that includes spatially explicit grazing impacts and the redistribution of nutrients and seeds across a range of spatial scales, from plants to patches and landscape units. The model will be linked to ECOTONE (Sub-objective 4.A), and used to predict vegetation responses to herbivore nutrient redistribution, and seed depletion and dispersal.

Contingencies. Although observer error and bias are reduced, studies using novel electronic techniques and software to remotely sense animal behavior can be time consuming and expensive. To ensure that useful data are obtained in the event of electronic failure, these approaches will be coupled with observer-based methods. ***We will also continue to test the usefulness of commercial collars, and to investigate additional approaches, such as IGER grazing behavior monitoring units and IceTag monitors, as needed to test this hypothesis.***

Collaborations. ARS Locations: None. Other Cooperators: New Mexico State University (Andres Cibils); (provide input parameters to animal movement model).

Objective 4: Predict responses of ecosystem dynamics and livestock distribution across time and space to changes in climate and other management-dependent and -independent drivers and develop an integrated management, monitoring and knowledge toolbox that can be easily applied by individuals with a range of management experience, from minimal to extensive

Sub-objective 4.A. Relate vegetation dynamics in time and space to variation in environmental conditions. (Peters, Betelmeyer, Havstad)

Research Goal 4.A. To understand historic vegetation dynamics and to predict future dynamics with variations in soils, management regime, landscape context, and climate.

Experimental Design. We will build upon an established simulation model of vegetation and soil water dynamics (ECOTONE; Appendix 9) to integrate the various components and processes of our research (Fig. 1) in order to simulate historic dynamics and to predict future conditions.

Model development - ECOTONE is an individual, plant-based gap dynamics model linked with a soil water model (SOILWAT, Appendix 12) developed to simulate arid and semiarid grasslands and shrublands (Peters 2002b). The model has been parameterized and tested for black grama-creosotebush communities at the JER (Peters and Herrick 2002). We have been generalizing ECOTONE for the remaining major plant communities and key plant species, as well as modifying the model to include animal (Objective 3) and microbial components (Objective 2.A). We will include additional processes and expand the spatial complexity of ECOTONE in order to examine the relative importance of vegetation-soil-animal feedbacks, resource redistribution, foraging behavior, and patch size to ecosystem dynamics (Fig. 1). Key processes and feedbacks identified in Objectives 1-3 will be incorporated into the model either as parameters or additional functional relationships. Transfers of water, seeds, and nutrients among patches or ecological units will be measured as part of Sub-objectives 2.C and 3.C through our collaborative efforts with the Jornada LTER (http://jornada-www.nmsu.edu/). Effects of plant chemistry will be incorporated explicitly for tarbush selectivity (Sub-objective 3.A). Preference for other forage species will be obtained from the literature. Variation in foraging behavior by different breeds of cattle (Sub-objective 3.C) will be used to simulate effects of cattle on plant community structure and dynamics, as well as responses of cattle to landscape features. Management decisions will be incorporated into the model based on the outcomes from our analysis of historic and new remediation treatments (Sub-objective 2.C), and our ability to dynamically adjust stocking densities (Sub-objective 3.B). The model will be tested by comparing output with short- and long-term data from the JER that were not used in model development or parameterization (Appendices 5, 10). In addition to the historical analyses described below, we will further test the model by simulating long-term manipulative experiments described in the appendices.

ECOTONE will be used in association with Objectives 2 and 3 to generate and select testable hypotheses. The simulation model will be used to investigate the consequences of endophyte-modified seedlings to influence vegetation dynamics (Sub-objective 2.A), to identify thresholds and to establish the probability that a threshold will be crossed (Sub-objective 2.B). We will use parameters collected in our new studies and published information to examine the role of vegetation-soil feedbacks in driving ecosystem dynamics under different climate and management scenarios. The improved version of this model will also allow us to predict how differences in foraging behaviors across multiple spatial and temporal scales will affect plant community dynamics (Objective 3). We will initially focus our efforts on several areas at the JER where long-term data sets exist and where new intensive, coordinated studies will be conducted. Each area will be spatially heterogeneous in vegetation, soils, and topography. One area will be used for model development and the other areas will be used to test model predictions.

Framework development – We will develop a framework for facilitating the application of ECOTONE with available remote sensing imagery and GIS layers. The first stage of framework development will involve creating a prototype for selected parts of the JER. Existing GIS layers of vegetation, soil, elevation, and past management history (Appendices 5, 10) will be combined with new findings from Objectives 1-3. Monitoring efforts will be established in these areas based on indicators developed in Sub-objective 1.A. Various levels of spatial and spectral remote sensing data will be acquired and compared to ground-based indicators. Remote sensing technologies will be critically assessed in order to develop recommendations for tool selection. Remote sensing data will be used to extend the ground-based indicators across broader areas (Sub-objective 1.C). Remote sensing will also be used to stratify sites among geomorphic, soil, and vegetation units (Sub-objective 1.B). In addition, digital elevation data will be combined with soil maps to stratify associations (two or more soil series) into individual soils. The ECOTONE model will then be applied based on these strata. This level of stratification will facilitate predictions of locations where changes are likely to occur using state-and-transition models (Sub-objective 1.A).

Model testing using historical dynamics - We will conduct historic simulations of our validation areas starting in 1850, when perennial grasslands were prevalent, and ending in 2007 to test the ability of the model to represent shrub invasion processes. Historic vegetation and soils maps and documents will form the basis for initial conditions. We will run ECOTONE using historic weather data, parameterized for vegetation, soils, and animals, from our experiments and information in the literature. Daily weather daily from 1850 to 1914 will be created using a first-order Markov process based on data from the JER from 1915 to present. Runs will be conducted both with and without fluxes and flows of materials (seeds, soil, water, nutrients) to determine the relative importance of within- and between-unit processes. Historical dynamics will be tested using retrospective analysis of changes in vegetation over the past 150 years from the Jornada (e.g., Gibbens et al. 2005), and over the last 25-40 years from allotment monitoring data collected by the BLM Las Cruces Field Office. ***This verification, testing, and sensitivity analyses will be conducted with data that were not used to parameterize the model.*** Monitoring transects were established in key grassland areas within each BLM grazing allotment from the late 1960's to early 1980's. Allotment monitoring data will be or have been databased for ca. 200 sites distributed across southwestern New Mexico (an area of 25,000 km^2) representing several ecological sites. Soils have already been fully characterized at these sites from 2003 to the present. Vegetation data collected by BLM include “step point” procedures (see Herrick et al. 2005) and ground photographs that can be used to classify vegetation state as a categorical variable (e.g., perennial grass present or absent). Changes in vegetation will be statistically analyzed as a function of climate history, soil properties, landscape context, and land-use history. The results of this analysis will be used to interpret which ecological sites and climatic conditions have been most resilient or susceptible to grass loss/shrub invasion in recent history, and will be used to test ECOTONE output for the same time period and environmental conditions. Sensitivity analyses on model output will be used to determine the relative importance of separate and interactive processes and factors in shrub invasion for different vegetation, soils, and topographic positions. Differences between observed and predicted results will lead to new experiments on important but insufficiently studied processes, and will provide insight to Sub-objective 2.B.

Model Predictions - After the modeling framework has been well tested and modified to accurately represent previous dynamics and current patterns, we will use it to predict future dynamics under different climate and management scenarios. A large number of potential scenarios are possible; only a few are noted here. We will examine potential responses of different vegetation and soil associations to directional changes in climate, as well as to drought cycles. We will also predict responses using dynamic stocking rates made possible by our virtual fencing technology. Long-term consequences of alternative remediation technologies will be investigated, as well as the differential use of patches and ecological units by alternative breeds of cattle. Because our goal is to develop a general problem-solving approach for understanding, managing, and predicting dynamics of arid rangelands, our future plans include testing this approach across a broad range of vegetation, soils, and climatic conditions and management scenarios that will be useful to our customers.

Contingencies. The equipment and personnel necessary to complete the work are in place. Ability of the simulation model to accurately predict future dynamics depends on our ability to identify key processes and to quantitatively represent them.

Collaborations. This objective can be addressed by Jornada staff working alone. However, the quality of the results and breadth of knowledge will be greatly improved through continued collaborations with Tony Parsons, Sheffield University, England (water modeling).

Sub-objective 4.B. Develop an integrated management, monitoring and knowledge toolbox that can be easily applied by individuals with a range of management experience, from minimal to extensive. (Herrick, Havstad)

Research Goal 4.B. Integrate existing knowledge through a suite of decision trees to facilitate the practice of hypothesis-based adaptive management by land managers.

Experimental Design. An integrated management, monitoring, and knowledge toolbox will be developed. The toolbox will include a set of simple, expert systems (decision trees) that will guide the user in the integration and application of state-and-transition models, and assessment and monitoring protocols to guide policy and management. Our objectives are to increase managers' ability to correctly apply existing tools that are appropriate, and to facilitate the more rapid adoption of new tools and, through updated state-and-transition models, more rapid communication of new knowledge. Conceptual state-and-transition models (Sub-objective 1.A) describe ecological site-specific responses to different management and remediation practices, and integrate our evolving understanding of the underlying ecological processes (Objectives 2, 3, and 4.A). These models used together with assessment protocols (Sub-objectives.1.B, C) and a computerized field data entry, storage, and automated indicator calculation system that has been developed over the past 5 years (see: http://usda-ars.nmsu.edu/monit_assess/rangedb_main.php) will guide the development and selection of policy and management options, and will establish management hypotheses that are then tested using monitoring indicators (Sub-objectives 1.B,C). Individual decision trees will be developed to guide the user in selecting, integrating, and applying the appropriate tools for specific questions, such as off-highway vehicle monitoring and management. ***The toolbox will also include a module that allows managers to determine the ecological sites they are working with and the specific state of each site. The decision trees will include multiple indicators in order to address the different types of transitions that can occur between the same two states.*** We will focus on Southwestern rangelands, while working with other ARS and non-ARS locations to make these decision trees as generic as possible (e.g., Appendix 13).The decision trees will also identify and provide web-based links to supplementary tools that can be applied where technical expertise exists. These supplementary tools include simulation models of erosion, runoff, and ecosystem dynamics, and advanced remote sensing analysis methods. These tools also include web-based portals to improve data accessibility, such as two recently developed tools by the Jornada (http://www.ecotrends.info; http://www.p2erls.net).

This objective will be completed in two steps: decision tree development and evaluation.

First, the decision trees will be developed in collaboration with managers and policymakers through new and existing collaborations with NRCS and BLM. Appendix 13 shows a preliminary, prototype decision tree that was developed in response to a BLM request for guidance on where and how to apply rangeland health assessment and monitoring protocols to help guide the management of off-highway vehicle impacts.

Second, we will evaluate the potential effectiveness of decision trees with a second set of managers. The decision trees will be applied to a suite of management actions that have already been completed. We will compare the actual and recommended scenarios based on assessment and monitoring data collection costs, the proportion of the data that are relevant to the decisions, and differences between the outcomes and projected outcomes.

Contingencies. Adoption of rangeland toolbox requires continuation of close collaboration with state and federal agencies and other user groups. Modification of toolbox will be required if fewer collaborators are involved.

Collaborations. NRCS and BLM will contribute to the development of the decision trees. (William Puckett, Pat Shaver, Jim McCormick); USDA-ARS Boise (Fred Pierson)

VI. Physical and Human Resources

The research unit is based on the campus of New Mexico State University in a modern, 29,000 sq ft federal facility constructed in 2002. This building contains modern laboratory, office, and conferencing space to fully support the 11 Category I scientists within the research unit. Laboratories include modern instrumentation required for proposed projects. The facility is supported by appropriate networking and communication systems, and has adequate work spaces to house and accommodate all technical staff and support required for this project and associated research activities.

The research unit also directs the operations of the 192,000 acre Jornada Experimental Range located 25 miles northeast of the NMSU campus. The JER is a 95-year-old research facility with an extensive long-term record of field research experiments dating to 1915. All historical data from this long-term history are stored, managed, and accessed following procedures established by the National Science Foundation for long-term research programs (see: http://jornada-www.nmsu.edu/index.php?withJS=true).
Protocols are well-established for controlling site access and use by scientists (see: http://jornada-www.nmsu.edu/site/dm/readme.php?withJS=true). In addition, interactive spatial data are fully accessible (see: http://jornada-www.nmsu.edu/maps/JRN_Map/viewer.htm). This facility has all necessary components, including housing, shop facilities, networking capacities, sample preparation facilities, equipment storage and repair, and maintenance facilities to support all proposed research activities. The facility also maintains rangeland livestock and necessary husbandry capacities, and utilizes the NMSU Institutional Animal Care and Use Committee for oversight of all animal-based research. The JER is also part of the National Science Foundation's Long Term Ecological Research Network (see: http://www.lternet.edu/), a member of the American Institute of Biological Sciences Organization of Biological Field Stations (see: http://www.obfs.org/), an original member of the UN Man and Biosphere Reserves program (see: http://www.unesco.org/mab/BRs.shtml), and under consideration for inclusion in the developing National Ecological Observation Network as a remote site within the southwest

domain. A federal staff of 5 FTE, including a station superintendent, are assigned to the JER in support of all daily maintenance, repair, and research assistance activities.

The research unit scientists are also supported by approximately 20 federal FTE non-category I technical staff (an average of 1.8 FTE per category I scientist). This support includes 15 GS 7-9 field and laboratory technicians, most with MS degrees, and 5 GS 12 support scientists or post-doctoral research associates. The unit is also supported by 5 federal FTE providing administrative and office support. In addition, approximately 20 additional state FTE technical staff or post doctoral research associates funded through extramural grants and contracts, and hired through a Specific Cooperative Agreement with NMSU, provide additional technical and scientific support to unit scientists. Through this combination of federal and state FTE, approximately 7 post doctoral research associates are in residence within the unit at any point in time. The technical staff also includes 3 geographic information specialists to support spatial data analyses. There are also 2 USDA rangeland/soil scientists with the Natural Resource Conservation Service housed within the unit in support of unit research activities. Typically, the total federal and state staff within the unit is approximately 65 FTE, of which approximately 20 FTE are scientists holding terminal PhD degrees.

VII. Project Management and Evaluation

All 11 Category I scientists participating in the proposed project have been with this unit for a minimum of 5 years. All scientists have participated in extensive discussions that developed the 2002-2007 project plan, and in the discussions that resulted in the proposed plan for 2007-2012. For all scientists, this is their sole ARS research project supported through appropriated funds. The unit Research Leader provides personnel and administrative management, and the Lead Scientist provides overall research management. Each objective of the proposed project has a lead scientist that coordinates activities among scientists working within that objective and its sub-objectives. Several scientists work on more than one objective which facilitates communication and interactions. For each scientist, their annual performance plan includes specific goals related to milestones associated with the proposed project. This structure links project outcomes to individual scientist's performance. In addition, the unit operates numerous extramural research agreements that link project research objectives to similar objectives of partner agencies and institutions (see the "Related Projects" tab at: http://www.ars.usda.gov/research/projects/projects.htm?ACCN_NO=406494). These numerous and extensive agreements closely link ARS milestones within the unit project plan with deliverables of partner institutions. These linkages not only provide research synergies and additional staffing resources, but provide a mechanism to promote development of specific useable outcomes from research by the unit.

VIII. Milestones and Expected Outcomes

Project Title	Management Technologies for Arid Rangelands			Project No. 6235-11210-005-00D	
National Program	NP 215 – Rangeland, Pasture and Forages				
Objective 1.	Develop an integrated assessment and monitoring approach for vegetation structure and composition, soil stability, watershed function, and biotic integrity of spatially and temporally heterogeneous rangelands at landscape, watershed, and regional scales.				
Sub-objective 1.A	Develop data-supported conceptual models and general methods to describe the states and transitions of rangelands in response to variation in climate and soils.				
NP Action Plan Component	Component I. Rangeland management systems to enhance the environment and reconomic viability.				
NP Action Plan Problem Statement	A. Need for economically viable rangeland management, practices, germplasm, technologies, and strategies to conserve and enchance rangeland ecosystems.				
Hypothesis 1.A	SY Team[1]	Months	Milestones	Progress/ Changes	Products
Soil and climate gradients condition threshold and feedback behavior of rangelands such that relatively small differences in climate and soil properties can have large effects on ecosystem resilience.		12			
	BB, JH, KH	24	Complete sample vegetation and soils across climate and soil gradients in the Chihuahuan Desert		
	BB, JH, KH	36	Complete statistical analyses of data to identify threshold behavior for different ecological sites		
	BB, JH, KH	48	Complete Identification refinements to existing state-transition models in Chihuahuan Desert		
	BB, JH, KH	60	Provide sampling guidance and collaborate in development of state-transition models in other deserts of the U.S.		State-transition models

Sub-objective 1.B	**Develop and calibrate ground-based indicators of ecosystem processes, including resource redistribution, at scales that are relevant to threshold changes in ecosystem function.**				
NP Action Plan Component	**Develop data-supported conceptual models and general methods to describe the states and transitions of rangelands in response to variation in climate and soils.**				
NP Action Plan Problem Statement	**Component I. Rangeland management systems to enhance the environment and reconomic viability.**				
Research Goal 1.B	**SY Team**	**Months**	**Milestones**	**Progress/ Changes**	**Products**
Develop tools that increase the ability of managers to detect and anticipate critical changes in ecosystem function.		12			
	JH, KH	24	Measurement of connectivity indicators, soil and water redistribution in existing plant removal experiments		

[1] SY list of investigators for initials key: AR=Al Rango; BB=Brandon Bestelmeyer; DA=Dean Anderson; DCP=Deb Peters; EF=Ed Fredrickson; JB=Jerry Barrow; JH=Jeff Herrick; KH=Kris Havstad; ML=Mary Lucero; RE=Rick Estell; ST=Sandy Tartowski

Research Goal 1.B	SY Team	Months	Milestones	Progress/ Changes	Products
	JH, KH	36	Develop protocol for adapting existing assessment and monitoring for linear impacts and connectivity indicators		
	JH, KH	48	Develop sampling guidance for dynamic soil properties		
	JH, KH	60	Develop sampling guidance for dynamic soil properties		Monitoring Manual

Sub-objective 1.C	**Improve the accessibility and utility of different remote sensing technologies, and integrate them with ground-based measurements to increase assessment and monitoring sensitivity and cost-effectiveness.**				
NP Action Plan Component	**Component I. Rangeland management systems to enhance the environment and reconomic viability.**				
NP Action Plan Problem Statement	**A. Need for economically viable rangeland management, practices, germplasm, technologies, and strategies to conserve and enchance rangeland ecosystems.**				
Research Goal 1.C	**SY Team**	**Months**	**Milestones**	**Progress/ Changes**	**Products**
Evaluate remote platform, sensors, and image-analysis for their potential as effective sensing technologies for monitoring patterns in soil and vegetation across a range of spatial and temporal scales, and integrate these remote sensors with ground-based measurements for application at landscape, regional, and continental scales.		12			
		24			
		36			
	AR, JH, BB	48	Collect and compare images from different remote sensing and aircraft-mounted platforms for different locations		
	AR, JH, BB	60	Compare remotely sensed measures with ground-based data (Objective 1.A)		High resolution indicators

Project Title	**Management Technologies for Arid Rangelands**	**Project No. 6235-11210-005-00D**
National Program	NP 215 – Rangeland, Pasture and Forages	
Objective 2.	**Identify key plant and soil processes, and environmental factors, such as landscape position, land use history, and climate, that influence the potential for remediation success.**	
Sub-objective 2.A	**Quantify key biotic processes that limit remediation and affect arid land ecosystem dynamics.**	
NP Action Plan Component	**Component I. Rangeland management systems to enhance the environment and reconomic viability.**	
NP Action Plan Problem Statement	**A. Need for economically viable rangeland management, practices, germplasm, technologies, and strategies to conserve and enchance rangeland ecosystems.**	

Hypothesis 2.A	SY Team	Months	Milestones	Progress/ Changes	Products
Transfer of bacterial and fungal endophytes from desert shrubs to native grasses will increase the remediation success of these grasses.	ML, JB	12	Isolate and sequence microbial DNA bands from Denaturing Gradient Gel Electrophoresis (DGGE) profiles		
	ML, JB	24	Evaluate changes in vigor and growth habit of inoculated grasses relative to control under varied environmental conditions		
	ML, JB	36	Construct a database of DGGE profiles		
	DCP, ML, JB,	48	Simulation modeling of grass establishment under variety of soil and climate conditions		
	ML, JB,	60	Evaluate persistence of transferred endophytes and associated traits across two or more generations of recipient grasses.		Fungal-endophyte enhanced plant materials.

Sub-objective 2.B	**Quantify the importance of landscape context to ecosystem dynamics and biotic patterns associated with remediation success.**				
NP Action Plan Component	**Component I. Rangeland management systems to enhance the environment and reconomic viability.**				
NP Action Plan Problem Statement	**A. Need for economically viable rangeland management, practices, germplasm, technologies, and strategies to conserve and enchance rangeland ecosystems.**				
Hypothesis 2.B	**SY Team**	**Months**	**Milestones**	**Progress/ Changes**	**Products**
Importance of biotic processes and soil properties to the rate and pattern of rangeland degradation and remediation depends on different climatic conditions, landscape position, and spatial context.	BB, JH, DCP	12	Conduct survey of vegetation (adults, recruits), soils, and landscape context		
		24			
	BB, JH, DCP	36	Conduct image classification		
	BB, JH, DCP	48	Analyze local and landscape variable effects on recruitment and vegetation structure		
	JH, BB, DCP	60	Analyze data from long-term soil surface disturbance plots		Optimal timing, location, spatial scale of interventions

Sub-objective 2.C	Quantify the importance of connections among spatial units to rangeland dynamics and biotic patterns associated with remediation success.				
NP Action Plan Component	Component I. Rangeland management systems to enhance the environment and reconomic viability.				
NP Action Plan Problem Statement	A. Need for economically viable rangeland management, practices, germplasm, technologies, and strategies to conserve and enchance rangeland ecosystems.				
Hypothesis 2.C	**SY Team**	**Months**	**Milestones**	**Progress/ Changes**	**Products**
The success of rangeland remediation practices can be increased and the rate of degradation reduced by controlling the location and timing of management actions that alter the availability of plant resources by modifying connectivity at multiple spatial scales.		12			
	JH, ST, BB	24	Analyze historic aerial photo and ground-based data from dikes (Jornada)		
	JH, ST, BB	36	Analyze historic aerial photo and ground-based data from dikes (region)		
	JH, ST, BB	48	Sample vegetation and soils on paired plots		
	JH, ST, BB	60	Analyze vegetation and soils data on paired plots		Optimal timing, location, spatial scale of interventions

Project Title	Management Technologies for Arid Rangelands			Project No. 6235-11210-005-00D	
National Program	NP 215 – Rangeland, Pasture and Forages				
Objective 3.	Develop adaptive strategies for livestock management across multiple scales based on animal foraging behavior.				
Sub-objective 3.A	Identify biochemical principles of diet selection on individual shrubs to modify livestock foraging strategies.				
NP Action Plan Component	Component I. Rangeland management systems to enhance the environment and reconomic viability.				
NP Action Plan Problem Statement	B. Need for improved livestock production systems for rangelands that prvide and use forages in ways that are economically viable and enchance the environment sustainability.				
Hypothesis 3.A	**SY Team**	**Months**	**Milestones**	**Progress/ Changes**	**Products**
Mixtures of specific volatile chemicals affect intake by ruminants.		12			
		24			
		36			
	RE, EF	48	Conduct studies of terpene mixtures and diet selection		
	RE, EF	60	Identify mixtures of terpenes influencing selection of tarbush		Biochemical profile of model shrub

Sub-objective 3.B	Control livestock distribution to optimize management of resources.
NP Action Plan Component	Component I. Rangeland management systems to enhance the environment and reconomic viability.
NP Action Plan Problem Statement	B. Need for improved livestock production systems for rangelands that prvide and use forages in ways that are economically viable and enchance the environment sustainability.

Hypothesis 3.B	SY Team	Months	Milestones	Progress/ Changes	Products
Directional Virtual Fencing (DVF™), an evolving humane and effective methodology to hold, "rotate" and gather free-ranging cattle without ground-based fences, can be used to manage the spatial and temporal distribution of cattle on landscapes with or without tree cover in various geographical regions including deserts.	DA, KH, EF	12	Design and field test compact prototype DVF™ equipment package		
	DA, KH, EF	24	Design and field test compact prototype DVF™ equipment package		
		36			
	DA, KH, EF	48	Gather 30 to 50 head group of cattle on JER using DVF™ equipment		
	DA, KH, EF	60	Hold, move and gather 30 to 50 head of cattle at several sites off the JER		Virtual fence technology

Sub-objective 3.C	**Identify aridland-adapted traits associated with different breeds of cattle that influence multiscale interactions with their environment.**				
NP Action Plan Component	**Component I. Rangeland management systems to enhance the environment and reconomic viability.**				
NP Action Plan Problem Statement	**B. Need for improved livestock production systems for rangelands that prvide and use forages in ways that are economically viable and enchance the environment sustainability.**				
Hypothesis 3.C	**SY Team**	**Months**	**Milestones**	**Progress/ Changes**	**Products**
Cattle breeds with different evolutionary histories will respond differently to landscape heterogeneity such that nutrients and propagules will be redistributed differently across arid landscapes with differential effects on vegetation dynamics.		12			
	EF, RE	24	Map vegetation patterns of three diverse vegetation types in arid environments with different ratios of grass to shrubs		
		36			
	EF, RE	48	Map animal movements in three environments with differing proportions of grass and shrubs		Selection for aridland-adapted traits, breeds
		60			

Project Title	**Management Technologies for Arid Rangelands**	**Project No. 6235-11210-005-00D**
National Program	NP 215 – Rangeland, Pasture and Forages	
Objective 4.	**Predict responses of ecosystem dynamics and livestock distribution across time and space to changes in climate and other management-dependent and -independent drivers and develop an integrated management, monitoring and knowledge toolbox that can be easily applied by individuals with a range of management experience, from minimal to extensive.**	
Sub-objective 4.A	**Relate vegetation dynamics in time and space to variation in environmental conditions.**	
NP Action Plan Component	**Component I. Rangeland management systems to enhance the environment and reconomic viability.**	
NP Action Plan Problem Statement	**A. Need for economically viable rangeland management, practices, germplasm, technologies, and strategies to conserve and enchance rangeland ecosystems.**	

Research Goal 4.A	SY Team	Months	Milestones	Progress/ Changes	Products
To develop an integrated management, monitoring and knowledge toolbox that can be easily applied by individuals with a range of management experience, from minimal to extensive.		12			
		24			
	DCP, BB, KH	36	ECOTONE model parameterization and testing for different plant communities and soil types		
		48			
	DCP, BB, KH	60	ECOTONE predictions for selected sites at the Jornada and BLM plots		ECOTONE Model

Sub-objective 4.B	**Develop an integrated management, monitoring, and knowledge toolbox that can be easily applied by individuals with a range of management experience, from minimal to extensive.**				
NP Action Plan Component	**Component I. Rangeland management systems to enhance the environment and reconomic viability.**				
NP Action Plan Problem Statement	**A. Need for economically viable rangeland management, practices, germplasm, technologies, and strategies to conserve and enchance rangeland ecosystems.**				
Research Goal 4.B	**SY Team**	**Months**	**Milestones**	**Progress/ Changes**	**Products**
		12			
	JH, KH	24	Decision tree development and refinement		
	JH, KH	36	Release first version of toolbox		
		48			
	JH, KH	60	Release updates of toolbox online and through collaborative outreach efforts with existing partners in state and federal agencies		IMMA toolbox

IX. Accomplishments from Prior Project Period

1. Terminating ARS research project number – NP 205 [6235-11210-005-00]
2. Technologies for Management of Arid Rangelands
3. Project period (October 2002 – September 2007)
4. Investigators and FTE

Debra Peters, lead scientist	100%	
Dean Anderson	100%	
Jerry Barrow	100%	
Rick Estell	100%	
Ed Fredrickson	100%	
Kris Havstad	100%	
Jeff Herrick	100%	
Al Rango	100%	
Keirth Synder	100%	June 30, 2002 – January 7, 2006
Sandy Tartowski	100%	December 1, 2002 - present

5. Project accomplishments and impact

Monitoring

a. A monitoring manual and qualitative assessment were published that provide quantitative and qualitative protocols and indicators of rangeland health.
b. No changes in objectives
c. These accomplishments are the foundation for proposed Objective 1.

Pellant, M., Shaver, P., Pyke, D. and Herrick, J.E. 2005. Interpreting indicators of Rangeland Health. Version 4. Interagency Technical Reference 1734-6. U.S. Department of the Interior, Bureau of Land Management, National Science and Technology Center, Denver, CO. BLM/WO/ST-00-001+1734/REV05. 122 pp.

Herrick, J.E., Van Zee, J.W. Havstad, K.M. and Burkett, L.M. 2005. Monitoring Manual for Grassland, shrubland, and Savanna Ecosystems. Volume I-II: Design, Supplementary Methods and Interpretation Tuchson, Arizona. University of Ariozna Press. 200 p.

Remediation

a. Small (15-cm high) ponding dikes were found to be effective in capturing water and promoting grass and shrub growth, although extended time periods (i.e., decades) were required to observe results.
b. No changes in objectives
c. These accomplishments are the foundation for proposed objective 2B.

Livestock management

a. Proof-of-concept was established that Directional Virtual Fencing (DVF™) can effectively hold as well as move livestock over an arid landscape. Field trials demonstrated that GPS hardware and software were effective in locating free-ranging animals on arid rangeland landscapes allowing the DVF™ system of animal control to function autonomously, and DVF™ was successfully used to move cattle temporally and spatially across an arid landscape within a defined area.
b. No changes in objectives

c. These accomplishments are the foundation of the proposed objectives for objective 3b.

Anderson, D.M. 2007. Virtual fencing – past, present and future. The Rangeland Journal 29:65-78.

Synthesis

a. We developed a synthetic conceptual framework that integrates processes across scales to understand and predict ecosystem dynamics across heterogeneous landscapes.
b. No changes in objectives.
c. These accomplishments are the foundation of the proposed Objectives for objective 4.A.

Peters, D.P.C., Bestelmeyer, B.T., Herrick, J.E., Monger, H.C., Fredrickson, E. and Havstad, K.M. 2006a. Disentangling complex landscapes: new insights to forecasting arid and semiarid system dynamics. BioScience 56:491-501.

X. Figures.

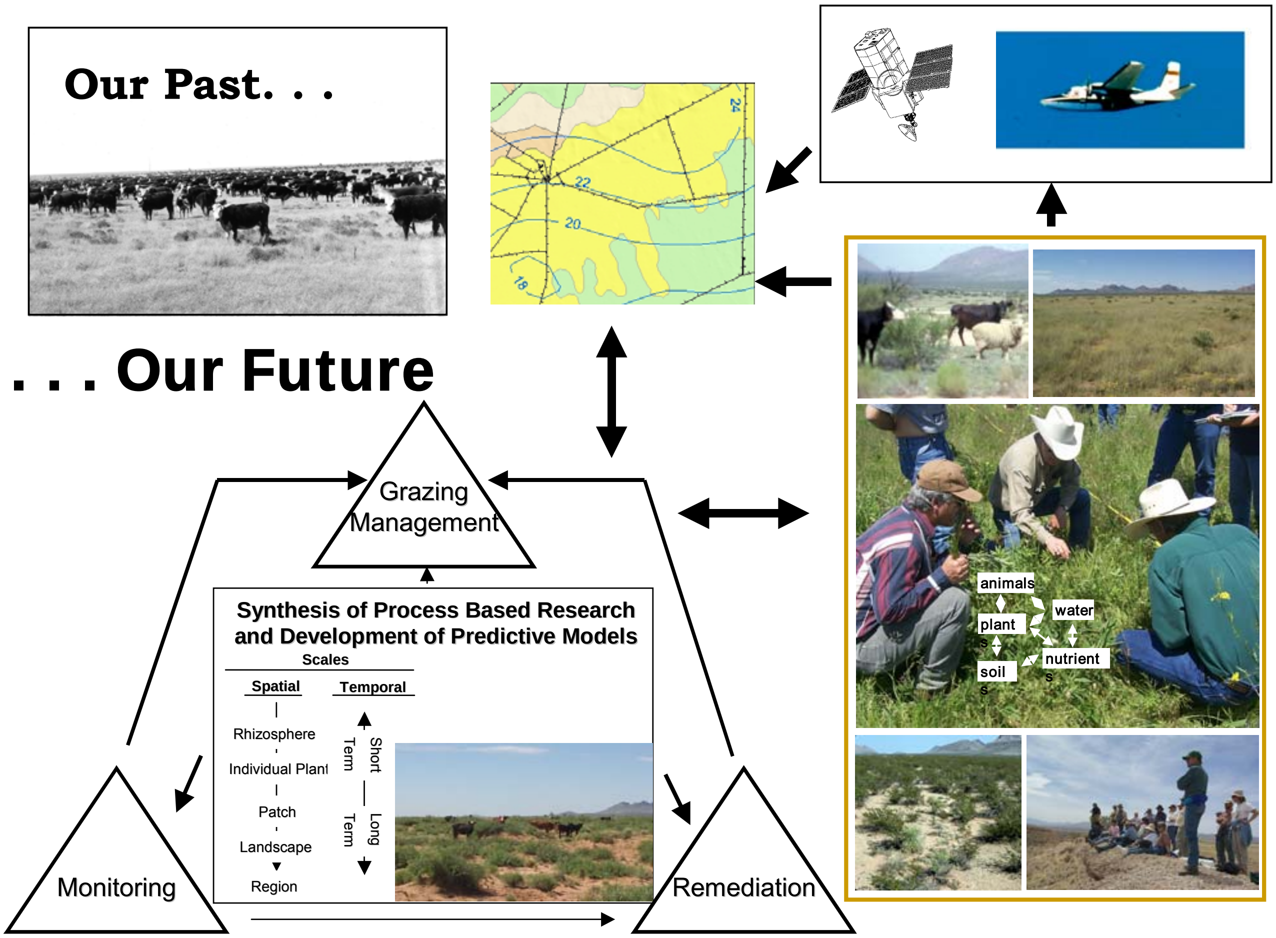

Fig. 1. Our goal is to develop ecologically based technologies for monitoring, remediation, and grazing management in desert environments.

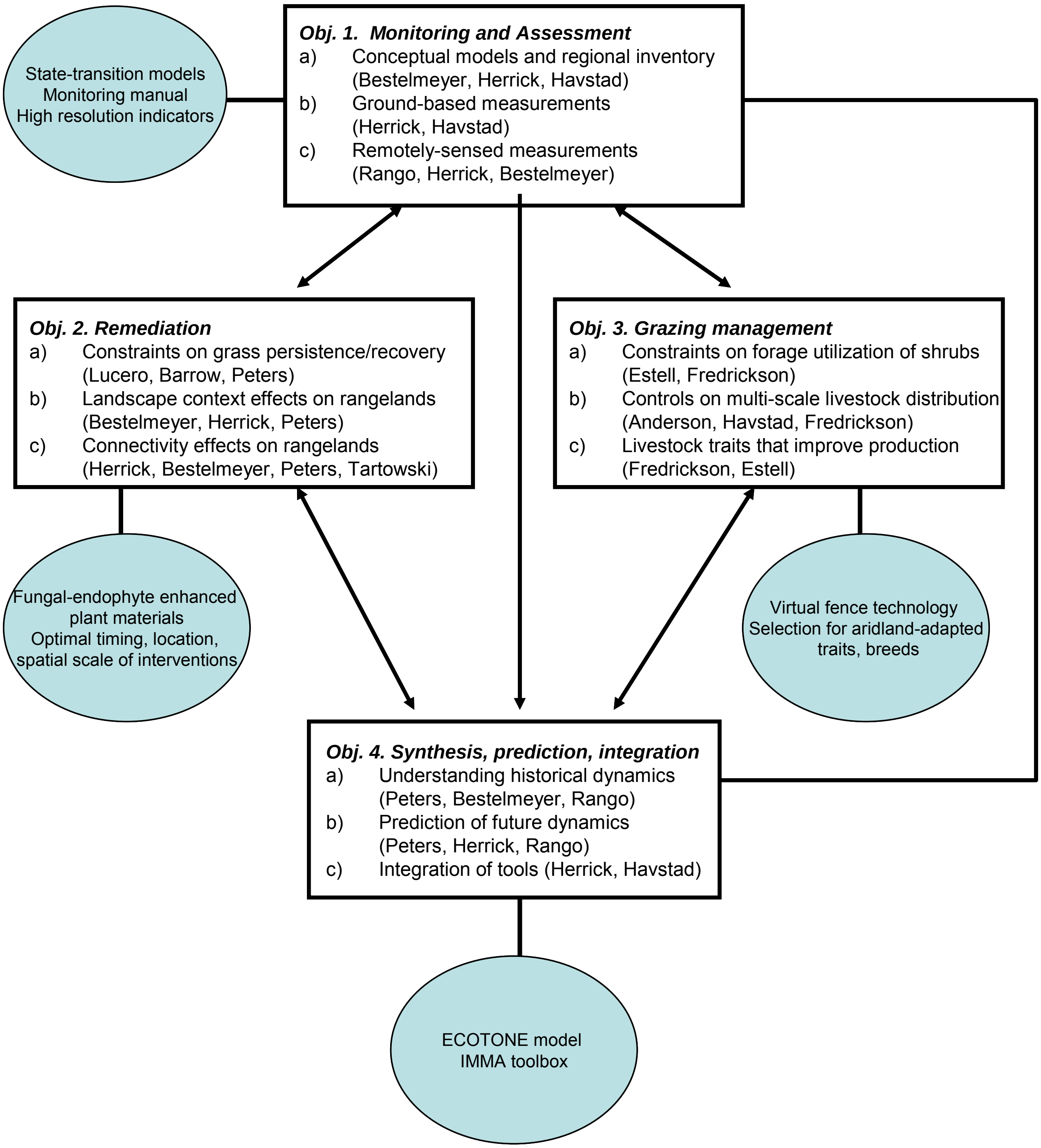

Fig. 2. Our four objectives are linked through information flow. Responsible scientists are shown in parentheses. Key products are shown in blue circles.