

Section I. Results from Prior Support

The Sevilleta (SEV) LTER Program has focused on a suite of ecological hypotheses concerning climate dynamics and the responses of organisms in biome transition zones (BTZ) in central New Mexico since 1989. The area of the SEV straddles several major biome transitions, and its large size (100,000 ha) is important for multi-scale studies that range from genetics and physiology at the organismal level to the dynamics of the transition zones themselves (Gosz et al. 2000). The region is strongly influenced by the El Niño Southern Oscillation (ENSO), with major fluctuations in precipitation on semi-decadal and multi-decadal time scales (Milne et al. in press).

In 2000, in response to the reviews on our previous proposal, we increased our focus and integration of studies on a 40 km² area in the transition zone (**fig. I.1**) for Chihuahuan Desert and Great Plains Shortgrass steppe. Our new conceptual framework emphasizes the patterns and dynamics of patches in the mosaic making up this portion of the BTZ. Below we summarize our results with an emphasis on 2000 to present.

Broad-scale patterns within the BTZ

Remote Sensing. In the initial years of the SEV LTER program, we used a wide variety of satellite-based imagery and species-specific percent cover (Gosz 1995a, Anand & Li 2001) to estimate spatio-temporal patterns of Aboveground Net Primary Production (Knapp & Smith 2001). Directly measured field net primary production (NPP) studies were begun at the major research sites in February 1999, using the same volumetric techniques used at the Jornada LTER (Huenneke et al. 2001). Species-specific NPP and seed production measurements are collected from an array of permanent quadrats co-located with the rodent trapping sites.

Initial efforts to assess the patch patterns on the Sevilleta NWR focused on a high-resolution vegetation map of the BTZ, generated using spectral mixture analysis (SMA) of low altitude AVIRIS data (3.2 m pixels) collected 10-20-99 and 10-21-99. The SMA endmembers or spectral signatures of ground components are being derived from the AVIRIS imagery using the manual endmember selection method (Bateson & Curtiss 1996) and simulated annealing algorithms (Bateson et al. 2000). The strategy is to find endmembers from a given scene and to use those endmembers for nearby scenes. Results to date are for SMA for the 20 m AVIRIS and the 3 m AVIRIS of the study area (**fig. I.2**). Current work is fusing low-resolution fraction images from SMA with a high-resolution panchromatic band (Robinson et al. 2000), registering the AVIRIS fraction images with 4 m IKONOS imagery, and using IKONOS spectra, the fraction values and the IKONOS panchromatic band to generate a 1 m vegetation map. The final project will consist of fraction images of blue grama, black grama and creosotebush.

Field Mapping. Three, 6 km vegetation transects were established across the study area (**fig. I.1**) and contiguous 10 m x 10 m plots analyzed for plant community composition. The results support basic hypotheses that much of the study area contains soils with mixtures of blue and black grama that are maintained in a “shifting mosaic” (**fig. I.3**). Few plots have combinations of blue grama and creosotebush because of an apparent inability of creosotebush to invade the “stationary patches” dominated by blue grama.

Initial soil mapping was performed on the 6 km transects using an electro-magnetic scanner (EM-38) to assess subsurface soil characteristics (**fig. I.4**). These patterns and subsequent survey results are being correlated spatially with the vegetation patterns to further identify soil boundaries. This technique will aid many studies on moisture and soil factors

controlling patterns and processes across broad scales in this BTZ and across the region (Muldavin et al. 2001).

Patch characterization and properties

In 2001 we began ground-mapping patches of dominant species located throughout the 40 km² study area. To date >250 patches of creosotebush have been geo-referenced with GPS, number of shrubs counted, and vegetation characterized inside and outside each patch (**fig. I.5**). Many blue and black grama patches also were mapped.

Soil texture and plant species composition were determined for a number of blue grama- and black grama-dominated patches (Kroel Dulay et al. submitted). The two species occupied a broad range of the textures, although only blue grama patches are found on soils with the highest clay content, and only black grama patches were found on soils high in sand content (**fig. I.3**). Many other plant species were associated with one of the two patch types. Of the 52 species found, 16 were significantly associated with blue grama patches and 12 were associated with black grama patches.

Patterns in species diversity were evaluated across multiple spatial scales (individual plants, patches, and the landscape) to determine if encroachment by creosotebush results in a reduction in diversity of the plant community compared with black grama grasslands (Hochstrasser, in press). The shrubs increased the spatial heterogeneity of the vegetation and as a consequence, species diversity increased. These results are in contrast to our previous studies where creosotebush-dominated areas were found to have decreased diversity compared with black grama grasslands. Thus, initial encroachment by shrubs leads to higher species diversity. As shrubs increasingly dominate the community, grasses and forbs are lost and species diversity declines.

Further evidence of changing conditions in shrub patches are the differences in ¹⁵N and ¹³C levels in leaf tissue in different patch sizes (**fig. I.6**). This reflects the different conditions of N cycling and moisture availability within patches as does the different N loss rates from ¹⁵N addition studies between creosotebush and grassland core areas (**fig. I.7A**, Cross & Schlesinger 2001). Changes in atmospheric nitrogen deposition may alter competitive relationships between species (**fig. I.7B**). N additions, simulating deposition rates in 2015, caused significantly greater NPP and biomass for blue grama.

Differences in water availability between patches of different types and dimensions may strongly influence patch dynamics. Field studies examined the spatial and temporal acquisition of soil water by the three dominant species (Peters 2002). Watering experiments using time domain reflectometry (TDR) for three depths (0-5, 0-20, 0-30cm) in early spring (April) and summer (late May) show that blue grama acquires water at cooler temperatures than black grama, and that creosotebush acquires water across a broad range of temperatures and soil depths. Spatial and temporal partitioning of soil water can allow coexistence by these three species at this BTZ.

A collaboration with SAHRA (NSF Science and Technology Center for Sustainability of semiArid Hydrology and Riparian Areas (www.sahra.arizona.edu)) is studying how rainfall variability influences ecosystem processes in grassland, shrubland and at their transitions. SAHRA's contribution supports the hydrology and soil work, as well as application of the drought and water addition treatment. Experiments are described in the proposal. Infiltration is typically higher beneath shrub canopies than beneath adjacent interspaces; shrub canopies are oases where soil moisture is higher than in the surrounding areas. In contrast, infiltration is equal

beneath canopies and interspaces for black grama habitat (**fig. I.8**, Bhark & Small, submitted). This difference in infiltration could enhance shrub productivity, 1) by increasing the fraction of soil water absorbed by plant roots, rather than lost to bare soil evaporation, and 2) by promoting more intense and longer-duration pulses of nitrogen mineralization following rainfall in shrubland.

Patch dynamics

Analyses of creosotebush patches for the 1988 to 2001 period were performed with aerial photos and ground reconnaissance. The results demonstrate no extension by new creosotebush individuals into either black grama or blue grama grasslands. Creosotebush seedling establishment did occur during a wet period (summer/fall of 1996 and winter of 1997) around existing patches resulting in an increase in patch size consistent with the hypothesis of how the patch size-frequency relationship is formed (**fig. I.5**). Our working hypothesis is that at least a decade of altered climate (e.g., drought of the 1950's) is required for range extension of creosotebush into grassland but an extreme event (e.g., extremely wet period in 1996-97) can change existing patches.

Distributions of patch sizes of creosotebush, blue and black grama grasses follow log-normal distributions and a scaling relationship (**fig. I.5**, Anand & Li 2001). While the creosotebush pattern appears to be stable, analyses of fluctuations for grass species show they are unstable. The data imply that the spatial patterns of both grass species are aggregated, a special type of resource partitioning which promotes coexistence (Ives 1991). These results support the model of a shifting mosaic and over the decade of analysis, species interactions have not had sufficient time to stabilize or environmental conditions continually shift preventing stabilization. The extremes of wet (El Niño) and dry (La Niña) years occurring several times during a decade prevents stability of these patch types on many of the soils of the area.

Field studies showed that black grama and blue grama have different strategies related to seed production and seed presence in the soil (Peters 2002). High seed production but low viability by black grama resulted in few seeds stored in the soil. By contrast, blue grama produced fewer seeds with higher viability and a greater proportion of seeds produced were found stored in the soil. The recruitment of black grama is limited by the availability of viable seeds and blue grama is limited by conditions affecting seedling establishment.

Certain soils greatly limit patch dynamics. Some of the blue grama patches occur on deeper soils with finer texture (**fig., I.3**). We identify these areas as stationary patches in that environmental change is insufficient to allow changes in species composition. Our decade of analyses showed no invasion of creosotebush into these sites and no further increase in patch size for the few established creosotebush individuals. Black grama invasion was limited to the edges of these soil types or to rodent disturbance areas (e.g., Kangaroo rat mounds, Fields et al. 1999).

Disturbance

Fire. We resampled patches of blue grama and black grama burned in a lightning-ignited fire in 1998. Preliminary results show that black grama mortality was lower than predicted based on previous studies (Gosz & Gosz 1996) and can recover quickly if heavy summer precipitation occurs following the fire. This does not always occur as shown by studies on a 1995 natural burn in which black grama still had not developed pre-burn biomass by 2001 when a second fire burned to the edge of the 1995 burn but not into the burn because of low fuel. Line intercept measurements across the burn edge show black grama plant size had not returned to pre-burn

levels by 2000. Experimental burns on creosotebush demonstrated that small individuals in a grassland are susceptible; however, larger individuals can resprout (**fig. I.9**). Exotics may play a role in increasing fuel levels in some patch sizes. Time of fire and time since fire are important in this BTZ.

Species Removals. Vegetation cover by species has been monitored annually on 3m x 4m plots where the dominant species was removed. Initial results show that removal of blue grama, black grama or creosotebush have very different effects on the remaining plant community (Peters 2000). Removal of blue grama and creosotebush results in recovery by other perennial grasses whereas removal of black grama results in recovery by perennial forbs. We also investigated the role of kangaroo rats in generating and maintaining plant species diversity at patch to landscape scales (Fields et al. 1999). The area affected by the burrowing activity of kangaroo rats is twice as large in black grama patches compared with blue grama patches. Furthermore, plant species on mounds in blue grama patches generally were different than off-mound areas. Kangaroo rats create islands of plant communities that differ from the rest of the blue grama area and play a keystone/engineering species role (Ryerson & Parmenter 2001).

Faunal Studies

Arthropods. Studies on arthropods, including surface-active arthropod assemblages (pitfall trap studies), plant-dwelling arthropod assemblages (D-Dac studies and insecticide application studies), and grasshopper assemblages (belt transects) have documented spatio-temporal patterns in the BTZ. Analyses of surface-active arthropods have focused on compositional differences and spatial patterns of taxa across the Sevilleta ecotones (Edgar et al., in prep.). Species with general- and microhabitat preferences have been identified (Gosz et al. 1999, Lightfoot, in prep.), and new studies concerning the environmental factors that limit their distributions have been initiated. Many grasshopper species have specific associations with plant species (e.g., black grama and blue grama, **fig. I.10**) or with bare soil between plant canopies. The population structures of these groups can be related closely to landscape patterns of vegetation.

Sanchez and Parmenter (2002) examined the arthropod communities on creosotebush across the ecotone of desert scrub to grassland. They found the patterns consistent with Island Biogeographic Theory, with fewer species of creosotebush “specialists” being found on distant “island” shrubs in a “sea” of grassland. Population sizes of herbivorous arthropods were smaller on distant “island” shrubs, in concert with increased numbers of predatory arthropods (spiders and mantids). This significantly small herbivore load may be one of the factors for successful creosotebush invasions.

Mammals. The LTER has continued studies on rodents, rabbits, and coyotes (**fig. I.10, I.11**) and developed comparisons with other sites and climate influences (Ernest et al. 2000, Koontz et al. 2001, Schooley & Wiens 2001). Five years of results from the Small Mammal Exclosure Study (SMES) demonstrate that excluding rabbits or a combination of rabbits and small rodents can have significant effects on plant species abundance through herbivory, granivory, and soil disturbance (**fig. I.10**). The densities of the 3 species of kangaroo rats vary markedly between habitats on an interannual basis (**fig. I.11**) that can be related to changes in vegetation over the entire study area.

Data from the rodent studies were incorporated into analyses testing the “Trophic Cascade Hypothesis” to ascertain the drivers of rodent population increases and crashes, and to predict outbreaks of zoonotic diseases (hantavirus and plague). Yates et al. (submitted) incorporated satellite AVHRR NDVI values, ground-truthed percentage cover data of vegetation

in the same area, climatological data, and the rodent data to develop a predictive model for the trophic cascade and eventual risk of zoonotic disease.

The rodent data set, along with plant cover data, arthropod data, and rabbit data, were synthesized in a study of coyote diet shifts with climate fluctuations. These analyses showed that coyotes exhibited high dietary breadth, but seemed proficient at preying on rabbits regardless of rabbit abundance (Hernandez et al., in press). The 10-year data set (**fig. I.10**) revealed that jackrabbit and coyote populations do not show the typical 9-11 year cycles that are common in the Great Basin Desert; this lack of cycling was attributed to the greater diversity of prey types available on the Sevilleta, and the less severe winter conditions that “de-coupled” the coyote populations from their primary prey, the black-tailed jackrabbit (Hernandez et al., in press).

Simulation modeling

The ECOTONE individual based model currently evaluates long-term effects of climate, small disturbances, and soil texture on species dominance and plant community composition. Simulation analyses were conducted on the importance of soil texture to patterns in species dominance and composition under current climatic conditions and under a directional change in climate (Peters in press). Blue grama and black grama codominated sandy loam soils and black grama and creosotebush codominated loamy sand soils under current climatic conditions (**fig. I.12**). Under a directional change in climate that increased summer precipitation and temperature, black grama clearly dominated sandy loam soils and increased in importance on loamy sand soils. These results suggest that an increase in summer precipitation could alter the species dominance patterns at the SEV with an increase in dominance by black grama.

A multi-layer, daily time step soil water model (SOILWAT) was used to evaluate the probability of seedling establishment for black grama and blue grama (Peters 2000). The effects of climatic variation were evaluated across multiple temporal scales (seasonal, inter-decadal, and long-term directional) on the probabilities of establishment for each species at the SEV. Blue grama has a broad pattern of establishment that occurs from May through September, and includes years with high year-to-year variation in precipitation. By contrast, black grama has a narrow distribution of establishment events that occur primarily in July when precipitation amounts are most reliable. The climatic conditions from 1949-1968 were more favorable for black grama compared with the cooler, wetter period from 1969-1988 that favored blue grama. These results suggest one mechanism by which blue grama and black grama can either co-dominate or shift dominance through time as the weather conditions change.

Simulation model analyses also were conducted of the effects of disturbance frequency on dominance by blue grama, black grama or creosotebush (Peters and Herrick 2002). The dominance by blue grama decreases and dominance by black grama increases as disturbance frequency increases; creosotebush was unaffected over the range of disturbance frequencies investigated. These simulation results complement previous field studies showing that black grama responds positively to the presence of kangaroo rat mounds whereas blue grama is affected negatively (Fields et al. 1999).

This brief summary of results demonstrates that we have maintained a broad, interdisciplinary approach to understanding the structure and function of our BTZ study site and the processes that are related to how a BTZ may change. The proposal further develops this research with increased focus, a more elaborate conceptual framework, and new experiments and measurements.

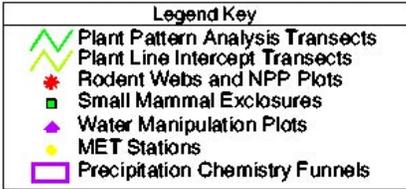
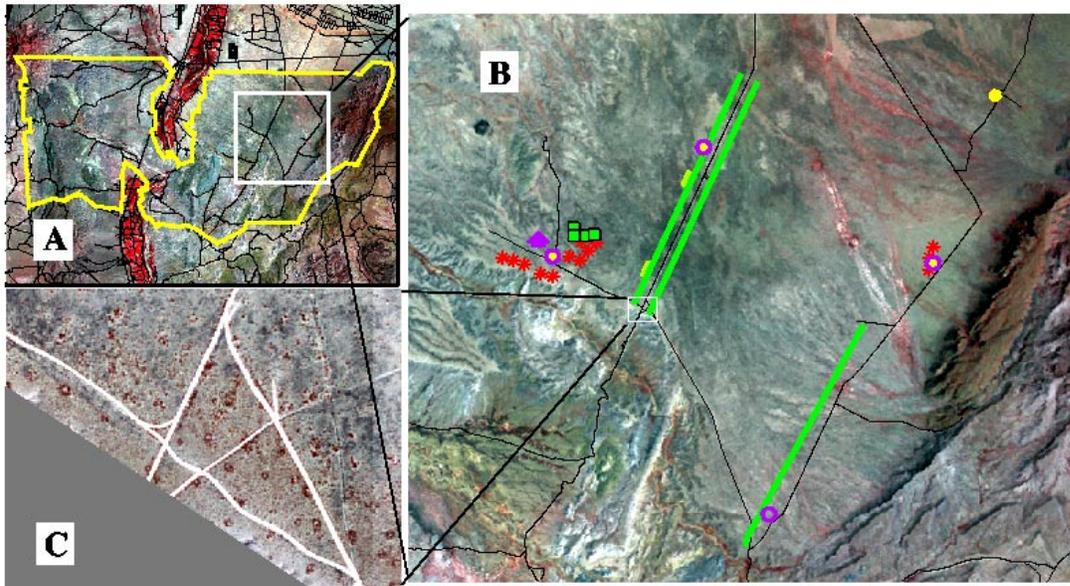


Figure I.1. **A.** The Sevilleta National Wildlife Refuge (boundary in yellow). **B.** The primary study area on the Sevilleta National Wildlife Refuge and locations of the long-term studies of vegetation and fauna (see legend).

The background image for A and B is a Landsat, false color image from August 1992 (30 m resolution). **C.** Location of the creosotebush core area and transition to grassland. In this false color ADAR image from January 1998 (1 m resolution), red color identifies the green foliage of creosotebush and the gray to black foliage of senescent blue and black grama, respectively. The red clumps are vigorous, dense creosotebush patches on kangaroo rat mounds.

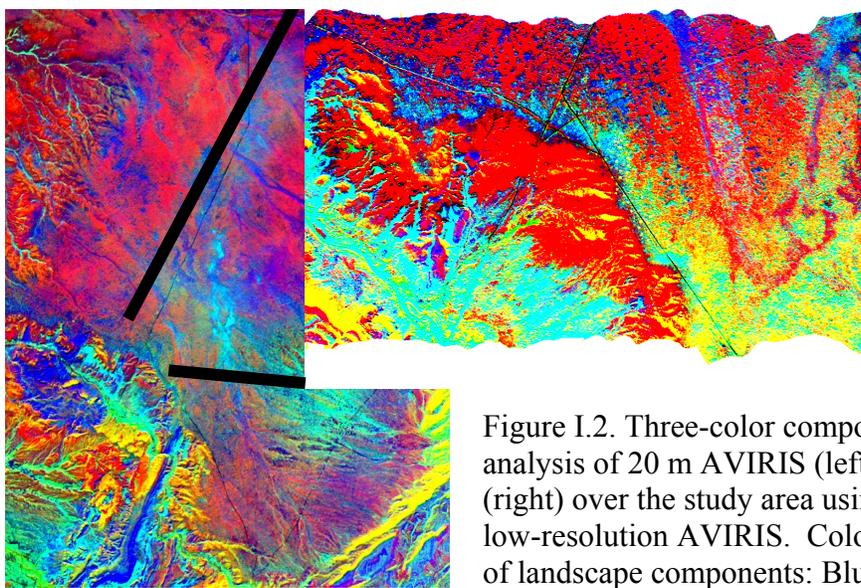


Figure I.2. Three-color composite of spectral mixture analysis of 20 m AVIRIS (left) and from 3.2 m AVIRIS (right) over the study area using end members derived from low-resolution AVIRIS. Colors represent fractional cover of landscape components: Blue= blue grama, Red = black grama, Green = creosote/green vegetation. Because creosote occurs in an open canopy, end members are mixed in creosotebush-dominated areas (i.e., Cyan = blue grama + creosotebush, Yellow = black grama + creosotebush).

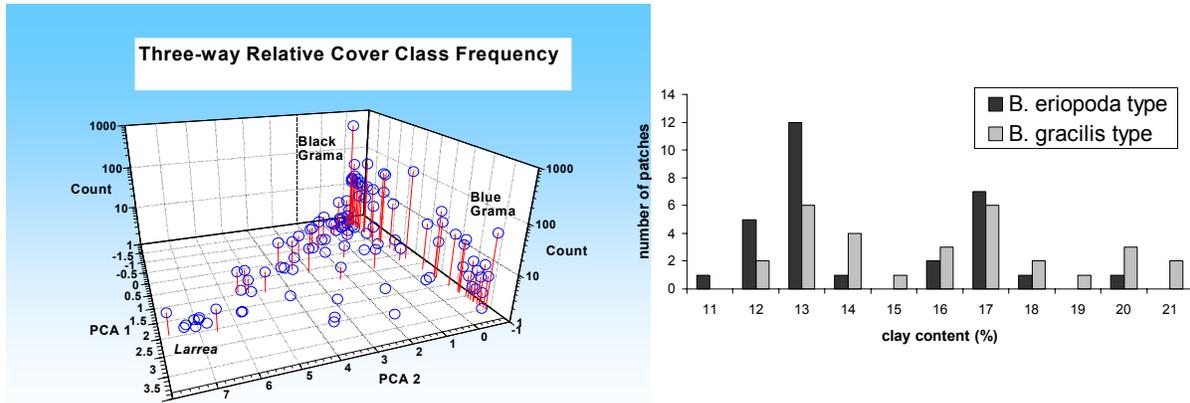


Figure I.3. (Left) PCA analysis of 100 m² plots along 3, 6 km transects in the study region. The number of plots reflects the conditions controlling the degree of dominance (creosotebush, black grama, blue grama corners of the triangle) and intermediate conditions reflecting mixtures of dominants (i.e., ecotones). The combination of deep soils with high clay content results in the dominance of blue grama as a “stationary” patch type and shallow, low clay soils results in a black grama “stationary” patch (Right). The high counts of blue-black plots reflect the large area of intermediate soils and conditions causing a “shifting mosaic” pattern. The low number of creosotebush-blue grama ecotones reflects the inability of creosote to establish in blue grama patch types (i.e., stationary patches). There are few conditions allowing an equal mixture of all three dominants. The relatively few creosotebush patches and creosotebush-black grama mixtures is a result of the short history of invasion by creosotebush into the grassland (directional dynamics).

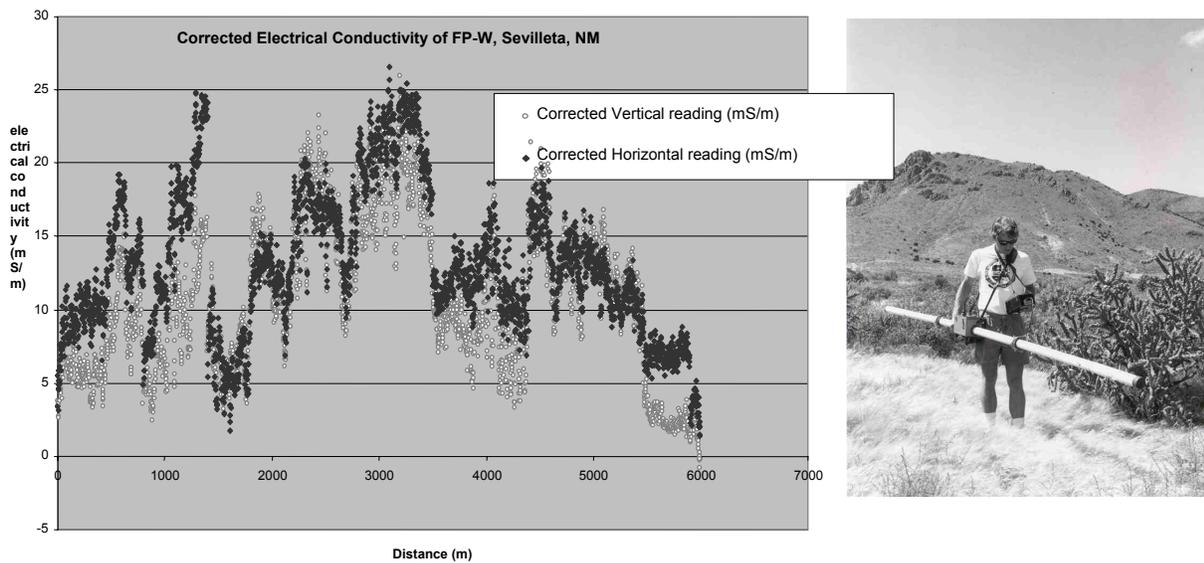


Figure I.4. Electro-Magnetic (EM) allows rapid field scale determination of major relative changes in soil type, soil boundaries, and soil water regime (Hendrickx et al. 1992, Sheets and Hendrickx 1995). The EM38 works without electrodes and does not need ground contact, thus measurements can be taken at walking speed (Right). These data are for the western 6 km transect and show potential soil boundaries (Left).

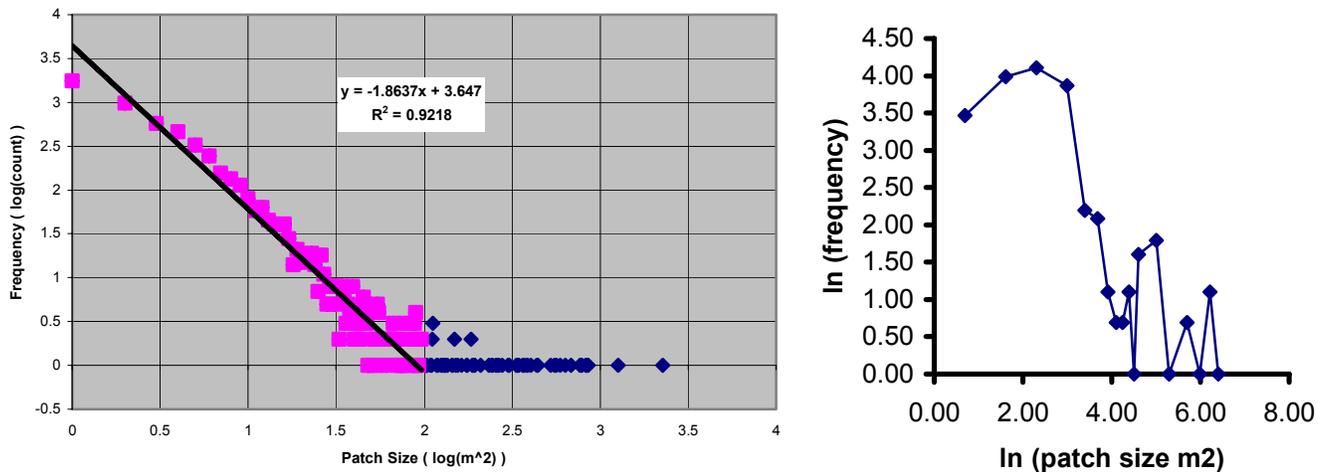
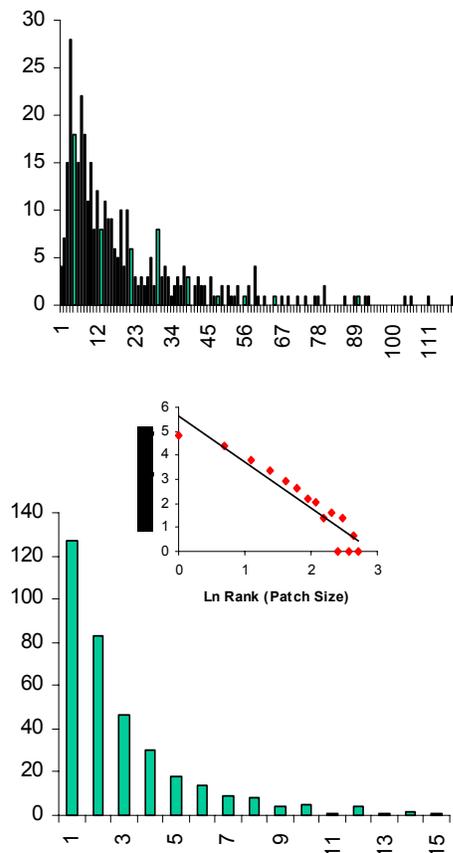


Figure I.5. Patch size distributions for creosotebush (Left) by remote sensing analysis of a 600 x 600 m area and (Right) by ground GPS mapping 242 patches in the study area. The straight-line slopes of each log-log distribution identify patch patterns that are scale-invariant. The power law scaling indicative of stochastic processes is created by dispersal, mortality and episodic natality (Milne 1998). These results suggest important biological-ecological processes are involved in creating the distribution of patch sizes. Large patches (along the X axis) have characteristics similar to creosotebush communities in the core biome area. The break point may indicate a threshold for one end of the transition boundary. Resolution is 1 m.

Power-law distributions of patch size (Upper) or rank (Lower) for black grama (fall 1991) from one of the line-intercept transects on the blue grama – black grama transition. Both species have similar distributions. The transects are 400m long and data are intercept measurements of each species, litter, soil and rocks at a 1cm resolution. Additional analyses on variance vs. black grama size over 10 years show the spatial patterns of both species are aggregated; a special type of resource partitioning that promotes coexistence. Hurst exponents calculated were found to be less than 0.5, indicating non-stable or oscillating conditions for these species patches (Anand & Li 2001).



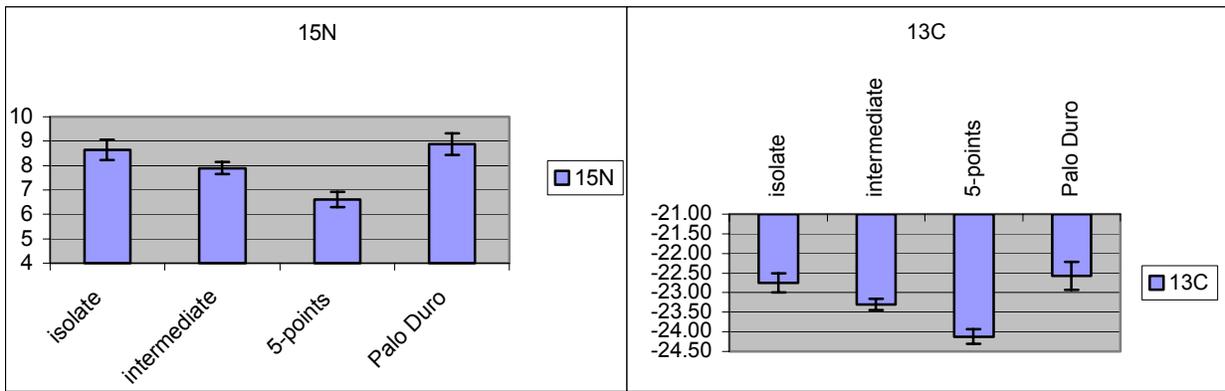


Figure I.6. Preliminary ¹⁵N and ¹³C values in creosotebush leaf tissue from individual shrubs in grassland (isolate), intermediate sized patches and the creosotebush core area (5-points). The decreasing ¹⁵N and ¹³C values with larger patches or the core area reflect altered N dynamics and water availability in the older (larger) patch sizes. The Palo Duro data are from a different area with different soils and biotic crust types (M. Mangiron, unpublished). The lower ¹⁵N values may be the result of the recent acquisition of atmospheric N in a stand of creosotebush (lower ¹⁵N values) from decomposing fresh litter by AM fungi during the dry season, and higher ¹⁵N in individuals within the grass stand, by using older, deeper, leached NH₄⁺ and NO₃⁻ only during the wet season (e.g., Nakamo et al. 2001). Differences in biotic crusts (i.e., N fixation) and decomposition/mineralization rates from differences in tissue quality could cause more new N in the older patches (Evans & Belnap 1999, Evans et al. 2001).

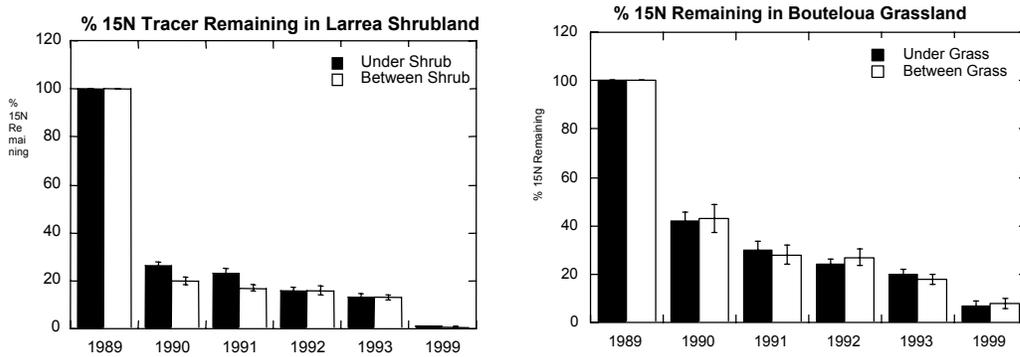


Figure I.7A. ¹⁵N addition experiments show higher rates of N loss from shrubland vs. grassland reflecting different N cycling processes over the course of a decade (Cross, unpubl.). Figure I.7B. (Right) Influence of 20 kg/ha N addition on growth in black grama and blue grama stationary patches. Only blue grama biomass demonstrated a marked response. The blue grama patch also had access to additional soil water because of finer textures and deeper soils. Experiments will be performed on areas of a shifting mosaic for these two patch types. This N level is the anticipated N deposition rate by 2015.

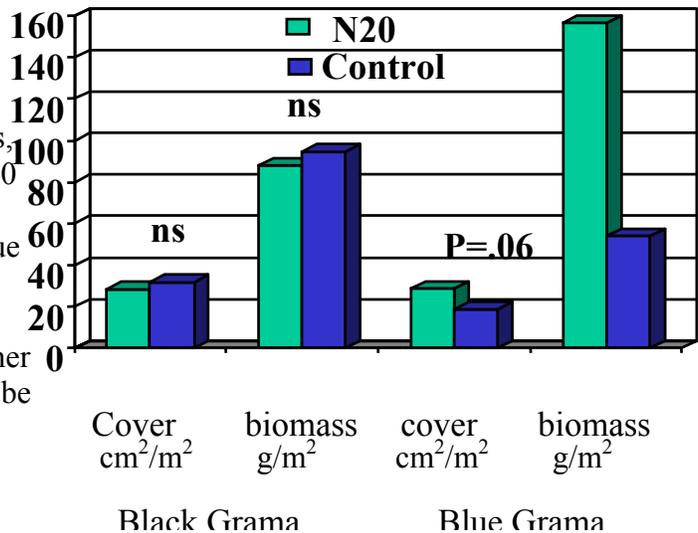


Figure I.8. (Below) Infiltration profiles and variograms obtained from creosotebush and black grama sites. The spatial correlation beyond the range is related to canopy-canopy spacing. Rainout shelters will allow drought and water addition experiments to simulate decadal patterns of climate.

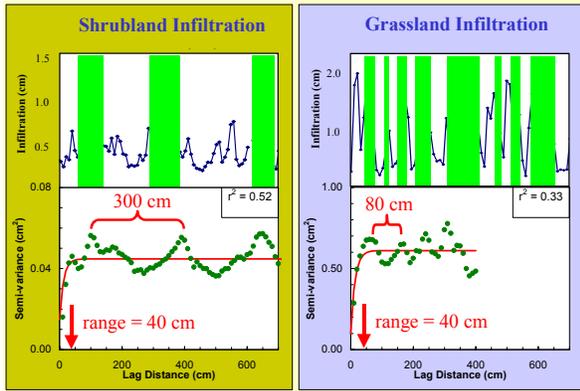
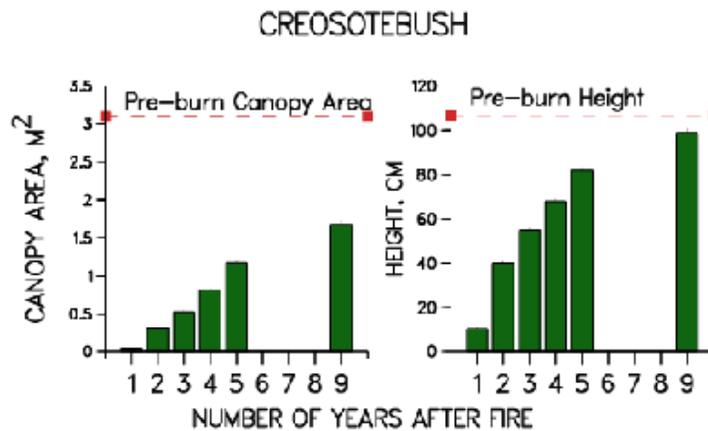


Figure I.9. (Right) Creosotebush in core areas occurs in stands with little ground cover. In such situations, fire would be ineffective causing mortality of adults. An interaction with an exotic; however, could provide a different result. Tumbleweed (*Salsola kali*) moves long distances over the landscape after senescence and is trapped by intermediate patch sizes. These conditions create the hot fire necessary to cause shrub mortality. (Below) Experimental fires on creosotebush in open grassland resulted in mortality (11%) of mostly smaller individuals and caused resprouting of larger individuals. The figure below shows recovery of these resprouting individuals following the fire in 1992 relative to their preburn conditions. Natural fire under normal climate conditions may be an important factor in the inability of creosotebush to invade grasslands by removing seedlings. During the decade-long drought conditions, fire frequency may be reduced because of the reduction in the grass fuel load, which contributes to creosotebush seedling establishment (Parmenter, unpubl).



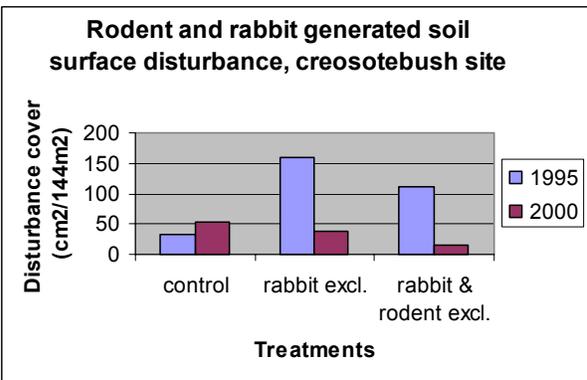
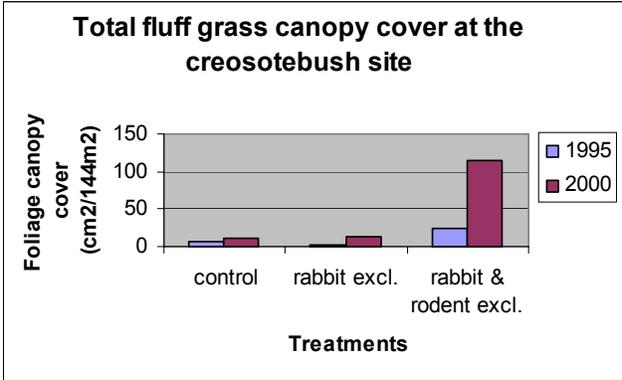


Figure I.10. (Above) An example of five-year patterns developed in the Small Mammal Exclosure Study (SMES). These experiments excluded rabbits or the combination of rabbits and small rodents. The figures show differences due to herbivory and granivory for an important grass species in the creosotebush core area (fluffgrass, *Erioneuron pulchella*). Soil disturbance caused by rodents and rabbits is an important factor in plant community pattern and process. (Right) Coyote and rabbit densities (and standard error bars) are determined seasonally along a 35 km road on the study area (i.e., line transect technique). The strong seasonal patterns imply significant patterns in the predator-prey relationship that may relate to impacts on vegetation properties. (Below) Grasshopper distributions for 2 grasshopper-specialists on black grama (BOER) and blue grama (BOGR) along a 6 km transect. These species have distinctive spatial patterns associated with the vegetation patch patterns.

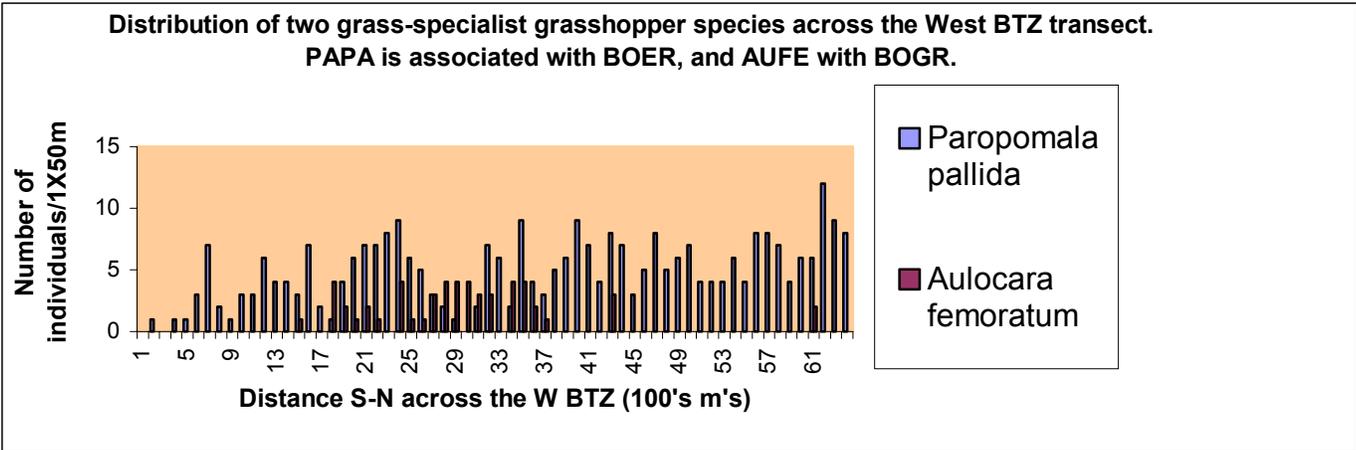
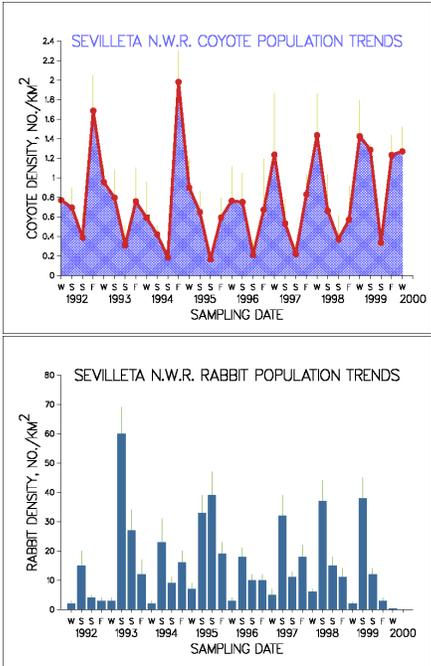


Figure I.11. (Right) Interannual patterns in density for 3 kangaroo rat “keystone” species in the creosotebush and black grama core areas. These large differences in density in different habitats and over time have substantial effects on the vegetation patterns and processes. Mounds (Banner-tailed Kangaroo rat) are dispersed throughout the study area (Below). Dark areas are black grama; mounds show as light spots from white caliche brought to the surface. Light areas are blue grama; mounds are dark from black grama and other species establishing on and around the mounds.

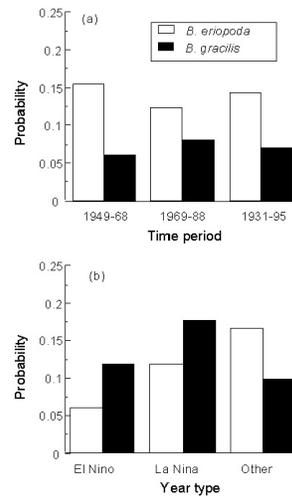
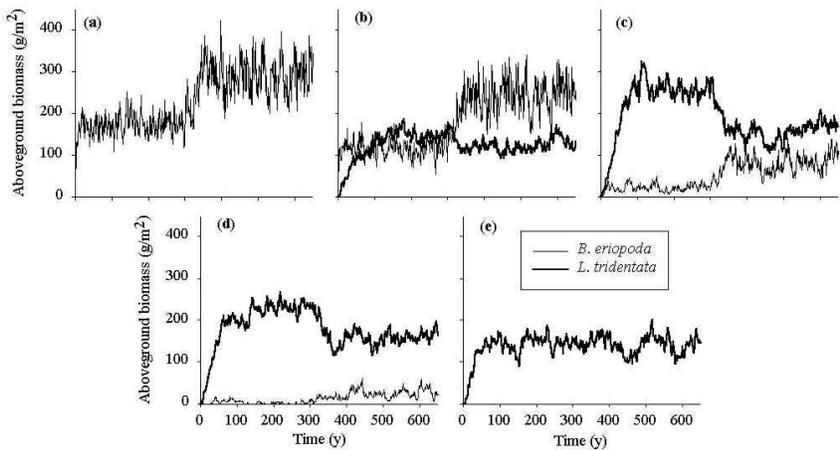
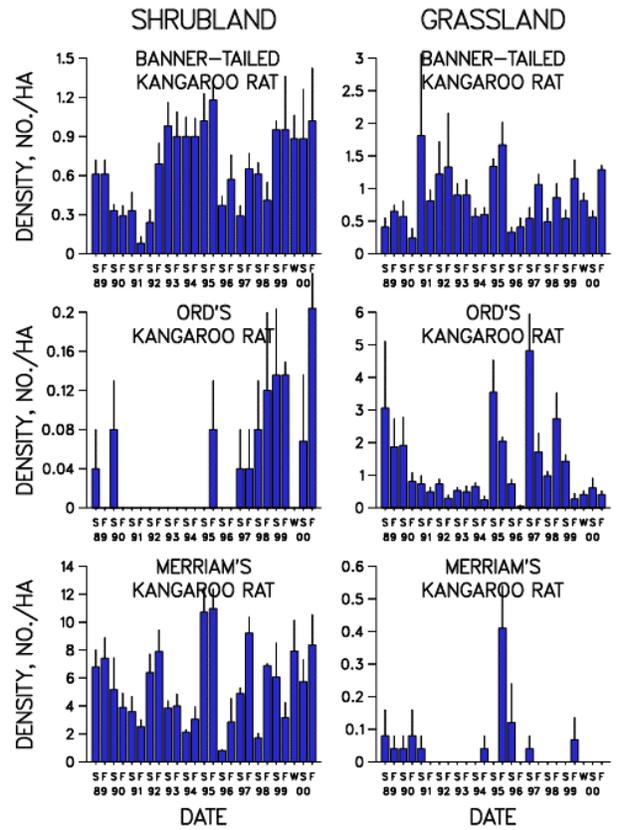
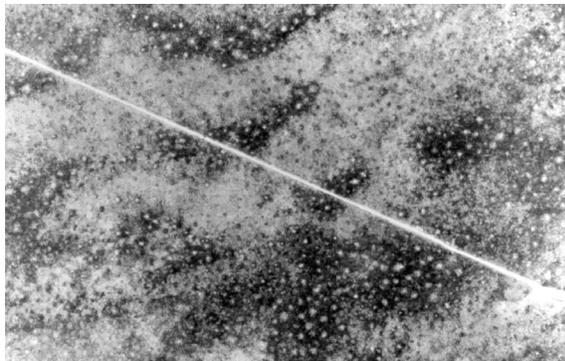


Figure I.12. (Left) ECOTONE simulation results for: (a) sandy loam, (b) degraded sandy loam, (c) gravelly loam, (d) degraded gravelly loam, and (e) very gravelly sandy loam. Climate change was imposed over a 50-year period beginning 300 years after initialization. Model runs were conducted that incorporated feedbacks from plant production to soil organic matter and plant available water that influenced seedling establishment (Peters & Herrick 2002). (Right) Simulated probability of establishment of blue grama and black grama using weather generated from (a) one of three time periods (1949-1968, 1969-1988, 1931-1995) and from (b) one of three types of years (El Nino, Las Nina, Other, Peters 2001).

Section 2. Project Description (proposal is online at <http://sevilleta.unm.edu>)

I. Introduction

The Sevilleta LTER research site is located on the Sevilleta National Wildlife Refuge in central New Mexico where a junction of four biomes (Great Plains Grassland, Great Basin Shrub-steppe, Chihuahuan Desert and Montane Coniferous Forest) provides a rich assortment of Biome Transition Zones (BTZs) that are expressed over many km. Interacting with a highly variable climate, the large area (100,000 ha), elevational range (1,350 – 2,797m), complex topography, geology, and soils, provide a complex spatial and temporal template for these BTZs. The Sevilleta (SEV) LTER program focuses on the dynamics of these complex interfaces. In our next funding cycle we will build upon and expand our foundation studies of Sevilleta BTZs, and initiate new long-term landscape experiments and measurements to develop and test a general theory of BTZs.

Biotic assemblages that characterize transitions at any scale, including BTZs, exhibit mosaic patterns resulting in unique properties relative to adjacent communities (Kotliar & Wiens 1990, Gosz 1993). However, most research on boundaries has been descriptive and has focused on comparing structural properties of adjacent communities with little emphasis on either internal properties or spatial and temporal dynamics of the boundary (Murcia 1995). While ecotones have attracted attention for their roles in landscape ecology, monitoring climate change, and in ecological theory, few hypotheses have been adequately tested and the literature repeats speculation (Lloyd et al. 2000).

In response the SEV general research goals are to:

Definitions

For purposes of consistency, we use boundary to represent a transition between adjacent communities at any scale (e.g., between adjacent patches in a landscape or between adjacent biomes in a region). We define a patch as a uniform plant community characterized by a dominant species representing a particular biome. Different patch types are distinguished by differences in their dominant species. Ecotone is reserved for fine-scale boundaries within a BTZ that occur between adjacent plant communities representing different life forms (e.g., shrubs vs. grasses) or patch types.

- 1. Develop and test a general theory of BTZ structure and function based on grass/grass (Chihuahuan desert grassland/Great Plains shortgrass steppe) and grass/shrub transitions within the Chihuahuan Desert biome.**
- 2. Identify the key biotic (faunal, floral, microbial) and abiotic (topography, soils, microclimate, hydrology, biogeochemical cycles, fire) variables and their feedbacks to determine the current mosaic structure of the landscape within the BTZ, and the degree to which those processes produce emergent properties general to all boundaries.**
- 3. Predict future properties, dynamics, and locations of patches, landscapes, and the BTZ as biotic and abiotic processes change (e.g., climate change).**

The SEV is one of the few places in the world with a major research program dedicated to examining BTZs and their internal boundary characteristics through long-term research and an increasing array of collaborative, short-term research efforts that range from genetics to remote sensing of the landscape. Most regional and continental-scale vegetation models predict location of biomes based on vegetation/climate/soils interactions and assume BTZ are linear boundaries without special properties (Neilson 1991). An October 2000 Institute of Ecosystem Studies workshop

proposed: 1) boundaries are 3-dimensional entities (i.e., ecosystems) that occur over relatively steep gradients for at least some environmental factors, and elicit a reaction(s) in organisms or processes that differ from adjacent community types, 2) boundaries are areas of unique ecological interactions compared to adjacent community types, and 3) boundaries connect adjacent systems through fluxes of organisms, energy, material and information across a differentially permeable or reactive interface on many spatial and temporal scales.

The SEV is uniquely poised to study these boundary concepts because of the juxtaposition of multiple BTZs in the research area. We study: 1) specific roles of species and ecological processes that contribute to BTZ structural and functional properties; 2) nonlinear relationships (i.e., ecological thresholds) manifested in space and their controls (e.g., top down vs. bottom up processes); 3) hierarchical relationships among processes at multiple scales; and 4) BTZs as the sources of enhanced alpha species diversity and, therefore, gamma diversity. Our work to date suggests that a BTZ has unique properties compared to core areas of the various biomes. With our integrative experimental and modeling approach we can understand and predict properties and dynamics of BTZs across multiple scales. We have refocused our efforts to understand interactions among biotic and abiotic processes that influence the initiation, maintenance, expansion and disintegration of patches across the landscape (**fig. II.1**). Positive and negative feedbacks are important influences on patch dynamics and shifts in ecotones through time (**fig. II.2**). These feedbacks operate across a range of spatial and temporal scales with important implications for landscape and regional patterns in species distributions and biogeochemical cycles (**fig. II.3**). Because our approach includes boundaries at multiple scales, our conceptual model and results have broad applicability to other terrestrial ecosystems.

We are focusing on the floral and faunal properties of transitions between grass and shrub life forms represented by two components of the Chihuahuan Desert biome and their junctions with the Great Plains shortgrass steppe biome. Our findings provide an important regional context for studies conducted within the shortgrass steppe biome at the SGS LTER and within the Chihuahuan Desert biome at the JRN LTER. Future studies on other BTZs and ecotones present on the SEV will further develop and test a general theory for BTZs applicable to understanding and predicting ecosystem response to global change. Future studies will expand to other major biome representatives at SEV (e.g., shrubsteppe of the Colorado Plateau, Piñon -Juniper woodlands).

II. Conceptual Framework and Summary of Proposed Work

A. Conceptual Framework

Our conceptual framework for a BTZ focuses on the importance of interactions and feedbacks among biotic components (plants, animals, and microbes) and abiotic constraints (climate, soils, and disturbance) in generating and maintaining patches and ecotones across a landscape (**fig. II.1, II.2**). Feedbacks are particularly important to responses that vary across temporal scales relevant to LTER research. In our conceptual model: 1) patches and intervening ecotones result in mosaics with functional properties that vary for different organisms, 2) local dynamics within patches depend upon interactions and feedbacks among plants, animals, and soils (e.g., animals are affected by patch patterns and, in turn, have effects on plant and soil nutrient dynamics that influence patterns), 3) the species that determine patch types respond differently to climate and disturbance, and interact differently with soils and fauna, 4) patch size is critical to these responses and interactions; size or area reflects the length of time for internal ecosystem processes to change properties relative to the surrounding matrix, 5) patch configuration affects the dynamics of

organisms and processes at landscape scales, 6) ecotones between patches have complex patterns and behavior, and 7) the generation of patches is a self-reinforcing process.

There are three essential elements to our model:

1. Patches vary in both structural and functional properties due to differences in dominant and associated species, patch size, and adjacent ecotones. Associations among dominant and subdominant plants, animals, microbes, and ecosystem processes are poorly understood for patches within a BTZ. We expect that patches dominated by different species will vary in these relationships. Patch size is a critical characteristic; a change in size reflects a change in properties over time (i.e., patch ontogeny, **fig. II.4**). Ecotones between patches may be narrow (i.e., sharp) or broad as a result of substrate influence and distance between patches (**fig. II.5**). Strength of interactions change through time as patches change in size and the distance between patches becomes larger or smaller. The structural edge of a patch is defined by a change in dominance based on plant cover. The functional edge of a patch has been less well studied, and may or may not overlap with the structural edge. Patches have typically been defined as internally homogeneous (Forman & Godron 1986); however, edges and centers may function differently due to differences in microenvironment and edge effects that vary in importance as patch size increases. We also expect an interaction between patch size and the surrounding vegetation matrix. Small patches may function similarly to the matrix for processes such as aboveground production, nutrient cycling, and influences on fauna (**fig. II.4**). Plant species richness and animal effects on a small patch may be disproportionate to patch area, especially for small patches. As patch size or the number of plants of the same species aggregated within an area increases, the patch is expected to function differently from the matrix vegetation. After a patch reaches a critical size, it is expected to function similarly to its biome core area. For this reason, very large patches at SEV are referred to as core areas reflecting their similarity with the core biome area.

2. Different patch types vary in their dynamics. Key driving variables (e.g., precipitation, temperature, soil texture, and disturbance) that affect patch dynamics (e.g., patch initiation, maintenance, and disintegration) have spatial and temporal characteristics that affect interactions and feedbacks among plants, animals, microbes, and soils (**fig. II.1, II.2**). Effects of driving variables on patch dynamics depend upon patch type and the ability of species to respond to different variables. We expect dynamics in a BTZ to be more sensitive to environmental variation than in biome core areas (Gosz & Sharp 1989). We recognize three general types of patch dynamics for a BTZ landscape (**fig. II.6**).

a) Stationary (dynamics controlled by substrates): Patches controlled by soil physical properties are expected to be stationary over time periods of multiple decades. Small-scale fluctuations in ecotone location may occur through time. However, because soil properties change very slowly through geologic time, substrate-controlled patches are expected to be stationary and maintained by strong positive feedbacks.

b) Directional dynamics: Patches initiated by extreme, infrequent events and reinforced by positive feedbacks are expected to exhibit directional change (e.g., invasion of shrubs into grassland) in the mosaic pattern. Patch initiation rates vary through time as establishment occurs during favorable climatic conditions and not during unfavorable conditions. Following establishment, the patch either disappears (plant dies) or expands in size or area through positive feedbacks from soil biological, physical, and chemical properties, microclimate amelioration (e.g., nurse plant facilitation), and animal activities (e.g., rodent caching, **fig. II.2**). Positive feedbacks which cause directional changes in the BTZ require sufficient time under an altered climate. Thus, the importance of processes (e.g., facilitation vs. competition) varies during patch ontogeny and with changes in environmental

conditions (**fig. II.4**). A decade of altered climate may be required for directional movement of a dominant species (**fig. II.2**). Intervening periods allow patch expansion and mosaic structure development, but not range extension of a biome.

c) Shifting mosaic dynamics: Patch types may alternate through time and generate a shifting mosaic of patches across the landscape. Shifts in dominance and species composition are related to climatic variation, changes in disturbance regime (e.g., fire) and their interaction that favors one species over another. With the return to the previous climate or recovery from disturbance, the previous vegetation type dominates again. These ideas are comparable to the “shifting mosaic” originally described by Bormann and Likens (1981). Changes in drivers do not persist sufficiently long to totally remove species from the regional pool; thus a return to previous species is possible when previous conditions return. Large differences in precipitation between wet (El Niño) and dry (La Niña) years, and the 3-4 year regularity of these extremes, contribute to this shifting mosaic

3. Patch-scale dynamics and interactions among patches are needed to generate landscape-scale dynamics. The landscape consists of a complex mosaic of stationary, directional, and shifting mosaic types of patch dynamics that involve: 1) the creation of new patches and ecotones, 2) the maintenance, enlargement, and coalescence of current patches, and 3) the loss or disintegration of patches and ecotones through time. Changes in patch structure and function affect the locations, distances, and composition of ecotones across the landscape (**fig. II.5**). Non-linear patterns and thresholds exist that require consideration of spatial processes (fluxes and flows within and among patches) and feedbacks to predict dynamics at different spatial scales. Landscape features such as water, nutrient, and soil redistribution from nearby mountains, and use of the landscape by fauna (e.g., birds of prey, coyotes, herbivores) also are important in these broad-scale dynamics.

Our conceptual model of a BTZ is hierarchical, and consists of understanding dynamics at three spatial scales: individual plants at scales from 0.1 to 10 m², patches and their ecotones ranging from 10 to 500 m², and a 40 km² landscape within the BTZ (**fig. II.3**). Although we define patch type by the dominant plant species and typical interplant distances characteristic for its biome, patch types may also differ in associated biota, soil properties, and ecosystem processes (NPP, N-cycling). We are focusing on the dominants: blue grama (*Bouteloua gracilis*; long-lived perennial C₄ grass, Great Plains shortgrass steppe), black grama (*Bouteloua eriopoda*; short-lived perennial C₄ grass, Chihuahuan Desert), and creosotebush (*Larrea tridentata*, long-lived C₃ shrub, Chihuahuan Desert). The vegetation surrounding a patch may be a core area of a different biome type (e.g., creosote patch in black grama grassland, **fig. II.3**) or mixtures of species from adjacent patches (**fig. II.5**).

B. Introduction to Proposed Work

Our research approach is an ongoing, iterative process of synthesis and field observation. We are combining a synthetic simulation model (ECOTONE) with the aggregation of short- and long-term data to test hypotheses, provide insight into system behavior, and predict future dynamics. ECOTONE is used to synthesize and integrate our process-based studies in order to: 1) identify key processes and factors affecting dynamics at multiple scales, 2) generate new testable hypotheses about the relative importance of different processes to dynamics at different spatial scales and to design new experiments to test these hypotheses, and 3) predict long-term changes in patch and landscape scale dynamics as environmental conditions change, such as with global warming. We will continue analyses of our long-term data sets to examine relationships between different components of the system. For example, analyses conducted to date show strong correlations between rodent populations and El Niño and La Niña cycles with important implications for the spread of Hanta virus (Yates et al. submitted). New analyses will include NPP, species diversity, and

arthropod densities that are part of our long-term measurements. We are preparing a site volume that will synthesize short- and long-term research results and model analyses from the SEV.

Synthetic simulation model

ECOTONE is a spatially explicit vegetation model linked with hydrologic and nutrient cycling models. Plant processes include the recruitment, growth, and mortality of individual plants on a small plot at an annual time step (Peters 2002). Driving variables include climate, soil texture, and disturbance. A daily time step, multi-layer model of soil water (SOILWAT; Parton 1978) has been incorporated into ECOTONE to allow seasonal water dynamics to affect and be affected by the vegetation (Peters & Herrick 2002). A soil development sub-module (soil-dev) also has been added to allow vegetation to affect soil properties with feedbacks to plant growth and establishment (**fig. I.12**). EPA funding is supporting the incorporation of nutrient cycling feedbacks with the vegetation and a collaboration with JRN LTER scientists is modifying ECOTONE to simulate the redistribution of water, nutrients, seeds, and soil particles among spatial units.

Patch types and sizes are being incorporated into ECOTONE whereby patches can change in size, plant and animal species composition, NPP, rates of nutrient cycling, and proportion of dominant species (**fig. II.7**). Explicit interactions and feedbacks among small animals (**fig. II.2, 8**), vegetation, and soil properties and processes will be included based on our patch-scale studies. Our modeling effort involves synthesizing known information about the role of animals (e.g., **fig. I.12**), soil, and climate to generate patterns in vegetation across multiple spatial and temporal scales. Model predictions are the basis for a number of hypotheses in the proposal. We will use data from our new studies to parameterize the model, and will use existing short- and long-term data to test model predictions. Sensitivity analyses of model output will be used to identify key processes affecting ecosystem dynamics at multiple spatial scales. From these analyses we will generate new hypotheses about major controls on ecosystem processes that will then guide new experiments. Finally, we will use ECOTONE to predict future patch and landscape dynamics under different climate change and land use scenarios.

Field studies

Many of the long-term experiments and measurements being conducted at the SEV were established within areas dominated either by creosotebush or black grama (i.e., core areas), selected to represent Chihuahuan desert shrubland and grassland habitats, or in mixtures of blue grama and black grama. We will continue those studies that are relevant to our new focused effort, and will add a number of new studies critical to testing our hypotheses. New experiments that characterize properties and dynamics of patches and ecotones within the BTZ will be described in subsequent sections. A hierarchy of hypotheses/predictions is proposed for our work. Each section will list primary hypotheses and subsequent predictions or expectations. These studies address all *five LTER core areas*: pattern and controls on NPP, spatial and temporal distributions of populations representing trophic structure, pattern and control of organic matter and decomposition, patterns of inorganic nutrient inputs and movement of nutrients, and patterns and frequency of disturbances. The four major parts of our research program build upon results obtained over the past 12 years:

- 1. Determine the configuration and dynamics of patches and ecotones (section III)**
- 2. Measure and experimentally manipulate the key processes hypothesized to influence properties and dynamics of the mosaic structure (section III),**
- 3. Examine faunal interactions with mosaic dynamics (section IV)**
- 4. Extrapolate from patch dynamics to the landscape and region (sections V, VI).**

III. Mosaic patterns, patch dynamics, and properties

A. Mosaic patterns in the BTZ (Gosz, Harrison, Hendrickx, Li, Muldavin, Peters, Wessman)

In our model, patches are the fundamental unit for landscape change; mosaic patterns and dynamics within and among patches are critical in determining landscape dynamics that affect changes in the structure and function at the scale of a BTZ. Based on our previous work for each patch type, patch size distribution and arrangement are a function of a combination of distance from core vegetation, soil/topography patterns, disturbance, and biological factors. We expect that relationships between biotic and abiotic factors depend upon patch type and dynamic.

Our approach is to first document the current pattern of patches across the landscape. We will then use these methods with historical images to identify for intensive study, a subset of patches that are stationary, shifting, or directional. Because of SEV's large area, we will rely on aerial photos (starting in the 1930s) and remotely sensed images to determine the spatial configuration and location of different patch types and sizes across the landscape. We recently used imagery of relatively high spatial resolution (e.g., IKONOS multispectral imagery at 4 m and/or low-altitude AVIRIS data < 4 m and air photos) to map the location of patches and soils. Images were analyzed using linear spectral mixture analysis to compute the fractional cover by species as well as to generate maps showing the distribution of black grama, blue grama, and creosote bush patches for a portion of our study area (**fig. I.2**). Intensive field sampling is being used to geo-locate patches for each species to validate the image analysis. Based on this classification we will select focal areas to be mapped and validated at a higher resolution (1 m) using digitized aerial photography and/or ADAR imagery. The classification also will be a template for temporal studies using AVHRR, AVIRIS and IKONOS.

Hypothesis III.1. We hypothesize that, irrespective of species or life form, the pattern of patch sizes will follow a power law for a given soil type identifying an emergent property of mosaic formation (i.e., self-organizing factors, fig. I.5, II.4).

We will test this hypothesis on a variety of patch and soil types by: 1) analyzing the patch structure across the landscape to determine patch size by distance relationships and 2) overlay vegetation maps with maps of soil texture and disturbance history, and fine-scale DEMs in order to determine the best physical correlates with patch size. The time course for this pattern formation (**fig. II.4**) is **predicted to be nonlinear with slow rates of change following the initial establishment of individuals (strong abiotic control), increased rates after some threshold number of individuals occurs (facilitation, faunal interactions), and subsequent decreased rates as the density of individuals in a patch approaches conditions typical of the biome type (increased intraspecific competition).**

We will also identify locations of "critical densities" of patches in the mosaic that affect distributions and movements of animals (Milne et al. 1996). Quantitative measures will express the statistical properties of spatial patterns measured over a spectrum of scales (Ludwig & Cornelius 1987) and record scale-dependent changes in variance or fractal dimension (Krummel et al. 1987, Milne 1988, Milne et al. 1998). These measures will provide multiple features of mosaic patterns that correlate faunal densities and movements and lead to hypotheses about how different species respond to different scales.

In 2001 we established three, 6 km long parallel transects that traverse the study landscape (**figs. I.1, I.3**). Belt transects allow for structured sampling in nested scales of choice and

identification of other sampling locations and transects described later. Initially, these transects are being used to capture broad-scale patterns and dynamics of populations and ecosystem processes that are not possible at the finer scale of the patch studies. We are using the transects to detect multiple boundaries throughout the landscape that can be then measured at sub-m² resolution and tested for unique properties of BTZs at the landscape scale. The belt transects will identify ecotones differing in dominant species and steepness of environmental gradients that will be analyzed over time for changes in ecotone locations and composition.

B. Patch dynamics

Many factors may influence both the ontogeny of patches and changes in the location of patch boundaries or ecotones through time and space (**fig. II.1, II.2**). We have three hypotheses related to the dynamics of patches:

Hypothesis III.2. Directional changes in patch type are initiated by extreme climatic events and decadal changes in climate. Establishment of individuals may or may not be substrate-specific, but the presence of an individual results in an increase in positive feedback processes that modify dynamic mycorrhizal fungal communities and soil properties, interactions with fauna and other plant species, and increase the probability of additional individuals becoming established. These positive feedbacks result in patch maintenance and/or expansion over time.

Hypothesis III.3. Patch types in a shifting mosaic are not substrate controlled or maintained by biotic feedbacks. These patches are very responsive to abiotic drivers (i.e., wet-dry cycles and fire) resulting in reversible changes in patch type over time.

Hypothesis III.4. Because stationary patches are primarily substrate controlled, extreme events have little effect on changes in patch type. Biotic feedbacks act to maintain patches following establishment.

Based on our previous studies, we expect that creosotebush invasion into perennial grasslands is an example of directional changes in patch type where positive feedbacks between shrubs and their microenvironment lead to increased probability of seedling establishment and survival of this species. Shifting mosaic patches occur on areas with frequent disturbances or on soils that are not controlling plant species composition. Stationary patches of each species can also be found where soils control plant species establishment: blue grama patches on soils with higher clay content and deeper soils, black grama patches on shallow soils with high sand content (**fig. I.3**), and creosotebush patches on gravelly sandy loams with a shallow depth to caliche. Thus, the landscape depicted in **fig. II.3** consists of a complex mosaic of different patch types, sizes, ecotones, and dynamics. These observations form the basis for our three hypotheses that will be tested using a combination of long-term measurements, field experiments, and simulation modeling analyses.

Directional patches (Allen, Gosz, Muldavin, Peters, Pockman). **We expect that extreme climatic events promote the initiation of patches dominated by an invading species, and that patches are maintained or expanded through positive plant-soil-animal feedbacks.** A sequence of events may be necessary for patch initiation (e.g., decade-long drought, mortality of existing patches, increased seedling establishment by invaders, facilitation and modification of soil/microclimate). We will test hypothesis III.2 for creosotebush using process-based studies of recruitment in combination with pattern analyses. Studies conducted at the JRN LTER and elsewhere have documented the strong relationship between mature shrubs and local resources (Schlesinger et al.

1990). These “shrub islands” form over time as a result of localized plant inputs that act to reinforce the dominance by shrubs. At the SEV, we are in a position to examine the factors that control the initiation of new creosote patches, the development of shrub islands, and the coalescence of patches/islands over time. We will use the aerial photos and 6 km transects to determine the initiation of new creosote patches relative to climatic events and soil substrates. **We expect that successful establishment will occur most frequently in association with existing large patches that have some ability to modify microclimate.** One such event occurred in 1997 when a cohort of shrub seedlings established near the creosotebush core area. This cohort will continue to be monitored annually.

To test the importance of positive plant-soil feedbacks in initiating and maintaining creosote patches, we will initiate a new study to examine the composition of mycorrhizal fungi associated with creosote and grass patches. Mycorrhizal fungi influence plant communities by differentially altering the growth of various species (e.g., Allen 1991, Allen et al. 2001). However, the symbiosis does not appear to discriminate between highly responsive combinations and cheaters (e.g., Johnson et al. 1997, Bever et al. 2001). Bever and colleagues described a model for maintaining a diverse assemblage of mycorrhizal fungi, but as patches expand, we would predict that composition would shift to favor a more positive community for the increasing plant species. **We predict that mutualistic fungi must be present for the establishment of individuals into different patch types. They must be in the soil or disperse simultaneously but independently with the seed for successful establishment.** Species of AM fungi in the core areas will largely reflect those that support the core plant. However, in the transition areas, both groups of fungi will be found. Root tips and soil will be sampled using expandable-wall tubes. We will determine composition using molecular techniques (Friese and Allen 1991, Harney et al. 1997) and determine the host using ^{13}C (Allen and Allen 1990; Nakano et al. 1999) at each location where minirhizotron tubes are imaged. This study will be supplemented by information on soil properties and nutrient availability that also will be affected by the presence of shrubs.

We are continuing a long-term study of responses of black grama-creosotebush ecotones to changes in precipitation using a set of rainout shelters and associated control plots (http://www.ees.nmt.edu/Hydro/faculty/Small/research_2000/drought_folder/drought_main.html). **We predict that increases in summer precipitation will increase black grama biomass (i.e., dominance) but not cause creosotebush mortality, whereas increases in winter precipitation or summer drought will favor creosotebush patch expansion.** This study is critical to testing results from global change models for this region (Neilson & Drapek 1998; Peters 2002). The study site consists of nine plots (10 x 15 m) assigned to control, water addition and water removal treatments. Plots are instrumented with thermocouple psychrometers, TDR probes, and heat dissipation sensors arranged in vertical profiles (5 cm – 60 cm) under grass, shrubs, and interspaces. Whole plot runoff is measured and physiological performance of plants is measured seasonally via gas exchange and water potential methods. Additional plots will be established in the black grama and creosotebush core areas for comparison with the current the drought plots in ecotones.

We will continue our long-term plant removal plots started in 1995 (Peters 2000) to test whether invasion can occur in the absence of an extreme climatic event. These plots examine changes in dominance following the continued removal of the current dominant species; thus, we are allowing a potential for directional change in dominance during “normal” years. Plots also allow comparisons of dynamics within patches dominated by one of the three species with patches located at the ecotones. Plots (12 m²) were created by removing all plants of the dominant species in patches

dominated either by blue grama, black grama or creosotebush. Removal plots were also created in ecotones. Control plots without removals were established in all patches.

Shifting mosaic patches (Gosz, Li, B. & R. Pendleton, Peters). We will continue our 400m transect studies established in 1989 across the black grama-blue grama mosaic that demonstrated a shifting mosaic dynamic (Anand & Li 2001). **We predict the ENSO frequency of 3-4 years will maintain the shifting mosaic pattern of this site.** Each transect is sampled bi-annually to capture plant cover for cool and warm season species (live and dead), soil, and litter.

Studies of natural burn areas and experiments show fire to be an important factor that negatively impacts black grama and shifts communities towards blue grama dominance in the short-term (Gosz & Gosz 1996). However, recent studies from the SEV and JRN indicate that black grama sensitivity to fire is highly dependent upon rainfall received in the growing season of the fire. Thus, **we expect the timing of fires and ENSO dynamics are critical in the rate of the shifting mosaic patterns.** Previous studies also indicate that fire may remove creosotebush individuals that have recently invaded grassland (**fig. I.9**). Thus, fire can cause a shifting mosaic for creosotebush-grassland mosaics. **We predict that mortality of shrubs following fire will be nonlinear as a function of patch size: single shrubs and mid-sized patches that accumulate fuel (e.g., the exotic tumbleweed transported by wind and trapped by shrubs) have the greatest mortality while small patches (reduced grass understory but low ability to accumulate tumbleweed) and core areas with low grass and tumbleweed fuel may not burn.**

Long-term measurements on existing fire and experimental burns will evaluate the role of fire in shifts in dominance. In collaboration with the USDA ARS, Jornada Experimental Range, we will continue to study natural burn areas from 1990, 1992, 1995, 1998, and 2001. Prescribed and experimental fires conducted by the FWS are planned at the SEV starting in 2002. Prior to ignition, we will geo-reference ten replicate patches of each of 5 sizes dominated by creosotebush (including single shrubs) and also 50 plants of each of 4 size classes. Heat sensitive tablets, designed to melt at temperatures between 50 and 1200°C, will be established to examine the effect of patch size on fuel load and fire intensity (methods follow JRN LTER). Following the fire, we will monitor mortality, survivorship, and resprouting characteristics for all marked creosotebush plants.

Stationary patches (B. & R. Pendleton, Peters). Image and pattern analyses described above will be used to identify patches that appear to be stationary through time (i.e., decade time scale) and strongly correlated with soil properties. Our experiments will focus on ecotones between blue grama and creosotebush since preliminary data suggest that creosotebush rarely invades large blue grama patches, and ecotones between blue grama and creosotebush are expected to be stationary through time. We will conduct a series of experiments (described in next section) on processes limiting recruitment of creosote into blue grama patches and vice versa. These studies will be coordinated with soil studies to distinguish abiotic and biotic controls on ecotone location and species dynamics.

B. Patch properties and function (Allen, Belnap, Cross, Gosz, Lightfoot, Harrison, Hendrickx, Parmenter, Peters, Pockman, Small, Vanderbilt)

Patch processes and functions change as a result of spatial and temporal dynamics. Differences caused by these changes in the properties and functions characterize the internal aspects of the mosaic pattern and the potential relationships with adjacent areas. We will examine the relationship between patch type and size for: 1) physical properties (soil, microclimate), 2) nutrient dynamics, 3) aboveground vegetation properties (species composition, plant structure, nutrient content, reproduction, physiology), 4) belowground properties and mycorrhizal associations, and 5) biological crusts. Whenever possible, the same patches will be used to allow comparisons among

response variables. Relationships between animal populations and patch dynamics, size, and type are discussed in Section IV.

Hypothesis III.5. Ecosystem processes, feedbacks, and dynamics have a non-linear relationship to patch size; patches larger than a critical size (threshold) are key in shifts in species dominance and changes in processes. Patches smaller than a critical size have functions similar to the matrix; those larger than the critical size are similar to the core.

Most of our research has been conducted on core areas where ecosystem processes are similar to those of their respective biome (Kieft et al. 1998). We will continue our long-term studies of biogeochemistry, phenology, NPP, and plant and animal diversity and density in the three core areas and compare these core areas to other locations in the region to verify that our areas reflect biome properties (Section VI). Preliminary results suggest that there is a critical patch size representing a threshold for changes in function (fig. II.4). We predict the critical size for each patch type will vary with climate variations (e. g, ENSO events). Wet years will decrease critical patch size for blue grama; dry years will decrease critical patch size for creosotebush and black grama. New studies will evaluate changes in processes under different climate conditions for selected patch sizes. These studies will examine: 1) the relationship between patch size and ecosystem processes, 2) the critical size at which a patch begins to function similarly to a core area, and 3) the role of biotic feedbacks in changing patch number, size, and function through time. Five patch sizes for each type will characterize the range from small (1 plant) to large patches (hundreds of plants) typical of a core area. We expect that the relationship between patch size and similarity with the core area varies depending on patch type and ecosystem response variables (fig. II.4). The dominant species have different life history characteristics and relationships with their environment that result in important differences among patch types. Key characteristics that distinguish the dominants are their longevities (long vs. short), timing of growth (cool, warm), and structural morphologies (e.g., high vs. low root:shoot ratio) and rooting depths. Additionally, creosotebush causes the modification of local soil properties and results in high spatial heterogeneity in soil (Schlesinger et al. 1990). **Soil, microclimate properties (Harrison, Hendrickx, Small)**. Soil physical and nutrient properties will be characterized within each patch and core area. Particular attention will be paid to carbonate levels since they store atmospheric carbon (Monger et al. 1991), alter soil water movement and storage (Cunningham and Burke 1973), and are an indicator of soil age (Cole and Monger 1994). We will document vertical and horizontal patterns in carbonate content and stages of calcic horizon development for each soil horizon. Spatial/temporal patterns in infiltration and soil moisture will be examined using TDR rods at multiple depths located within patches and electromagnetic techniques (**fig. I.8**). Soil and air temperature within and between patches will be monitored with thermocouples and data loggers. Air temperature will be obtained using thermocouples located in a vertically stratified sampling design near plants and in bare interspaces (5 cm intervals to the top of the canopy). Alteration of the microclimate may be particularly important in allowing increases in patch size for creosotebush (i.e., facilitation). Our studies will allow us to determine the patch size at which this plant-microclimate feedback becomes operative. **Nutrient dynamics (Cross, Gosz, Vanderbilt)**. Our biogeochemistry studies focus on understanding nitrogen, phosphorus, and carbon dynamics, their relationships with energy and water fluxes, and their consequences for patch dynamics (**fig. II.1**). We expect that nutrient resource availability varies across the mosaic pattern of a BTZ as a function of the type of dynamic controlling changes in processes (Ludwig et al. 2000). The complex pattern of patch types, sizes, and intervening ecotones produces an even more complex pattern of nutrient resource levels and changing patterns of

availability. However, the positive feedback between patches and resource concentration processes creates self-organizing patterns in landscapes that may be characterized by scaling-rule relationships between patch size and N levels (Ludwig et al. 2000).

Hypothesis III.6. Mosaics characterized by directional dynamics demonstrate a non-linear pattern in resource levels from small to intermediate patch sizes; shifting patch dynamics have a non-significant change in resource availability over the mosaic pattern, and stationary patches have a strong contrast in nutrient resource levels with adjacent patch types in the form of a step-function change at the very sharp patch boundary (ecotone).

These hypotheses will be tested by studies of nutrient availability, N and ^{15}N additions (**fig. I.7A**), plant uptake, and decomposition. We will coordinate these studies with others directed at root and mycorrhizal dynamics, NPP, and Bigfoot II validation studies (Section V).

New studies of nutrient acquisition and storage will be initiated to test for effects of dominant species and patch size on nutrient availability with feedbacks to plant recruitment and growth (**fig. II.1**). The ^{15}N and ^{13}C studies of creosotebush in different patch sizes demonstrate differences likely due to different water availability and N cycling processes (**fig. I.6**). The NPP studies and tissue analyses for C, N, ^{15}N , and P will allow calculations of annual uptake by each dominant species (Robertson 2001). New minirhizotron techniques will allow samples of root tissue to be independently harvested and analyzed (Kosola 1999). We will use a subset of expandable-wall minirhizotron tubes to sample individual tips. Senescent leaf tissue collected for decomposition studies also will be analyzed to calculate nutrient retranslocation. Nitrogen availability studies will be performed in all patch types and sizes using resin exchange techniques and direct measures of extractable N from soils and crusts. For studies of N levels within the same soil, we will use a combination of resin capsules (UNIBEST, PST-1 Resin Capsule for Inorganics placed in permanently located access tubes at 10cm and 20cm depths) and resin membranes at surface and 10 cm depths. For comparisons of N between different soil and patch types, we will use field extractions of NO_3^- and NH_4^+ from soil samples. The sensitivity of ion-exchange media to soil water content is described as a "concern" by Lajtha et al. (1999a); however, the technique is valuable in detecting subtle differences in ion supply in the field when water flux changes rapidly (Fisher & Whitford 1995, Lajtha et al. 1999a, b). Soil methods will follow Robertson et al. 1999. Standard litterbag techniques will be used for decomposition studies of aboveground leaf and stem decomposition in each patch and core area. Root decomposition will be estimated by minirhizotron techniques. Collected material will be analyzed for C/N ratios and weight loss and remaining tissue will be archived.

Aboveground vegetation (Peters, Muldavin, Pockman). Many aspects of the aboveground vegetation are unknown for patch types and sizes in a BTZ mosaic. We expect that properties will not simply be a result of the presence of one dominant species or another.

Hypothesis III.7. Species presence and individual plant characteristics (e.g., N conc., morphology) vary as a function of patch size resulting in structural and functional differences for individuals across a patch size distribution.

We will use the same measures to characterize patches that are used in core areas: species composition and diversity, NPP by volumetric method, peak growth of C_3 and C_4 species, seed bank, interplant distance, and percentages of bare soil and litter cover. Based on studies since 1989, we expect similar species diversity for blue grama and black grama core areas and large patches, but lower diversity in large creosotebush patches (Peters 2000, Kröel-Dulay et al. submitted). **We**

predict a nonlinear function for species area curves (for patch area) that relates to the critical patch size. These nonlinear functions will vary with patch type. The critical size reflects the fragmentation processes in mosaics and biodiversity relationships.

Our plant population-level measurements will focus initially on recruitment of the three dominant species (blue grama, black grama, creosotebush). Our previous studies showed that blue grama produces fewer total numbers of seeds with higher viability than black grama, although black grama seeds are more effectively stored in the soil (Peters, in review). We will expand these studies to different patch sizes, and **predict that patch size will affect resource availability or granivory rates with feedbacks to seed availability (fig. II.1, II.2)**. Because little is known about controls on recruitment of creosotebush in the Chihuahuan desert, a major new effort in collaboration with the US Forest Service Experiment Station (Albuquerque) will examine processes for this species based on methods used for similar shrubs (Pendleton et al. 1995, Pendleton & Pendleton 1998, Pendleton et al. 1999): 1) reproductive output as a function of shrub size, precipitation, and herbivory, 2) seed dispersal by wind, and 3) seed germination/seedling establishment. Established seedlings will be monitored for mortality, herbivory, and growth. A daily time step simulation model of soil water dynamics will predict the effects of soil and climate in patch types and sizes on the establishment probability for all three species (Peters 2000).

New studies will examine the relationship between shrub physiological status and abiotic and biotic properties of patches (**fig. II.1**) based on differences in water availability (**fig. I.8**). **We predict that isolated shrub seedlings (i.e., in grassland) established under a decade of drought conditions will have favorable physiological conditions for growth following the drought due to lack of intraspecific competition and interspecific competition for soil moisture (e.g., by utilizing different soil depths). By contrast, isolated grasses growing in a shrub matrix are expected to have unfavorable physiological conditions due to degraded soil conditions (loss of soil OM, soil fines).** The role of climate in creating necessary conditions for establishment and subsequent growth under competitive conditions is critical to the directional dynamics model. Important new data will include plant predawn and midday water potential, soil water potential, and diurnal gas exchange measurements. Carbon isotope discrimination will be used to integrate stomatal behavior in creosotebush. Leaves from different patch sizes will be analyzed for C/N, ^{13}C , and ^{15}N . We will expand our xylem embolism measurements obtained in creosotebush core areas to patches. Xylem embolism occurs as a result of drought or freezing conditions where a loss of water transport through the xylem produces increased mortality rates. **Under normal climate conditions we expect highest mortality during the first several years for seedling shrubs because of competition with grasses for water and the lack of moderated microclimate (i.e., nurse effects).** These conditions explain the slow rate of patch growth in the initial stages of patch ontogeny. During the winter, xylem wood temperatures will be measured to quantify the freezing conditions. The presence/absence of freezing exotherms in the wood will indicate the number of freeze/thaw cycles experienced by plants for comparison with embolism measurements. Stable isotopes of water (D/H and $^{18}\text{O}/^{16}\text{O}$) will quantify the water sources (depth) utilized by plants.

Belowground production and mycorrhizal associations (Allen, Pendleton). Deeper rooting distributions in creosotebush compared with blue grama and black grama, as well as differences in timing of growth, suggest that these species have different strategies for obtaining soil resources (Gibbens and Lenz 2001; Peters in press). All three species form arbuscular mycorrhizae (AM), but only near the developing root tips. Horizontally, there are distinct differences between grasses and shrubs. Shrubs have distinctive spatial structure (i.e., islands of biotic and abiotic fertility) in infection, spores, and hyphae (Allen and MacMahon 1985, Klironomos et al. 1999). In creosotebush,

the most intense AM (80% infection) is associated with new white root tips in January whereas infection in the C₄ grasses predominates in August (Allen et al. 1984, Johnson et al. submitted). **We predict that there are important phenological differences between creosote mycorrhizae and grass mycorrhizae that result in different levels of nutrient uptake for different patch types and ecotones.** Because AM fungi extract N from decomposing litter (Hodge et al. 2001) and use primarily NH₄⁺ (Yoshida and Allen 2001), a creosote plant may have access to different water and N sources within grass patches vs. creosote patches. These differences are expected to vary non-linearly as patch size increases. Preliminary studies show differences in changing N mineralization rates and ¹⁵N signatures (**fig. I.6**).

Root and mycorrhizal production under both creosotebush and grasses will be estimated using minirhizotron readings obtained during the growing season. We have been measuring root dynamics for 4 years on blue grama and creosotebush core areas. The production and disappearance of individual mycorrhizal infection units typically occurs in about 1 week (Friese & Allen 1991, Treseder and Allen, in preparation). These studies will be expanded with additional tubes in black grama and blue grama core areas, in large and medium creosote patches in black grama grassland, and under individual creosote plants in the grassland. Differential phenology of mycorrhizal roots will be linked with measures of root production and turnover. Root lengths are determined by the program ROOTS (Hendrick & Pregitzer 1996) and production and mortality by a mark/recapture program (<http://mercury.bio.uaf.edu/~rruess.faculty/Programs.htm>). We developed a counts approach to reduce the image analysis time (Crocker et al., submitted). By carefully developing regression relationships between counts and digitized root length, the time for assessment of individual tubes can be reduced from >30 min to less than 4 min/tube making it possible to analyze an adequate number of samples for determining changes between patches. Our studies will be undertaken in collaboration with the BIGFOOT measurements of NPP (which also uses minirhizotron measurements) to assure comparability of values.

Biological crusts (Belnap). Biological soil crusts play many critical roles in arid ecosystems. Soil crusts fix carbon (C) and nitrogen (N), create soil aggregates (thus increasing soil stability and C sequestration), increase soil water, and increase vascular plant productivity. In general, the influence of crusts on ecosystem functions at a given site is dependent on the structure and composition of the soil crusts. Structure and function is influenced by site characteristics such as climate (rainfall, freeze-thaw events, temperature), soil texture, soil chemistry, and the structure of the vascular plant community. Thus, the influence of crusts on ecosystems can vary between different types of landscape patches (Belnap & Lange 2001).

Various crust types occur at the Sevilleta. The black grama grass community supports a flora with significant amounts of *Nostoc* and *Scytonema*, as well as occasional *Collema* patches. **This community is expected to have the high N and C fixation rates, high soil stability, and higher nutrient availability in surface soils.** Intermediate is the blue grama grassland, where the soil crusts are heavily dominated by *Microcoleus*, with occasional patches of *Nostoc/Scytonema* crusts. The creosote community, sparsely colonized by *Microcoleus* and only a few other cyanobacteria present, is **expected to have the least N and C input from soil crusts, the least soil stability of the three patches, and the least soil nutrients available from surface soils.** Because patch type and size varies in the properties influencing soil crust characteristics and development, **we expect that the distribution and types of crust differ among patch sizes as well as patch type.**

Crust cover by species will be estimated using point frames. For cyanobacterial biomass estimates, ten samples per patch will be collected dry, extracted with acetone, centrifuged, and then analyzed with HPLC for chlorophyll a. Samples will be analyzed for ¹⁵N as an initial test of

differences in N-fixation capabilities. Subsequent work will determine the role of crusts in N flux for different patch types and sizes.

IV. Faunal patterns and interactions with BTZ mosaic dynamics

Animals both respond to patch structure and dynamics and have important effects on patch dynamics. Animals exert these effects through species specific modifications of dispersal, seed availability, establishment, growth, and mortality of dominant plant species (**fig. II.1**). Assessing the importance of faunal effects on patch dynamics requires information linking process rates and animal distribution and abundance with the structure of the BTZ mosaic.

A. Faunal Influences on Mosaic Dynamics

Our goal is to characterize the functional roles of animals (herbivory, granivory, seed dispersal, soil disturbance, predation) in the development and/or modification of patches and ecotones. Ongoing and new experiments and observations will directly test the interactions between key animal taxa and particular plant taxa. We will focus on small mammals (rodents and lagomorphs), grasshoppers, and predators (birds, coyotes) because of their central roles in the trophic structure of these ecosystems and their potential strong effects on plant dynamics. Because animals may respond at spatial scales larger than those of patches, we will add studies on the 6 km belt transects that traverse multiple patch types, sizes, and ecotones.

***Herbivory* (Joern, Lightfoot, B. & R Pendleton).** The Small Mammal Exclosure Study (SMES) will continue to provide valuable information on the effects of rodents and rabbits on vegetation, soils, and arthropods within creosotebush and black grama core areas. Over a five-year period, small mammal herbivory has had no significant impact on black grama grass canopy cover at the black grama site, but did have significant impacts on perennial grasses at the creosotebush site (**fig. I.10**). Animal-generated soil surface disturbance patches, which may be important for plant seeding establishment, were also significantly greater at the creosotebush site than at the black grama site.

Hypothesis IV.1. Small mammals are keystone/engineering species determining plant species diversity and vegetation structure across Chihuahuan grassland and shrubland ecosystems.

SEV data are being compared with similar data being collected at the Jornada LTER, Portal, Arizona LTREB site, and the Mapimi Biosphere Reserve in Mexico. We will add new studies to examine the effects of animals on seedling mortality of blue grama, black grama, and creosotebush using a series of caged and non-caged seedlings in different patch types and sizes. All seedlings will be followed over a 5-year period for growth rate, herbivory, and causes of mortality. Plant biomass, flower production, and seed production will be measured during periods of peak production.

We are also examining the importance of small animals to recruitment and growth of perennial grasses across black grama/creosotebush and black grama/blue grama ecotones. An NSF-supported cross-site project (Peters 2000) installed small rodent exclosures with cage controls, and full controls at three locations (monodominant patches and adjoining ecotones) across three replicate boundaries for each ecotone type. All plants of the dominant grass were removed within a 40 cm-diameter area in the center of each 1.5 m² plot. Tiller or stolon regrowth, seed production/availability, seedling establishment, and herbivory are monitored monthly during the growing season. We will transplant seedlings of blue grama and black grama with and without cages along each boundary in June (2002) and monitor seedlings weekly during the growing season for herbivory rates and plant survivorship.

Grasshoppers are probably the most significant herbivores across the SEV grasslands in terms of biomass and quantities of plant tissue consumed (unpublished SEV data). Grasshopper herbivory may have significant impacts on host plant reproductive success, affecting host plant distribution and abundance. For example, the snakeweed grasshopper (*Hesperotettix viridis*) is known to affect the spatial distribution, abundance, and reproductive potential of snakeweed near the SEV through selective herbivory (Parker & Root 1981).

Hypothesis IV.2. Individual grasshopper species metapopulation (patch occupancy and patch animal density) and their impacts on host plants (herbivory) will be non-linearly distributed across the BTZ as a function of interacting host plant patch spatial patterns, and host plant density and nutritional quality within patches.

We will focus on several abundant grasshopper taxa associated with the major vegetation communities across the BTZ (see section IV.B) utilizing observational sampling of grasshoppers and plants among vegetation patches, and grasshopper time budget and diet selection studies (Mulkern 1967, Heidorn & Joern 1984). Since grasshopper herbivory can impact plant seedling establishment and plant reproductive success, we will coordinate these studies with those of seedling establishment. Grasshopper species distributions reflect patterns of both habitat and food resource spatial and temporal distributions across the BTZ (fig. I.10).

Metapopulation theory (Hanski 1999) predicts patch occupancy by mobile animals such as grasshoppers to be a function of habitat patch size and isolation relative to animal dispersal. The resource abundance hypothesis (Hunter 1992) and the resource concentration hypothesis (Root 1973) both predict that grasshopper density, diversity, and herbivory should vary across the SEV BTZ as a function of host plant patch size and density. Spatially concentrated host plants should support greater numbers of herbivores, and thus, a greater intensity of herbivory. SEV grasshoppers should be most abundant and their rates of herbivory greatest in the largest and least isolated host plant patches, as a function of host plant availability. Yet, ecological stoichiometric relationships between plant tissues and grasshoppers should play a critical role in grasshopper patch occupancy and plant consumption rates. Consumer-resource interactions follow stoichiometric rules in that mass must balance when resources are partitioned into consumer biomass and waste products (Sterner 1994). If resources are limiting, consumer secondary production should be greatest when elemental ratios in food best approximate the elemental needs of consumers. We predict that C:N:P elemental ratios of grasshopper host plants will vary in non-linear ways among different patches across ecotonal boundaries, which in turn will constrain feeding, population dynamics and overall biomass production of grasshopper herbivores. Thus, individual grasshopper species metapopulation structure, the intensity of grasshopper herbivory, and grasshopper secondary production, all will be a function of the spatial distribution, size, plant species diversity, and nutritional quality of host plant patches. Our studies on the nutrient resource levels as a function of patch size will be important in understanding the distributions of this herbivore.

We will test the above hypothesis by conducting spatial distribution and abundance and foraging studies of grasshopper species that are specific to creosotebush, black grama, and blue grama by comparing on habitat and diet specialist grasshopper taxa, to habitat and diet generalists that occur across the entire BTZ. This research will not only tell us how grasshoppers are distributed across the BTZ, but also how the impacts of those herbivores on their host plants are distributed across the BTZ.

Granivory, seed dispersal, and soil disturbance (Lightfoot, Parmenter). Previous studies show that granivorous rodents (kangaroo rats, pocket mice) have significant impacts on plant dynamics resulting from seed consumption, seed dispersal activities, and creating soil disturbance that enhances seedling establishment. In contrast, rodent seed hoarding and caching activities aids in the dispersal of some plant species (**fig. II.2**). **We expect that selective rodent granivory on preferred plant species can alter plant species dominance and distribution patterns** (Longland et al. 2001). We will initiate new studies to assess the role of rodent granivory relative to plant dispersal utilizing seed foraging preferences (e.g., seed cache surveys and examination of seed pouch contents) to supplement field observations. Seed trays, baited with inert color-dyed seeds of preferred plant species, combined with seed cache surveys will determine seed dispersal distances for the three dominant kangaroo rat species. Information from this study will be integrated with soil disturbance and seedling establishment studies to reveal the roles of granivorous rodents in seed mortality, seed dispersal, and seedling establishment. Soil disturbances created by animals digging for seeds have been monitored as part of our SMES project in core areas dominated by creosotebush or black grama. Our data show that these disturbances by kangaroo rats, rabbits, ants, and termites are considerably more frequent in creosotebush shrubland than in black grama grassland. It is unknown how the relationship between frequencies of occurrence of digging varies across the BTZ and with patch types and sizes. Soil surface disturbance studies will document animal-caused soil disturbances across the belt transects, and include patches of different sizes dominated by different species. We will examine potential positive effects of animal digging activities by studying simulated and naturally occurring disturbances to determine if they provide more favorable microsites for seedling establishment than undisturbed surfaces (**fig.II.2**).

Predation (Kelly, Parmenter, Waide, Wolf). Top-down control of key herbivore and granivore populations may moderate their effects on BTZ dynamics. However, given that predator distributions over the landscape may be discontinuous, their effect on other populations may be patchy. Predator distribution may reflect factors unrelated to vegetation mosaic structure (e.g., nest or den sites, foraging perches). **We predict that predation may act to reinforce boundaries if predator distribution is controlled by the factors controlling plant and prey distribution or blur boundaries if predation responds to other factors than those controlling vegetation mosaic patterns in the BTZ.**

Top predators in terrestrial ecosystems typically impose trophic cascade effects that often influence not only prey populations (e.g., Lindstrom et al. 1994) but also plant growth, productivity and survival via reduction of herbivorous prey species (Schmitz et al. 2000). Of the large mammalian predators at SEV, the coyote (*Canis latrans*) is the most abundant and widespread, and has been shown to exert “top-down” controls on its prey populations in nearby west Texas (Henke & Bryant 1999). Their influence on the flora and fauna of BTZ landscapes has not been investigated.

Coyotes have been shown to consume a wide variety of prey on the SEV (Hernandez et al., in press), and could exert top-down control of herbivore populations (small rodents and lagomorphs) in patches and across ecotones, particularly if they preferentially forage in these areas (fig. I.10). In collaboration with the Fish and Wildlife Service, we will initiate GPS radio telemetry studies of coyote movements to assess their use of patches and ecotones as foraging habitat. Personnel of the FWS Wolf Recovery Program will assist in trapping coyotes. We also will initiate new studies to examine habitat use and predation on invertebrates (particularly grasshoppers) by three avian predators (kestrels, roadrunners and shrikes) through observations and radio telemetry. These studies will examine whether predator distribution may create a mosaic of cascading effects that

interact with physical controls of BTZs. The initial data will be correlational, but will identify subsequent hypotheses and predator exclusion experiments that can test the hypothesis.

B. Faunal distribution and abundance (Lightfoot, Parmenter, Waide, Wolf, Yates)

Quantitative measures of mammal and invertebrate abundances and habitat use across the mosaic will estimate faunal impacts on the processes determining BTZs via energetics models (e.g., Parmenter et al. 1984, Nagy et al. 1999) as well as our direct experiments and simulation modeling. These measures will further allow us to assess how trophic structure changes across the BTZ as a result of differential responses by animals to changes in patch size and type. Trophic links characteristic of core areas may be broken as species wax and wane across the BTZ, resulting in a restructuring of the trophic web. **We expect that patch occupancy and animal density will vary across the mosaic. The rate of change will reflect the threshold and scale of patch sizes and frequencies that each species responds to in the mosaic. Cascading effects of consumer control will be disrupted by reorganization of trophic structure in the BTZ.**

A simple example is one in which the top predator from each biome avoids the BTZ. This releases lower trophic levels from top-down control, allows increased herbivory, and changes the importance of herbivory as a structuring force compared to the core biomes. Our studies will address whether patterns of diversity 1) increase within ecotones relative to patches (due to habitat conditions being suitable for a larger suite of species), 2) decrease due to proportionate habitat reductions and subsequent species exclusions, or (3) exhibit no change within the ecotone (due to one-for-one replacement of species). We will investigate the temporal nature of the above patterns, as we expect that environmental conditions (e.g., ENSO events) will drive population cycles and create an “ebb and flow” dynamic of species distributions across the mosaic. Dynamics in faunal patterns may influence processes (nutrient cycling, NPP) within the BTZ, and contribute to dynamics within the mosaic.

Small mammals (Parmenter, Yates). Temporal and spatial patterns in rodent population dynamics (abundances, demographics, and movements) will be quantified across boundaries between shrubland and grassland habitats. We will maintain our sampling of rodent community composition and population densities on our core trapping webs, and our road survey line transect sampling of lagomorph population densities to estimate potential levels of herbivory and granivory. Additional studies will examine species-specific patterns across the grassland-shrubland mosaic.

Mark-recapture methods will be conducted along 3 new trapping sites that will straddle the creosotebush/grass critical patch density (see section III.A). These sites will include extended trap lines deeper into the creosotebush and grassland habitats to determine the extent and timing for species that extend their distributions across the mosaic into less-preferred habitat. **We predict the El Niño driven changes in C₃ annual production (high spring NPP), which reduce resource differences among patch types, will precede such movements.** We will measure carbon isotope ratios of small mammal tissues to establish baseline resource use patterns (C₃ vs. C₄) across the BTZ. These species' specific isotope baselines will provide comparative data for examining the penetration of C₃ resources into the food web across the BTZ during El Niño years.

Grasshoppers (Joern, Lightfoot). These herbivores represent the animal taxa most likely to exhibit both spatial and temporal distributions similar to plants. We will continue our monitoring of 49 grasshopper species from our core sites. Of those, 18 are bare soil specialists, 21 are grass specialists, 5 are forb specialists, and 5 are shrub specialists. New studies will document species distributions and abundance patterns for species that are associated with each of the patch types. We will also initiate new studies to characterize grasshopper species distributions across the mosaic

patterns on our 6 km transects.

We will develop predictive models of rodent and grasshopper dispersal across large areas that include multiple patch types, sizes, and ecotones. The distributional data will allow us to characterize the directions, rates, spatial extents, frequencies, and magnitudes of dispersal events. Analysis of the demographic components of dispersal stages will test recently published models of dispersal (e.g., Hanski & Gilpin 1997, Kean & Barlow 2000).

V. Scaling From Patches to the Landscape (Gosz, Hendrickx, Li, Lightfoot, Muldavin, Parmenter, Peters, Small, Wessman)

We will extrapolate from patches to the landscape to determine changes in the location and composition of the BTZ over time, and to estimate the contribution of the SEV to regional biodiversity and biogeochemical cycles. We expect that this extrapolation will require additional information beyond our studies of mosaics. The null hypothesis is that one can linearly extrapolate patterns or processes at a small scale to those at larger scales. Alternatively, spatially explicit processes (e.g., overland and subterranean flow of water; redistribution of seeds, soil particles, and nutrients; atmospheric patterns of N deposition) are necessary to extrapolate patch patterns to the landscape. Weather patterns (e.g., localized precipitation), topography, and soil patterns can also have effects at the landscape scale.

Hypothesis V.1. Patch mosaics (sizes, numbers, and locations of patches relative to other patches) and patch-patch and patch-matrix interactions influence broader landscape-scale patterns and dynamics. These interactions and feedbacks result in thresholds and nonlinear responses across spatial and temporal scales. A simple aggregation of patch-scale responses is insufficient to explain patterns at the landscape scale.

We will test this hypothesis by comparing linear extrapolations of our patch-scale results with patterns obtained at broader spatial scales. There are a variety of sampling and analytical techniques that can be applied to detect boundaries and thresholds at multiple scales (Fortin et al. 2002). We will use a combination of long belt transects, remote sensing, and spatial modeling to identify broad scale patterns. Belt transects (Section III) were evaluated in 2001 for percent canopy cover of all shrubs, subshrubs, and perennial grasses and forbs using consecutive 100 m² quadrats and a modified Domin-Drjina cover scale (Mueller-Dumbois & Ellenberg 1974). In the first phase, we are applying sliding window boundary analysis (SWBA) of Ludwig & Cornelius (1987) to detect ecotones at scales greater than 100 m². Over time, we will use SWBA along with other methods to identify significant shifts in patch pattern and changes in composition and structure along the transects. We will sample and analyze selected abiotic and biotic processes and substrate controls that may determine ecotones and be unique properties of BTZs at the landscape scale. Broad-scale patterns in soil moisture will be measured along each transect using EM technology (fig. I.4). These patterns will be related to measures of vegetation and soil texture. We are also developing maps using high-resolution aerial and satellite imagery (Section III) to delineate boundaries and biome core areas. Using available soils and geomorphic maps (or their surrogates), along with hydrological and topographical surfaces, we will conduct spatial modeling analyses to detect substrate controls on boundary patterns, and to compare these patterns to belt transect and patch mosaic pattern and process studies.

Our measurements of climate, nutrient deposition, and energy/water flux will continue to provide the environmental drivers and broad-scale context for our multiple-scale studies. Precipitation demonstrates high temporal (seasonal, annual, and decadal) and spatial variability

(localized monsoon patterns) with important implications for patch and landscape scale dynamics. Retrospective analyses based on SEV tree rings demonstrate a number of drought cycles, notably, a decade-long drought that last occurred in the 1950's and returns at a ~60 yr frequency (Milne et al. in press). *The next decadal drought is possible within the next LTER funding cycle.*

Our climate data come from ten Level III weather stations with wireless transmission capabilities distributed throughout SEV (**fig. I.1**) These data also serve as validation for remotely sensed precipitation from lightning location data (Gosz et al. 1995b) and NEXRAD and TRMM data. Remote sensing is being used to map localized precipitation and vegetation response to pair “natural” experiments on drought and wetting with our artificial drought and wetting experiments (section IV). We will identify areas with long-term above, below, or average precipitation to evaluate the role of climate on ecosystem dynamics.

Our network of 11 bulk precipitation collectors identifies patterns in nutrient deposition. Two wetfall/dryfall collectors evaluate the ratio of inputs. Collaboration with the NADP/NTN CASTNet programs through EPA will result in additional wet and dry deposition equipment for more accurate estimates of deposition rates (www.epa.gov/castnet; <http://nadp.sws.uiuc.edu/>). Growth in regional cities is increasing nitrogen deposition rates at SEV, which, in other arid regions, causes vegetative type conversions due to changing plant community interactions (Allen et al. 1998, Minnich & Dezzani 1998, Padgett & Allen 1999). Preliminary studies of N addition demonstrate significant differences in NPP for blue vs. black grama (**fig. I.7B**, Gosz, unpublished), thus, our N deposition data are critical to testing our hypotheses on dominance shifts between blue grama and black grama in the BTZ.

The SEV is collaborating with several non-LTER supported studies collecting additional broad-scale information. The grassland in our study landscape is a BigFoot II validation site where estimates of NPP are calculated by remotely sensed images at 1 km² resolution (www.fsl.orst.edu/larse/bigfoot/). Collaborating with the JORNEX project at the Jornada LTER, we are estimating carbon and water flux across the landscape. A variety of instruments (ground, airplane, and satellite) are used to estimate carbon and water flux across a range of spatial scales, and to extrapolate among scales.

The new studies on the 6 km transects and landscape mapping are designed to examine patch-level interactions and the consequences of these interactions to spatial structure of the landscape. The information on movement of invertebrates, rodents, and predators among patches will allow us to estimate fluxes of materials as a function of mosaic properties. The presence of altered faunal assemblages in patches of different sizes, as well as modified compositions across ecotones, will likely affect ecosystem processes (NPP, nutrient cycling) in the BTZ.

We will also use our synthetic simulation model (ECOTONE) to predict patch and landscape-scale dynamics in response to cyclic (e.g., drought-wet, El Niño-La Niña) and directional changes in climate and disturbance regime (e.g., fire frequency). We will be able to predict future changes in patch distributions and patterns because we will know how each type responds to changes in environmental drivers (**fig. II.8**).

Hypothesis V.2. Landscapes composed primarily of stationary patches will remain stable with little change in the location or dynamics of the BTZ under cyclic or directional changes in climate or fire. Landscapes composed primarily of shifting mosaic dynamics will experience reversible shifts in patch types with changes in climate or fire that correspond to shifts in the BTZ. Landscapes composed primarily of mosaics demonstrating directional dynamics will experience large changes in patch type with changes in climate or fire as dominant species from one biome invade into an adjacent biome to shift the location of the BTZ.

The long-term studies and analyses of historical photos will provide validation for our modeling results. Although we cannot test our hypotheses through modeling, our efforts will be critical in predicting future dynamics of the BTZ throughout much of central New Mexico under different management scenarios. For example, our modeling results can provide management with data to make informed decisions on the role of fire in modifying ecosystem dynamics and biodiversity in the face of changes in climate. Modeling will contribute to our ability to evaluate the role of positive and negative feedbacks among plants, animals, soils, and microbes in generating and maintaining dynamics at BTZs under different scenarios.

VI. Cross-site and Regional Analyses

There are a number of cross-site studies that will help extrapolate our site-scale information to the region (**Table VI.1**). Most of our cross-site studies provide comparisons with sites either in the shortgrass steppe biome (SGS LTER, Comanche NG, Kiowa NG) or the Chihuahuan Desert (JRN LTER, Big Bend NP, Mapimi Nature Reserve). These studies are mostly supported by external funding, and provide critical comparisons of pattern and process across climate, soils, and vegetation type gradients. We will continue to evaluate the unique properties of BTZs compared with core areas of biomes. Using a regional latitudinal and longitudinal transect of data points collected over the past decade, the floristic and environmental characteristics of the BTZ will be put into a regional context. Using non-metric multidimensional scaling ordinations, patch and belt transect data will be compared to other biome core areas and to ecotonal sites that straddle the Chihuahuan to shortgrass steppe BTZ (see Ludwig et al. 2000). We intend to synthesize the patch to landscape characteristics to arrive at an integrated definition of the BTZ that incorporates the floristic biogeography of each biome and the quantitative ecological attributes of the BTZ.

VII. Synthesis and overview

The overall objective of the SEV LTER program is to understand and predict ecosystem dynamics across multiple spatial and temporal scales at biome transition zones (BTZs). Over the past 12 years, we have conducted short- and long-term experiments designed to examine broad-scale patterns and processes characteristic of biome core areas and their ecotones. We propose to build upon and expand these studies to focus on patch-scale dynamics, biotic and abiotic drivers, and the consequences of different patch types, sizes, and their mosaics to landscape and regional scale dynamics. We will continue a number of long-term studies and measurement efforts, and will initiate a series of experiments focused on the importance of plant-soil-animal-microbe interactions and feedbacks with ecosystem dynamics. Our iterative approach of combining a synthetic simulation model with data collected from short- and long-term interdisciplinary studies will provide a framework for extending our conceptual model of BTZs to additional transitions in the future. We expect to find common properties and patterns that can be used for many types of boundaries at many scales. We will also use the simulation model to predict changes in the location and composition of BTZs through time under changes in climate and disturbance regime. Because the region is likely to experience a decade-long drought, directional changes in climate, and increases in atmospheric deposition, an understanding of the key processes driving patch and ecotone dynamics is critical to our ability to manage and preserve the biodiversity and natural resources of these systems. Extrapolating from patch mosaics, processes, and dynamics to the landscape and region will also be critical in determining the contribution of the SEV to regional and global biodiversity and biogeochemical cycles. We expect that our novel, multi-scale approach to understanding patches, ecotones, and BTZs will be applicable to other ecosystems where boundaries are important.

Table VI.1. Cross-site Collaborations							
TITLE	SITES	SEV PIs	Collaborators	Funding			
Removal of dominant species	SEV/JRN	Peters	L.F. Huenneke (JRN-LTER)	NSF/LTER			
Patterns in biodiversity and disturbance characteristics across spatial scales	SEV/JRN/SGS/Comanche NG/Kiowa NG/3 sites in Hungary	Peters, Gosz	E. Kovacs Lang (HAS) Gyuri Kroel Dulay (HAS)	NSF/INT			
Simulated effects of climate change on semiarid grasslands	SEV/JRN/SGS/Comanche NG/Kiowa NG/3 sites in Hungary	Peters, Gosz	E. Kovacs Lang (HAS) Gyuri Kroel Dulay (HAS)	NSF/INT			
JORNEX project (remotely sensed data on biological and physical properties of arid ecosystems)	SEV/JRN	Gosz	A. Rango (JRN-LTER), J. Ritchie (ARS)	ARS, NSF/LTER			
Quantifying grassland-to-woodland transitions and the implications for carbon and nitrogen dynamics	SEV, Jornada, Texas	Wessman	G. Asner, S. Archer	NASA			
Effects of indigenous small mammals on species composition and structure of Chihuahuan Desert communities	SEV/JRN/Mapimi, Mexico	Lightfoot	L. Hernandez	NSF/LTER/CONCYT			
Factors regulating below-ground carbon allocation in terrestrial ecosystems: A cross-site experiment	SEV, many other sites	M. Allen	Pregitzer, Ruess, Hendrick	NSF			
Biocomplexity: Common mycorrhizal networks-Active or Passive Channels? Interacting roles of mycorrhizal fungi, soil resources, and plants in carbon and nutrient transfers	SEV, southern California, northern California, southern Oregon	M. Allen	C. Bledsoe, D. Southworth, W. Horwarth, D. Rizzo, R. Zazoski	NSF			
Relationships between climate change and topography on ground-dwelling arthropods in the Southwest	SEV/JRN/Bandelier National Monument/Los Alamos National Lab	Lightfoot	C. Allen, T. Harrmann, R. Fagerlund, S. Brantley	NSF/LTER, USGS/BRD, DOE			
Effects of grazing and climate change on vegetation and grasshoppers in New Mexico semi-arid grasslands	SEV/Bosque del Apache N.W.R./JRN/Fort Bliss Military Reservation /White Sands Missile Range	Lightfoot	L.F. Huenneke (JRN-LTER), M. Bogan	USGS/BRD			
Microbiotic crusts and arid ecosystems	SEV/JRN/Negev Desert, Israel	Cross	G. Kidron (Israel), Pregenzer	NSF/LTER, Mitrani Center			
Regional variation in recruitment of blue grama and black grama	SEV/JRN/SGS	Peters		NSF/LTER			
Long-term ANPP monitoring	SEV/JRN	Gosz, Lightfoot	L.F. Huenneke (JRN-LTER)	NSF/LTER			

Effects of fire, grazing, and small mammals on vegetation, grasshoppers, rodents, lizards, and birds	SEV/JRN	Gosz, Lightfoot, Peters	K. Havstad (JRN-LTER)	NSF/LTER, BLM, ARS
Vegetation-soil feedbacks and response of grasslands and shrublands to climate change	SEV/JRN	Peters	J. E. Herrick (JRN-LTER)	NSF/LTER, ARS
Effects of small animals on perennial grass recruitment and dominance	SEV/JRN/Big Bend NP	Peters	B. Bestelmeyer (JRN-LTER)	NSF/DEB
Generalization of ECOTONE to arid and semiarid communities in the Chihuahuan Desert	SEV/JRN/Fort Bliss, TX	Peters	K. Havstad (JRN-LTER), J. Feighmy (CERRL)	US Army/CERRL
Carbon sequestration potential of Southwestern rangelands	SEV/JRN/Los Alamos	Peters	C. Monger (JRN-LTER), J. Herrick (JRN-LTER), J. Harrington (NMSU)	EPA
Variation in precipitation, plant production, and grasshopper population dynamics	SEV, JRN, Mapimi, Mexico	Lightfoot		NSF/LTER
The response of grasshopper assemblages to variation in precipitation and plant production in the northern Chihuahuan Desert	SEV, JRN, Mapimi	Lightfoot	E. Rivera	NSF/LTER
Harbingers of anthropogenic ecosystem stress: mycorrhizal fungi and weedy plants	SEV, many other sites	M. Allen	E. Allen, C. Dahm	EPA
Mycorrhizal responses to nitrogen eutrophication at five mesic to semiarid Sites	SEV; 4 other sites	M. Allen	E. Allen, N. Collins Johnson	NSF/LTER
Isotope and genetic studies to assess microbial carbon storage in natural and human-altered environments	SEV, southern California, Bonanza Creek LTER	M. Allen	K. Treseder, C. Masiello	Lawrence Livermore National Laboratory
Cross-site contrasts of global change and ecotonal dynamics	SEV, Flagstaff, AZ	Gosz	C. Gehring, T. Whitham	NSF
Ecological stoichiometry of North American grasshoppers along a latitudinal gradient	SEV, JRN, SGS, KONZA	T. Joern		NSF

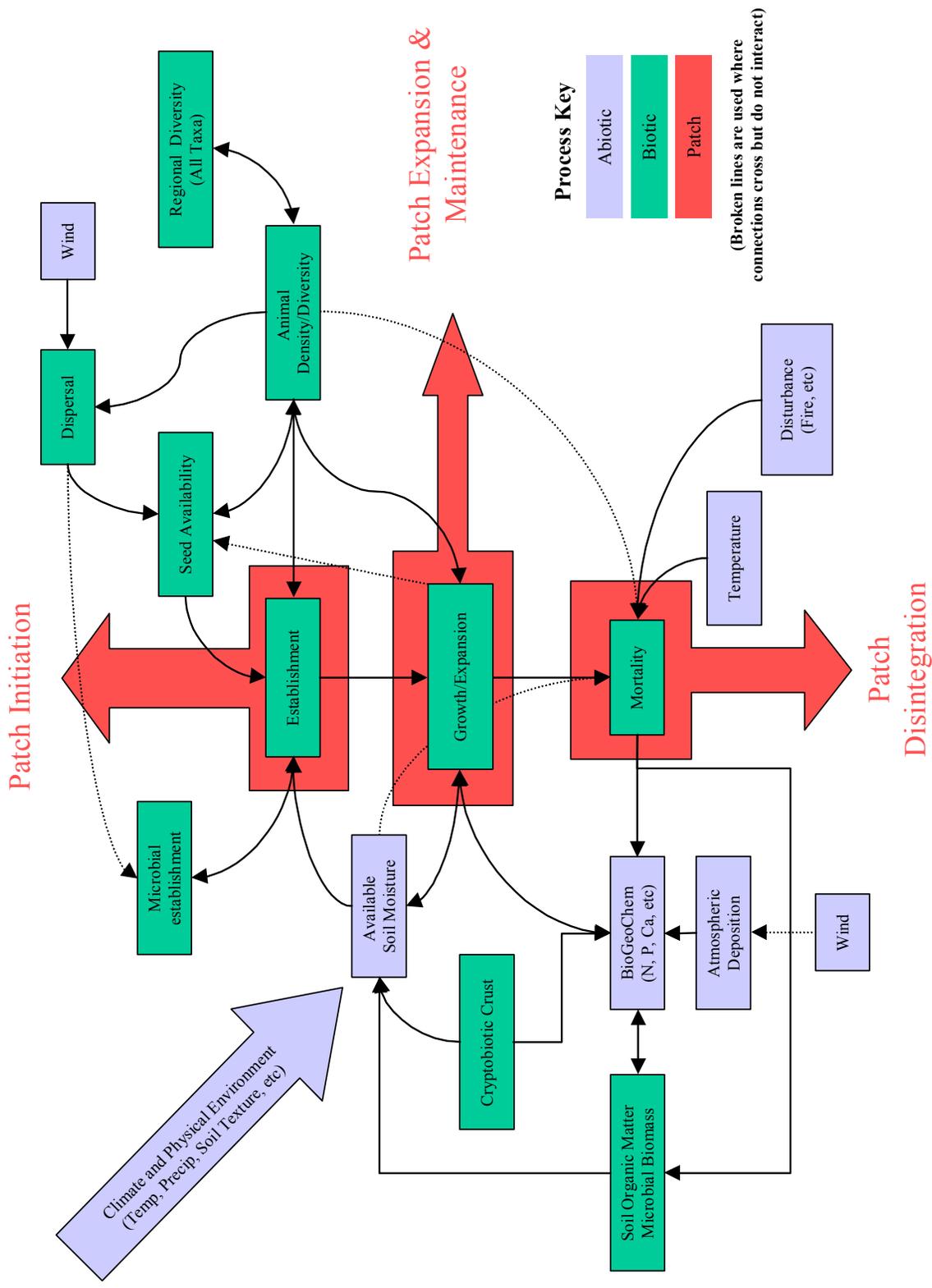


Figure II.1. Conceptual model for factors influencing the dynamics of patches in a BTZ mosaic; initiation, maintenance or expansion, and disintegration. Details on faunal influences on patch dynamics are shown in figure II.2.

Duration of Climate Extremes

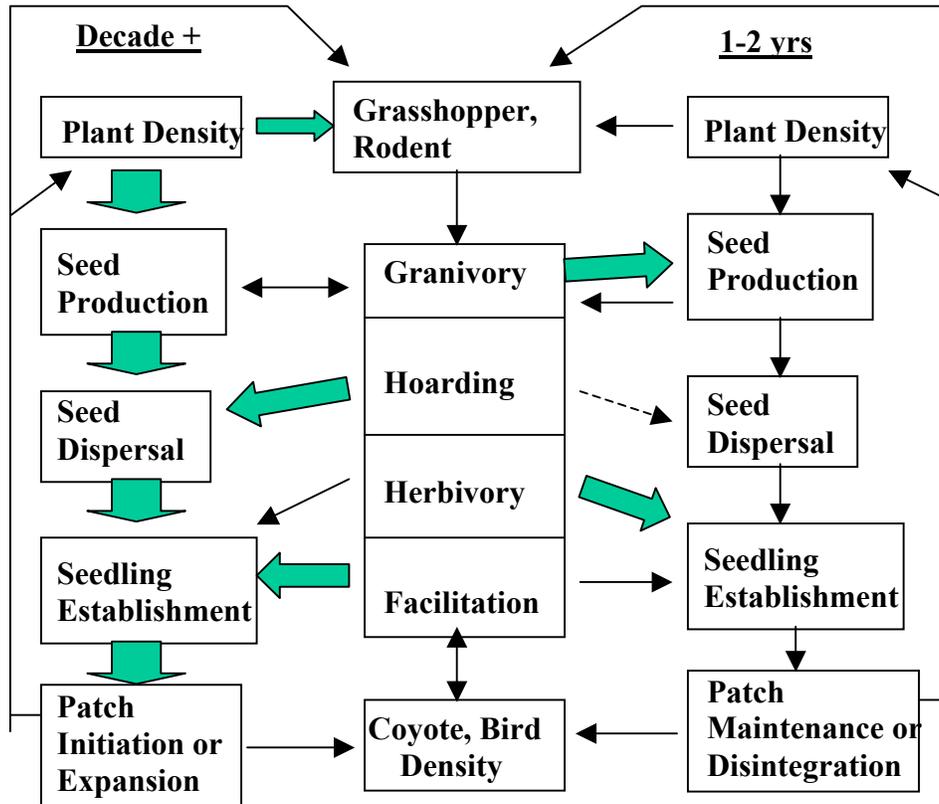


Figure II.2. Conceptual model for the interactions of climate and internal, biotic factors that lead to seedling establishment, patch formation, and changes in the mosaic dynamics. The *relative* strengths (indicated by broad or small arrows) vary as a function of duration of the climate change. Long duration climatic situations, both drought and wet periods, strengthen positive feedback. Drought causes this for desert species invading more mesic habitats (i.e., Shortgrass Steppe) and wet periods cause this for mesic species moving into drier habitats. Short duration wet periods oscillating with dry periods inhibit one or more of the phases to prevent a positive feedback from occurring. The role of fauna varies from intensifying processes that contribute to positive feedbacks during long climate duration to processes that result in negative feedbacks during short duration. Our experiments and long-term measurements are designed to test these relationships. Changes in patch patterns may influence predator activities.

Fauna can play important roles in facilitating seedling establishment in the BTZ. Rodent digging can create microsites and cache seeds leading to seedling germination when climate conditions are appropriate. The figure shows creosotebush seedlings established around a kangaroo rat mound in the black grama habitat. Mounds also affect diversity of annuals in the grassland.



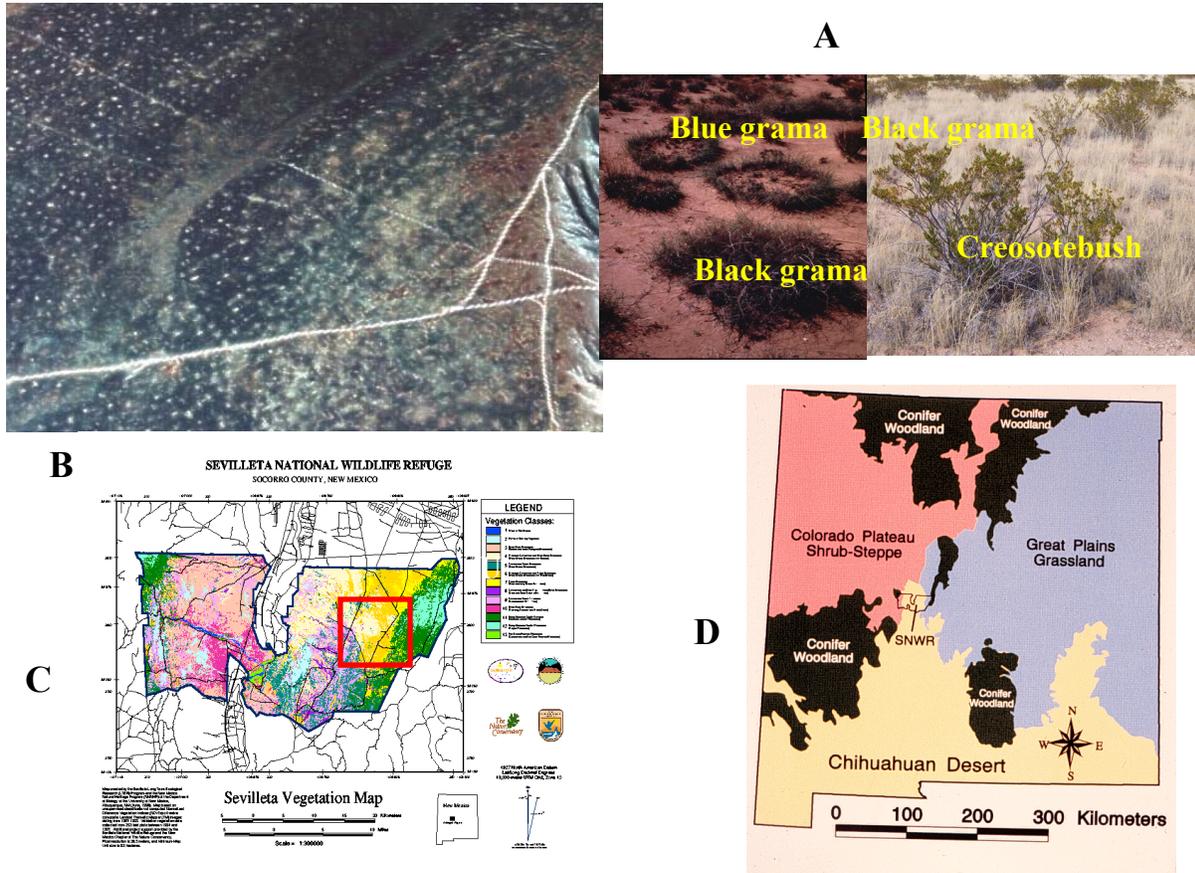


Figure II.3. Multiple scales of study in the Sevilleta BTZ. **A**. Individual plant studies on blue grama and black grama and black grama and creosotebush. **B**. Studies across blue, black and creosotebush patch types and ecotones between dominant patch types: blue grama patches are gray, black grama patches are black, and creosote patches are red. The light spots in black grama areas are kangaroo rat mounds (~5/ha) that influence species diversity. **C**. The study area (box) is a 40 km² landscape area within the 100,000 ha SEV containing the northern limits of a creosotebush zone (purple) interacting with C₄ grasslands of black grama (pale yellow) and blue grama (bright yellow). These 3 dominant species represent the major plant communities and their ecotones found in the study area at the SEV (Chihuahuan Desert shrubland (creosotebush), Chihuahuan Desert grassland (black grama) or the Great Plains Shortgrass Steppe (blue grama)). **D**. Location of the Sevilleta (SNWR) in the state of New Mexico and approximate limits of the major biomes of the region.

(Right) Patches are defined by the typical interplant distance found in core areas. Individuals exceeding 2X the typical interplant distance are considered outside of the patch. The two individuals in the foreground represent a patch. Patch sizes for multiple individuals range from 10 m² to 500 m².



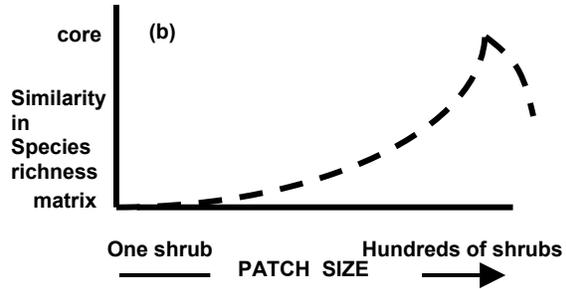
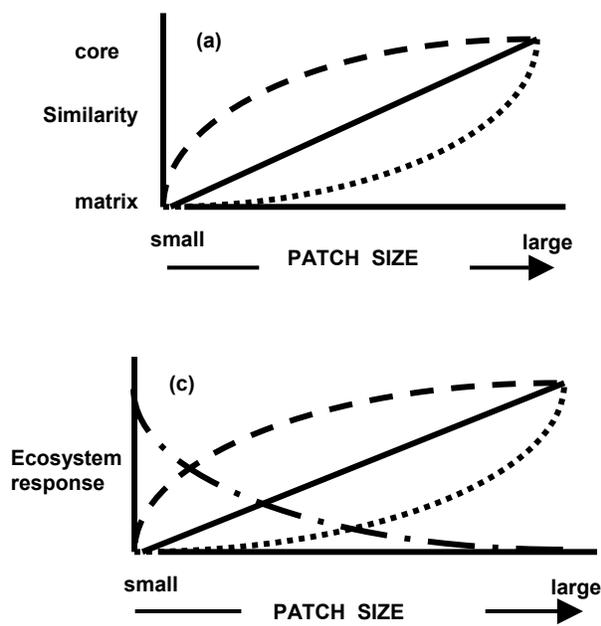
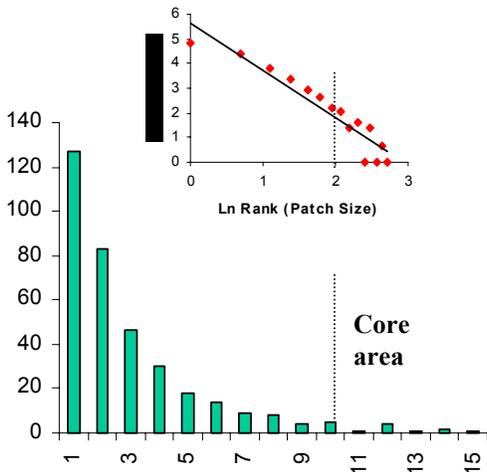
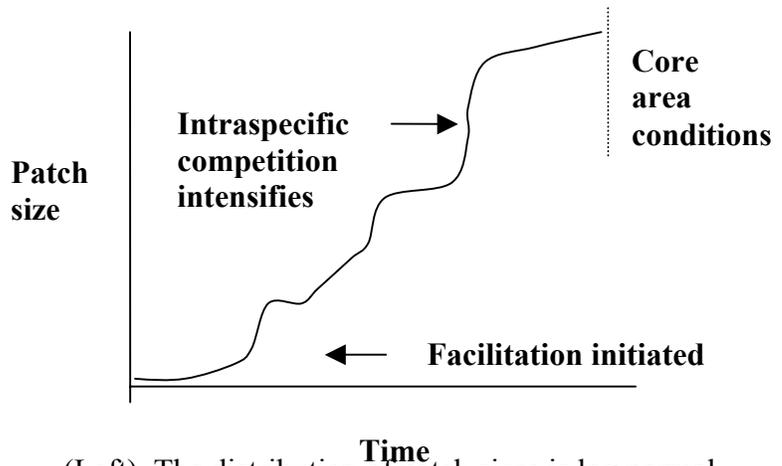
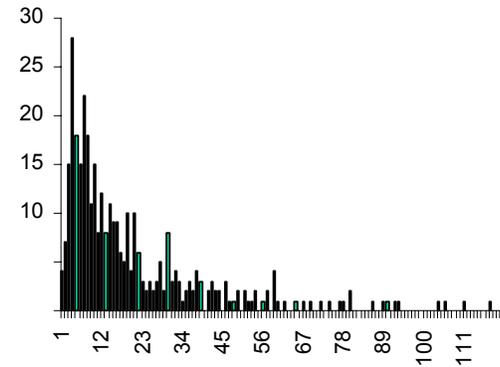


Figure II.4. Relationship between ecosystem response variables and patch size. (a) All responses are expected to become more similar to the core area as patch size increases, although the form of this function may be linear or nonlinear. (b) For example, species richness increases as shrub patches increase in size, then decreases to be similar to the core area. (c) The relationship between ecosystem response (e.g., g/m^2) and patch size will depend on the response of interest. Some variables may increase (linearly or nonlinearly) with patch size whereas others may decrease.



(Left). The distribution of patch sizes is log normal (i.e., power law relationship, from **fig. I.5**). The power law slope represents patch ontogeny, a period after initial establishment when facilitation (e.g., microclimate modification, faunal activities) increases seedling establishment and patch size increases. This is expected to increase episodically (right) when climate allows establishment. At some point, patches merge and intraspecific competition creates conditions similar to the core area for the patch type.

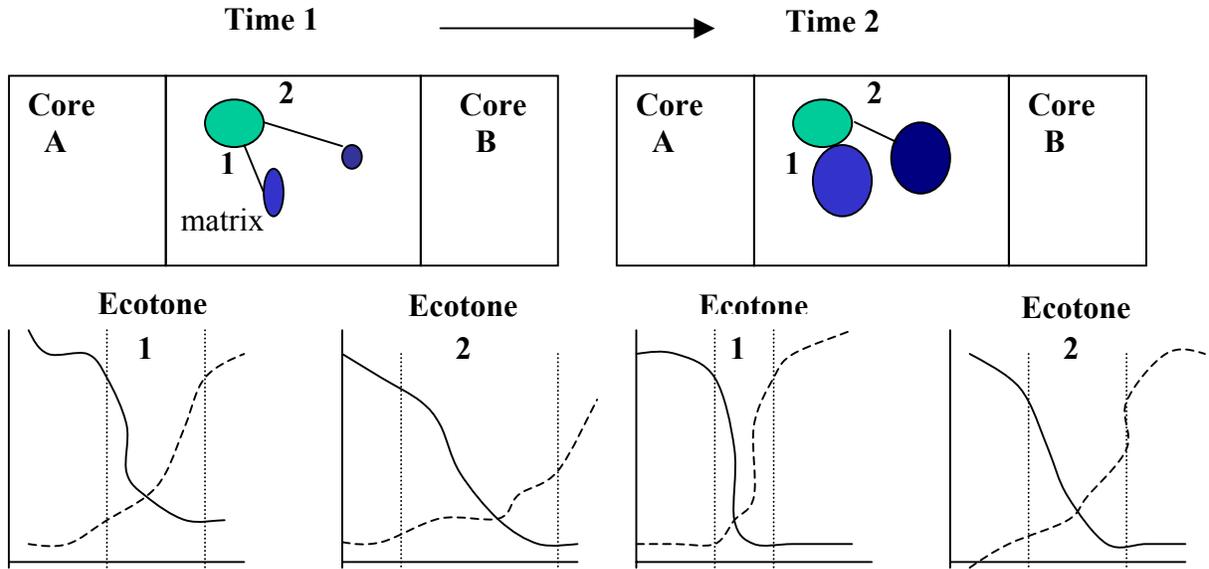
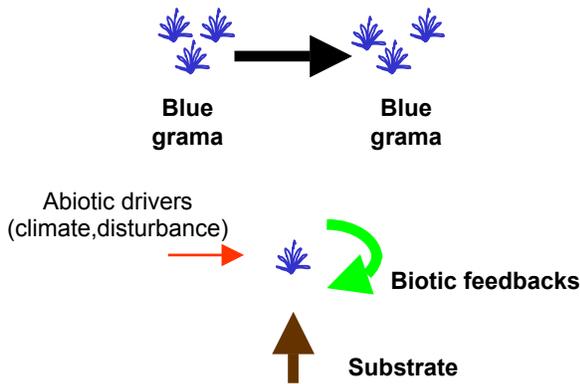
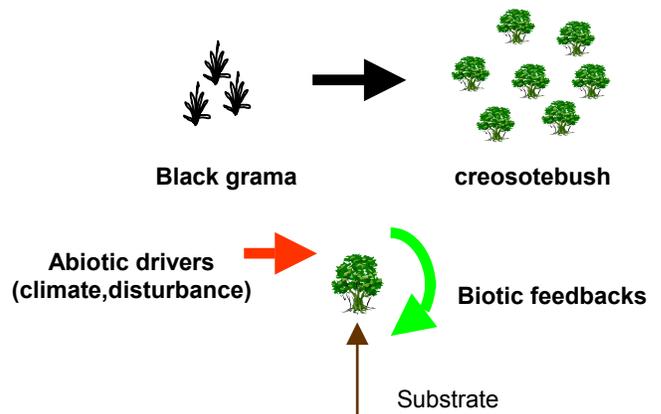


Figure II.5. Potential patterns in response variables (e.g., biomass) for patch dominants across ecotones between patches as a function of distance between patches. Other species (not shown) may have higher biomass in ecotones. At time 1, Ecotone 1 is sharper than Ecotone 2 due to shorter distances between patches. At time 2, both ecotones become sharper as patch sizes increase and distance between patches decrease. Core areas (A, B) are sources of patches. The matrix vegetation consists of a mixture of species from the core areas (i.e., ecotones).

a) Stationary



b) Directional patch type



c) Shifting mosaic

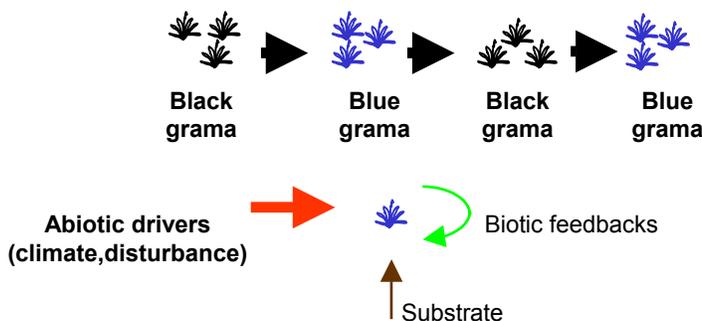


Figure II.6. Three basic dynamic patterns for patches in the BTZ. Stationary patches are strongly controlled by substrate and biotic feedbacks, directional changes in patch type are driven by abiotic variables that are reinforced through time by biotic feedbacks. Shifting mosaic patches are weakly connected to substrate and biotic feedbacks.

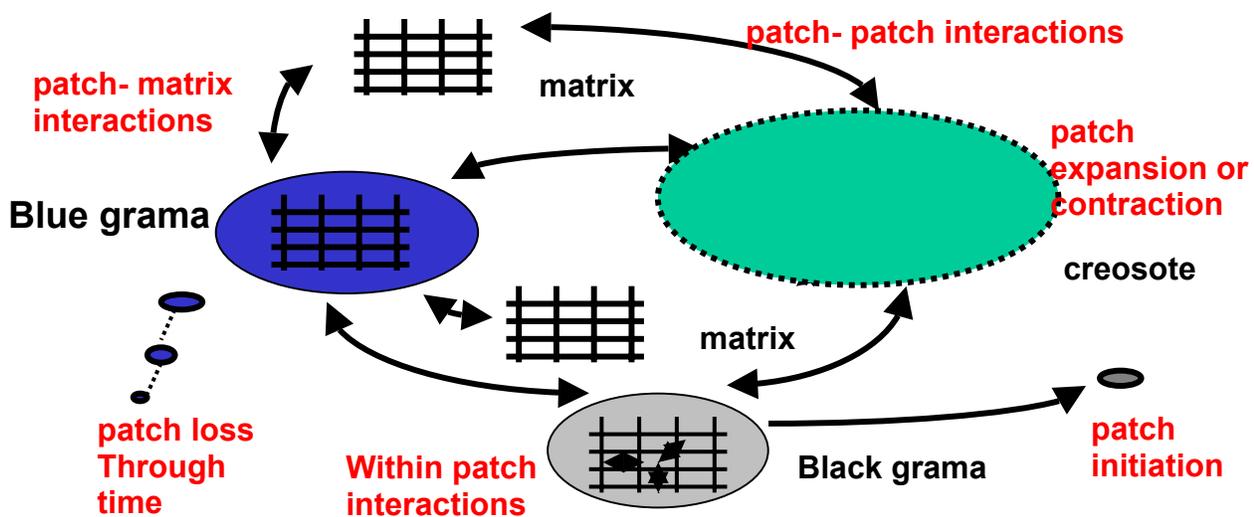
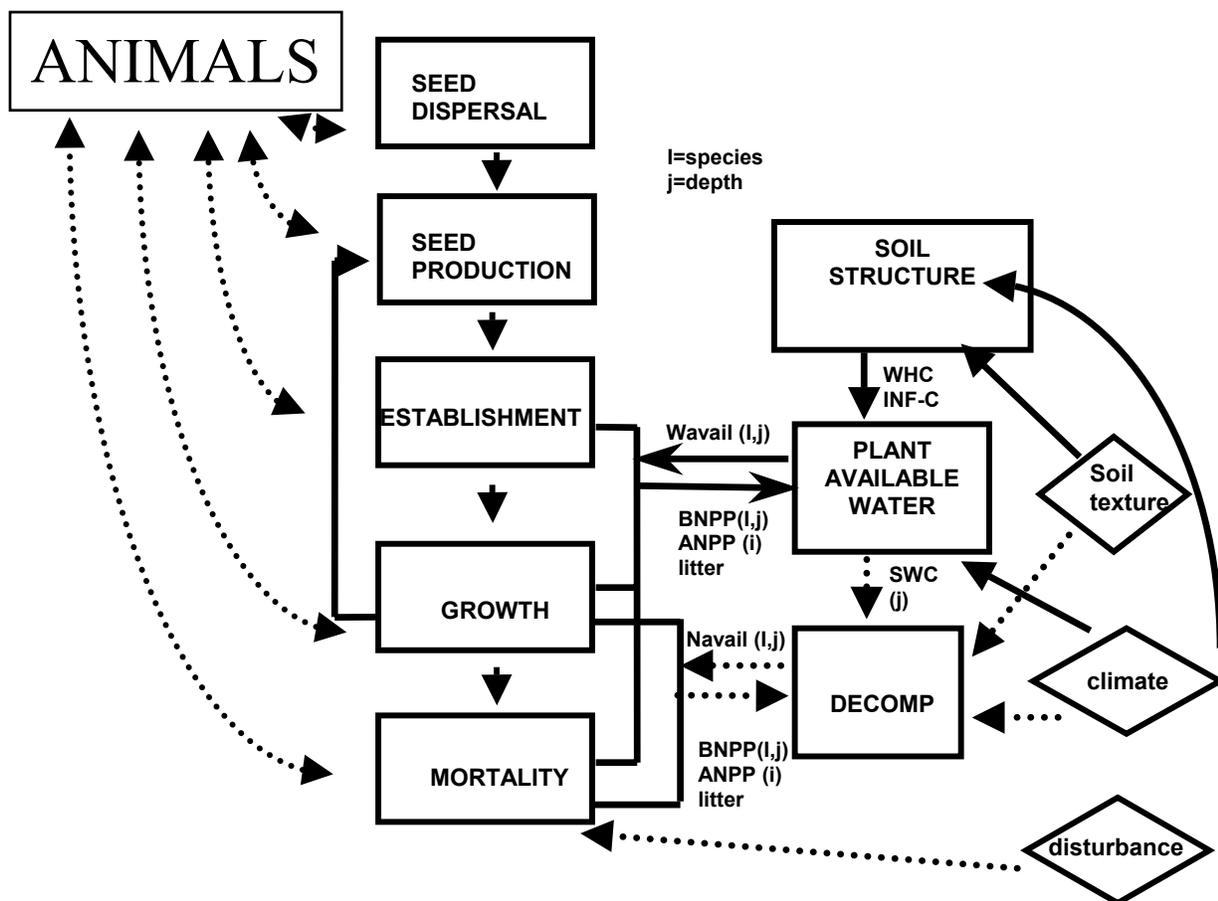


Figure II.7. (above). The ECOTONE model of patch dynamics. The model simulates the recruitment, growth, and mortality of plants through time on small plots (0.5 to 1 m²). (below) Through collaboration with the JRN LTER, we will incorporate redistribution of seeds, soil particles, and nutrients by water, wind, and animals within and among patches. Each patch consists of a grid of interconnected plots. Our new efforts at the SEV LTER will focus on simulating complex landscapes consisting of the initiation of new patches, contraction or expansion of current patches, and loss of patches through time. Dashed lines indicate new processes added to the model.



Section 3. Site Management

The proposal submitted in 2000 developed our current site management. That management strategy was the result of 2 years of deliberation following our site review in 1997. It reflects a reorganization of effort, reduction in scope in terms of areas on the SEV that were involved in previous LTER efforts, but intensification of integrative efforts on the key areas that formed the initial SEV theme – biome transition areas. The renewed focus on the science of these transitions is enhanced by additional expertise from additional PIs at other universities. We have continued to develop interactions and collaborations with agency scientists; U.S. Fish and Wildlife Service, U.S.F.S. Experiment Station (Albuquerque), ARS Jornada Experimental Range, The Heritage Program, U.S.D.A. Laboratory, Beltsville, MD, USGS (Tucson, Moab, Utah), NASA, and Bureau of Reclamation. This broadened set of collaborations requires more organized efforts at communication and clear channels of responsibility. The figure at the end of this section is a schematic of interactions of the principal individuals and groups in the SEV management plan. The letters in the figure are explained here.

A. The number of PIs plus non-LTER scientists at other universities and agencies requires designation of two individuals that provide the contacts for the SEV program. People outside UNM need a primary contact to obtain information, request assistance, logistical details (e.g., field station lodging, vehicles), and field technician help. Gosz and Parmenter serve this role. They also are responsible for passing information to the broader SEV community. There will be information flow among all PIs regarding scientific results, discussions of new research topics, etc. Gosz, Parmenter, and the Administrative Assistant will manage finances, schedule activities, and field station operations relevant to the SEV LTER.

B. An executive committee of five (Gosz, Allen, Peters, Waide, Molles) will have final authority in decisions of allocating resources or setting policies. This committee will organize formal reassessments of the progress made in our various research efforts at least every other year during the LTER funding cycle, with the possibility of reallocation of funding among projects or participants.

C. All staff members have clear responsibilities developed in the research plan. The PI (Gosz) is responsible for scheduling the activities of staff for physical measurements (Moore), remote sensing/GIS (Shore), and analytical laboratory management & analyses (Craig). This chain of command is required to reduce demands on the staff time for work that may not have been scheduled. PIs that need work performed by these staff request this assistance through Gosz and Parmenter.

D. Field staff are under the supervision of Parmenter and Lightfoot for the same reasons as outlined in C. The schedule of field activities, data collection and data management performed by the field crew is developed in Sevilleta-wide meetings. Requests for field crew assistance is through Gosz, Parmenter and Lightfoot and priorities are set in SEV meetings.

E., F. The immediate supervisors for technicians in the analytical laboratory (Craig) and field crew (Wetherill) manage the time and activities of permanent and student technicians.

G., H. Samples and voucher specimens collected in the research program are archived in the Museum of Southwestern Biology. Physical samples (e.g., soil, water, plant tissues) are archived under the direction of the Laboratory Manager (Craig) and invertebrate and vertebrate specimens under the direction of the Field Crew Leader (Wetherill), Lightfoot and Parmenter. All voucher specimens and associated nomenclature are verified under the direction of taxonomic experts in the Museum of SW Biology. Physical samples are archived by established protocols (e.g., Robertson et al. 1999) in a new facility at the Sevilleta field station.

I. Data generated by laboratory analyses, field measurements of both staff and PIs are incorporated in the Sevilleta Information Management System (SIMS). All projects, analyses, and measurements have identified staff or PIs that are responsible for data entry and QA/QC into SIMS. The Sevilleta data manager (Vanderbilt) is responsible for training of staff and PIs in appropriate QA/QC, metadata formats and SIMS management. The PI (Gosz) is responsible for ensuring that there are appropriate resources for SIMS and the communication of needs from Sevilleta PIs and the broader scientific community.

J. The data manager is the supervisor for staff performing systems maintenance on SIMS computers and the network of PCs and workstations used by UNM scientists.

K. The data manager manages the overall design and maintenance of SIMS and requests for information from the broader community. She also maintains the SEV web page and keeps abreast of developments in information management that need to be communicated to the scientific community. The data manager also is responsible for interactions with the data management community in the LTER Network and participation in the LTER Network Information System.

Sevilleta meetings of UNM PIs and staff are held weekly to monthly during the academic year, opportunistically during the field season. Results are communicated to all SEV PIs and associates. These meetings involve discussions of results, planning activities, and decisions on current or new projects. All projects developed by the PIs are subject to review and approval by the U.S. Fish and Wildlife Service that provides another level of security against inappropriate use or damage to previous studies.

The annual Sevilleta symposium (typically held in January) is a way for all investigators to get together. There will be a 1 to 1 1/2 day PI meeting during that time that allows field trips to view research efforts, discussion of new projects, ways to integrate among projects, and discussion of budgetary issues.

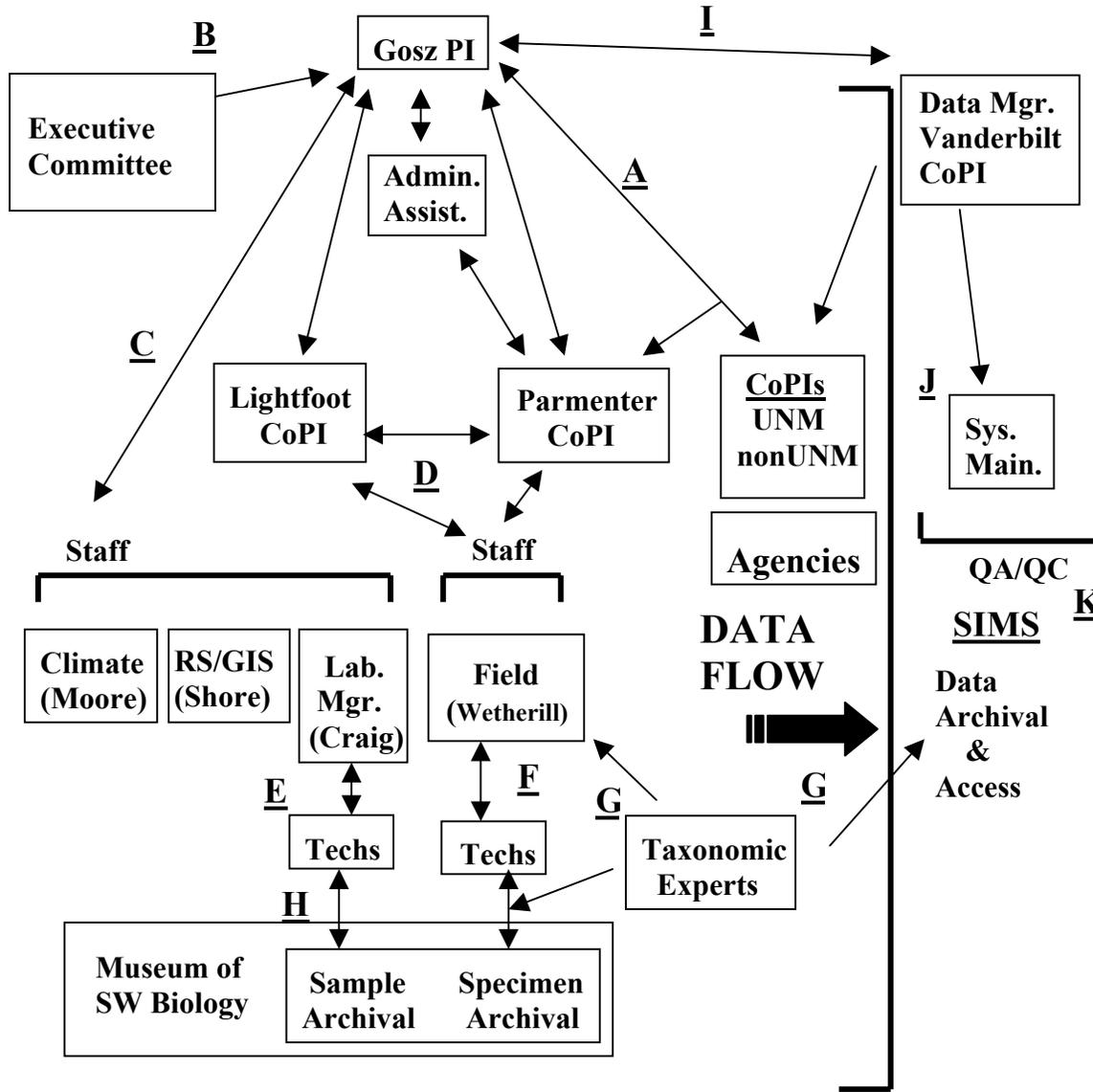
The Sevilleta LTER program has been very successful in attracting non-LTER scientists to use the site as a research platform. As a federally recognized Minority Institution, UNM has excellent opportunities and has had great success in involving minority students in its research efforts. We have had REU site programs for many years and currently have a UMEB program that will involve minority students in many research efforts on the SEV.

The LTER Network Office maintains statistics on all sites (www.lternet.edu/sites/site_char.html). While the average number of non-PI scientists for the entire network is ~30 per site, Sevilleta can document 150 through the FWS special use permit system. These permits allow individuals to work on the refuge and they utilize the Sevilleta Field Station as their base of operations.

There are numerous other scientific and non-scientific conferences that make use of the field station. One hundred and eleven workshops/conferences have been held at the field station since 1996, 35 in 2000 alone. These provide important advertisement for the LTER program, Sevilleta LTER and the University of New Mexico Field Station. Many individuals involved in scientific workshops return to do research. This is a very diverse group and results in a natural process that enhances the diversity of scientists at the site. We anticipate additional use of the field station and SEV for independent and collaborative research during the next grant phase.

We are planning for the long-term management of the LTER program. The UNM administration has provided resources to hire a senior ecologist who will initially work with Gosz on the current proposal, take over as lead PI after a year, and assume the lead PI role for future Sevilleta LTER proposals. Gosz will remain a co-PI.

Communication Flow Chart and Responsibilities.



Section 4: Information Management at the Sevilleta LTER

The objectives of the Sevilleta LTER Information Management system are to:

- support Sevilleta researchers during metadata preparation and data acquisition, data entry, QA/QC and archiving to ensure that data and metadata are of high quality;
- maintain an archive of web-accessible data for public use; and
- encourage data synthesis and data sharing by contributing to LTER network-wide databases and by cooperating with other LTER data managers to standardize data and metadata structures.

A. The Sevilleta Information Management Program

The Sevilleta LTER project researchers have been dedicated to building a quality information management program from the very first Sevilleta proposal. This commitment made the Sevilleta an early leader in the area of ecological research information management. Protocols and procedures in use at the Sevilleta have been incorporated into the information management systems of other research projects including several LTER sites. For example, the Intersite Archive File (IAF; Conley and Brunt 1991) format was adapted for use at Niwot Ridge LTER, Department of Energy research parks, Jones Ecological Research Center, and in the Chinese Ecological Research Network (CERN) (Ingersoll et al. 1997). The Sevilleta information management process has been taught in training courses nationally and internationally. The core Sevilleta Information Management System (SIMS) is documented in the published literature (Brunt 1994), and can be studied in greater detail at <http://sevilleta.unm.edu/data/management/>.

Significant Sevilleta staff resources are devoted to information management. Personnel with expertise in web technology, programming, system administration, databases, remote sensing and GIS provide technical support to investigators throughout the research process. The 2000 hire of a permanent field crew that collects, enters, and QA/QC's data from several long-term research project assures that data collection is consistent. This crew's extensive experience ensures accurate plant and animal identification in the field and efficient and meticulous data curation.

Researchers must contact the Sevilleta data manager before initiating a project, and are educated about SIMS procedures and the LTER data accessibility policy. The data manager advises investigators about project documentation, data analysis, selection of data collection media (paper, cassette tape, digital recorder, palmtop computer), and design of field data collection sheets or computer entry programs that reflect the experimental design of the project. The data manager also oversees the entire time-intensive data management process for Sevilleta long-term data sets, such as the Rodent Population study (Fig. 4.1).

In compliance with LTER network policy, Sevilleta data are made publicly available two years after project completion. Data collected by permanent technicians on long-term projects are now web-accessible within a year after collection. The Sevilleta LTER data archive contains 76 data sets that are available online (Supplementary Materials II Table 1). Students, educators, and scientists in the public and private sector frequently use Sevilleta data sets (Fig. 4.2), and data requests have been received from as far away as Costa Rica and the UK.

An incentive employed by the data manager to motivate timely data submission is the establishment of "Project Pages" on the Sevilleta website that showcase individual research projects. Project pages contain links to a complete description of the project, pictures and maps of the project location, methods, data, publications related to the project, project contacts, and

related studies (e.g. <http://sevilleta.unm.edu/research/local/plant/kratdominance/>). Scientists feel that this centralized and web-accessible project documentation is an asset and submit metadata to enhance their project pages.

Sevilleta information management staff is dedicated to promoting data access, data sharing, and cross-site research by participating in Network-level databases and outreach opportunities. The Sevilleta contributes to the LTER Network Office's cross-site bibliography, cross-site personnel database, and climDB, a cross-site database of LTER climate data. Since the field of data management is constantly changing and growing, maintaining relationships and dialogs with other data managers is crucial. The data manager participates in outreach activities including organizing data management workshops for International LTER audiences in the East Asia-Pacific (http://intranet.lternet.edu/archives/documents/Newsletters/NetworkNews/fall01/fall01_pg11.html) and Central and Eastern European regions. The latter workshop was co-sponsored by GTOS (Global Terrestrial Observing System), a UN program. Future outreach will include cooperating with other LTER data managers and LTER Network Office staff to organize and teach workshops for data managers from the Organization of Biological Field Stations (OBFS).

B. Anticipated Changes to the Sevilleta Information Management System

Online Submission of Metadata: The ideal time for researchers to submit metadata is before they begin collecting data. We will therefore establish an electronic mechanism for gathering metadata prior to initiation of a research project. Before a researcher receives permission to begin their study on the Sevilleta, they will be required to enter metadata into an online form. This basic metadata will be used to generate a web page describing the project for the Sevilleta website. Not only will this change assist in capturing metadata, but it will also be a valuable means of tracking the location and nature of projects underway at the Sevilleta.

Tracking System for Data Set Use: Accessibility to Sevilleta data sets is currently unrestricted from the Sevilleta website. A message on the web page asks potential data users to email the data manager with details about how the data will be used and who will be using it. Based on web log files of the number of hits on our data pages, however, this procedure is probably only capturing information about a fraction of the people actually perusing Sevilleta data. We will improve our accounting of data set usage by implementing a web form that will require that those downloading data identify themselves and the uses that they will make of the Sevilleta data. Access to the data will be denied until this form is submitted.

Improved Data Delivery System Through Structuring Metadata: Sevilleta data are extensively documented and each data file contains not only the data but also all the necessary metadata content for reuse of the data and re-sampling of the sites. These metadata are loosely structured following Conley and Brunt (1991). To be useful today, these metadata must be structured so that they can be parsed into machine readable and transferable formats. Community efforts in this area have resulted in the development of Ecological Metadata Language (EML) that uses eXtensible Markup Language (XML) to describe ecological metadata after Michener et al. (1997). EML provides the necessary representation and semantics for producing machine-readable data sets. The Sevilleta LTER program will collaborate in this effort to produce structured metadata that will make our data conform to community standards

and easier to integrate with other ecological data sets. EML documents from all LTER sites will be stored in a Metacat, a database system developed by the National Center for Ecological Analysis and Synthesis (NCEAS), that will be queriable online.

Platform Independent Data Entry Programs: Data entry programs at the Sevilleta exist in a variety of formats: SAS/AF applications that run on UNIX, QuikBasic programs that run on DOS, and MS Excel templates and MS Access forms that use Windows. The diversity of programs is challenging for the field crew to learn. We will lessen field crew data entry training time and streamline data entry by developing web-based data entry forms. Quality control checks can be readily built into this system, representing an improvement over some of our older programs. This data entry system will be implemented using SQL Server and Perl 5 scripting language.

Data Collection Innovations: Voice recognition software and palmtop computers are being explored as possible means of increasing efficiency of data collection and reducing data entry errors. Microcassette tape recorders are presently used for data collection for several research projects. Technicians then enter the data into computers using dictaphones. Voice recognition software exists that can be used to translate digitally recorded field data directly into an Excel spreadsheet. The accuracy of this method will be tested at the Sevilleta. Palmtop computers will also be adopted as a data collection device. MS Access data entry forms running on the palmtops will provide drop-down lists of species and range limit checks to improve data quality at the point of collection.

An Improved Metadata Catalog - The Sevilleta LTER maintains a very rich data catalog that contains information (metadata) about each data set. The catalog documents information about originators, sampling frequencies, and data set status in a highly structured text file. This file is parsed by a number of SQL-like operators. This method is functional for managing Sevilleta data sets but was developed long before the onset of the World Wide Web and the plethora of cross-platform tools and interfaces that have now come to be standard implementations. We will convert our structured text catalog file to a fully relational database in SQL Server that can take advantage of these web-based tools to present and modify the information about Sevilleta data sets. These improvements will make it easier to interface with network and community wide data and information discovery systems such as the LTER Data Table of Contents (DTC) and Global Change Master Directory (GCMD).

A System of Sample Archiving - The long-term storage and management of physical samples is an issue that has not been addressed in most ecological research projects. The Sevilleta has water, soil, vegetation and animal tissue samples that must be managed for long-term reuse. While some examples of sample archives exist, such as the soil archive at Roth Amsted, U.K. and the hydrologic sample storage system at Hubbard Brook LTER, no standard system for developing an archive for physical samples is in place for the ecological community. Sevilleta will research the use of physical sample archival storage and laboratory information management systems (LIMS) to either adopt or adapt a suitable system. The results of this research will be made available to the LTER and broader ecological communities through the published literature and our web pages.

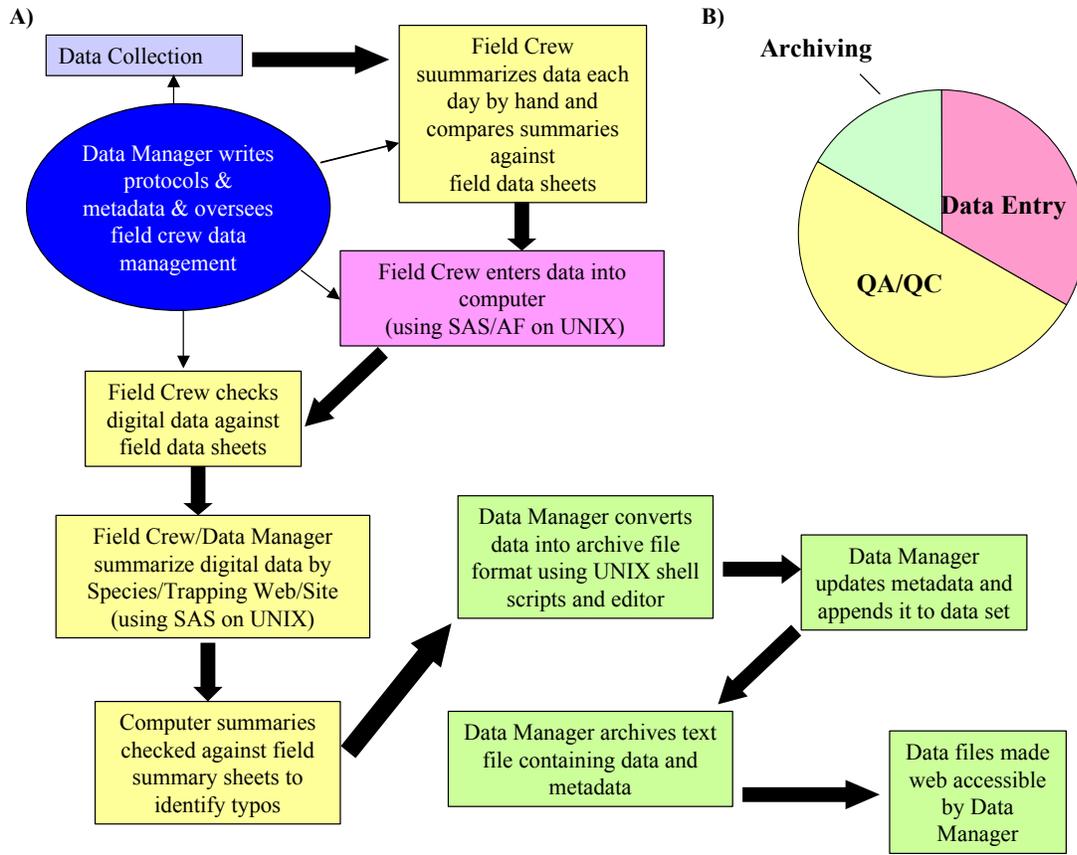


Figure 4.1. A) Data flow diagram for the Sevilleta Rodent Populations study. Box colors represent different data management activities: data entry (pink), QA/QC (yellow), and archiving (green); B) Relative amount of data management effort spent on data entry, QA/QC, and archiving for the Rodent Populations study.

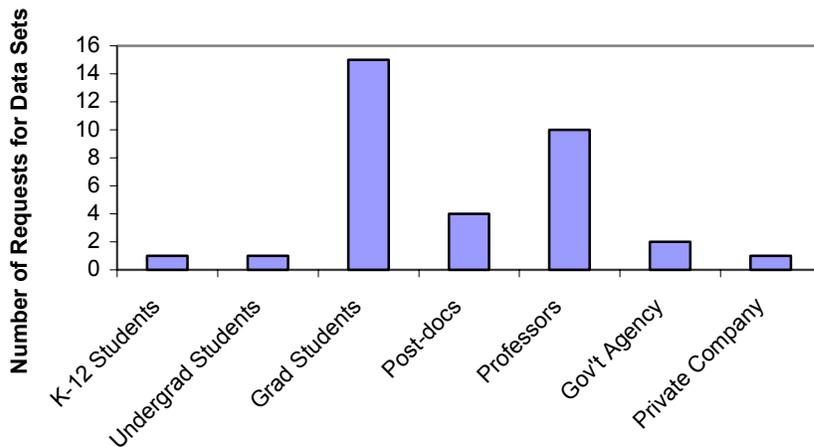


Figure 4.2. Number of requests to use Sevilleta data sets by educational level or organization (May 2000 – January 2002).

Section 5. Outreach

Educational Television Broadcasts: The Sevilleta LTER Program has been featured on public television several times in the past six years, and has recently participated in four productions for PBS/Educational TV in USA, and with a major production with the BBC in the UK. The four PBS productions deal with: 1) teaching the use of mathematics in solving problems using ecological experiments (the NSF-funded series, *Math in the Middle of Nature*); 2) a program on biodiversity and the future of Man on the planet (another NSF-funded production, entitled *Can We Survive?*, based on Sevilleta LTER data integrated with a National Academy of Sciences symposium on global biodiversity); 3) a series produced by UNM and the New Mexico Museum of Natural History entitled, *Ecosystems of New Mexico*, that was broadcast to public school science classes throughout the state, and 4) a PBS 3-part series entitled *Treasuring Our Natural Heritage*, an NSF-sponsored documentary produced at Idaho State University that explores the importance of biological diversity in today's world; this latter program will air on PBS stations sometime in mid-2002. The BBC Production was for the UK's Open University (the UK's distance-learning public university with 170,000 students/yr), and developed a web-based basic environmental science course using ecological comparisons between a watershed in Great Britain and a watershed on the Sevilleta NWR. This class is scheduled for fall semester, 2002, and is expected to attract several thousand students each year. Finally, we are developing a new 15-minute video of the Sevilleta LTER Program for public distribution and educational use.

Newspaper Articles: Numerous newspaper articles have quoted results produced by Sevilleta LTER researchers, including major stories in USA Today, U.S. News and World Report, The Scientist, Associated Press, and the local New Mexico papers (Albuquerque Journal, Albuquerque Tribune, the Socorro El Defensor-Chieftain, and the Farmington Sun-Times).

Television News Broadcasts: In recent years, the Sevilleta LTER was featured on the CBS, NBC, ABC, and CNN News in regard to possible Hantavirus problems associated with the 1998 (and future) El Niño events. As a number of our predictions have come true, Sevilleta researchers Terry Yates and Robert Parmenter have been on national (CBS, ABC, NBC, CNN) and local news presentations discussing the relationships between climate, ecosystem productivity, animal populations and diseases. Parmenter also appeared on the CBS local news, explaining climate dynamics (droughts) and impacts on water availability and ecosystem responses in New Mexico based on the LTER studies. With respect to transferring LTER concepts and Sevilleta LTER results (as examples) in the international community, James Gosz has appeared on television broadcasts in a number of countries. This list includes Ireland, Spain, Taiwan (China-Taipei), Mongolia, Israel, Canada, Hungary and South Africa.

Public access to GPS CBS: Greg Shore (Sevilleta LTER GIS Specialist) designed and implemented a system for WWW and anonymous FTP public access to the Sevilleta LTER GPS Community Base Station (CBS) system. This provides C/A code and L1 phase code GPS base data access for all Internet-connected GPS users within a 300 km radius of the Sevilleta NWR.

UMEB/REU Program: The Undergraduate Mentorships in Environmental Biology (UMEB) Program (P.I. Robert Parmenter, plus many faculty mentors), a collaborative program with the Sevilleta LTER, was renewed in 2001 through 2005. In addition, in the summers of 1999-2001, we conducted our REU Site Program (P.I.'s Robert Parmenter and James Gosz) at the Sevilleta; the major emphasis of this program was to related biodiversity to ecosystem NPP in various ecosystem types across the Sevilleta NWR. The goals of both of these programs are to: 1) instruct undergraduates in the principles of scientific research; 2) expose the students to a wide variety of ecological research techniques and career opportunities; 3) facilitate individual student

research projects, and 4) encourage students to continue their scientific education in upper-division courses and graduate school. The programs include: 1) orientation meetings and a seminar series devoted to the variety of scientific opportunities in ecological research at the Sevilleta; 2) faculty-student one-on-one instruction of hypothesis development and research protocols in ongoing Sevilleta LTER projects; 3) field and laboratory experiences in sampling and data collection; 4) implementation of individual student research projects, carried out under the guidance of student-selected faculty members; and 5) preparation and submission of project manuscripts to scientific journals. These activities integrate all theoretical and technical aspects of the LTER and promote a holistic approach to large-scale ecological studies. Information on our undergraduate programs can be found on the Sevilleta web homepage.

Sevilleta Schoolyard LTER Activities: The Sevilleta's Schoolyard LTER Program is directed by Dr. Clifford S. Crawford, who has established our educational outreach program known locally as the *Bosque Ecosystem Monitoring Program* (BEMP). The major focus of this educational program is on the Rio Grande riparian cottonwood-forest ("bosque") corridor through central New Mexico (including the Sevilleta National Wildlife Refuge). The Sevilleta LTER Program has conducted a number of research studies in the Rio Grande bosque at Sevilleta NWR and other local sites, and due to its popularity with, and importance to, New Mexican populations (particularly schoolteachers and K-12 students), we have chosen this particular ecosystem in which to develop the Schoolyard LTER. The BEMP has four main educational goals. These are to: 1) involve students and citizen volunteers of all ages in the coordinated monitoring of key processes and populations of the endangered Middle Rio Grande riparian forest ecosystem; 2) enable these participants to "learn by doing" about the natural history and ecology of the bosque near their communities; 3) use these students and volunteers to convey to their communities an appreciation of the scientific and social significance of long-term environmental research; and 4) give the students and informed citizens an opportunity to become involved in the management of a critical environmental resource.

The BEMP uses mainly secondary school teachers and their students to collect data relevant to the long-term management of bosque functioning. Data collection occurs synchronously and according to a predetermined schedule. The sites are identical in layout and located between northern Albuquerque and the smaller city of Belen, NM, near the Sevilleta NWR. Site specific, abiotic data collected include soil and air temperature, precipitation and groundwater depth. Biotic data include litter production, plant diversity and indicator arthropod activity. Years of restoration related research on the bosque by UNM biologists have demonstrated the value of such data types and the relative ease of collecting them in the field.

The BEMP program and data sets webpage: <http://www.bosqueschool.org/BEMP/bemp.htm>

Future plans for outreach development. A new facility at the Sevilleta National Wildlife Refuge was dedicated in October 2001 that includes a research-training laboratory/classroom and a new conference center. The building, co-funded by NSF's Field Stations and Marine Laboratories Program (Parmenter & Gosz, PIs), The Nature Conservancy, and the U.S. Fish and Wildlife Service, contains a 1200 sq. ft. fully-equipped laboratory for use by public school children. The laboratory has 12 teaching stations (for 24 students), complete with computers (on the Internet via the station's T1 line), dissecting scopes, compound microscopes, and wide variety of instrumentation for analyzing plant, animal, soil, and water samples collected in the Middle Rio Grande Valley. The building also has a large conference room and institutional kitchen, as well as offices for FWS and UNM personnel. We intend to continue our past outreach programs utilizing this new, modern facility in conjunction with our LTER Program.

Data on Sevilleta usage by non-LTER researchers and educational groups.

Table 5.1. Summary of Sevilleta research projects and researchers (1996-2000). Note: Data from US Fish and Wildlife Service reports (not yet available for 2001).

Item	1996	1997	1998	1999	2000
Number of Projects	38	40	52	41	48
Number of Researchers	148	133	203	214	228

Table 5.2. List of education activities at the Sevilleta.

Institution	Activity	Max Number of Persons
University of New Mexico	Research Experiences for Undergraduates	8/year
	Desert Field Biology Class	16/year
	Mammalogy Class	25/alternate years
	Natural History of New Mexico Class	30/year
	Flora of New Mexico Class	30/year
	New Mexico Geology Class	25/year
	Ecosystem Research Techniques	12/year
	Environmental Laws and Conservation	8/year
New Mexico Tech	Surficial Geology Class	25/year
	General Ecology Class	25/year
	Hydrology Class	25/year
	Sedimentology Class	25/year
	Conference of SW University Biology Clubs	60
New Mexico State University	Field Mammalogy Class	15
Harvard University	Landscape Ecology Class	10/year
Johns Hopkins University	Epidemiology Field Class	12/year
Kansas State University	Field Ecology Class	15
Iowa State University	Field Ecology Class	16
St. Louis University	Field Biology Class	15
University of Colorado	Ecosystems of the Western U.S. Class	15
Colorado College	Environmental Management Class	15
University of Texas	Biogeography Class	15
Augustana College, Illinois	Field Geology	18
NM Museum of Natural History	Ecological Research Demonstrations for Museum Staff and Volunteers	25/year
NM Public School System	Natural History and Ecology of New Mexico	75/year
	Tours for High-School Biology Classes	
NM Continuing Education	Ecosystems of New Mexico Class	60/semester