THE JORNADA LTER PROGRAM

LONG-TERM ECOLOGICAL STUDIES IN THE CHIHUAHUAN DESERT

SUBMITTED BY THE JORNADA LTER-III CONSORTIUM

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Project Summary

The Jornada LTER is a program of long-term ecological research to investigate the processes leading to the desertification of semiarid grasslands in southern New Mexico and the changes in ecosystem properties that accompany this desertification. The central hypothesis is that during desertification the distribution of soil resources changes from spatially homogeneous, as seen in semiarid grasslands, to heterogeneous, as seen in shrublands (Schlesinger et al. 1990) and that these changes in soils act as a positive feedback to further the invasion and persistence of shrubs. For the continuation of LTER activities, we propose a variety of studies to address this hypothesis, including investigations of the magnitude and spatial distribution of plant production, animal populations, soil resources and movements of water and soil nutrients in comparative grassland and shrubland communities. We also propose a major, new long-term experiment to investigate the effects of cattle grazing, as a long-term disturbance to semiarid grassland ecosystems. The results of these various field studies will be synthesized and extended to larger regions by developing models that simulate ecosystem function at the patch, patch-mosaic and landscape level. The proposed continuation of the LTER effort includes the archiving and maintenance of long-term data sets that can be used to further LTER network comparisons and contribute to the U.S. Global Change Research Program.

TABLE OF CONTENTS

THE JORNADA LTER PROGRAM

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RESULTS FROM PRIOR NSF SUPPORT.--a brief history of the Jornada LTER-II program (1989-1994), currently supported by:

NSF BSR 88-11160, $ 2,400,000 awarded to New Mexico State University, for the period 1 January 1989 - 15 October 1994, for the project: "Responses of Arid Landscapes and Ecosystems to Resource Redistribution, Jornada LTER-II," from which

$ 1,200,000 was transferred to Duke University for the period 15 October 1991 to 15 October 1994, under NSF grant BSR 92-40261 with the same title.

The Jornada LTER is a program of long-term ecological research to investigate the processes leading to the desertification of semiarid grasslands in the Jornada basin of southern New Mexico and the changes in ecosystem properties that accompany this desertification. Historical records show that during the last 100 years, large areas of black grama (*Bouteloua eriopoda*) grassland have been replaced by communities dominated by shrubs, especially creosotebush (*Larrea tridentata*) and mesquite (*Prosopis glandulosa*)(Buffington and Herbel 1965). Similar changes have been observed in other areas of the southwestern U.S. and in deserts on other continents (Bahre 1991, Milchunas and Lauenroth 1993). The transition in vegetation appears to be driven by both natural and human-induced factors that have resulted in fundamental changes in various ecosystem processes such as net primary production, water flux, and nitrogen cycling. The consequences of such changes are poorly understood, but they are significant to the socioeconomic disruptions that accompany desertification on all continents and to changes in biospheric properties at the global level. Arid-land problems now plague about 20% of the world's population and are a focus of much-needed global change research (OIES 1991). An upcoming international symposium on desertification in developed countries (Tucson, October 1994) heralds growing recognition that changes in arid lands are important to the human dimensions of global change.

Since the formal establishment of the USDA Jornada Experimental Range in 1912, field ecologists have conducted a program of long-term research in the Chihuahuan desert of southern New Mexico. Today, the NSF-supported LTER investigators join the USDA efforts--building on the early USDA datasets and developing new long-term core datasets for the LTER program. Presently, William H. Schlesinger (Duke University) heads the Jornada LTER consortium, which includes James F. Reynolds (Duke),

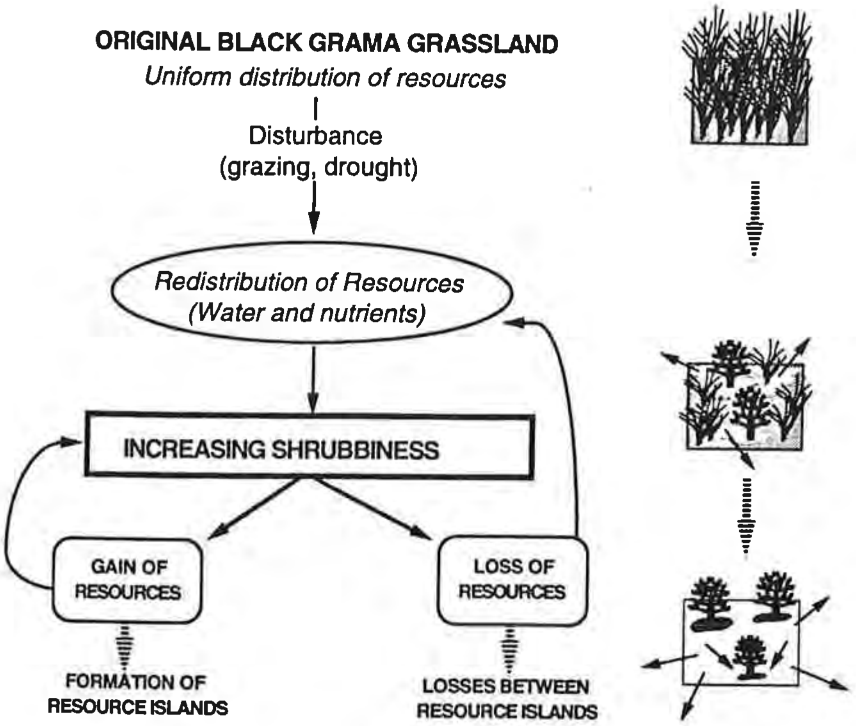

Figure 1. A central hypothesis of the Jornada LTER effort is that changes in vegetation are accompanied by a redistribution of water and soil resources on the landscape, which act as a positive feedback mechanism to promote the desertification process.

Laura Huenneke (New Mexico State University), Kris Havstad (USDA-ARS), and Ross Virginia (Dartmouth College). New colleagues (Drs. Peter Herman, Vincent Gutschick, Curtis Monger, David Lightfoot, Athol Abrahams and Dale Gillette) have been asked to join the continuation of our LTER program. Our current investigations of desertification at the Jornada utilize the USDA data sets dating to the early 1900s, IBP data sets from 1965-1975, the NSF LTER-I data sets established in the early 1980s, and new projects established during the current LTER effort.[1]

The central hypothesis of the LTER-II effort is that during desertification the distribution of soil resources changes from spatially homogeneous, as seen in semiarid grasslands, to heterogeneous, as seen in shrublands (Schlesinger et al. 1990). We suggest that the invasion of desert shrubs in semiarid grasslands is initiated by one or more allogenic factors--overgrazing, climatic change, fire suppression, and/or the rise in atmospheric CO_2 (Humphrey 1958, Neilson 1986, Grover and Musick 1990, Milchunas and Lauenroth 1993, Johnson et al. 1993). However, the proliferation and persistence of shrubs derive from autogenic factors. Shrub dominance leads to a greater spatial heterogeneity of soil properties because the infiltration of rainfall to the soil profile is confined to the area beneath shrub canopies, while barren intershrub spaces generate overland flow, soil erosion by wind and water, and nutrient losses from the landscape (Abrahams and Parsons 1991a). The cycling of plant nutrients and other biotic activity is progressively confined to the zone beneath shrubs, leading to the development of "islands of fertility" that characterize shrub deserts on many continents. These islands of fertility become preferred sites for the regeneration of shrubs, leading to a positive feedback of the "desertified" habitat (Fig. 1).

Research in each of the core areas of the LTER program is designed to test this hypothesis. For example, our investigations show that mean **net primary productivity** does not

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[1] The initial LTER effort (1981-1986), which we call LTER-I, was funded to New Mexico State University with Drs. Whitford, Cunningham, Ludwig, Wierenga, and Conley as co-principal investigators. Their goal was to understand variations in the spatial pattern of vegetation in the Chihuahuan desert, and they established a long-term experiment in which a major resource, soil nitrogen, was augmented across a gradient of vegetation types to examine the convergence of ecosystem function under conditions of resource abundance. Interim funding (1986-1988) allowed a reconfiguration of the Jornada LTER team, which submitted the current (LTER-II) proposal with funding beginning in January 1989. As a result of retirements (Whitford and Conley) and resignations in favor of other employment (Cunningham, Ludwig, Wierenga), none of the original LTER-I investigators remains on the project, although Dr. Whitford, who now works for the EMAP program of the Environmental Protection Agency, collaborates at the site. (See Appendix VI).

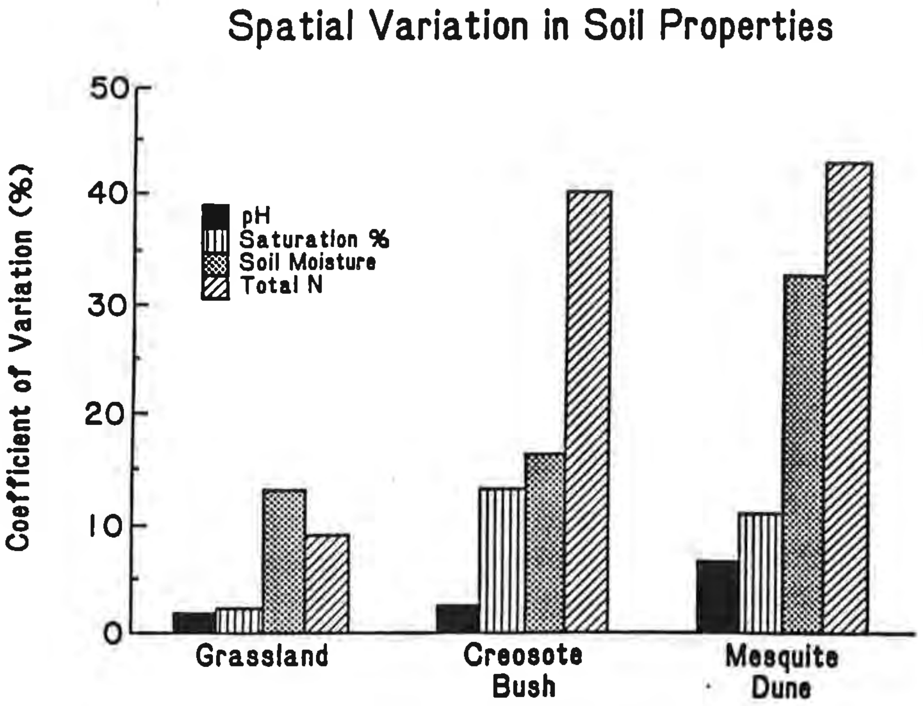

Figure 2. Coefficient of variation associated with mean values for soil properties measured in 200 samples taken in each of three habitats on the Jornada Experimental Range. From Schlesinger et al. (1990).

Table 1. Extractable nitrogen in dry soils and wet soils (24 h after watering), and microbial biomass-N in wet soils, in shrubland and grassland communities in the Chihuahuan desert. A minimum estimate of N-mineralization was calculated as the sum of microbial biomass-N and the change in the pool of extractable N. (NS) = Values are not significantly different from 0 (*t*-test). (*) Values are significantly different from 0, $p < 0.05$ (*t*-test). (1) Undershrub values.

	μg N g^{-1} soil				
Site	Dry soil extractable N	Wet soil extractable N	Difference	Microbial biomass N	Estimated 24-h mineralization rate
Tarbush-west (1)	12.4	13.2	+0.8 (NS)	40.4	41.2
Tarbush-east (1)	9.2	10.7	+1.5 (NS)	18.8	20.3
Mesquite-rabbit (1)	21.4	13.8	−7.6 (NS)	15.7	8.1
Mesquite-well (1)	12.8	14.9	+2.3 (NS)	10.5	12.8
Playa-college	36.1	26.4	−9.7 (*)	50.4	40.7
Playa-tabosa	11.8	7.4	−4.4 (NS)	24.9	20.5
Creosotebush (1)	9.8	5.4	−4.4 (*)	11.4	7.0
Grassland	3.5	2.6	−0.9 (*)	9.9	9.0

From Gallardo and Schlesinger (1992)

differ between ecosystem types (grassland vs. shrubland), but the spatial variation of NPP in shrublands is much higher than in grasslands. Thus, desertification is not accompanied by a loss of productivity but by a change in its display on the landscape. Our efforts in the core area of NPP are easily tied to the current efforts by NASA to use data from the LTER network to understand the relationship between ground-measured vegetation properties (e.g., NPP) and spectral reflectance as seen by satellites. Our seasonal measurements of vegetation biomass and NPP are made in 3 replicate 80 x 80 m plots in each of 5 different communities of the Jornada basin, which can be seen in various remotely-sensed images.

The Jornada has maintained a strong program in **consumer studies**, providing a variety of long-term data sets to the LTER archive. These data suggest that distribution and abundance of some vertebrate consumers (e.g., lizards, birds) are not affected by the development of heterogeneity in plant and soil properties during desertification. In contrast, jackrabbit populations are probably higher in modern habitats dominated by shrubs, which by their deep-rooting provide a year-round source of water in plant tissues. The diversity of invertebrates (e.g., ants) also differs considerably among the habitat types of the Jornada landscape--with diversity of ants highest in shrubland habitats. Our program of long-term measurements includes routine monitoring of key consumer populations in the 5 major habitat types of the Jornada basin.

Early field studies of LTER-II showed that **soil resources** were significantly more heterogeneous in distribution in shrubland than in grassland habitats (Fig. 2). We have now extended our studies of soil properties to the 15 NPP plots and applied standard geostatistical analyses to these data to document the scale of resource heterogeneity and its difference among habitat types. For comparisons to these areas of recent shrub invasion, we have traveled to the Mojave desert of southern California, to collect soil data from areas where creosotebush desert has existed for millennia. Our analysis suggests that physical processes (wind erosion and dust deposition under shrub canopies) contribute strongly to the development of islands of fertility in desertified habitats, and we have proposed a new initiative in studies of eolian transport for LTER-III.

Core area studies in **biogeochemical cycling** have examined changes in a variety of ecosystem properties as a result of shrub invasion. Shrubland habitats generate greater regional overland flow and greater rates of ammonia volatilization from soils. Over time, these processes act to deplete the landscape of soil resources, so that the remaining "islands of fertility" increase in their importance as a locus of biotic activity. Soil microbial biomass is concentrated in shrub islands, and soil nitrogen cycling is significantly higher in areas of low-lying fine-textured soils supporting tarbush and playa vegetation,

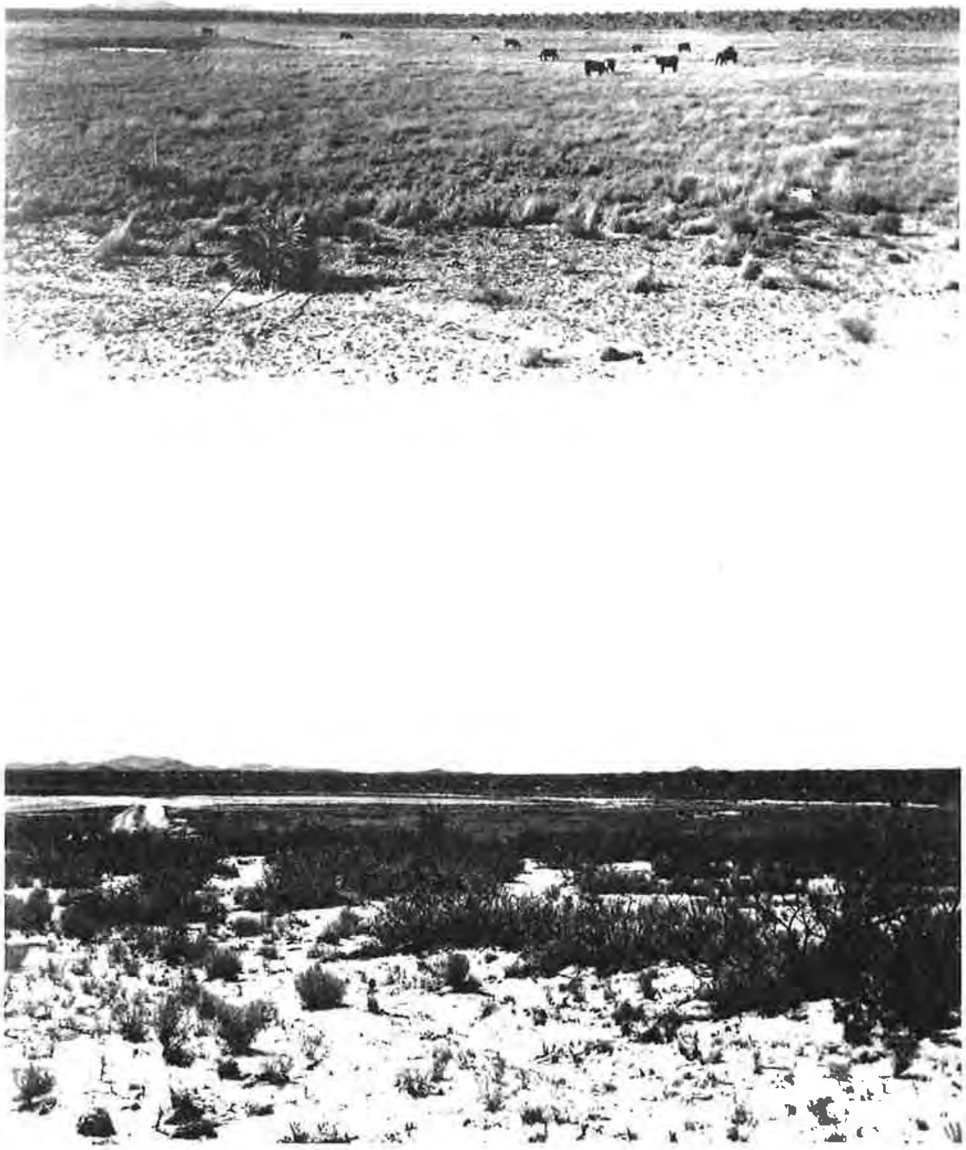

Figure 3. Change in vegetation between 1939 (top) and 1984 (bottom) on the Jornada Experimental Range, looking northeast from approximately one mile west of Red Lake Well. From Sallach (1986).

which receives "run-on" from the desertified shrubland habitats of higher landscape positions (Table 1).

The historical record of vegetation change in the Jornada basin speaks strongly for the importance of past **disturbance**--the fifth core area of LTER research (Fig. 3). Our analysis of past long-term climatic records (Conley et al. 1991) shows no correlation of shrubland invasion with periods of unusual climatic conditions. Rather, grasslands appear to have declined as cattle stocking increased. A long-term experiment established as part of Jornada LTER-I allows us to examine the changes in vegetation that have accompanied the exclusion of cattle from three habitats of the desertified landscape. Plant cover increased from an average of 20% in 1982 to 65% in 1992 following the exclusion of livestock grazing, with the greatest recovery seen in the lower landscape positions dominated by grasslands.

Over the long-term, our contributions to these core areas of LTER research establish data sets that will allow us to monitor changes in ecosystem structure and function in response to global change. Over the short-term, these data have allowed us to test and refine our basic hypothesis about the factors that lead to desertification of semi-arid grasslands. Long-term data sets in each of these core areas are also used to parameterize simulation models of desert ecosystem function at two scales. The PALS (Patch Arid Land Simulator) simulates ecosystem properties that operate in a single patch of desert vegetation, whereas the development of the REGALS (REGional Arid Land Simulator) will allow us to make basin-wide estimates of the change in ecosystem properties (e.g., ammonia volatilization) that have accompanied desertification.

These modeling efforts have already produced some provocative results. PALS shows that there is an increase in NPP and soil nitrogen mineralization with increasing infiltration of soil moisture in creosotebush desert (Reynolds et al., in press). However, there is less variation in the infiltration of soil moisture in years of low rainfall, than in years of higher rainfall. These observations have led to a major effort to use PALS to examine the role of environmental variability on ecosystem processes. Le Houerou et al. (1988) reported that the variability in annual NPP for 77 arid and semiarid sites (various mixtures of grasses, forbs, & shrubs) was 50% greater than the corresponding variability in annual rainfall. The great diversity of sites evaluated by Le Houerou et al. (1988) as well as a lack of data on seasonal dynamics make it difficult to understand what causes the high variability, but their conclusions contradict existing conceptual models of desert ecosystems. For example, Schlesinger et al. (1990) suggest that desert shrub communities should show less variation in NPP than grasslands because the former are deep-rooted. Noy-Meir (1973) states that the reserves of desert plants buffer vagaries in water input, thereby reducing variability in NPP relative to rainfall. With 100-year simulations of PALS, we have found that variation in NPP is largely derived from variability in the seasonal growth of annual--not long-lived--vegetation. As we extend our data sets for NPP over many years, we will be able to test this prediction using field data from individual species.

We maintain many of our long-term data sets in a GIS-based archive of the Jornada landscape, including base layers of geology, topography, soils and vegetation (both past and present). This information can be combined with our process-level studies of NPP, hydrology, and nitrogen cycling to produce derivative maps of basin-wide ecosystem function. Pixel summations of the basin-wide data can be used to validate the output of the regional model (REGALS).

Under our NSF LTER funding since January 1989, we have published >75 scientific papers, trained 17 masters and 4 doctoral students, and directly involved 12 undergraduates in our research efforts through the NSF-REU supplements program (see Appendix IX). Development of the LTER-II proposal resulted in a flagship paper in SCIENCE (Schlesinger et al. 1990), which has received over 36 citations through October 1993. During 1989-1993, LTER investigators and site visitors have attracted $3,150,000 of additional funding from 6 different agencies (BLM, NASA, NOAA, NSF, DOE and USDA) to support ancillary work at the site (Appendix I).

We participate in a variety of the LTER Network activities, including the LIDET experiment (comparative litter decomposition), TRAGNET (the U.S. trace gas network) and the USDA uv-B monitoring network. One of our collaborators, Daryl Moorhead (Texas Tech) is developing models for litter decomposition, which will be used throughout the LTER network, on the basis of the decomposition module of PALS. Another of our coinvestigators (Ross Virginia) is a coinvestigator at the Antarctic Dry Valley site, where he conducts parallel, comparative measurements in that cold desert ecosystem. We have also made comparative studies of soil geostatistics in desert and grassland habitats at the Sevilleta LTER site in north-central New Mexico and the Mojave desert of California. (See also Appendix VIII).

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JORNADA LTER-III
A Proposal for a Continuation of Long-Term Ecological Research in the Chihuahuan Desert.

PROJECT DESCRIPTION
Section 1

Currently arid lands cover about 12% of the Earth's land surface. Semiarid grasslands and woodlands occupy an even larger area, so the total extent of dryland ecosystems is about one-third of the Earth's land surface. Past and future changes in the borders between semiarid grasslands and desert shrublands and the potential expansion of arid lands-- desertification--offer a useful index of environmental change, including both human impacts and regional climatic changes. Recent changes in the extent of arid lands in the Sahel appear related to climatic change in that region (Tucker et al. 1991), and historical losses of semiarid grasslands and expansion of desert shrublands are well known in southern New Mexico and west Texas.

Future global climate change is likely to cause dramatic shifts in the distribution and extent of deserts, but our ability to predict the magnitude of such shifts is limited. Most equilibrium models of future global climate predict a contraction of the area of desert lands (Smith et al. 1992), but a transient increase in the extent of mid-continental drought and desert vegetation may dominate the dynamics of dryland vegetation during the next century (Rind et al. 1990).

As population increases, humans make increasing demands on arid and semiarid habitats. Already, some 20% of the world's population lives in these habitats, and we exploit dryland habitats for agriculture, animal husbandry, mining and other activities (OIES 1991, Walker 1993). In the southwestern United States, the use of public arid lands for grazing has received recent widespread attention, in an attempt to evaluate its environmental impact and economic value. Historical overgrazing by cattle has been linked to the demise of semiarid perennial grasslands over much of west Texas and central New Mexico, but field experiments to develop "strong inference" conclusions about the role of grazing in vegetation change are remarkably rare.

One of the goals of our proposed continuation of LTER effort is to establish a large, long-term field experiment to evaluate the role of intense grazing on ecosystem structure and function. This effort stems from comments made at our mid-LTER-II review (July 1991), as well as from our own interest in the disturbance effects caused by the substitution of large, exotic herbivores for native consumers. Our baseline data for NPP, native consumers, soil and plant processes are now sufficiently developed to allow us to expand into this new arena. Moreover, fundamental scientific knowledge that we may offer to the debate about grazing on western lands will contribute significantly to our understanding of the human dimension of global change in the southwestern U.S.

Thus, for LTER-III we propose a new, major, long-term experiment on grazing as a focus of the next phase of our research in the Jornada basin. At the same time, we will also maintain our ongoing program of field measurements that contribute long-term core data sets to the LTER network. Our proposed work in each of the core areas is outlined in more detail in Section 2 of this proposal (beginning on page 18), in which a variety of smaller new initiatives are also presented. Section 2 also describes the continuation of our efforts to develop simulation models of desert ecosystem function.

Cattle in the Southwest: Acute Herbivory in an Arid Habitat.

Cattle were brought to the Americas by Columbus on his second voyage in 1493, and they increased in number throughout the Spanish occupation of the Southwest. Following the Mexican revolution (1821), cattle numbers declined, but by the 1890's they had increased again; 1.5 million cattle occupied the Arizona Territory in 1891 (Hastings and Turner 1965, Bahre 1991). Currently, 610,000 cattle graze on more than 9000 ranches in New Mexico, generating about $500,000,000 annually for the region's economy. In Arizona and New Mexico, 37% of the forage is derived from federally managed lands (Torell et al. 1992).

Livestock management research in the Southwest dates to the 1880s with the first reports of cattle-induced damage to rangelands (Box and Traylor 1990). Early research focused on establishing guides for proper utilization of forage species (Canfield 1939, Jardine and Forsling 1922), which led to the development and testing of management systems that maximized animal performance (Paulsen and Ares 1962). However, decades of research have not resulted in a mechanistic understanding of ecosystem-level effects of cattle grazing in arid and semiarid environments (Bartolome 1993). As a focal activity for our LTER-III effort, we propose a large, long-term field experiment to improve our fundamental knowledge about the role of managed consumers in ecosystem function.

General theories describe the role of herbivores in shaping grassland and shrubland ecosystems. These include the autogenic hypotheses (Noy Meir 1979/1980), optimization theory (McNaughton 1979), evolutionary gradients of grazing history (Milchunas et al. 1988), keystone guilds (Brown and Heske 1990), and plant chemical mediated defoliation (Bryant et al. 1991). Many of these theories are hotly debated (see the forum on optimization theory in the February 1993 issue of *Ecological Applications*), and none easily accommodates the inclusion of a large exotic herbivore in an arid ecosystem.

West of the Rocky Mountains, desert grasslands have historically supported low, chronic levels of herbivory by native animals; bison were never part of the native fauna of this region (Mack and Thompson 1982). Herbivores typically harvested <10% of NPP (Pieper et al. 1983). As with most managed grazing systems (Oesterheld et al. 1992), the introduction of cattle was initially characterized by high levels of herbivory, which were quickly recognized as destructive (Wooten 1908) and beyond the carrying capacity of the landscape (Paulsen and Ares 1962). Annual forage consumption during the overstocked periods may have ranged from 30 to 60 g/m^2. Herbivory by livestock became more acute as grazing intensity, timing, and frequency were controlled. Livestock grazing management has resulted in shorter seasons of use and more infrequent use through the incorporation of systems such as best-pasture and deferred rotation (Holechek et al. 1989). Strict control of grazing to specific, widely-spaced acute events has been recommended as a potential tool for holistic resource management (Savory 1988). In some areas these acute levels of herbivory have persisted for decades.

Acute defoliation occurs both temporally and spatially. Mature cattle will consume 5 to 15 kg of forage daily. A classic recommended stocking rate for desert grassland is 1 cow/250 ha/25mm of annual precipitation. This results in a harvest of 7 to 21 $g/m^2/yr$ of net primary production in an area receiving 240 mm of annual precipitation. Long-term average NPP of semiarid grassland is 58 $g/m^2/yr$ under a conservative stocking density (Paulsen and Ares 1962). Thus, during some seasons even a conservative stocking can result in acute harvest rates. It is also likely that the distribution of use is uneven, due to physical, biological and structural features of the environment (Holechek et al. 1989).

Competition for forage among cattle and native mammalian herbivores is relatively slight in desert environments. Native ungulate (i.e., antelope) densities are low, and herbage consumption by small mammals has been estimated at < 5 $g/m^2/yr$. Dietary overlap is most pronounced between cattle and black-tailed jackrabbits (Wansi et al. 1992). Though jackrabbits can influence numerous processes, their effects on grass cover are relatively minor (Gibbens et al. 1993) and their population densities are highly variable and independent of cattle (Whitford 1976, Johnson and Anderson 1984).

Thus, on today's western desert rangelands, the primary consumer is a large, exotic ungulate whose population density is directly regulated by humans. The fundamental question is not grazing as an optimization process within the ecosystem, but the sustainability of grazing by livestock (Westoby et al. 1989). Over-grazing is widely implicated in the well-known changes in vegetation in the Southwest, but we lack an experimental basis to describe the effects of disturbance on plant responses and landscape dynamics. An assessment of the sustainability of desert ecosystems in response to acute herbivory requires an understanding of long-term multi-scale effects under conditions of vegetative change (Westoby et al. 1989, Baker et al. 1993, Dodd 1993).

To guide our LTER-III experiment, we **hypothesize** that periodic acute high levels of herbivory by cattle will lead to a change in plant community dynamics. The response will be characterized by an increasing proportion of woody perennials in plant community composition. Surviving seedlings will develop in clusters characteristic of a two-phase landscape pattern of woody species in a matrix of grassland (Archer et al. 1988). We assume that this two-phase pattern represents an intermediate stage in the conversion of grassland to a dense canopy of woody species, and that this conversion will eventually result in increasing spatial and temporal

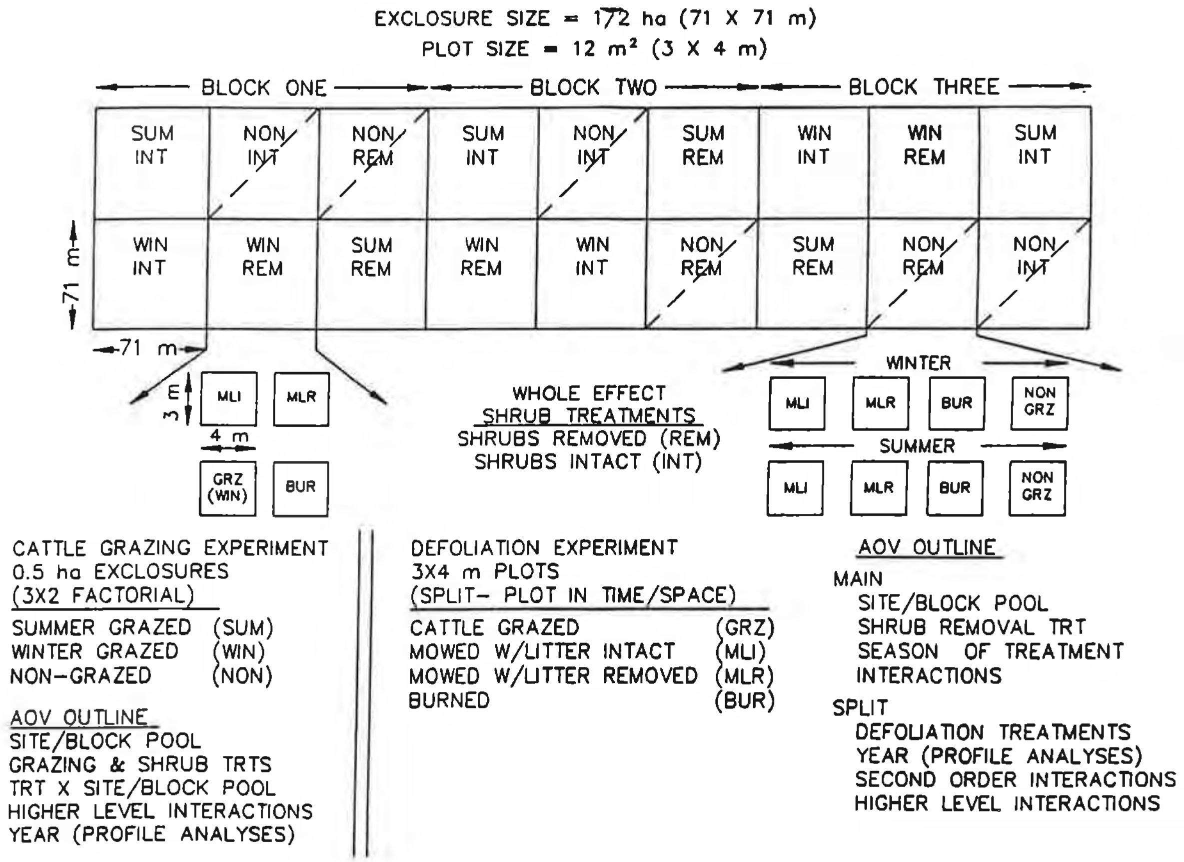


Figure 4. Proposed design for the cattle grazing and defoliation experiment. The cattle grazing is imposed on a plot scale in three blocks, while defoliation is imposed on nested subplots. Non-grazed exclosures will contain two sets of defoliation plots to accomodate defoliation treatments in different seasons.

heterogeneity in the distribution of water, nitrogen and other soil resources (Schlesinger et al. 1990). We also hypothesize that the changes in community structure will increase with the presence of woody species in grasslands, but they will be unrelated to the timing of defoliation.

To test these hypotheses, two large field plots will be established within a black grama grassland-mesquite woodland transitional area of the Jornada Experimental Range. The selected area is characteristic of a two-phase population ecotone of perennial grasses and mesquite in the Chihuahuan desert. Each plot will contain 18 0.5-ha exclosures (Fig. 4). Mesquite will be removed from a subset of these plots, by hand-harvest of the aboveground biomass and application of herbicide on surface cuts to minimize resprouting. New shoots will be removed annually to maintain treatment integrity.

Seasonally, cattle will be released into a subset of these exclosures in sufficient numbers to selectively defoliate 65-80% of the black grama NPP within a 12-hr period. Animal densities will be adjusted seasonally based on pre-grazing estimates of usable biomass.

In a split-plot design, 3 x 4 m subplots in each exclosure will receive other defoliation treatments. Some plots will be mowed to remove 60 to 80% of current season primary production. Other plots, surrounded by metal-sided frames, will be burned so that all aboveground biomass is removed. Defoliation treatments will occur after cattle graze within the entire exclosure. Non-grazed exclosures will contain two sets of defoliation plots for treatments in both winter and summer.

This experiment explicitly addresses one of the core areas of LTER research--disturbance--but in the experimental plots, we intend to measure long-term changes in ecosystem attributes that contribute to each of the other core areas. Vegetation responses (cover & composition) will be measured by vertical line-intercept and belt transects. Seven 70-m line transects will be randomly and permanently located within each exclosure. Vertical line intercepts of vegetation cover will be recorded at 20-cm intervals. One transect will provide a 0.5-m belt for recording the establishment of mesquite and other woody seedlings. These measurements of vegetation will coincide with the autumn estimates of NPP on the current LTER plots. Regressions relating plant size to biomass, developed during our current LTER work, will be applied to measure changes in biomass as an index of NPP in each cell of this new experiment.

Cattle grazing itself appears to increase the spatial heterogeneity of soil properties (Afzal and Adams 1993). Measurements of soil water infiltration and its spatial variation will be made in each of the experimental exclosures (Bach et al. 1986), and changes in the spatial variability of soil nutrients will be measured by repeated sampling of 70-m transects using a nested set of sample intervals (10 m, 1 m and 10 cm). We will focus on changes in the spatial variation of N and P as essential plant nutrients and Li and Br as elements whose cycling is controlled primarily by physical factors. As an index of changes in the activity of the belowground ecosystem, we will

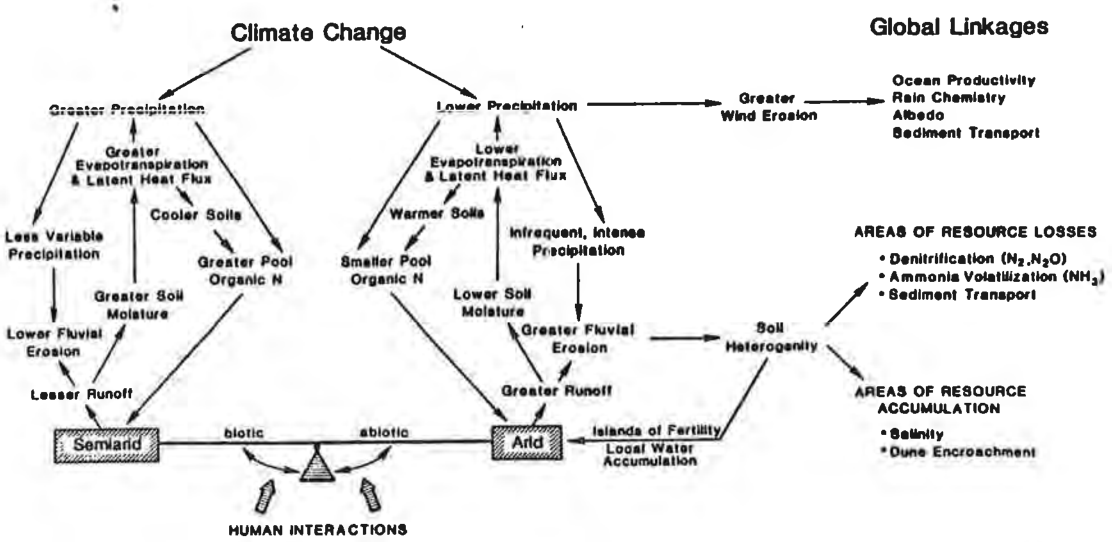


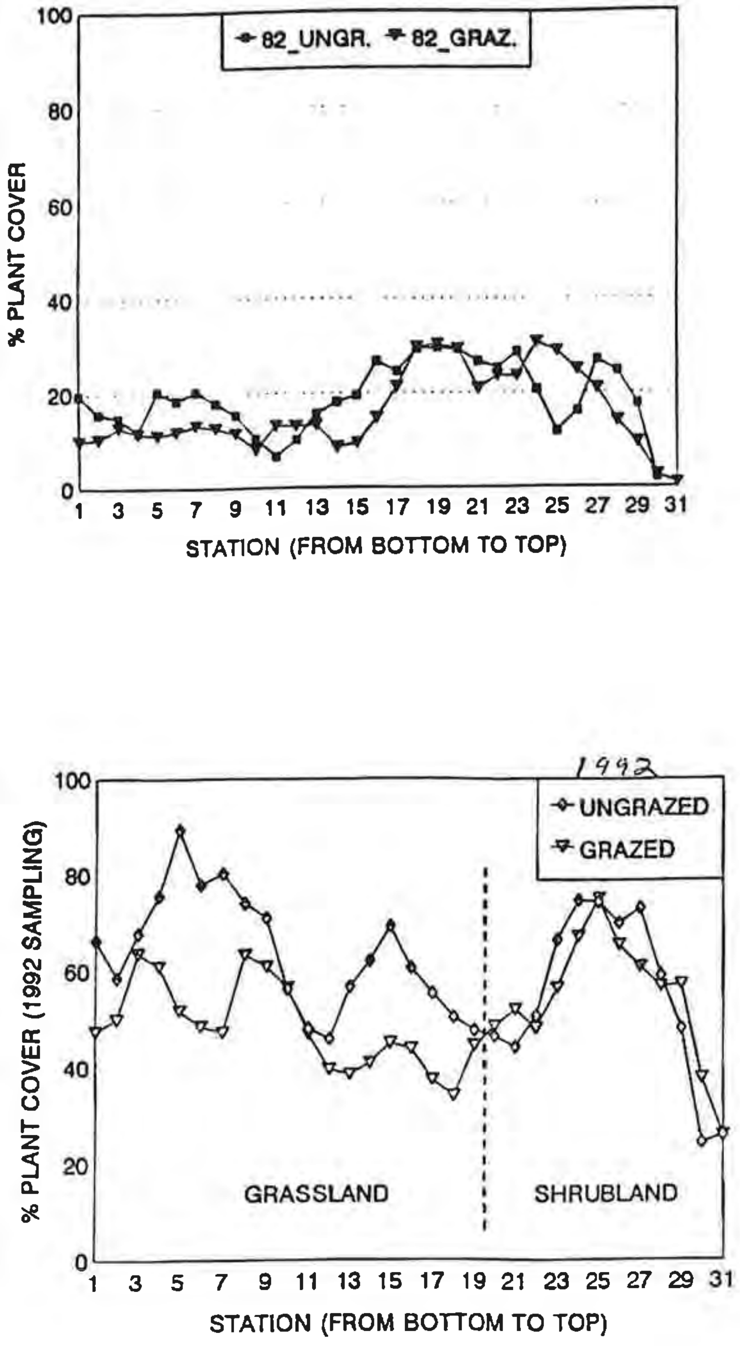
Figure 5. A model linking changes in ecosystem properties during desertification to changes in earth system function and biogeochemistry. From Schlesinger et al. (1990).

monitor changes in soil microbial biomass (see p. 27-28), and in the production and consumption of trace gases from soils in each of the treatments. We will focus on the *net* flux of methane as a key, integrative index of soil microbial activity (see p. 29). Finally, we will follow changes in the population density and its spatial distribution of a representative group of native consumers--grasshoppers--in each of the experimental plots. Again, these measurements will be made using the standard techniques that we apply in our ongoing LTER studies, allowing a direct comparison to other areas of the Jornada basin.

We anticipate that mesquite encroachment will proceed at an increasingly rapid rate in positive correlation with the gradient of applied treatment stresses. We expect to observe this encroachment at both a fine, plant-level scale in the defoliation experiment and at a coarser, patch-level scale under grazing treatments. Concurrent with this vegetative conversion will be an increasing heterogeneity in the temporal and spatial distribution of soil water and plant nutrients (Schlesinger et al. 1990). Abiotic feedbacks will eventually predominate over biotic factors (Fig. 5), and this change in feedbacks will represent a threshold in the transition of grasslands to mesquite-dominated shrublands. There are two key implications in these anticipated dynamics. First, we need to identify factors that force transitions from one vegetative state to another (Laycock 1991) and recognize threshold conditions for the effective management of systems that are undergoing change (Westoby et al. 1989). Second, we need to modify the current conceptual model of threshold changes from grassland to mesquite woodland (Archer 1989) to incorporate responses to acute herbivory and the functional importance of abiotic feedbacks driving this transition.

The importance of coupling mechanistic understandings of ecosystem processes with land management is a focus of the Sustainable Biosphere Initiative (SBI) of the Ecological Society of America (Lubchenco et al. 1991) and of the National Academy's recommendations for incorporating human dimensions into global change research programs (Stern et al. 1992). In part, the current controversies regarding livestock grazing in the southwestern U.S. are simply a subset of the broader national debate regarding management of our renewable resources. The condition of the rangelands of the Southwest is widely regarded as poor, yet the management of these resources is seen as controlled by historical users, principally the livestock industry (Wald and Alberseith 1989). It is not surprising that most recent attempts to reform the management of public rangelands (U.S. Department of Interior 1993) greatly dilute the control of the livestock industry over these lands. The proposed reform includes recommendations for increased grazing fees, broader public involvement in management, federal ownership of all future improvements (including water) and new grazing standards. However, we currently lack fundamental ecological knowledge that couples process-level mechanisms to a scale that is usable for the proper resource management of these lands. This LTER experiment will help fill that gap.

This proposed long-term experiment is planned as a joint activity between the LTER and the USDA Agricultural Research Service, which



Each station separated by 50 m along the topographic transect

Figure 6. Plant cover along the LTER-I exclosure shows little difference on each side of the fence when the grazed and ungrazed treatments were established in 1982 (top). Plant cover increased over the entire area during a 10-year period (1992, bottom), but the greatest recovery of vegetation was seen in grassland areas protected from grazing. (Gallardo et al., in prep).

manages the Jornada Experimental Range. Our work is also fully cooperative with the development of indicators of arid-land ecosystem function through the EMAP program of the Environmental Protection Agency. Changes in arid lands that accompany our treatments will be directly incorporated into the EMAP program as part of our ongoing collaborations with Dr. Walter Whitford--the former PI of the Jornada LTER.

PROJECT DESCRIPTION
Section 2

1. Long-term Experiments.

In addition to the new, long-term experiment described above, the Jornada LTER-III effort will continue to monitor vegetation changes in an existing long-term exclosure, established in 1981 as part of LTER-I. We will also establish two new long-term field experiments that focus on changes in the biodiversity of arid lands and on regional comparisons of the importance of native consumers in structuring plant communities in the Chihuahuan desert. These LTER-supported long-term experiments are described in this section; long-term studies supported from other sources, including a major study employing rainout shelters, are described in Section 2, # 7 (page 38).

a. **The Fenceline Exclosure Study.** As part of LTER-I, a large exclosure was established from the base of Mount Summerford to the College playa on the New Mexico State University Ranch. Comparisons of plant community structure and soils on each side of the fencelines allow us to monitor the long-term recovery of ecosystem properties following the cessation of grazing. Comparisons of vegetation along the fenceline, in samplings in 1982, 1986, and 1992, show the clear recovery of plant cover in the absence of grazing (Fig. 6). In 1982, immediately after fencing, there was little difference in the cover on each side of the fence, with cover ranging from 10 to 30% along the entire length of the transect. Following several wet years in the mid-1980s, plant cover increased to 30-80%, but the recovery of vegetation inside the exclosure was especially striking in grassland habitats at lower elevations. Following our established procedures, we will continue to monitor these vegetation dynamics, with proposed samplings in 1996 and 2000.

b. **Functional Role of Biodiversity.** The Earth Summit in Rio de Janeiro recognized the preservation of biodiversity as an international priority, but ecologists know little about the role of biodiversity in ecosystem function. Biodiversity can be viewed either as the particulars of species composition, or as overall richness or diversity as a variable in itself. A recent edited volume (Schulze and Mooney 1993) summarizes the rather weak empirical evidence and presents a number of hypotheses to be tested regarding the role of diversity in ecosystems (Table 2).

A general conclusion is that most ecosystems contain some redundancy in species--i.e., the removal of some species makes little difference to system behavior, perhaps because of the release of other

Table 2 . Hypotheses about the relationship between biodiversity and ecosystem function. (From Schulze and Mooney 1993)

Functional relationships:

a. More diverse systems will have higher rates of ecosystem function (e.g., productivity, decomposition).

b. More diverse systems will have higher rates of retention of nutrients or other resources (e.g., lower run-off or leaching losses).

Stability relationships:

c. More diverse systems will show greater stability (lower temporal variation) in ecosystem function.

d. More diverse systems will show some "substitution" of taxa (e.g., within a functional group), with some carrying out a given ecosystem function under certain conditions and other taxa carrying out that function under different conditions.

e. More diverse systems will show greater resistance to environmental perturbations.

f. More diverse systems will show greater resilience (more rapid recovery from a perturbation).

g. More diverse systems will show greater resistance to the invasion of non-native, weedy organisms.

species from competitive pressures. Desert ecosystems are ideal for testing these ideas: organisms are strongly limited by the extreme environment, so some species may be less able to respond to the removal of others. Plant species on the Jornada LTER sites differ markedly in growth form, photosynthetic pathway, and phenology, so it is relatively straightforward to assign them to functional groups (Reynolds et al., in press). Biotic influences have strong impacts on the physical environment (e.g., the development of islands of fertility), so we might expect clear, measurable responses to the removal of a species or an entire functional group of species (e.g., Carlson et al. 1990, Dugas and Mayeux 1991). The few systems where there is empirical information on the relationship between community composition and system function are nearly all in tropical forests (Ewel, 1986, Ewel et al. 1991) or in tropical and temperate grasslands (McNaughton 1993). Experimental work in the Chihuahuan desert would be an important extension to this body of knowledge.

We propose an experiment to test whether, and how strongly, species composition and diversity control ecosystem-level processes in Chihuahuan desert shrubland. Permanent plots will be established in a relatively diverse shrubland dominated by *Larrea tridentata*, where other plants include stem succulents, perennial grasses, and other growth forms. The experiment will involve species removals from individual plots, with monitoring of key indices of ecosystem function-- NPP, soil water and nitrogen availability, soil microbial activity, and plant recruitment and dynamics.

Thirty-six plots, each 20 x 20 m, will be established within the study area. Appropriate buffers will be maintained so that sampling falls within the central 10 x 10 m block of each plot, minimizing edge effects. Plots will be randomly assigned to each of the following 6 treatments:

- full species complement; no manipulation
- simplified diversity: only a single dominant species remains in each functional type (e.g., only *Larrea* remains as a shrub).
- reduced diversity: the dominant species of each growth form will be removed, with all others undisturbed.
- removal of all individuals of a given functional group, yielding 3 treatments (no shrubs, no perennial grasses, or no stem succulents).

These treatments will test a variety of current hypotheses. For example, the "simplified" treatment will examine whether species richness itself, as divorced from functional group representation, affects ecosystem properties. The "reduced" treatment will allow us to see if the remaining species can compensate for the removal of a dominant.

In this experiment, plant biomass and productivity will be measured on 10 randomly selected permanent 1-m^2 quadrats within the central area, using regressions developed in our ongoing measurements of NPP across LTER plots (see Section 2. #3 A, below). Seedling recruitment and mortality of individual perennial plants will also be monitored in permanent subplots. Soil water content will be measured with thermocouple hygrometers, as used successfully in previous studies of creosotebush communities (Fonteyn et al. 1987). Prior to the removal of any vegetation from the experimental plots, we will map its canopy area. After removal, we will monitor changes in the spatial distribution of soil nutrients in the absence of the shrub-induced positive feedbacks. Changes in soil nitrogen movements in the ecosystem will be monitored using buried cation/anion resin sheets in 3 seasonal periods of the year (Lajtha 1988, Magid and Nielsen 1992).

Dr. Vincent Gutschick (NMSU, Biology) will commence a long-term examination of comparative physiological behavior of the vegetation in these plots. He will examine changes in water relations and water-use efficiency (WUE) of vegetation in response to the manipulations of biodiversity, using measurements of δ^{13}C of plant tissues and field measurements of photosynthetic parameters using a LiCor field photosynthesis system. The δ^{13}C isotope ratio of plant tissues is an index of internal CO_2 and leaf WUE (Farquhar et al. 1989), so these data will show changes in the WUE of individuals in response to differences in soil moisture under the different experimental treatments and among individuals as an index of competitive ability in regimes of differing soil water availability (Ehleringer and Cooper 1988, Ehleringer et al. 1991, Schuster et al. 1992).

c. **Small Mammal Effects on Soil and Vegetation Heterogeneity.** Brown and Heske (1990, Heske et al. 1993) propose that kangaroo rats (*Dipodomys* sp.) play a "keystone" role in desert ecosystem function. In a 12-year experiment in southeastern Arizona, the exclusion of kangaroo rats from field plots led to an increase in a variety of grasses. Through their feeding and digging activities, kangaroo rats exert a significant effect on soil spatial heterogeneity (Mun and Whitford 1990). Our basic hypothesis for desertification would suggest that their removal from the ecosystem may allow grasses to reinvade as soil characteristics return to a more homogeneous state.

Small mammal populations may fluctuate considerably with variations in climate (Whitford 1976, Johnson and Anderson 1984). Such population fluctuations are thought to result primarily from variations in food resources. If small mammals are keystone species affecting plant community composition, then the impact of small mammals on vegetation is probably tightly coupled with climate. A reciprocal plant/herbivore feedback may result, where the effect of small mammals is initially determined by the climatic impact on available food. Thus, the effects of small mammals may be different during dry years and wet years--as determined by the effects of the El Nino cycle on precipitation in the southwestern U.S (Neilson 1986, Molles and Dahm 1990).

For LTER-III, we propose a regional intersite comparative experiment to observe the influence of small mammals (kangaroo rats and rabbits) on desert ecosystems. The objective of the experiment is to determine if the activities of small mammals influence the spatial pattern of soils and the composition of vegetation in the Chihuahuan desert. The study will be organized along a latitudinal/climatic gradient, with field sites located at the MAB Reserve near Mapimi,

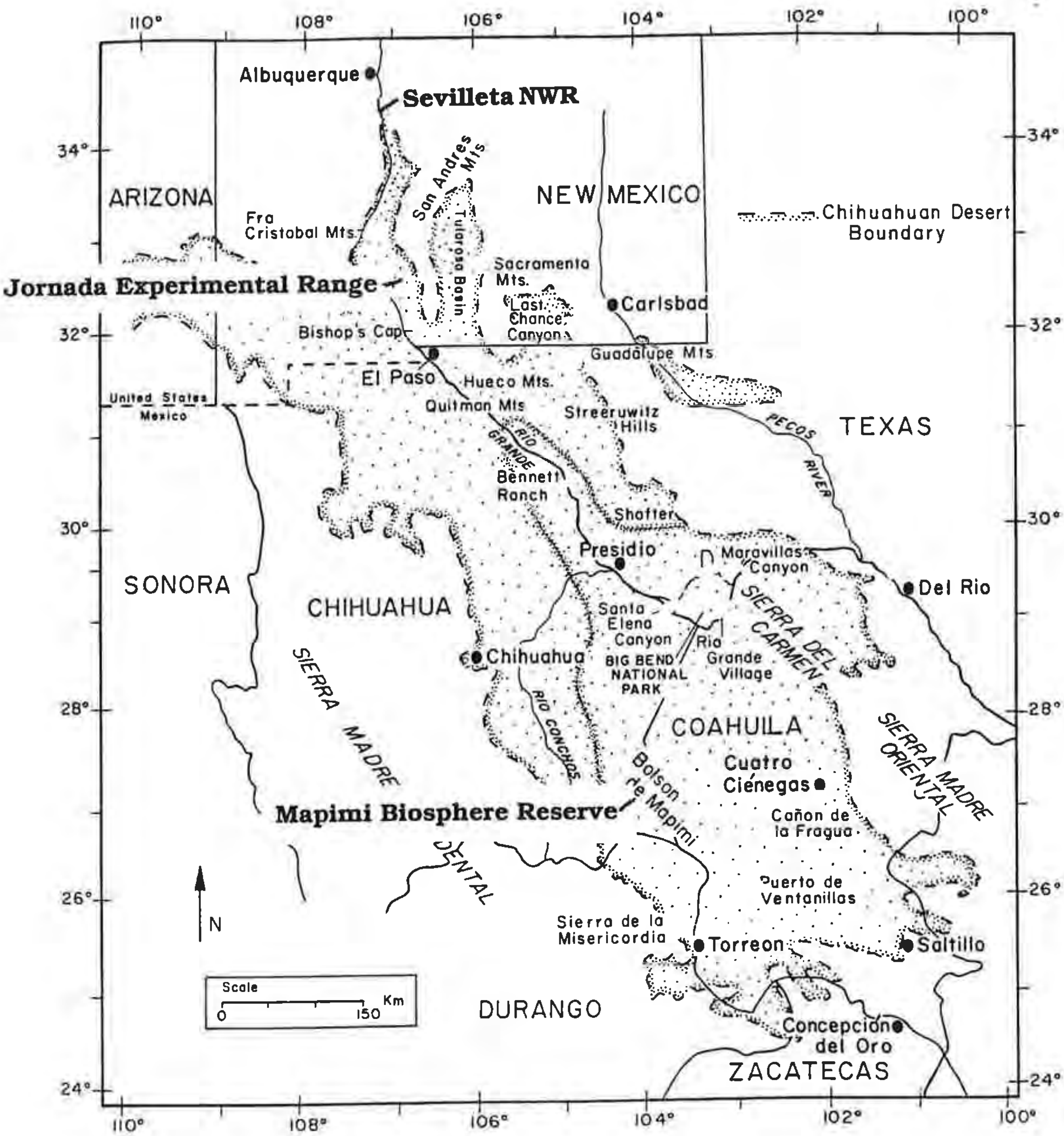


Figure 7. The Chihuahuan Desert, showing the study sites at the Sevilleta National Wildlife Refuge, The Jornada Experimental Range, and The Man and the Biosphere (MAB) Reserve near Mapimi. From Van Devender (1990). Reprinted with permission for the University of Arizona Press.

Chihuahua, Mexico, at the Jornada Experimental Range, and at the Sevilleta National Wildlife Refuge-- in explicit cooperation with the LTER program there (Fig. 7). At each site, an identical field experiment will be set up in grassland and shrubland communities. We will test the basic hypothesis that these small mammals are keystone species that determine community composition and ecosystem function in the Chihuahuan desert.

Each field site will contain four experimental blocks in grassland and shrubland communities that are not grazed by cattle. Each block will contain a small mammal census web, and two 30 x 30 m plots--one unfenced plot and one fenced plot from which kangaroo rats are removed. Fencing will consist of 3-foot hardware cloth screening with 1/4" mesh. The screen will be buried 8" into the soil (to exclude burrowing animals) and a 6"-strip of metal flashing will be placed along the top edge of the screen (to exclude climbers).

Small mammal census webs will be used to determine the composition and population density of the small mammal guild at each site (Buckland et al. 1993). Each web will consist of a series of 12 equally-spaced 100-m transects radiating from a central point. Each line will contain 12 live-trap stations-- at 0, 5, 10, 15, 20, 30, 40m intervals etc. up to 100 m. Such a field array has proven more robust statistically for sampling small mammals than traditional grid plots and mark-recapture analyses (Buckland et al. 1993). In each plot, a census of small mammals will be taken twice each year.

Within the field plots, basic characteristics of vegetation and soils will be monitored at regular intervals for the duration of the LTER program. Species composition and cover will be monitored twice annually in a grid of 36 1 x 1 m quadrats located within each plot. Net primary productivity will be monitored at the same time and following the same methods of NPP measurements in the core LTER plots, as described below. Animal disturbances of the soil will also be recorded on these 36 quadrats. At annual intervals, a separate grid of nested soil samples will be taken, analyzed for the content of N, P, Li, and Br, and the contents subjected to a spatial analysis of soil properties. As in the previous experiment, changes in the spatial heterogeneity of N and P, as essential plant nutrients, will show the effect of changing biotic processes, whereas changes in the distribution of Li and Br should be dominated by changes in physical factors in the environment.

2. Existing Long-Term Data Sets

A variety of long-term data sets are maintained as part of the Jornada LTER program (Appendix III), including those gathered during the course of earlier LTER investigations[2] and those gathered and maintained by the U.S. Department of Agriculture's program of research

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[2] Pages 143-156 of the Long-Term Ecological Research Network Core Data Set Catalog (Michener et al. 1990), published as Contribution No. 5 by the LTER Network office, provide further documentation for 12 long-term data sets maintained by the Jornada LTER.

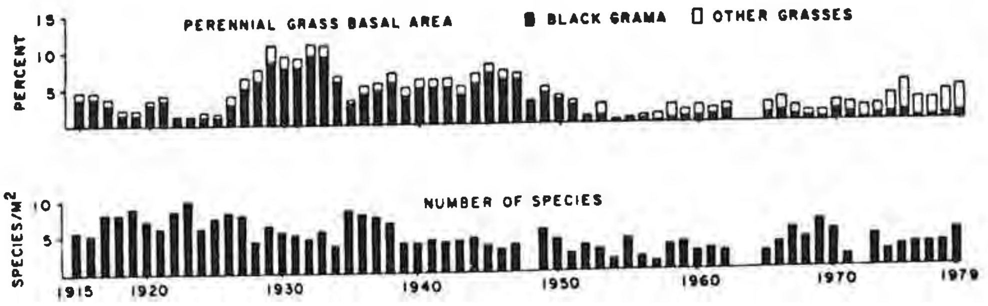


Figure 8. Changes in the cover of black grama grass on permanent quadrats sampled from 1915 to 1979 on the Jornada basin, showing the overall decline in grass cover and species diversity at the site. (From Gibbens and Beck 1988).

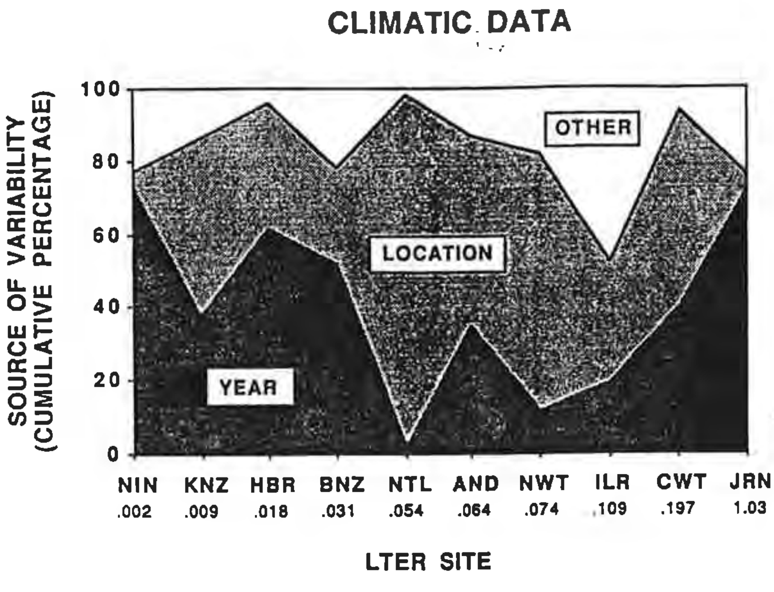


Figure 9. Sources of variance in climatic data for LTER sites. The Jornada is unique in having the largest relative variation among LTER sites (1.03) and in having a large portion of its climatic variance due to year-to-year fluctuations as opposed to variance among stations within the Jornada basin. The Alpine tundra site (NIN) shows a similar pattern, but with much less total variance (0.002) Kratz et al. (unpublished).

at the site. All are accessible through our program of data management (Section 2, # 5, below). These data sets are used in a variety of ways. For example, routine, long-term monitoring of net primary production, soil water contents, and lizard and termite populations in spatial grids allow us to test our basic hypotheses regarding changes in ecosystem heterogeneity with vegetation change. The USDA records provide the basic record of vegetation change--grassland to shrubland--that motivates our studies of the desertification process (Fig. 8). Laura Huenneke uses archival USDA data on plant species diversity and density for comparison to her current measurements on the LTER plots. Measurements of hydrologic parameters in grassland and creosotebush habitats allow formulation of the hydrology submodels of the REGALS simulation model of desert ecosystem function. Long-term monitoring of hydrology has proven invaluable, given the large variation in desert precipitation events. The long-term data sets for meteorological variables and precipitation chemistry are some of the most-requested data sets in our archive. John Magnuson's analysis of long-term data sets for meteorology have shown that the Jornada "anchors" one end of an axis of environmental variability across the LTER network (Fig. 9).

3. Contributions to Core Areas.

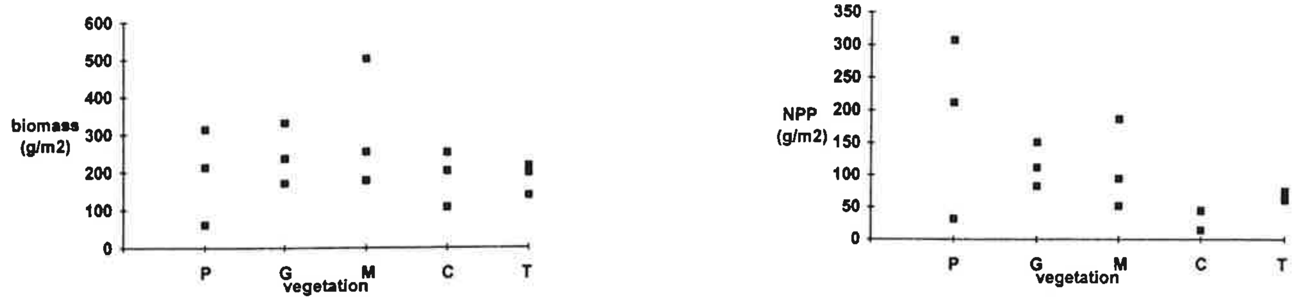
a. **Net Primary Production.** The Jornada LTER-I focused on patterns of net primary production on a single watershed; current work in LTER-II has expanded NPP estimates to cover a wider range of ecosystem types and geographic areas of the Jornada basin. We established 15 permanent sites for study of aboveground productivity: 3 in each of 5 ecosystem types (*Bouteloua* perennial grassland, *Larrea* shrubland, *Prosopis* dune systems, *Flourensia* flats, and dry lake or playa habitats). A grid of 49 permanent quadrats was established in each site, and these quadrats have been sampled non-destructively for the aboveground biomass of all vascular plant species 3 times each year since the spring of 1989. Biomass estimates are based on regressions of biomass to simple plant canopy dimensions (cover and height), which have been developed from harvests of roughly 160 species of plants growing adjacent to the study sites.

Productivity over an interval is estimated as the positive increment of biomass for each species in a quadrat, summed over all species. This is a recognized underestimate, as plant parts for some species may come and go during an interval, but we are confident that our results give a robust long-term index of productivity on these sites. Our ability to estimate and compare productivity on a unit-area basis is essential to the development and validation of simulation models for desert ecosystem function. Our existing data sets are also available for the upcoming NASA effort to validate satellite-based measures of NPP based on spectral reflectance.

Currently biomass/NPP estimates have been completed for 11 sample dates (spring 1989-fall 1992). In most ecosystems there is a strong seasonal pattern in mean live biomass. A few sites show trends over time; e.g., one mesquite site has increased in biomass throughout the study. Productivity is sometimes well correlated with aboveground biomass (e.g., in playas), but in most sites the persistence of

Mean biomass: Fall 1991

Mean net primary production: Spring 1991 - Fall 1991



Interquartile range in biomass: Fall 1990

Interquartile range in NPP: Winter 1992 - Spring 1992

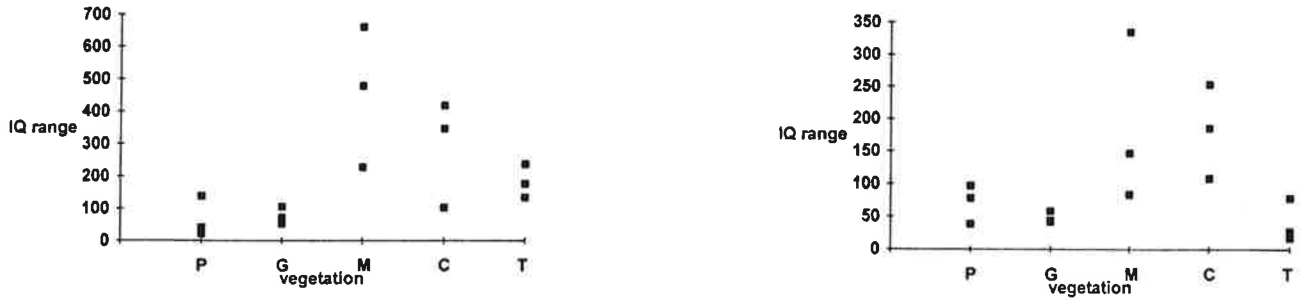


Figure 10. Means and ranges of variation for biomass and seasonal productivity in five Jornada ecosystem types. Four-letter codes indicate data from individual sites: C = creosotebush scrub, G = *Bouteloua* grassland, M = mesquite dune, P = playa, T = tarbush scrub.. **a**: mean aboveground biomass (g/m^2) for the 3 relicate plots in each vegetation type in fall 1991. **b**: Interquartile range (the range of the central 50% of the data as an index of variation) for biomass measured in individual samples in each of the 3 replicates in each vegetation type in fall 1990. **c**: mean aboveground net primary production (g/m^2) for the 3 replicate plots of each vegetation type between samplings in spring and fall 1991. **d**: Interquartile range for NPP.

perennial plant parts means that biomass is not a good indicator of NPP. We do not yet see long-term trends in NPP or correlations of NPP to climate over the existing 3-year record.

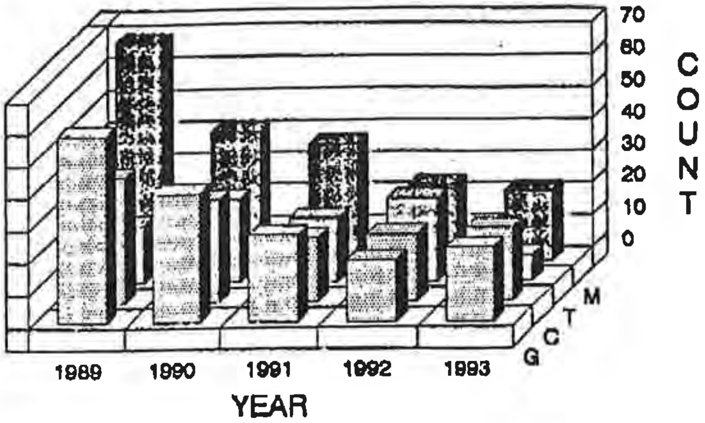
We have used these biomass and NPP data to address the central hypothesis of the Jornada LTER--that soil resources and biological activity are more heterogeneous in desert shrublands than in the original semiarid grasslands. Average aboveground biomass and NPP do not differ significantly among the 5 ecosystem types, but the spatial variability of biomass and NPP is significantly greater for shrub-dominated ecosystems than for grasslands and grass-dominated playas (Fig. 10).

Our field data on biomass have been used by Drs. Janet Franklin, Doug Stow and Alan Hope of San Diego State University to test a high-resolution low-altitude system for collecting spectral reflectance data (Phinn et al., in prep). Their results confirm that 1-m^2 plots in a 10-m grid are sufficient to describe some geostatistical features of the sites and the scale of variability within the sites (Muldavin and Huenneke, in prep.).

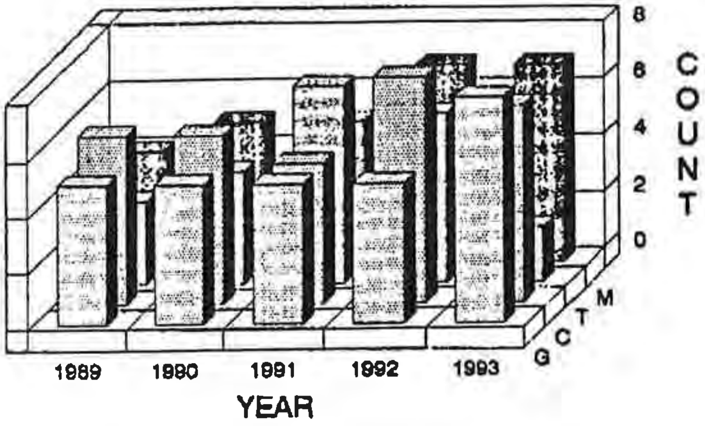
These studies are led by Dr. Laura Huenneke (NMSU, Biology), who is now using the data to describe basic community structure within the 5 Chihuahuan desert ecosystems represented. Her analysis shows that species richness and other measures of plant diversity are highest in grasslands and that the species composition of shrublands is essentially an impoverished version of the grassland flora, rather than a substitution of one assemblage for another. She is examining species' dominance and productivity patterns to determine whether the same species consistently act as dominants over time, and whether all species respond similarly to climatic variables. This analysis should show whether biotic interactions result in different species contributing a disproportionate fraction of NPP in different years, providing context for the biodiversity experiment. A related effort is the monitoring of perennial plant phenology in the 15 NPP plots. This data set, initiated in 1992, will be maintained for 5 years to provide finer temporal resolution of the relationship between plant behavior and climatic variables.

Thus, the first few years of monitoring NPP have provided some valuable insights to the structure and dynamics of these ecosystems. However, only a longer time-series will allow us to use these data to address basic questions about the temporal patterns of production. How strong is the signal of El Nino events in this region of bimodal precipitation? Can production and its variation be explained as a simple correlate of precipitation (Le Houreau et al. 1988) or are temperature and nitrogen availability of strong importance? Are there long-term trends in production that can be related to successional dynamics of these ecosystems (i.e., shrublands replacing grasslands) or to climatic forcings (recovery from periodic decadal droughts of the 1930s and 1950s)? In each case, the field measurements of NPP are an essential input to the patch (PALS) and regional (REGALS) simulation models (Section 2, # 4, below) that predict variation in NPP in response to seasonal and long-term changes in climate.

Numbers of individual lizards



Numbers of lizard species



CV's of numbers of lizards/all traps

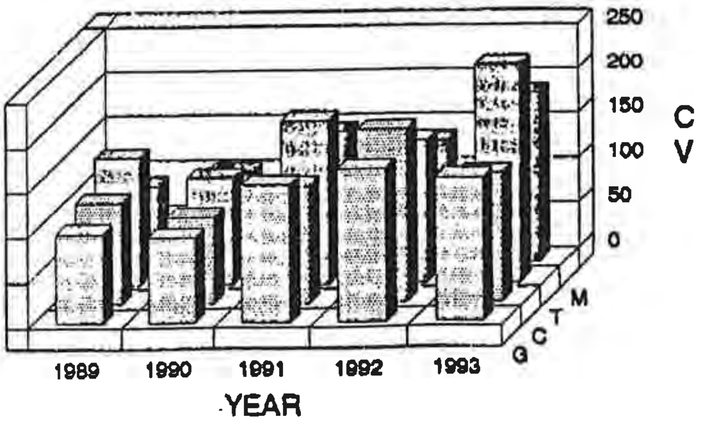


Figure 11. Number of lizards (a), lizard species (b) and the coefficient-of-variation for lizard captures (c) in the pitfall traps in 4 vegetation types (grassland, creosotebush, tarbush and mesquite) on the Jornada Experimental Range from 1989-1993.

We will continue sampling NPP at these sites for the duration of the LTER-III program, to provide long-term data sets for correlation with climatic records. Our NPP monitoring, and the regressions on which it is based, will provide a basis for the measurements of NPP in the various field experiments (Section 2, # 1 a-d, above).

b. **Studies of trophic relations: Consumers.** LTER-II consumer studies have focused on monitoring community composition of key consumer groups in grassland and shrubland habitats to determine how populations and species composition change over time. We hope to develop mechanistic links between precipitation, plant production, and fluctuations in consumer populations to see how changes in abiotic variables and primary production are reflected at higher trophic levels. Ongoing LTER-II consumer studies include monitoring of lizards, birds, rabbits, and ground-dwelling arthropods and termite consumption rates, coordinated by Dr. David Lightfoot.

As an example, we see that lizard populations show similar patterns over grassland and shrubland sites (Fig. 11a). Since 1989 there has been an overall decrease in the numbers of lizards captured (lizards are captured live and released), and this trend has occurred at all sites. In contrast, there has been a slight increase in the species richness of lizards over the same time period, and the increase in richness is seen over all sites (Fig. 11b). Coefficients-of-variation for the number of lizards caught over all traps in each community indicate the spatial heterogeneity of lizard abundance (Fig 11c). At the 10-m scale of our sampling grid, an increasing variance over time is probably a function of decreasing numbers of lizards captured. Grassland sites show similar patterns of spatial variance as shrubland sites. Lizard and other consumer populations at the Jornada do not appear to be tightly coupled to net primary production.

For LTER-III we propose to maintain the current monitoring program for the various consumer groups, extending the core long-term data sets for these trophic groups. Minor modifications of the experimental design (e.g., a few additional plots in some habitats) will allow us to make more direct comparisons to NPP and climatic data in the various habitats. In addition, we will add grasshoppers to our current list of key consumers. Grasshoppers will be measured on a grid of 21 quadrats in each of the NPP plots and in each of the subplots of the cattle grazing experiment (Fig. 4). The studies of small mammal populations-- part of our proposed new experimental study of kangaroo rats-- will also commence long-term data sets for this consumer group.

c. **Patterns of Resource Distribution.** A basic tenet of our central hypothesis regarding desertification is that a change in the spatial distribution of soil resources accompanies the invasion of grasslands by shrubs, developing a positive feedback for the persistence of shrubs. We have tested this hypothesis in a variety of ways. Simple measures of variation in soil properties along transects (e.g., Fig. 2) and detailed geostatistical analysis of soil properties in the 15 NPP plots support the basic notion of greater spatial heterogeneity in shrublands. More explicitly, the scale of

Jornada LTER
Digital Elevation Model

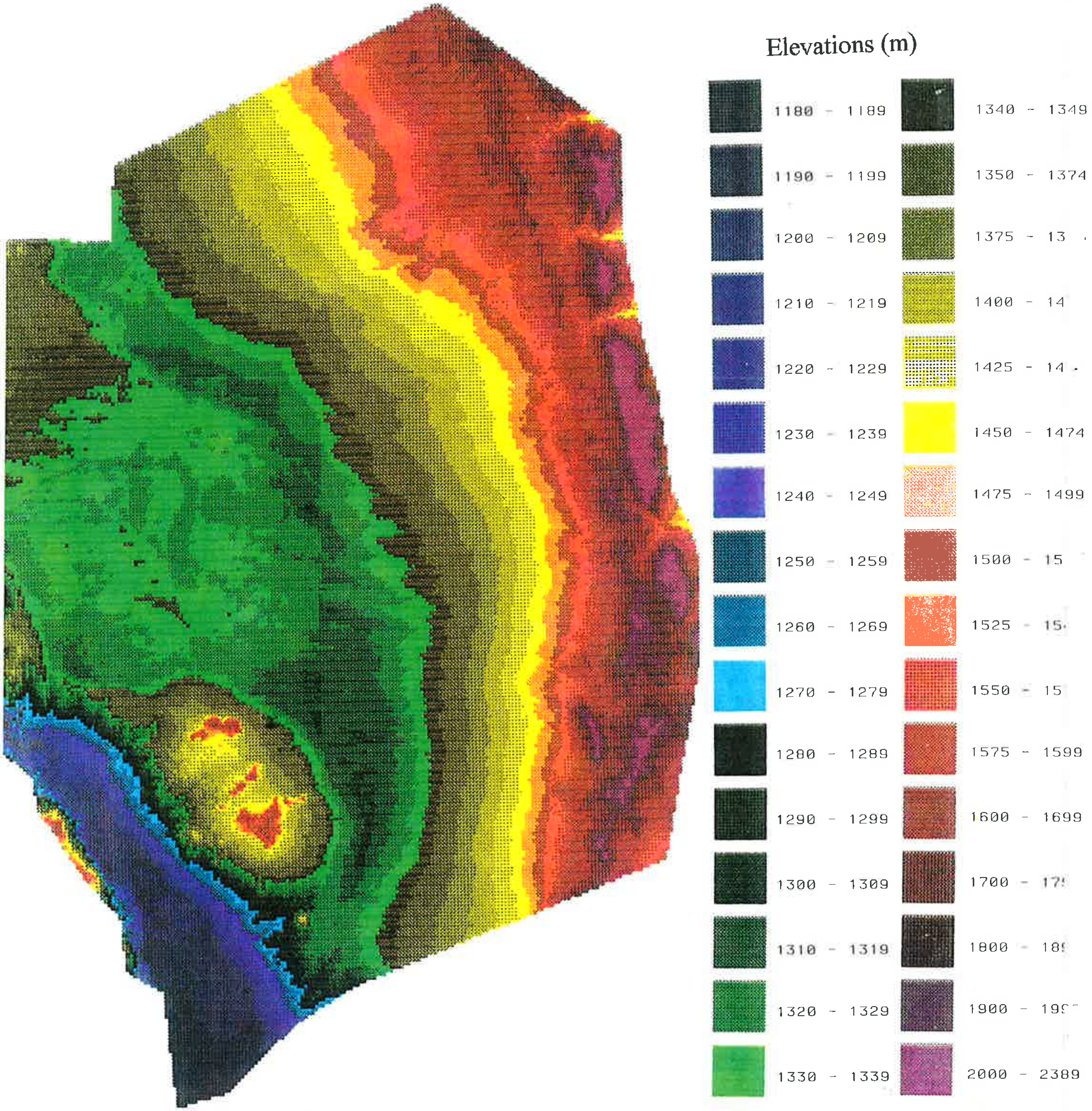


Figure 12. Digital elevation model for the Jornada basin at a scale of 1:25000, derived from U.S. Geological Survey topographic sheets.

heterogeneity appears to increase from grassland habitats (Hook et al. 1991) to shrublands. Similar levels of heterogeneity in the spatial distribution of non-essential elements (e.g., Na, Li, Cl and Br) and in the distribution of essential elements (N, P, K) suggest that physical processes (wind and water) may be as important as biotic processes in the development of spatial pattern in shrublands (Schlesinger et al. in prep.). For LTER-III, we will extend these measures of soil heterogeneity to record changes in soils in response to experimental manipulations of grazing intensity, biodiversity, and kangaroo rats, as described above.

We have long-term data sets for the seasonal distribution of soil water in the NPP plots at the Jornada, and a long-term data set for the seasonal variation of soil moisture along the topographic transects of LTER-I (Nash et al. 1991). Naturally, we propose to maintain the routine measurements that contribute to these core datasets for the duration of LTER-III. To relate variations in the availability of soil moisture to vegetation, Dr. Vince Gutschick will commence a long-term collection and analysis of plant tissues in the NPP plots for $\delta^{13}C$ isotope ratio--an index of seasonal and annual water-use efficiency. He will test the basic hypothesis that physiological WUE is negatively related to drought tolerance (DeLucia and Schlesinger 1991). The estimates of WUE in different sites are critical data for validation of the PALS simulation model, and for predicting changes in the regional distribution and function of vegetation in the REGALS model.

To record seasonal and annual changes in the belowground response of desert vegetation, we propose to add several minirhizotron tubes to each of the NPP plots. An existing Bartz Technology high resolution miniature color video camera will be used to obtain a record of root phenology, which has proven extremely useful in understanding the response of creosotebush and mesquite to the exclusion of summer and winter rainfall in Ross Virginia's and Jim Reynolds' ongoing studies employing rainout shelters on the Jornada.

Although our current LTER database includes a basic soil survey and a 1:25000 digital elevation model (DEM) for the Jornada in GIS format (Fig. 12), we have made only a limited attempt to understand how the major soil types have developed in relation to topography and geomorphic processes (Lajtha and Schlesinger 1988). Most soils are alluvial, derived from the mountains that surround the Jornada basin. Studies in other regions have shown that layers of desert alluvium contain a record of paleoclimate that can be extracted by studies of fossil pollen and stable isotope ratios in soil organic matter and soil carbonate (Freeman 1972, Cerling 1984, Amundson et al. 1988, Quade et al. 1989). Thus, an in-depth study of these soils will provide a long-term record of how desert ecosystem function has changed with past changes in climate (Fig. 13). For LTER-III, these studies of paleoclimate will be led by Dr. Curtis Monger (NMSU, Agronomy), who will refine the GIS dataset for soils to show how the distribution and development of soils have changed with past changes in climate and vegetation in this region.

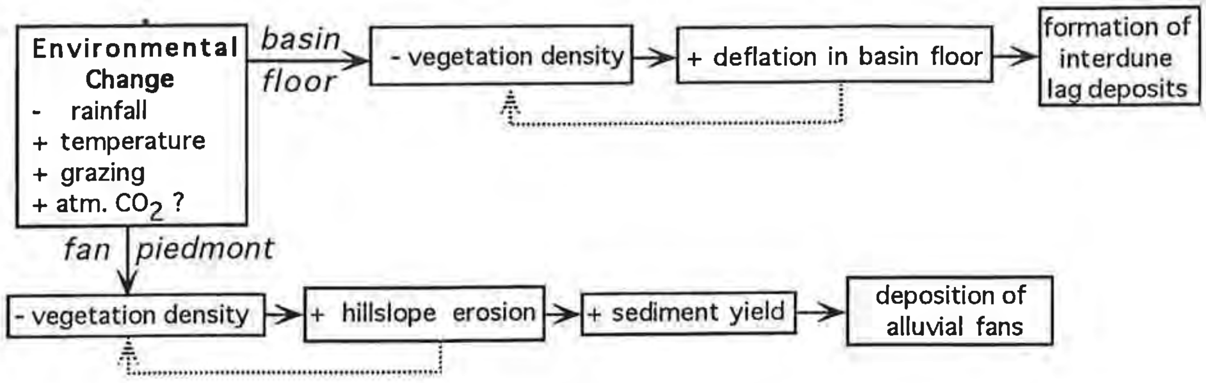


Figure 13. Hypothetical changes in soil development linked to climatic changes in the desert Southwest.

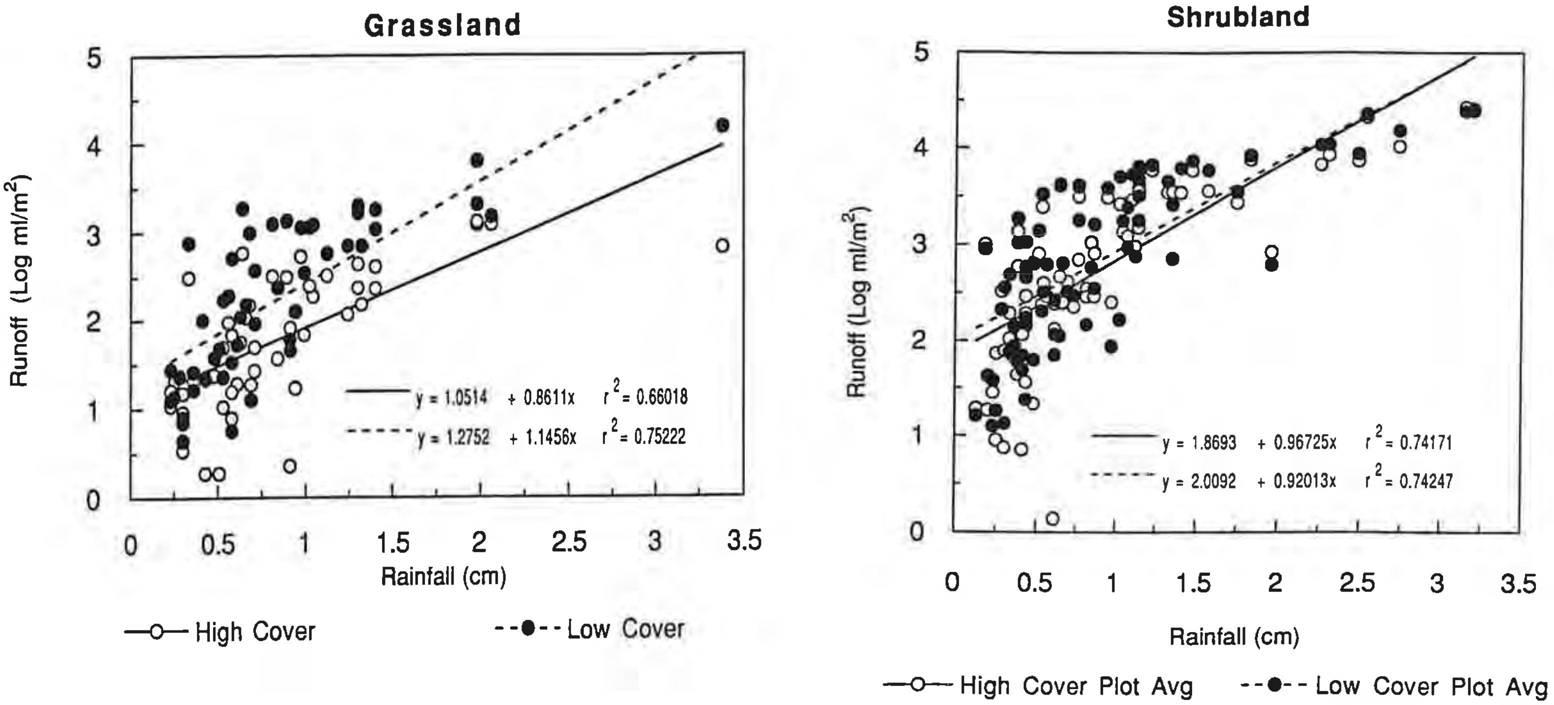


Figure 14. Runoff recorded on the LTER hydrology plots located in areas of high and low cover in grassland and shrubland on the Jornada Experimental Range, over a range of naturally occurring precipitation events, 1989-1992.

d. **Inorganic Movements: Biogeochemistry.** We currently are developing long-term data sets for a variety of biogeochemical processes that operate in the Jornada basin--including studies of surface hydrology, soil microbial processes, and trace gas emissions from soils. For LTER-III we propose to continue our studies in this core area, as well as add a significant new component in the area of eolian processes.

Studies of hydrology focus on a series of plots established in areas of grassland and creosotebush scrub on the Jornada. The record from some plots dates to 1982 (LTER-I); long-term measurements of runoff on these plots support the basic premise of our desertification model that shrublands generate greater surface flow in any given rainfall regime (Fig. 14). In most cases, nutrient concentrations in runoff from shrublands are slightly lower than from grasslands, so that the larger nutrient losses from shrublands are mainly determined by the amount of runoff.

Hydrology studies in LTER-III will be led by Dr. Athol Abrahams (SUNY, Buffalo). We propose to develop a dynamic rainfall-runoff model (HILLS, p. 31) that will be based on an enhanced (level 2) version of the Digital Elevation Model (DEM) that is currently available for the Jornada basin (Fig. 12) and field experiments to predict runoff hydrographs for various habitats of the LTER site. The DEM consists of a uniform, rectangular array of elevations with a horizontal spacing of 10 m. Flow paths will be determined from the DEM following Band (1993). Infiltration will be represented by the Green and Ampt equation, which will be parameterized for each habitat type from rainfall simulation experiments (Abrahams and Parsons 1991a), some of which have already been performed during LTER-I and LTER II (Bach et al. 1986). The finite difference solution to the kinematic wave equation will be used to predict spatial and temporal variation in water discharge (Scoging et al. 1992). This solution requires expressions for resistance to flow for hillslopes and channels. These expressions will be developed from field experiments, following the methods that Abrahams and his coworkers have used at the nearby USDA site in Walnut Gulch, Arizona (Abrahams and Parsons 1991b, Abrahams et al. 1994). The rainfall-runoff model will be validated using data from existing runoff plots (Fig. 14) and from a reactivated gauging station on the eastern bajada of the Jornada and a newly constructed gauging station near Mount Summerford. The HILLS model will provide input to the landscape models of plant production, decomposition and nutrient cycling described below (Section 2 # 4, p. 31).

We also propose to model the flux of water, sediment and solutes (especially forms of nitrogen) at the rill/interrill scale. The small-scale model (RILLS, p. 31) is intended to complement the foregoing large-scale efforts and to focus on the mechanics of runoff and erosion. Two sites, each approximately 1 ha in size, will be selected, one in grassland and one in shrubland. A dynamic rainfall-runoff model will be developed for each site, similar to that for HILLS described above, but at a smaller scale. Flow paths will be determined by applying Scoging's (1992) algorithm to field-surveyed topographic data with a horizontal spacing of 1 m. Expressions will be developed from rainfall simulation experiments for estimating the parameters of the Green and Ampt equation and the resistance coefficients for rill and interrill flow. The numerical modeling will employ a finite difference scheme. In addition to water discharge, sediment and solute flux will be measured during simulated rainfall experiments, and expressions will be developed for predicting their spatial and temporal variation from surface properties. The model for each site will be validated by installing a V-notch flume on the outlet rill and monitoring natural runoff events. The hydrographs for these events will then be compared to those predicted by the model.

Modeling the runoff and erosion processes operating in rill and interrill areas on grassland and shrubland will enhance our understanding of these processes and permit a more realistic parameterization of large-scale models, such as HILLS. The rill/interrill model may also be employed to postdict and predict, respectively, the impact on runoff and erosion of past and future changes in vegetation from grassland to shrubland at the Jornada. A similar study of runoff and erosion processes in grassland and shrublands is near completion at Walnut Gulch, in southeastern Arizona (Parsons et al. 1990, 1994, Parsons and Abrahams 1992). A comparison of these studies will allow us to assess the regional significance of the LTER findings in another area of the Southwest.

Patterns of soil water infiltration and the ultimate fate of surface runoff determine the seasonal and regional distributions of soil moisture, which we monitor as a long-term data set, as described above. Soil moisture determines the seasonal abundance of soil microbes in different habitats. Gallardo and Schlesinger (1992) found that soil microbial biomass was highest in the lowest topographic positions--areas of fine-textured soil that receive runoff from upslope (Table 1). Microbial biomass was positively correlated to soil organic carbon and extractable nitrogen, and the control of microbial activity is likely to shift from nitrogen to carbon as the C/N ratio of soils decreases during desertification (cf. Virginia et al. 1992).

Recognizing increasing scientific interest in microbial biodiversity, we propose to develop long-term comparative data sets for soil microbial biomass and cell number in the core NPP sites during LTER-III. Changes in microbial processes, especially those associated with mycorrhizae, are recognized as crucial to the degradation and restoration of arid lands (Allen 1989). By coordinating field measurements of the soil microbial community with measurements of NPP, we will be able to examine the relationship between higher plant and microbial activity across a range of Jornada habitats. This work will be coordinated by Dr. Peter Herman (NMSU, Biology). Using a standard grid of samples in each site, microbial biomass will be assessed using the fumigation-extraction method (Gallardo and Schlesinger 1992). Total and "living" bacterial counts will be estimated by the fluorescein isothiocyanate (FITC) method of Babuik and Paul (1970), and total and living hyphal lengths will be measured using the fluorescein acetate (FA) method of Soderstrom (1977). Because of the extreme importance of mycorrhizae in nutrient cycling in nutrient-poor, arid environments (Allen 1991), the VA-

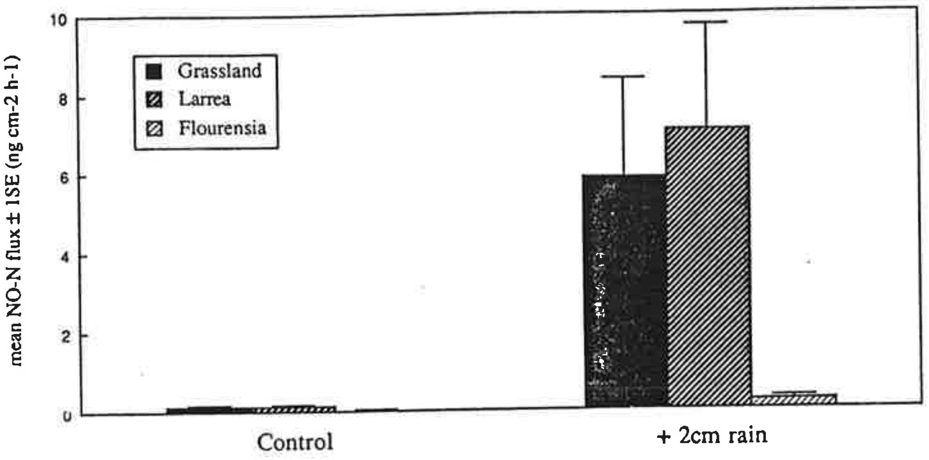


Figure 15. Flux of nitric oxide (NO) from grassland and shrubland (creosotebush and tarbush) habitats at the Jornada LTER under dry conditions and after the application of 2 cm of simulated rainfall. (Unpublished data of Anne Hartley).

mycorrhizal burden of the dominant plant species in each plot will be determined following Kormanik and McGraw (1982) and the soil propagule load following Daniels and Skipper (1982).

Estimates of microbial community structure and biodiversity will be made in each sample using the phospholipid fatty acid (PLFA) pattern method of Frostegard et al. (1991, 1993). This methodology allows for estimates of the contribution of any major microbial group to the total microbial community, and it provides a rapid estimate of spatial and temporal changes in community composition. Dr. Herman and his students have already made estimates of the diversity of bacteria in the nitrogen-efficient guild (NEG) by scoring individual colonies for morphology, gram reaction, acetylene reduction activity (ARA) (Herman et al., in press). We propose to monitor this guild as an index of microbial biodiversity in the NPP plots and changes of microbial biodiversity that accompany various treatments in our proposed long-term experiments with cattle grazing (Section 1) and manipulations of biodiversity (Section 2, #1b).

Most probable number (MPN) methods provide an index of the maximum number of viable heterotrophic bacteria in Jornada soils. As an index of oligotrophic bacterial flora, members of the nitrogen-efficient guild (NEG) will be estimated using a low-nitrogen medium as described previously for Jornada soils (Herman et al., 1993). A ratio of NEG/total heterotrophs will be calculated to estimate the relative importance of NEG members as a portion of the total community. Finally, the autotrophic guild--ammonia and nitrite oxidizers--will be estimated using the most probable number (MPN) technique (Donaldson and Hendersen 1989). These measurements will provide an index of nitrification activity for correlations to ongoing studies of nitrogen trace gas emissions, described below.

Through its control on soil microbial activity, the timing and availability of soil moisture controls the emission and consumption of a variety of trace gases from desert soils, including CO_2, CH_4, NH_3, N_2O and NO. Our current work seeks to understand the processes that regulate the flux of these gases. Schlesinger and Peterjohn (1991) found that the flux of ammonia from desert soils is strongly regulated by the availability of NH_4^+, which is determined by the seasonal availability of soil moisture that controls nitrogen mineralization. Despite high rates of nitrification in desert soils, competition by nitrifiers for NH_4 had little effect on ammonia volatilization, except in areas of black grama grassland. Anne Hartley, a doctoral student at Duke University, shows that the flux of NO increases to >20 times the background level of dry soils, within 10 minutes after the application of a simulated rainfall in creosotebush and tarbush communities (Fig. 15). Annual flux of NO and N_2O from desert soils may account for most of the "missing nitrogen" in a mass-balance model for nitrogen in desert soils (Peterjohn and Schlesinger 1990) and the progressive enrichments of the $^{15}N/^{14}N$ ratio in soils as arid lands are degraded (Evans and Ehleringer 1993). Schlesinger's studies of ammonia volatilization and Hartley's studies of NO and N_2O will be used with the GIS data sets of soil type and seasonal moisture content to calculate basin-wide flux of nitrogen losses under a variety of climatic regimes.

The emission and consumption of methane by desert soils is also of potential significance to understanding the contribution of these systems to global change phenomena. Desert soils have been recognized as candidates for significant methane emissions as a result of the diverse and abundant termite populations in these areas (Brauman et al. 1992). Nevertheless, our field studies in the Jornada and published values from other deserts (Striegl et al. 1992) show that desert soils can act as a significant sink for atmospheric methane. Recognizing that the balance between methanogenesis and methanotrophy may be a key index to changing ecosystem function, we propose to monitor methane emissions in the cattle-exclosure experiment (Section 1).

The proposed program for measurements of trace gas emissions in LTER-III is intended to allow our site to participate in the newly-established trace gas network (TRAGNET) including LTER and other sites worldwide (Section 2, # 6, page 36). Establishment of a routine gas sampling program will also provide important information on trace gas flux in arid ecosystems and improve our understanding of the response of the Chihuahuan desert ecosystem to human perturbation, specifically cattle grazing. Seasonal measurements of net gas flux will be made in each major habitat (and in each cell of the grazing experiment) using short-term measurements of the change in concentration under closed chambers (Steudler et al. 1989, Davidson et al. 1991).

Eolian processes are of extreme importance in deserts, and the production of dust by wind erosion is arguably the most important effect that increasing desertification will have on global function. Losses of plant cover in desertified habitats are associated with greater rates of wind erosion, transporting soil materials and their nutrients globally (Prospero and Nees 1977, Talbot et al. 1986, Swap et al. 1992, Zhang et al. 1993), with effects on the albedo of the Earth's atmosphere (Ackerman and Chung 1992), rain chemistry (Gillette et al. 1992, Roda et al. 1993, and oceanic productivity (Martin and Gordon 1988). The global influence of a greater expanse of desert land during the last glacial is shown by high rates of deposition of dust in the Vostok ice core from Antarctica (DeAngelis et al. 1987, Petit et al. 1990). In southern New Mexico, wind-driven soil aerosols dominate the tropospheric load in springtime (Pinnick et al. 1993).

Currently, our formulation of the REGALS model does not include a dust component; during LTER-III we propose to add this refinement by a program of field studies and model parameterization of this phenomenon. Joining the Jornada LTER consortium as a collaborator, Dr. Dale Gillette (NOAA, Research Triangle Park, N.C.) will lead studies examining the importance of soil crusting as a control over the process of wind erosion.

In the absence of protective vegetation or clastic (i.e., stone) cover, resistance of soil to wind erosion is largely a function of the development of a soil crust (West 1990). In-situ wind tunnel tests in the Mojave desert have shown that the surfaces most vulnerable to disruption were found on sandy soils or in areas where surface accumulations of salt maintain the soil with a dispersed (non-

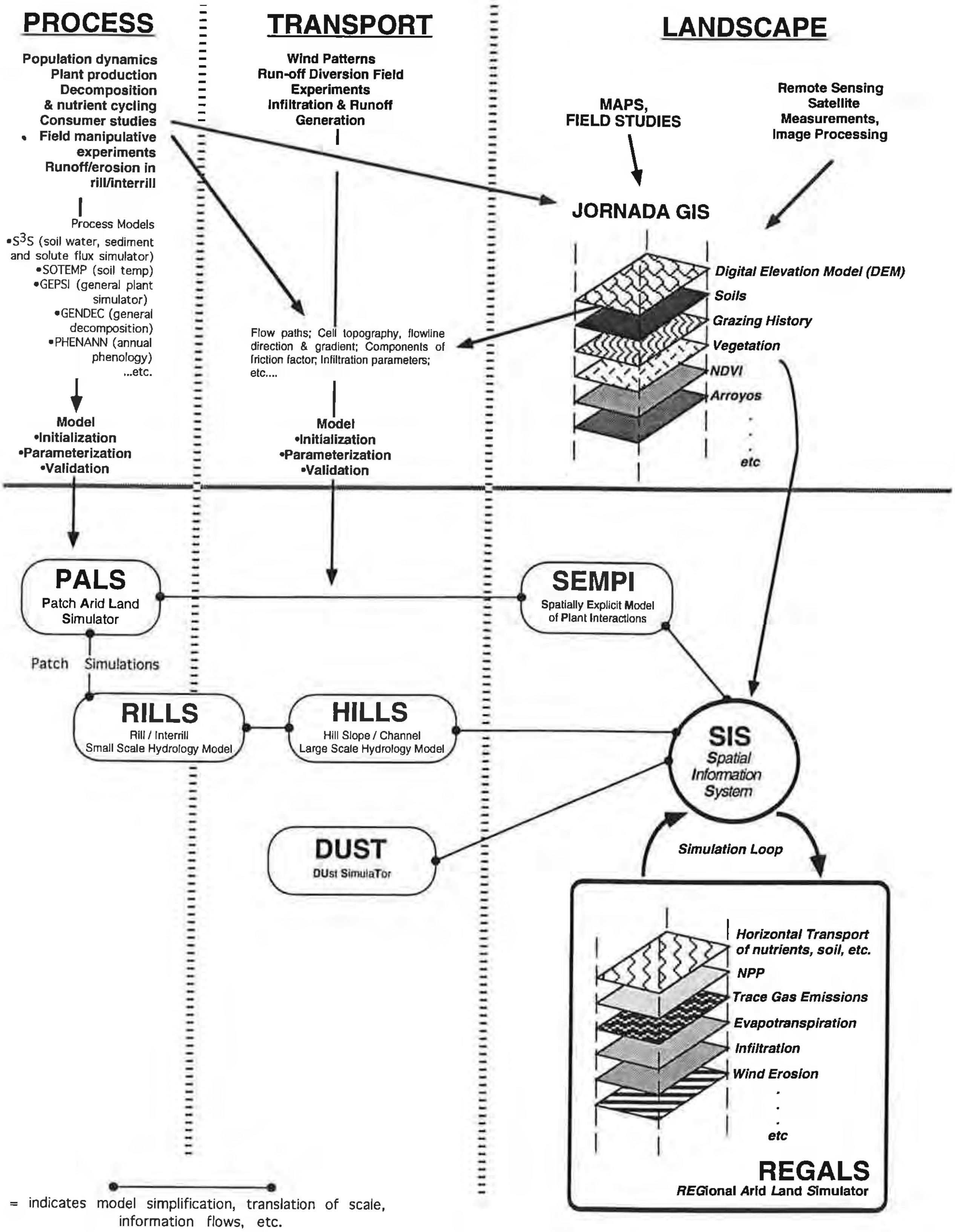


Figure 16. Scheme for linking process, transport and landscape models developed to predict ecosystem properties at the Jornada LTER.

aggregated) structure. Mojave crusts with more than 40% clay content were stable. Once a crust is broken by wind action, sandblasting by upwind material, or exogenous disturbance (e.g., cattle, Klopatek 1992), the destruction of large areas of crust may be quite rapid, since the kinetic energy of the wind is localized by approximately the ratio of the density of saltating grains to air (2500:1).

Currently the U.S. Geological Survey maintains a "Geomet" station at the Jornada Experimental Range, where winds and the concentration of wind-borne particles are monitored to develop a long-term data set. In conjunction with this effort, samples of soil crusts were taken from three barren areas with visible soil crusting at the Jornada Experimental Range. These soils ranged from 30-45% clay, with low concentrations of soil organic matter. Over the course of a year, the modulus of rupture remained fairly constant at all three sites despite rainfall events that caused wetting and reformation of the crusts. The thickness of the crusts for all three sites showed little change through the year despite seasonal changes in temperature and soil moisture (Gillette 1988). Only disturbance by animals and humans could break these strong crusts, lowering the threshold for wind erosion. In other areas of sandy soil, vegetation offered the major protection from wind erosion, and little material was lost despite winds in excess of the erosion threshold (Musick and Gillette 1990).

For LTER-III, Dr. Gillette proposes to expand on his previous work at the Jornada, by examining soils that span a greater range of clay content and crust development. Field studies of crust development will be followed by controlled experiments in the Duke University Phytotron, where the formation and aging of crust will be followed under a variety of environmental conditions. The NOAA wind tunnel will be used to measure threshold friction velocities for a variety of undisturbed and disturbed crusts in situ at the Jornada. The relationship of dust production to soil type, vegetation cover, and land use will be used to parametrize a dust-production module in our simulation models. Changing patterns of vegetation and land use (e.g., grazing) will allow us to estimate changing patterns of wind erosion over time.

e. **Disturbance.** Our current and proposed work on disturbance effects is described in the section on the Results of Prior Support (p. 4), in a description of ongoing experiments (pp. 18), and in our proposed new, major experiment to examine the effects of managed grazing regimes on ecosystem function (pp. 13-17). Thus, this section is not elaborated further here.

4. Synthesis and Modeling.

The long-term objective of the Jornada LTER is to develop models that lead to a synthetic understanding of the interacting processes that cause desertification and the subsequent changes in ecosystem properties in desertified habitats. Models focus on three scales: (1) processes that occur at specific locations (patch models); (2) transport of energy and materials between locations (transport models); and (3) links between local and transport processes leading

Fig. 17. Ecosystem Functional Types (EFTs) at the scale of patches are used to define patch mosaic and regional ecosystem functional types, each with a different distribution of soil resources.

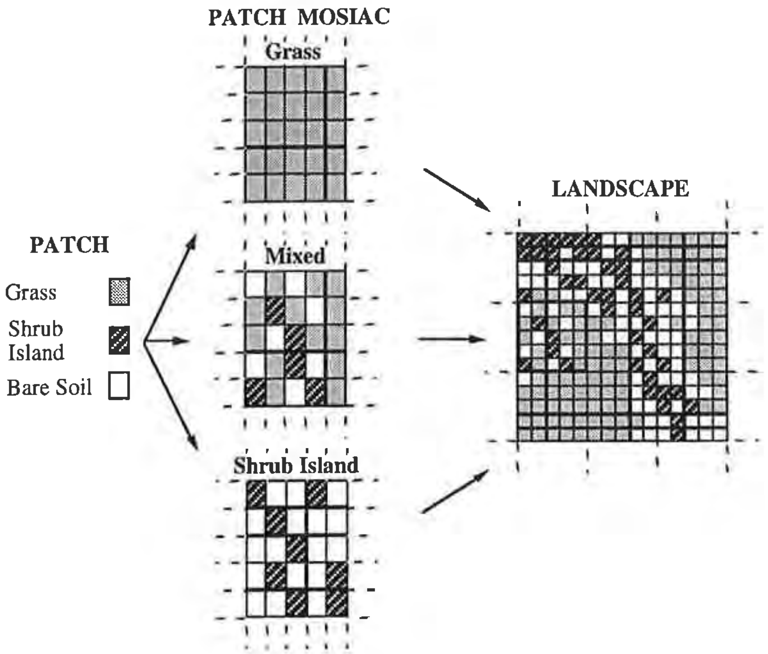


Table 3. Ecosystem functional types used in models of desertification.

	Typical Ecological Scales of Interest					
	Spatial	**Temporal**	**Internal Distribution of Soil Resources**	**Ecosystem Functional Types (EFTs)**	**Dominant Functional and Structural Characteristics of EFT**	**Typical Ecological Model Outputs**
Patch	c. 10 m^2	Hours, Days, Weeks	Uniform	Grass	High canopy cover Shallow-rooted Tight coupling of biological processes (e.g., photosynthesis) to soil moisture	•Primary production (photosynthesis, respiration) •Growth, allocation & herbivory •Phenology, reproduction, & mortality •Decomposition & nutrient dynamics •Water use & balance
				Shrub Island	Low canopy cover Shallow and deep-rooted Coupling of biological processes to soil moisture is species dependent	
Landscape	c. 1-10 km^2	Months, Years	Uniform	Grass Patch Mosaic	High infiltration rate of rainfall Infrequent horizonal transport of water and nutrients Biotic processes confined to upper soil layers Topographic position (determines input and outputs of nutrients due to horizonal transport) Standing biomass	•Water budgets and dynamics (e.g., overland flow, infiltration, run-on, run-off, etc.) •Spatial patterns of evapotranspiration •Fluvial patterns and processes (including movement of soil, nutrients, detritus) •Spatial patterns of trace gas fluxes (e.g., ammonia volatilization) •Net productivity
			Variable, depends on composition of Patch EFTs	Mixed Patch Mosaic	Frequent horizonal transport of water and nutrients Patch composition Patch configuration Directional flowpaths for water movement Standing biomass	
			Heterogeneous	Shrub Island Patch Mosaic	Cycling of nutrients confined to zone beneath shrubs Effective infiltration of rainfall confined to area under shrub canopies Frequent horizonal transport of water and nutrients Patch composition Patch configuration Directional flowpaths for water movement Low canopy cover Standing biomass	
Regional	c. 50-100 km^2	Years, Decades, Centuries	Variable, depends on degree of deserti-fication	Vegetation Functional Types	Percent plant cover Areas of resource accumulation Areas of resource losses	•Cover (LAI) •Deciduousness/Phenology •Vegetation height and patchiness •Trace gas fluxes

to a landscape and regional framework (landscape and regional models) (Fig. 16). Our approach is to build a suite of models that allow us to address questions at different temporal and spatial scales and then to use various simplification and aggregation schemes to translate this information to other scales (see Reynolds et al. 1993).

a. **Hydrology Models.** The hydrology modeling effort will be led by Dr. Athol Abrahams (SUNY, Buffalo), as described in Section 2, #3d (page 26-27). Hydrologic models will be developed at two scales--RILLS will describe small-scale processes and HILLS will describe large-scale, landscape processes. The transport models of water, sediment and solutes are critical in developing the landscape and regional models described below.

b. **Ecosystem Functional Types** (EFTs). The basis for our development of models of desertification in the Jornada Basin is the use of ecosystem functional types (EFTs). EFTs represent a simplification of vegetation into groups that show similar responses to environmental change (Gitay and Nobel, in press). However, rather than vegetation, we use the distribution of soil resources as an index of ecosystem structure and function to define patch mosaic and regional ecosystem functional types (Table 3). These EFTs possess heterogeneity at different spatial and temporal scales. We suggest that the characteristics of these EFTs represent distinct degrees of heterogeneity that are relevant to understanding and predicting ecosystem behavior at different scales (Kolasa and Rollo 1991).

Patch EFTs. We delineate patch size as a function of the size of a single type of plant (grass clump, shrub, or bare) growing on a homogeneous soil type (e.g., sandy-loam soil) (c. 1-10 m^2). We identify two general types of vegetation patches: grass and shrub island. In southern New Mexico, a grass patch is dominated by grasses such as black grama (*Bouteloua*) whereas shrub island patches are dominated by shrubs such as mesquite and creosotebush. A shrub island patch is composed of a single shrub, representing a "hot spot" or an "island" of biological activity within a matrix of relatively barren soil. The behavior of patch EFTs is determined by the functional and structural properties of the plants (grasses or shrubs), the interactions of the plants with their immediate abiotic and biotic environment (see Table 3), and the strength of autogenic factors operating at this scale.

Patch Mosaic EFTs. A unit of land consisting of contiguous patch EFTs forms a patch mosaic EFT. Patch mosaics range in size from c. 1 ha-1 km^2, although delineation of the size is arbitrary. We define three types of patch mosaics for modeling desertification: grass (composed solely of grass patch EFTs), mixed (grasses, shrubs and bare soil), and shrub island (composed solely of shrub island EFTs and bare soil) (Fig. 17). The behavior of a patch mosaic EFT is a function of its composition, configuration, and dominant flowpaths (Table 3). These characteristics are important in determining the behavior of a particular mosaic, e.g., the effect of vegetation on hydrologic flow (Pickup 1985, Rostagno 1989, Turner and Gardner 1991), seedling establishment (Montana et al. 1990), and exchanges of water, organic matter, propagules, nutrients, sediments, etc. (Sklar and Constanza

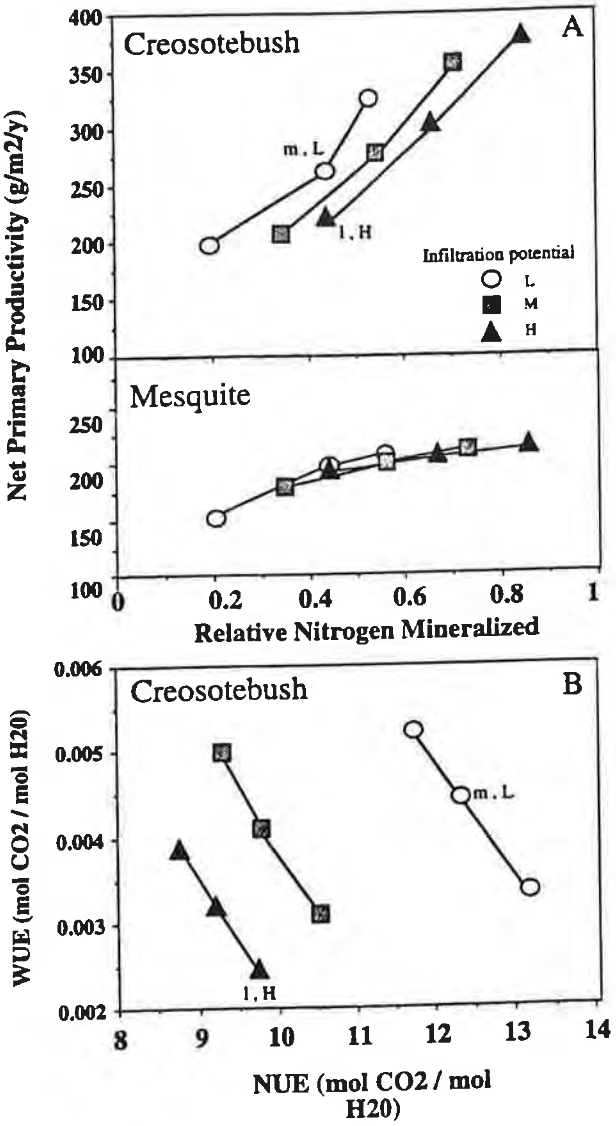


Figure 18. The behavior of creosotebush and mesquite patch EFTs as described by PALS. Recently established shrubs on bare or compacted soils are assigned low N-min potentials and low infiltration rates; well-developed islands are given high levels of each. Differing degrees of island formation are modeled by choosing values for parameters in PALS that control N-min potentials (l = low, m = medium, h = high) and infiltration (l = low, m = medium, h = high). All other parameters and initial states are held constant for 1-year simulations in a 3 x 3 factorial design of these combinations using the 1986 climatic data from the Jornada as driving variables. The relative responses of these two patch functional types are shown, where for each infiltration rate, there are three levels of N-min, representing different N-min potentials. From Reynolds et al. (in press).

1991). In the case of landscapes, distinct geomorphic surfaces (e.g., alluvial fans, piedmonts) or topographic features (e.g., watersheds) often form natural boundaries (Wondzell et al. 1987).

Regional EFTs. We define a region to be from ca. one half to a full grid cell (1° x 1°) in size, containing many complex landscapes. At this coarse scale, our definition of regional EFTs is analogous to the general Vegetation Functional Types of Walker (in press), that is, semiarid grassland and arid shrublands.

c. **Models of Desertification.**

Patch Dynamics. Over the last ten years, Reynolds and coworkers have focused on constructing various process models of biotic and abiotic controls on carbon, nitrogen, and water fluxes in deserts. This work has relied heavily on data collected and archived from LTER I. For example, we have models to simulate the vertical soil temperature profile based on surface conditions (SOTEMP, Kemp et al. 1992), decomposition (GENDEC, Moorhead and Reynolds 1991, 1992), vertical distribution of water in soil (SOWAT, Moorhead et al. 1989, Kemp et al. 1993), plant phenology (PHENAN, Bachelet et al. 1988), soil microfaunal dynamics (GENBUG, Moorhead et al. 1987), and plant growth (GEPSI, Reynolds et al. 1992).

Recently, we completed the initial version of an ecosystem model--coined the Patch AridLands Simulator (PALS), which is based on these various process submodels. We ran a series of simulations with PALS (Reynolds et al. in press) to examine the relationships between N-mineralization (N-min) rates, runoff/infiltration characteristics[3], and net primary production (NPP) in creosotebush and mesquite shrub island patches. We hypothesized that during the process of island formation (i.e., structure), changes in water (e.g., the amount and distribution of infiltration) and nutrients (e.g., rates of N-mineralization) have an important impact on the functional response of a patch EFT to its environment. In one set of simulations, there was an increase in net primary production and soil N mineralized with increases in infiltration in the creosotebush patch (Fig. 18). NPP was more strongly related to total N mineralized than to amount of infiltration.

Several different combinations of N-min potentials and infiltration caused similar amounts of N mineralization but showed differences in production. For example, the m,L island had 266 g of total shrub production compared to 219 g in the l,H island for the same amount of nitrogen mineralization (Fig. 18a). This probably occurred because the m,L island had both greater water-use efficiency (WUE) and nitrogen-use efficiency (NUE) than the l,H island (Fig. 18b). These resource-use efficiencies are not model parameters but instead are a function of the timing and amount of growth, N availability, and rainfall. For each level of N-min potential, increasing infiltration resulted in decreases in both NUE and WUE.

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[3] Initially approximated by Soil Conservation Service curves. These will eventually be replaced by the predictions of the RILLS model.

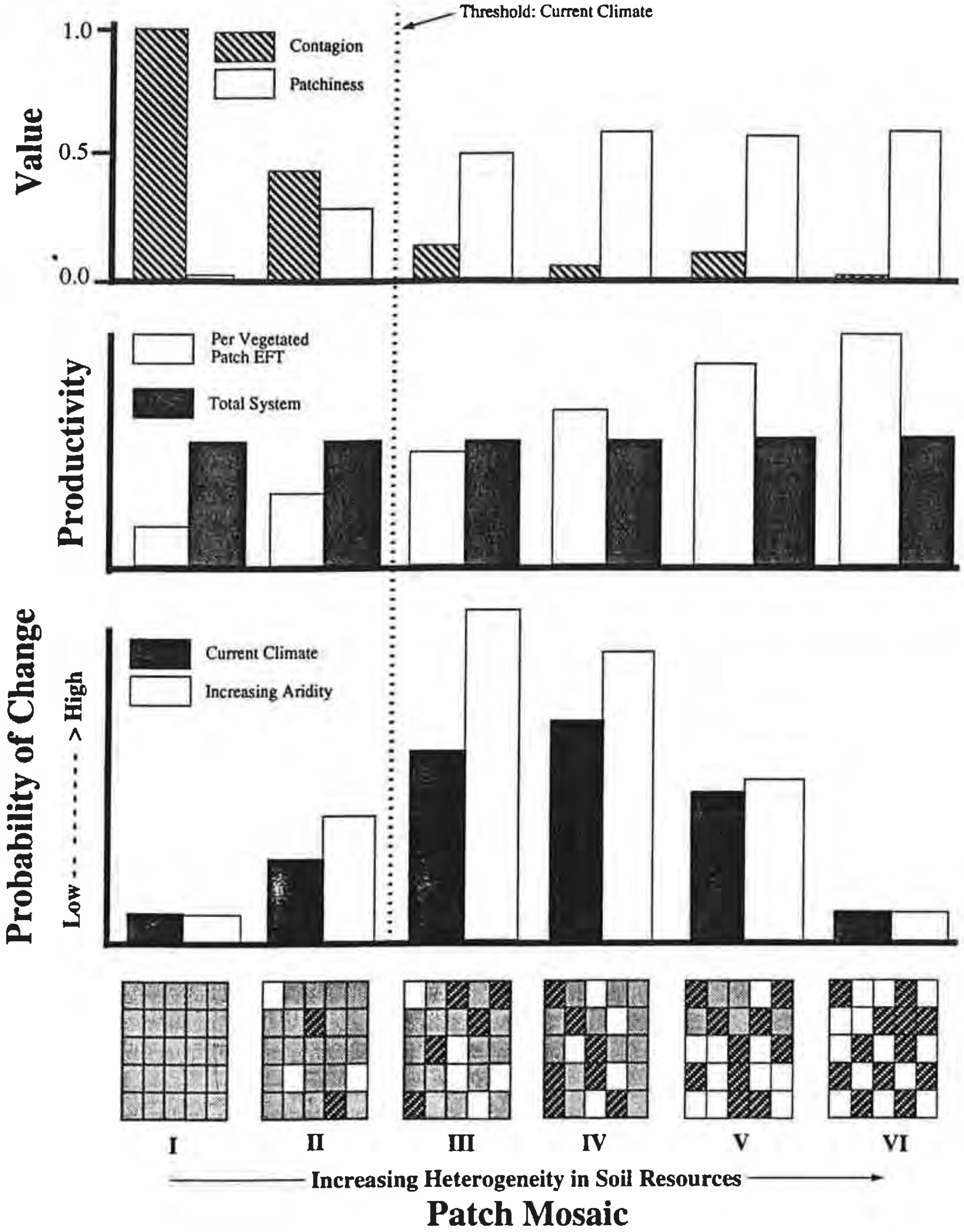

Figure 19. Patch mosaics of various compositions and configurations that occur during desertification are shown, ranging from grass (I), mixed (II-V), to shrub island (VI). For each mosaic, the probability that it will persist is shown for both current climatic conditions and for conditions of increasing aridity. These probabilities are a function of the composition and configuration of the specific patch mosaics shown; these same probabilities apply to regional dynamics, i.e., the balance of the "teeter-totter" model of Figure 5 (opposite page 17), if the region is dominated by landscapes of a given patch mosaic. In most cases regional stability will be a function of mosaics in various stages of desertification. From Reynolds et al. (in press).

In contrast, within each of the infiltration potentials (low, medium, high), increasing N-min potential caused decreases in NUE, but increases in WUE. Increases in soil water and N had much less effect in the mesquite shrub island EFT (Fig. 18a). During LTER-III these model predictions will be tested by Dr. Gutschick's measurements of water-use efficiency of vegetation in different habitats (p. 25).

Landscape Dynamics. When shrublands replace grasslands, landscape processes change (Schlesinger et al. 1990). Shrub encroachment may lead to the formation of erosion zones (Pickup 1985), which affect fluvial transport across the landscape. Greater overland flow during rainstorms lowers the recharge of soil moisture over large areas of the landscape, but it augments the infiltration of moisture to the soil beneath ephemeral streambeds, seasonal lakes, and other local areas where water accumulates (Stafford Smith and Morton 1990). As suggested by Noy-Meir (1985) when rainfall in arid lands is redistributed by local run-off, those parts of the landscape that are a source of runoff will have limited vegetation, while local areas that receive "run-on" will support significantly greater amounts of plant biomass, especially shrubs (Schlesinger and Jones 1984, Coughenour and Ellis 1993). Noy-Meir (1985) further suggests same amount of precipitation may result in a higher overall regional productivity than if it were distributed evenly across the landscape. In a number of arid zones the existence of dense vegetation stripes alternating with bare areas is attributed to heterogeneity in the redistribution of rainwater (Montana et al. 1990). Thus, the greater redistribution of moisture in arid shrublands vs. semiarid grasslands contributes to regional heterogeneity in the distribution of soil resources, promoting the establishment and persistence of shrubs.

We hypothesize that there is a threshold of stability (i.e., the balance of the "teeter-totter" in Fig. 5) between semiarid grassland vs. shrubland ecosystems that is predictable from the dynamics of patch mosaic EFTs. If a region is dominated by grass patch mosaics, it will persist as a grassland, both under current climatic conditions and with short periods of aridity (Fig. 19). These systems are relatively stable because the feedback mechanisms operating at the patch scale in our desertification model (Fig. 1) are strong and, hence, the distribution of resources (mainly water and nitrogen) will remain relatively homogeneous. In contrast, there is a high probability that a mixed mosaic will not persist in its present state. The various autogenic factors that contribute to greater redistribution of resources are operable, which will lead to a greater redistribution of resources and the further invasion of the mosaic by shrubs.

A patch mosaic dominated by shrub island EFTs and bare soil represents a highly desertified landscape. This system is stable (low probability of change) under both current climatic conditions and increasing aridity. Mosaics III-V represent landscapes at increasing stages of desertification. Under today's climatic conditions, these landscapes are not stable but are changing (at different rates) towards a configuration similar to the shrub island mosaic. We predict that the rates of desertification might be increased under conditions of increasing aridity. Since desertification is not so much associated with a loss of plant productivity as with a change in its local distribution on the landscape, our conceptual model predicts that total system production will remain unchanged in spite of differences in patch EFT production (Fig. 19).

Is it possible to quantify the threshold that tips the balance in favor of increasing desertification? Can knowledge about small-scale patch structure and function help us to better understand the larger-scale process of landscape desertification? Since our model predicts that desertification is largely driven by increasing heterogeneity of resources, we believe that an understanding of the mechanisms of patch formation and persistence (using patch EFTs) along with the use of landscape properties (using patch mosaic EFTs) will allow us to extrapolate to a regional scale.

REGALS: REgional General Arid Land Simulator. For LTER-III, we propose to develop REGALS, a spatially-explicit, coupled process transport model based on HILLS, SEMPI and DUST (Fig. 16). We have already developed the Spatially Explicit Model of Plant Interaction (SEMPI), in which we are investigating the consequences of neighbor interactions (intra- and inter-specific) using different model configurations of plant competition (e.g., compensatory vs. noncompensatory growth of root systems, canopy interactions of shrubs and grasses, etc., (Brisson and Reynolds, in press)). SEMPI is an individual-based model, with explicit spatial relations, that captures plant-plant neighborhood interactions (Pacala and Hurtt 1993). Our initial simulations show that the nature of the interaction can have important effects on population dynamics. Presently, plant growth in SEMPI is described empirically. Our next step is to couple PALS and SEMPI to obtain a process description of plant growth during competition and in an ecosystem context. We have a prototype module that couples PALS and SEMPI and interfaces to the Jornada GIS via a spatial information system (SIS). These LTER modeling efforts capitalize on the data gathered as a result of Laura Huenneke's current BLM-funded investigations of desert plant populations at the Jornada (see p. 38).

In REGALS, we will use the Spatial Information System (SIS), a C^{++} GIS toolkit developed in our laboratory and successfully applied in modeling arctic landscapes (Ostendorf and Reynolds, in press, Ostendorf 1993), to interface spatial data and process models (Fig. 16). The SIS is a library of computationally efficient C^{++} routines that allow mathematical operations on entire layers and a comfortable syntax to access single pixels. Several data formats can be read and written, which enables the easy exchange of information between different GIS and graphic applications (e.g., ERDAS, ARC-INFO, MPA, IDRISI, and the graphic formats GIF and HDF).

Given their differing physiognomy, grasslands and shrublands are easily differentiated in remote sensing (Warren and Hutchinson 1984, Prince and Justice 1991), and recognition of the striking differences in ecosystem function between semiarid grasslands and desert shrublands -- as distinctive functional types -- may allow us to predict the significance of such shifts to global ecosystem function (Schlesinger et al. 1990). If we recognize semiarid grasslands and desert shrublands as "vegetation functional types," we find that they differ in a variety of ecosystem properties (Table 3, Figure 19), and a change in the regional extent of desert shrubland has the potential to cause significant changes in global properties. REGALS will contribute to the refinement of these vegetation functional types for use in global modeling activities as described in Solomon and Shugart (1993).

5. Data Management.

Data management for the Jornada LTER project provides protocol and services for data collection, verification, organization, archives, and distribution. We conduct data management procedures in accord with recommendations and guidelines developed by the LTER Data Managers group.

Data managers interact with researchers during the entire scientific process--from the initial planning of sampling designs and field data collection to archiving and distribution of long-term data. The goal of data management is to build and maintain a database of Jornada LTER data files that are fully documented, error free, and organized in useful ways. Our protocol for data collection and processing seeks maximum interaction between researchers and data management personnel to avoid confusion and potential loss of data or problems with integrity of data.

The data manager helps researchers to construct data forms that allow convenient data entry and analysis. Data documentation forms are completed by principal investigators prior to data entry. Data are entered into computer data files by data entry personnel using programs that error-check and verify the data as it is entered. Computer files are subjected to further verification by graphing and/or error-checking programs, and/or examination by field investigators. Error-checked data files are stored with associated documentation files on floppy disks and on a hard-disk database. Back-up data files are maintained as "hard-copy," on multiple floppy disks, and on read/write 30-yr magneto-optical disks. Various sets of these data are stored at different sites on the NMSU campus.

LTER-II data sets and core data sets are currently fully documented and entered into a hard disk database. We are utilizing a 486-PC MS-DOS based computer as our database file server (see description of facilities, Appendix IV). Data files are arranged in a network of directories and subdirectories by subject. Data documentation files (now referred to as metadata) are present with all data files. We are developing a format to enter the metadata into the Foxpro relational database. Metadata for the GIS and remote sensing databases will also be maintained in the relational database. Data files are readily transferred through a local campus-wide network and Internet using an ethernet connection and communications software, allowing data transfer world-wide.

Data and documentation files are stored in ASCII format. ASCII files are readily transferred from one computer system to another via electronic mail, and ASCII files are readily imported into most statistical analysis software. Data manipulations and statistical analyses are made with Quattro Pro spreadsheet and Foxpro2 relational database management system PC-based software, and SAS on the NMSU mainframe computer. A data catalog and key word listing are maintained for Jornada data sets.

Data access is restricted to the Principal Investigator responsible for the data. Data requests are treated on a case-by-case basis. Meteorological data are the only data for which no prior authorization is required. All other data requests require that the principal investigator responsible for the data authorize its release.

Appendix VII contains a number of forms that illustrate our data management procedures, including a Research Project Abstract Form and a Data Set Documentation Form, filled in, as an example of data gathered from our long-term animal transects.

6. Intersite and LTER Network Activities.

Researchers from the Jornada LTER participate in a large number of LTER Network activities and other cooperative efforts, as outlined in Appendix VIII. The following describes the more important of these efforts:

LIDET (Long-term Intersite Decomposition Experiment Team). The Jornada is one of the core sites participating in the comparative study of decomposition, organized by Dr. Mark Harmon of Oregon State University. Foliage of *Larrea tridentata* is a particularly interesting addition to this project, since it has unusually high contents of both lignin and nitrogen. The site provides the extreme of high temperature and low moisture among those in the LIDET network (Fig. 9). One of our collaborating scientists, Dr. Daryl Moorhead of Texas Tech University is charged with the development of a predictive cross-site model of litter decomposition for the LIDET network, based on the litter decomposition submodel of PALS (Moorhead and Reynolds 1991).

TRAGNET (U.S. Trace Gas Network). Currently coordinated by Dr. Elisabeth Holland (NCAR) and Dennis Ojima (Colorado State University), the trace gas network is a plan to organize and coordinate a series of standard measurements of trace gas emissions from soils in a variety of ecosystems, in which LTER sites play a focal role. TRAGNET is part of an international network proposed by the International Global Atmospheric Chemistry (IGAC) project of the International Geosphere Biosphere Program (IGBP). The Jornada was represented at the initial trace gas workshop by Anne Hartley of Duke University, who will be responsible for the development of the TRAGNET effort at our site during the next few years. The overall goal of TRAGNET is to provide baseline data on trace gas fluxes in a form that can be incorporated to provide the land-atmosphere feedback in global circulation models of future climate.

Uv-B Network. Established by the U.S. Department of Agriculture, the uv-B network is to provide a set of sites around the U.S., in which changes in the surface influx of ultraviolet-B radiation are monitored. Coordinated by Dr. James Gibson of Colorado State University, the network includes core sites which maintain scanning spectral radiometers and ancillary sites with broad-band instruments. On the basis of its excellent site conditions and ongoing program of other meteorological measurements, the Jornada was selected as a core site in this network. Our participation in this network is particularly important inasmuch as we believe that uv-B radiation may be a major mechanism of litter decomposition in desert environments (Moorhead and Reynolds 1989).

The Desert Winds Project. The Jornada hosts one of the 5 Geomet stations established and operated throughout the Southwest by the U.S. Geological Survey. The project was established in 1979 by Dr. Carol Breed of the USGS in Flagstaff, Arizona. Each Geomet station collects continuous data on the concentration of wind-borne particles and boundary layer meteorological conditions that control wind erosion of soils. The data are relayed via the GOES satellite to the USGS computer center in Flagstaff.

Other Projects. The Jornada LTER is a cooperating site in two projects funded as NSF-supplements to the CPER LTER site. One project led by Dennis Ojima and Bill Parton seeks to modify the CENTURY model to serve in a wide variety of ecosystems, while the other project, led by Ingrid Burke and Debra Coffin, will make comparisons between *Bouteloua gracilis* ecosystems of CPER to the *Bouteloua eriopoda* ecosystems of the Sevilleta and Jornada LTER sites. We have sampled soils at both the Jornada and Sevilleta LTER sites for an analysis of spatial patterns using geostatistics (Schlesinger et al., in prep). Our proposed LTER experiment on small mammal effects on desert ecosystems (p. 20-21) also represents a cross-site activity within the LTER network. It is coordinated by Dr. David Lightfoot, who will be funded jointly by the Jornada and Sevilleta LTER projects.

With funding from the NSF Division of Polar Programs, Ross Virginia is collaborating with Diana Freckman (Co-PI for the Antarctic Dry Valley LTER) to conduct investigations of the ecology, spatial variation, and nematode distributions in the soils of the Dry Valley LTER. This work aims to compare the mechanisms causing differences in the scale of spatial variation in hot and cold desert climates.

Among international cooperations, Schlesinger was a co-organizer of an international workshop on the problems of arid lands in global change (October 1989) and Whitford organized a cooperative workshop (October 1991) with Chilean workers to coordinate comparative studies of desertification between continents. The Jornada is a site in the UNESCO Man and the Biosphere (MAB) Chihuahuan Desert Reserves of the US and Mexico, and our coinvestigators frequently represent the site at meetings of that consortium (see Appendix VIII). Laura Huenneke has initiated plans for comparative work on shrub demography and plant community structure with Dr. Carlos Montana (Mapimi Biosphere Reserve, Mexico). She is part of a NSF-supported group that will visit Mapimi in April 1994 to explore various ways of extending ecological research across the Chihuahuan desert. The USDA/ARS, the University of Juarez (Biomedical College), and the University of Mexico City (Chemical

Institute) have a formal MOU for ethnobotanical surveys in pursuit of pharmacological uses of native plants of the Chihuahuan desert.

7. Related Research Projects.

The presence of the LTER at the Jornada Experimental Range has attracted a variety of other research projects that offer added dimensions to the core LTER research (see Appendix I). Among the principal investigators, Dr. Laura Huenneke currently holds $95,000/yr in funding from the Bureau of Land Management's (BLM) Global Change Program to support her studies of plant community dynamics in the Jornada basin. The population dynamics of *Larrea tridentata*, its size-density relationships, and its seedling establishment have been investigated in a variety of habitats--providing an added dimension of population biology for our simulation modeling of ecosystem function. Dr. Huenneke's efforts in NPP and biomass studies are closely linked to a NASA-funded ($147,000) project of Dr. Janet Franklin (San Diego State University), who has developed methods for estimating shrub biomass in patchy habitats using remote sensing. Dr. Vince Gutschick holds $92,000 in funding from NOAA to develop a mechanistic understanding of the controls of transpiration by desert shrubs. His work interacts strongly with our LTER efforts to develop the transpiration submodel of PALS.

Throughout LTER-II, co-principal investigators Drs. Jim Reynolds and Ross Virginia have been funded by NSF ($844,000; Ecosystem Studies) to investigate the control by summer vs. winter rainfall of the activity of *Larrea tridentata* and *Prosopis glandulosa*. They have established a network of rainout shelters on the Jornada, in which a variety of physiological measurements are made on enclosed shrubs. The work is directly relevant to predicting the response of this species to various scenarios of global climate change, and with a favorable review of their renewal proposal in autumn 1994, we expect that it will continue for the duration of LTER-III. Finally, Wesley Jarrell (Oregon Graduate Center) holds $80,000 in funding from the U.S. Department of Agriculture to understand the dynamics of soil fertility during the transition from grassland to mesquite (*Prosopis glandulosa*) dunelands on the Jornada.

The LTER is fully cooperative with the ongoing research programs of the U.S. Department of Agriculture, Agricultural Research Service, Jornada Experimental Range, and the proposed new initiative to understand the effects of grazing on desert lands (Section I) is a cooperative USDA/LTER project. Dr. Kris Havstad is a principal investigator on both USDA and LTER proposals. The overall objective of the USDA program at the Jornada is to understand the effects of natural and anthropogenic stressors in desert environments. Through the collaboration of Dr. Walter Whitford, the USDA and the Environmental Protection Agency (EMAP) have entered into a cooperative research agreement to identify indicators of stress in semiarid and arid ecosystems at the Jornada (Appendix VI).

Several investigators have projects that are currently under agency review for potential funding to support work on the Jornada during LTER-III. These include Jack Schultz (Penn State; for studies of chemical controls on herbivory), Andrew Stephenson (Penn State; for studies of the population biology of *Cucurbita*), and William Boecklen (NMSU; for studies of the relationship between the distribution of *Ephedra* and soil nutrients on the LTER-I transect). Dr. Kay Gross (Michigan State) hopes to develop an EROL proposal to NSF to investigate the distribution of desert annual plants relative to soil microsite heterogeneity at the Jornada.

8. Dissemination of Information

Communication of knowledge gained by Jornada scientists has been achieved in five primary areas: student training and education, the annual "Friends of the Jornada" symposium, creation of a Jornada research bibliography, participation of Jornada scientists in professional meetings and conferences, and consultations with federal and state agencies.

Many graduate students, postdoctoral researchers, and undergraduates have received research training in the Jornada LTER program (see Appendix IX). Most notable has been our participation in the REU program, in which 3 NMSU undergraduates (frequently including female and minority students) each year have been supported and trained in ecological research. In the past 2 years, REU student support has been the genesis of interest that has drawn additional NMSU faculty into LTER activities (P. Herman and C. Monger).

The "Friends of the Jornada" Symposium is held each May in Las Cruces, to bring researchers together to exchange results and plans, and to facilitate collaborations and interdisciplinary work. A full day of research presentations is followed by a day of active discussions and working group meetings; attendance and participation have grown steadily (the third annual meeting, in 1993, attracted about 100 people to the scientific session). The program from the 1993 symposium is included as Appendix X.

A bibliography of Jornada basin research, first compiled by Conley and Conley (1984), has been updated, computerized, and maintained in the Jornada LTER office. We are currently arranging with the NMSU Agricultural Experiment Station to publish and distribute the updated version as a N.M. Agricultural Station Bulletin.

Jornada researchers consistently participate in regional, national, and international meetings. Over the past few years, Jornada scientists have presented results to meetings of the Ecological Society of America, the Association of American Geographers, the Annual USGS PACLIM Workshop, the BLM Global Change Research Workshop, the American Society of Microbiology, the Annual New Mexico Water Conference, the Soil Science Society of America, the Association of Ecosystem Research Centers, the American Association for the Advancement of Science, and the International Association of Geomorphology.

Several Jornada researchers (Schlesinger, Huenneke, Whitford, Havstad) have provided extensive consultations to the US Bureau of

Land Management (BLM) regarding desertification and management of arid southwestern rangelands. Whitford continues to provide a formal link between the LTER and the EMAP program for arid lands organized by the Environmental Protection Agency, and Reynolds and Havstad have provided formal input to the EMAP program. Schlesinger has been asked to testify before several congressional committees on the scientific issues key to the preservation of desert ecosystems in the Southwest.

9. Archives and Inventories of the Jornada LTER

Plant vouchers from the Jornada LTER site are maintained as a separate collection within the NMSU Biology Department Herbarium. The LTER collection is continually being expanded to include all plant species present on the Jornada Basin. The herbarium at NMSU was founded in 1888 and now houses 50,000 specimens. Its present emphasis is to develop an excellent collection of the floras of New Mexico, the Chihuahuan Desert, and northern Mexico. The collection is curated by Dr. Richard Spellenberg, who maintains an active loan and identification program.

The Museum of Entomology in the Department of Biology of NMSU has approximately 50,000 specimens in its collection. Of those about half have been identified. Material from New Mexico and the Chihuahuan Desert is best represented. The taxonomic groups best represented are those families that are most abundant in lowland areas such as the Jornada Experimental Range. This is the oldest and largest collection in the state of New Mexico. An appreciable number of the specimens were added to the collection at the turn of the century, providing a good basis for studies of change in insect biodiversity. A joint Entomology/Plant Pathology Department collection consists of approximately 25,000 pinned specimens with an alcohol reference collection of arachnids. In addition to these collections, the LTER maintains an archive of arthropods collected from the LTER-II pitfall grids, from June 1988 to the present (about 525 specimens). The voucher collection has code names referable to the names in the LTER-II long-term data sets. A similar archive of soil microarthropods from the Jornada basin and other areas in New Mexico is maintained as a collection of 1040 permanently fixed and mounted slide specimens.

The Vertebrate Museum in the Department of Biology includes approximately 10,000 specimens of mammals, 2,000 of birds, and 6,000 of reptiles. Geographical representation stresses the southwestern U.S.

A variety of photographic archives are also maintained by the LTER. All stations on LTER-I control and treatment transects, 0.5 x 0.5 m quadrats, were photographed at 2-week intervals during period August 1982 - June 1986. At the start of LTER-II, slides were taken of the 15 core NPP sites in Spring 1989, and aerial photographs were taken in July 1989. The U.S. Department of Agriculture also maintains a photographic archive of more than 3000 frames taken from 1915 through the 1940s of sites in the Jornada basin and southern New Mexico. Many of the points can be relocated in the field for contemporary repeat photography (e.g. Fig. 3 of this proposal).

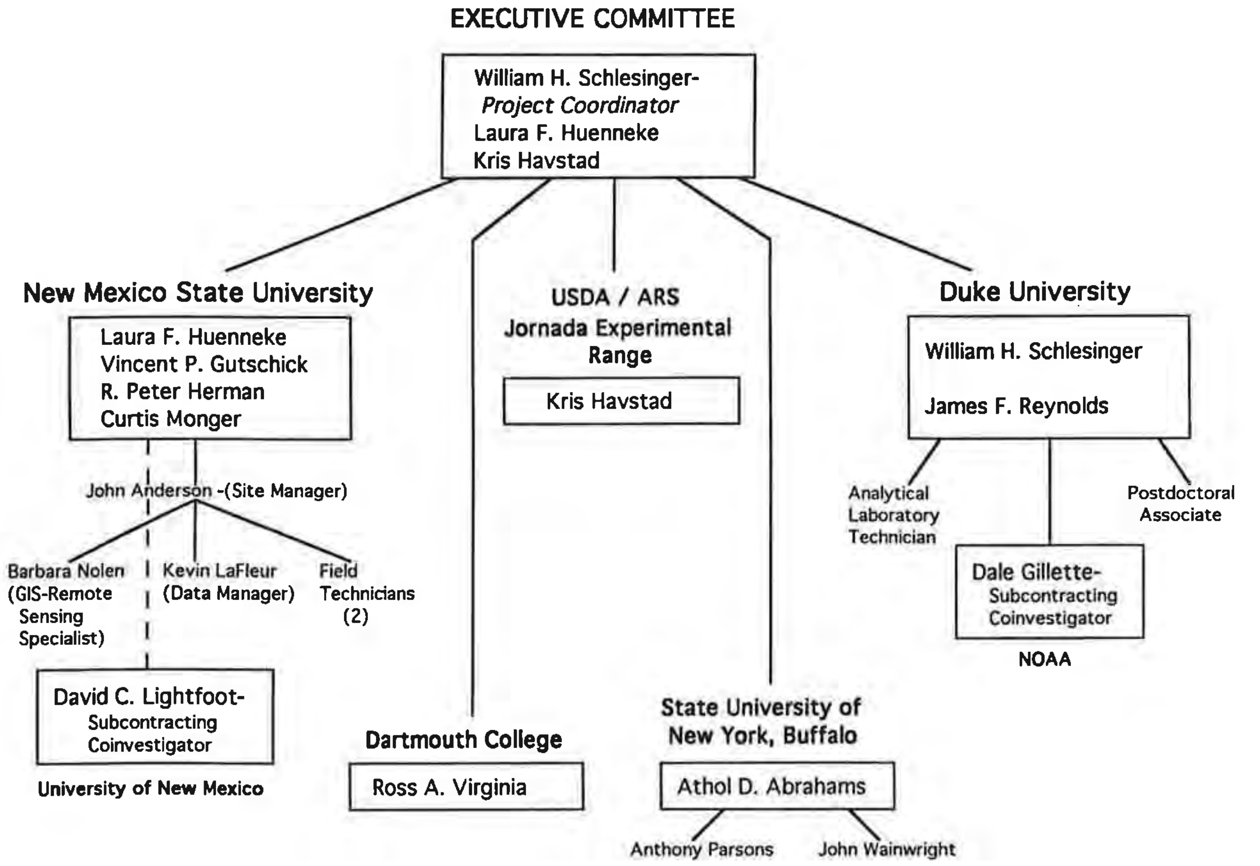

Figure 20. Management chart for Jornada LTER-III; Principal Investigators are enclosed in boxes.

The Jornada Data Management Office maintains a variety of regional data in a Geographic Information System, including (with source) layers for:

Elevation	USGS	(see Fig. 12)
Hydrology	BLM/USDA	
Roads	USGS/BLM/USDA	
Land Ownership	BLM	
Rain gages	LTER/USDA	
Watering points	LTER	
Fences	LTER/USDA	
Geology	N.M. Department of Mines	
Soils	USDA/SCS	
Stream channels	USGS	
Vegetation	USDA	
Grazing History	USDA	
Digital Landsat Images	LTERNET	

The location of anthropogenic features in these data sets has been validated by use of the Global Positioning System (GPS) in the Jornada basin in October 1992.

10. Leadership, Management, and Organization.

The Jornada LTER has undergone a complete transition of scientific management (see footnote, page 2), yet it has survived with a vibrant ongoing program of field research. Moreover, through an active program of networking, we are able to maintain a research program in which a large proportion of the investigators are "non-resident." We make daily use of electronic mail (Internet and LTERnet), monthly use of conference telephone calls, and quarterly convening of meetings at the site to maintain all levels of communication. The "Friends of the Jornada" symposium is an important forum for the exchange of ideas and for the development of group unity among graduate students, technicians, and principal scientists in the pursuit of a common goal. Our local site director, data manager, and GIS-expert, as well as several graduate students, have all participated in the preparation of this proposal.

Our plan for management of LTER-III is shown in the organizational chart (Fig. 20). Decisions regarding the conduct of science are made at group meetings of the principal investigators, with consultation of the site manager, John Anderson, regarding potential site conflicts. Decisions regarding the reallocation of financial resources are made by the Executive Committee.

Daily operation of the site at New Mexico State University is coordinated by John Anderson, who reports to Dr. Peter Herman. John Anderson maintains daily budgetary oversight at NMSU, with Dr. Vince Gutschick holding the official NMSU faculty signatory power. Dr. Laura Huenneke represents the site in collaboration with the Sevilleta LTER and with our international cooperations at Mapimi.

We have a standing committee of external advisors, Drs. William Lauenroth (Colorado State), Pamela Matson (UC, Berkeley), and John

Pastor (U. Minnesota, Duluth). This group met at the site in May 1991 to offer fresh perspectives on our progress and to make recommendations for improvement. The site was also reviewed by NSF in July 1991 by a team headed by Dr. James Schindler.

11. New Projects and Technologies

We are investigating several innovative technologies to apply to our long-term research. Dr. Vince Gutschick is developing enhancements for time-domain reflectometry (TDR) to measure spatial variations in soil moisture. These involve structural and electrical modifications of the probes to generate signals (echoes) from intermediate locations along their length, allowing measurements of soil moisture in individual depth intervals. Dr. Jan Hendricx of the New Mexico Institute of Mining and Mineral Resources (Socorro) is also developing new ways to measure moisture in desert soils using electromagnetic induction. He uses our measurements of soil moisture along the LTER-I transect as validation data to test his instrumentation.

The Spatial Information System (SIS, p. 34) developed by Dr. James Reynolds was initially designed to facilitate the exchange of spatial information with ecological models. However, the system components are useful for a wide variety of other modeling and software development activities. The SIS is raster-based with input routines for polygon data sets. It was derived to allow multivariate floating point arithmetic within a GIS environment, to convert data layers to a traditional integer or byte format that can be used in GIS systems and commercial drawing packages, and to allow basic GIS operations to be called from user programs. The SIS allows software-unlimited (size and storage) access to spatial data, facilitates access of single pixels and entire maps, writes and reads different graphic formats so as to allow the exchange of data with different graphic packages. This speeds visualization and enables data exchange with commercially available GIS packages.

12. Supplemental Support.

Supplemental NSF support during the duration of LTER-II is listed in Appendix I. Research Experience For Undergraduate (REU) Supplements in 1990 ($12,000), 1991 ($14,918), 1992 ($18750) and 1993 ($23,694) have supported 12 students for field projects on the Jornada. These have included 5 females, and 2 students of Hispanic origin--all from the New Mexico State University campus. Supplemental support in 1989 upgraded the computation facilities in the LTER office at NMSU, providing ERDAS and ARC-INFO software, a digitizer, and plotter that are currently used for image processing. A Sun Sparc-4 workstation was also purchased at that time, and while it has been replaced by newer computers in our LTER office, it will be employed by Dr. John Wainwright (Kings College, London) to develop the HILLS and RILLS hydrologic submodels for LTER-III (Fig. 16). The 1993 supplement from NSF included an upgrading of office computer equipment at Duke University for electronic transfers of text and data, including materials used in the preparation of this proposal.

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APPENDICES

Appendix I: Other Related Support

Incremental Funding in effect at the Jornada LTER, 1981-1993

Ludwig, J. (NMSU). "Monitoring desertification trends in desert grassland." $ 120,357 from the U.S. Department of Agriculture (USDA/SEA # 59-2351-1-2-085-0), 1981-1985.

Ludwig, J. (NMSU). "Plant succession as influenced by soil-geomorphic processes." $46,289 from the USDA, Forest Service (RM-81-192-gr), 1981-1982.

Schlesinger, W.H. (Duke) "Processes of soil carbonate deposition in arid ecosystems" $ 450,000 from the National Science Foundation (BSR 82-12466), 1983-1986.

Whitford, W.G. (NMSU) "Role of Nematodes in Litter Decomposition in the Chihuahuan Desert." $ 3000 subcontract a National Science Foundation grant to the University of California, Riverside, 1983-1984.

Wierenga, P. (NMSU). "Solute transport in soil profiles. $28,125 from Battelle Pacific Northwest Labs, 1983-1984

Whitford, W.G. (NMSU). "Decomposition and nutrient cycling in a desert ecosystem." $735,549 from the National Science Foundation (BSR 82-15398), 1983-1986.

Schlesinger, W.H. (Duke) "Plant phosphorus cycling and phosphorus availability in calcareous desert soils." $ 7,680 from the National Science Foundation (BSR 84-13986) as a Doctoral Dissertation Improvement Award for K. Lajtha, 1984-1986.

Conley, W.H. (NMSU) "Implementing a computing support environment for ecological research teams." $65418 from the National Science Foundation (BSR 84-19780), 1985-1987.

Wierenga, P. (NMSU). "Validation of stochastic flow and transport models." $613,228 from Battelle Pacific Northwest Labs, 1985-1989.

Virginia, R.A. (SDSU), W.M. Jarrell and D.W. Freckman (UC, Riverside) and W.G. Whitford (NMSU) "Root symbionts: their role in the productivity of desert ecosystems." $749,000 from the National Science Foundation, 1985-1988.

Reynolds, J.F. and W.G. Whitford (NMSU). "Primary productivity, decomposition, and nitrogen cycling in a desert ecosystem: A modeling synthesis." $270,000 from the National Science Foundation (BSR 85-07380), 1985-1988.

Fisher, F.M. (NMSU) "Decomposition and nitrogen cycling processes in a Chihuahuan Desert ecosystem." $557,958 from the National Science Foundation (BSR 86-04979), 1986-1990.

Wierenga, P. (NMSU). "Validation of the transport equation in unsaturated soil." $$178,166 from the U.S. Environmental Protection Agency, 1986-1990.

Schlesinger, W.H. (Duke) "Denitrification in desert ecosystems of the southwestern United States." $ 12,868 from the National Science Foundation (BSR 87-15128) as a Doctoral Dissertation Improvement Award for W.T. Peterjohn, 1987-1989.

Whitford, W.G. (NMSU) and J.R. Gutierrez (U. La Serena, Chile), " Workshop on desertification: a landscape-ecosystem perspective," $19,431 from the National Science Foundation (INT-89-09480), 1989

Whitford, W.G. (NMSU) NSF/REU (Research Experience for Undergraduates) supplement to "Desertification: Responses of Arid Landscapes and Ecosystems to Resource Redistribution." from the National Science Foundation (NSF) for Grant BSR 88-11160. $12,000 in 1990; $14918 in 1991.

Schlesinger, W.H. (DUKE) "Nitrogen trace gas loss in desert ecosystems." $66,000 from NASA to support Ms. Anne Hartley as a global change fellow during the conduct of her doctoral research. (NASA NGT-30069), 1991-1994.

Huenneke, L.F. (NMSU) "Global change and the dynamics of plant communities in the Chihuahuan desert of southern New Mexico" $285,000 from the Bureau of Land Management (BLM). 1991-1993.

Gutschick, V. and W.G. Whitford (NMSU). "Climatic and 88atmospheric research (climate and global change)" $285,082 from the National Oceanographic and Atmospheric Administration (NOAA NA16RC0435-02), 1991-1994.

Schlesinger, W.H. (DUKE) NSF/REU supplement to "Desertification: Responses of Arid Landscapes and Ecosystems to Resource Redistribution" from the National Science Foundation (NSF) for Grant BSR 92-40216. $18750 in 1992; $23694 in 1993.

Franklin, J. (SDSU) "Canopy reflectance modeling of semiarid vegetation" $147,000 from the National Aeronautics and Space Administration (NASA).

Gutschick, V.P. and W.G. Whitford (NMSU) "Physiological control of evapotranspiration by vegetation: Patterns in plant communities and role in atmospheric coupling of regional ET" $91,853 from the National Oceanographic and Atmospheric Administration (NOAA).

Virginia, R.A., J.F. Reynolds and W.G. Whitford. (DUKE & Dartmouth) "Resource islands: Their role in the stability of desert ecosystems" $844,000 from the National Science Foundation (NSF)

Schultz, J.C. (PENN STATE) NSF/EROL (Expanded Research Opportunities at LTER Sites) supplement to "Impact of Damaged-induced changes in oak Leaves on susceptibility of gypsy moth to a Baculovirus" $ 48230 from the National Science Foundation (NSF) as a supplement to Grant BSR 89-18083.

Jarrell, W.M. (OGC) "Resource Availability in Mesquite/Grassland Systems in the Jornada Basin." $79,732 from the U.S. Department of Agriculture, National Competitive Grants Initiative. 1992-1993.

Monger, H.C. (NMSU). "Soil-geomorphic record of climate change and Quaternary landscape evolution in southern New Mexico." $10,000 from the New Mexico Agricultural Experiment Station.

Reynolds, J.F. (DUKE) "Modeling the response of plants and ecosystems to climatic change." $1,200,000 from the U.S. Department of Energy.

Appendix II: Project Bibliography

(20 representative, significant papers published over the history of the Jornada LTER, 1981-1993)

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Peterjohn, W.T. and W.H. Schlesinger. 1991. Factors controlling denitrification in a Chihuahuan desert ecosystem. Soil Science Society of America Journal 55: 1694-1701.

Reynolds, J.F. and G.L. Cunningham. 1981. Validation of a primary production model of the desert shrub, *Larrea tridentata* using soil-moisture augmentation experiments. Oecologia 51: 357-363.

Santos, P.F., N.Z Elkins, Y. Steinberger and W.G. Whitford. 1984. A comparison of surface and buried *Larrea tridentata* leaf litter in North American hot deserts. Ecology 65: 278-284.

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Appendix III. JORNADA Long Term Data Sets

X Indicates study is listed in Long-Term Ecological Research Network Core Data Set Catalog.

	RESEARCH PROJECT	PERIOD	DESCRIPTION
X	Animal Transects	89-now	Biweekly; flush transects: birds, lizards, rabbits
X	Jornada LTER Weather Station	83-now	Meets Participation Level 2 & 3, Standardized Meteorological Measurements for LTER sites
X	Jornada Precipitation	81-now	Tipping bucket and graduated gage precipitation
X	Hydrology (LTERI)	83-92	Soil surface rainfall runoff and sediment transport data from termite exc
X	Hydrology (LTERII)	89-now	Soil surface rainfall runoff and sediment transport data from desert shru
X	Net Primary Production	89-now	Yearly; Winter,Spring,Fall biomass measurements
X	Pit Fall Traps - Lizard/Arthropod	89-now	Quarterly; lizards-mark/release; arthropods-collection
X	Soil Water Content - NPP	89-now	Monthly; 10 depths; 30-300cm
X	Soil Water Content - Transect	83-now	Monthly; 5 depths; 30-150cm
X	Termite Baits	89-now	Yearly; termite foraging activity
X	Vegetation - Penceline (LTERI)	82-now	Every 5 yrs, spring & fall; vegetation response to grazing release
X	Vegetation - Transect (LTERI)	83-now	83-88 yearly then every 5 years; spring & fall; vegetation spatial & temporal pattern
X	Wet-Dry Precipitation Chemistry	83-now	NO_3,NH_4,Cl,SO_4,Ca,Mg,Na,K,total N,total P

USDA Jornada Experimental Range Long-Term Data Set

Abiotic

- -precipitation, monthly, 29 locations, 1915-present
- -precipitation, daily, 27 locations, 1976-present
- -precipitation (summer), intensity, 27 locations, 1976-1986
- -soil movement, 5-yr measurements, 160 sample points along 2 transects, 1933-1990
- -soil moisture, weekly (soil moisture blocks), numerous sites, 1956-1976

Biotic

- -basal cover, annually, 104 1m*2 quadrats, 1915-1979 (intermittent later years). Quadrats grouped within vegetation types and along grazing gradient.
- -vegetation production, annually, clipping methods, variable locations, 1941-1988
- -vegetation utilization, annually, transects, plant height measurements, 1939-1989
- -vegetation composition, annually, transects, grouped by soil type, intercept measurements, 1957-1977

Livestock

- -stocking, animal days, by pasture, 1920's-present
- -performance, annually, various measures, 1972-present

Appendix IV. Facilities and Equipment

The Jornada LTER investigators capitalize on a wide variety of facilities available at their respective institutions.

Las Cruces, New Mexico:

New Mexico State University The Jornada LTER maintains its local office in the Department of Biology at NMSU. This office houses the site manager (John Anderson), data manager (Kevin LaFleur) and GIS-Remote Sensing Specialist (Barbara Nolen). Their efforts are supported by four 486-personal computers[4], linked via ethernet and modem to the NMSU computation center. The office is a focal point for workers visiting the site and for communications among all investigators throughout the year.

One computer is devoted exclusively to GIS-data management; it contains pcARC/Info and ArcView (display and query) software for GIS, and ERDAS software for image processing. For additional capabilities, LTER workers have access to the NMSU Geographic Applications and Research Laboratory (GARL), where a wide variety of image processing and GIS software is available. Hardware includes a Sun-LX, digitizing tablets, and f/sized color plotters. These capabilities allow field researchers to have immediate access to GIS and remotely-sensed data from the Jornada as they visit Las Cruces.

Most data management (Section 2, # 5, pp. 35-36) is performed within the LTER office, but the ethernet link to the NMSU computation center also makes the services of an IBM Ex/9000 mainframe and a variety of multi-user workstations available to LTER users. Machines on the computer network support a full range of data reduction and statistical services, including SAS and BMDP. These capabilities allow researchers to enter field data and perform initial data analysis while they are visiting the site.

The Biology Department at NMSU also provides the LTER with a large (1820 sq.ft) laboratory, which is fully equipped for the routine field studies of the Jornada, including the processing of vegetation samples (NPP and biomass), consumer studies (e.g., pitfall samples), and basic collections and analysis of soils (drying ovens, balances, grinding mills etc.). The laboratories of individual researchers provide additional equipment for routine measurements, as well as all equipment necessary for the proposed new initiatives in physiological plant ecology (Gutschick) and studies of soil microbes (Herman). The Biology Department maintains 2 vans and 3 pick-up trucks for field work.

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[4] The computer systems at New Mexico State and Duke University described here represent a considerable upgrade of our capability over that reported in the 1991 assessment of comparative technology development within the LTER network, as described in *Technology Development in the LTER NEtwork*, LTER Publication No.12 (Foster and Boose 1991)

New Mexico State University also manages the NMSU Ranch (See Figure 21), where LTER researchers have access to the usual variety of ranch facilities, including storage sheds, a tool shop, 2 wells, and 120/240v power. An 800-gallon water trailer is also available for field irrigation studies. On the NMSU Ranch lands, the LTER maintains 2 equipment trailers, which contain basic equipment for field sampling of vegetation, soils and animals. The LTER weather station is also located on NMSU Ranch property, with a 240v power link to the Ranch. The weather station consists of the standard installation for the LTER network, including instrumentation for recording wind speed, wind direction, total incident solar radiation, relative humidity, precipitation, air temperature, soil temperature (at surface, 1cm, 5cm, 20cm, 50cm, 100cm, 200cm, 400cm, 600cm and 880cm). The Campbell CR10 Data logger for these instruments is linked via telephone line to the NMSU computation center for downloading of field data.

At part of LTER-I, a large ca. 5-m deep trench was excavated on the alluvial slope of Mt. Summerford, for studies of soil water infiltration (Hills et al. 1991, Wierenga et al. 1991). This trench exposed a chronosequence of alluvial deposition and soil development, and it is now roofed and maintained to allow access, examination, and sampling of buried soils.

The U.S. Department of Agriculture, Jornada Experimental Range maintains 2400 sq. ft of laboratory space, and 5000 sq ft. of shop space that is available, if needed, for LTER workers. Its ranch includes all basic facilities for handling livestock, and a wide variety of tractors and earth-moving/fence-building equipment (2 bulldozers, 2 road graders, 1 front-end loader, assorted tractors, portable welders and cutting torches, and a Giddings soil corer).

Laboratory facilities include a gas chromatography/mass spectrometer, high performance liquid chromatography, visible spectrometer, LiCor 6200 field photosynthesis system and leaf area meter, and Troxler neutron probe. Other equipment includes various grinding mills, drying ovens, furnaces, shaker baths, balances and pH meter.

Durham, North Carolina:

Duke University's Department of Botany and its Phytotron Facility provide, in the laboratory of Dr. William H. Schlesinger, full capabilities for the analysis of soil, plant, gas, and aqueous samples for chemical content, including a Perkin Elmer 3100 atomic absorption spectrophotometer, Varian 3700 gas chromatographs, Bran and Luebbe Traacs 800 autoanalyzer, and Dionex 2010I ion chromatograph. The laboratory also contains a wide assortment of balances, pH meters, ovens, shaker baths and centrifuges. The Duke Phytotron facility includes a VG Isotech Sira Series 2 mass spectrometer for analysis of plant tissue isotope ratios, and a wide variety of growth chambers in which constant, specified environmental conditions can be maintained for studies of plant growth and soil crusting.

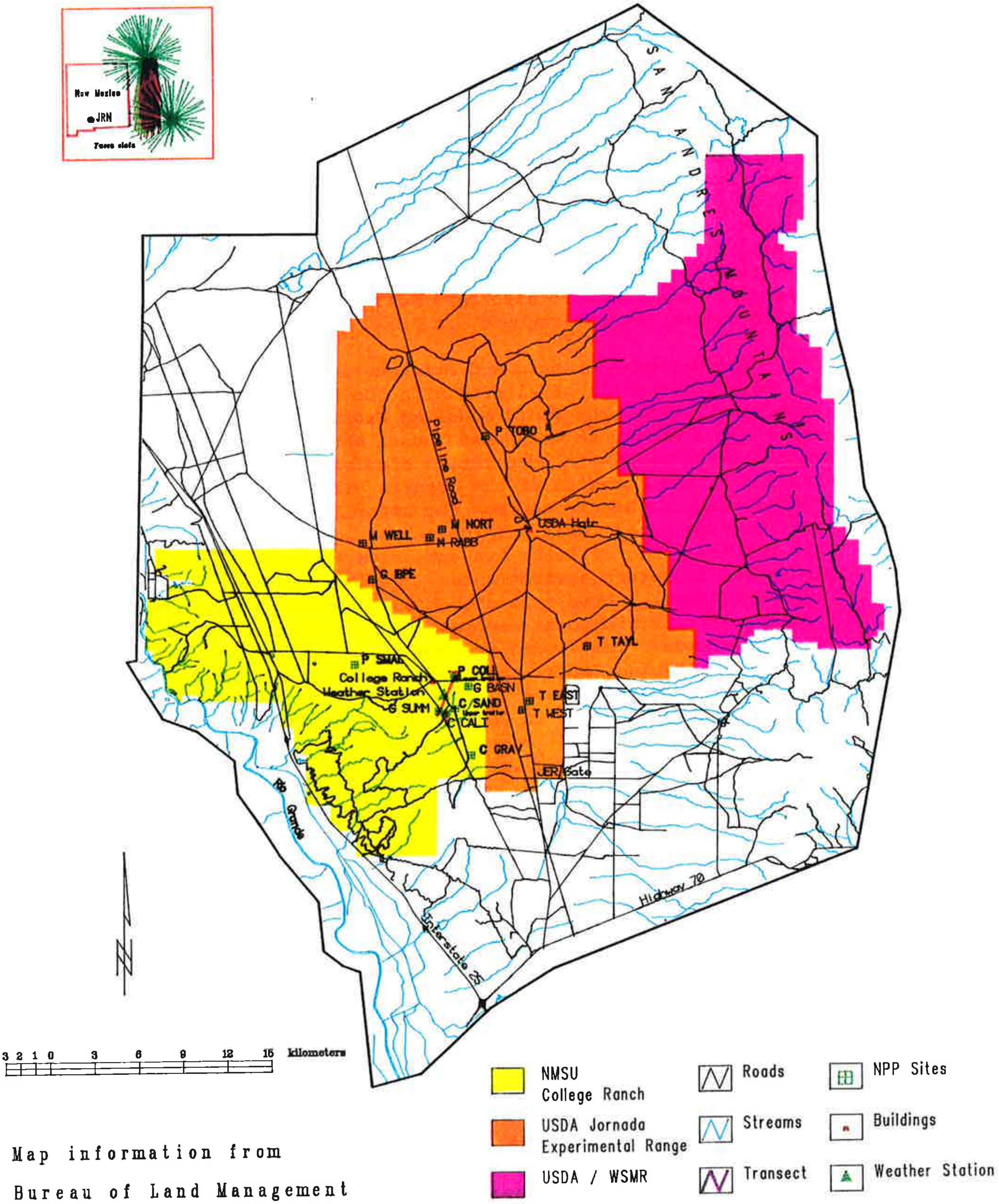
The Duke University Phytotron has a computer and image analysis laboratory that are available to the LTER. The computer laboratory consists of a network of Sun workstations, including a SPARC System 10, 2 SPARC Classics, a 4/110, and an IPC, along with several laser printers. There is also an image analysis lab that is equipped with a Quadra 650 and NEC Multisync 6FG screen, a Raster Ops 24XLTV Video board, a Toshiba SV 771 Super VHS VCR, a UMAX UC840 Color Scanner, and a Tektronix Phaser 200e color printer. In addition, the LTER has access to two 486 PCs, several Quadras (950 and 700s), and numerous other personal computers and printers. The local network is LocalTalk and Ethernet. LTER workers also have access to the GIS laboratory in the School of the Environment.

The National Oceanic and Atmospheric Administration. Dr. Dale Gillette is affiliated with the NOAA Air Resources Laboratory, whose the Fluid Modeling Facility contains the various instruments needed to make wind tunnel estimates of the friction velocity thresholds in comparative studies of wind erosion. Most studies of wind erosion at the Jornada will employ a portable wind tunnel that can be placed over the natural soil surface. This suction-type tunnel uses a 30-horsepower gasoline engine to power its turbine. Dr. Gillette has extensive experience using this equipment in desert environments. During the first summer of LTER-III (1995), three automated meteorological towers that collect data on windborne sediment at four levels will be deployed at the Jornada. The towers are powered by solar panels and record data on a DOS-based POQET computer located in a weather-proof data logger shells on each tower. These towers are currently employed in a wind erosion study in Owens Valley, California, scheduled for completion during 1994. Other equipment is available at the NOAA Fluid Modeling Laboratory for soil particle separation and measurements of the modulus of rupture of soils.

Hanover, New Hampshire:

Dartmouth College, through the research laboratory of Dr. Ross A. Virginia and the Environmental Measurements Laboratory in the Environmental Studies Program, provides analytical support for the elemental analysis of plant and soil samples. Instrumentation includes a Carlo Erba 1500 C/N analyzer, a Lachat multiple channel ion analyzer, a Jarrel Ash atomic absorption spectrophotometer with graphite furnace, and gas chromatographs. The laboratories also include balances, drying ovens, muffle furnace, pH meters, block digestor, shakers, and a fume hood for the preparation of samples. Also available are a VG MicroMass 620D and a Finnigan mass spectrometer for the analysis of plant and soil samples for stable isotope ratios. This facility, D-LITE, is managed jointly by the Environmental Studies Program and the Department of Earth Sciences.

Jornada LTER Research Area



Map information from

Bureau of Land Management

and Jornada LTER

Prepared by:B. Nolen III NMSU Geographic Applications Research Lab 6-3-92

Appendix V. Site Description

Description and Administration

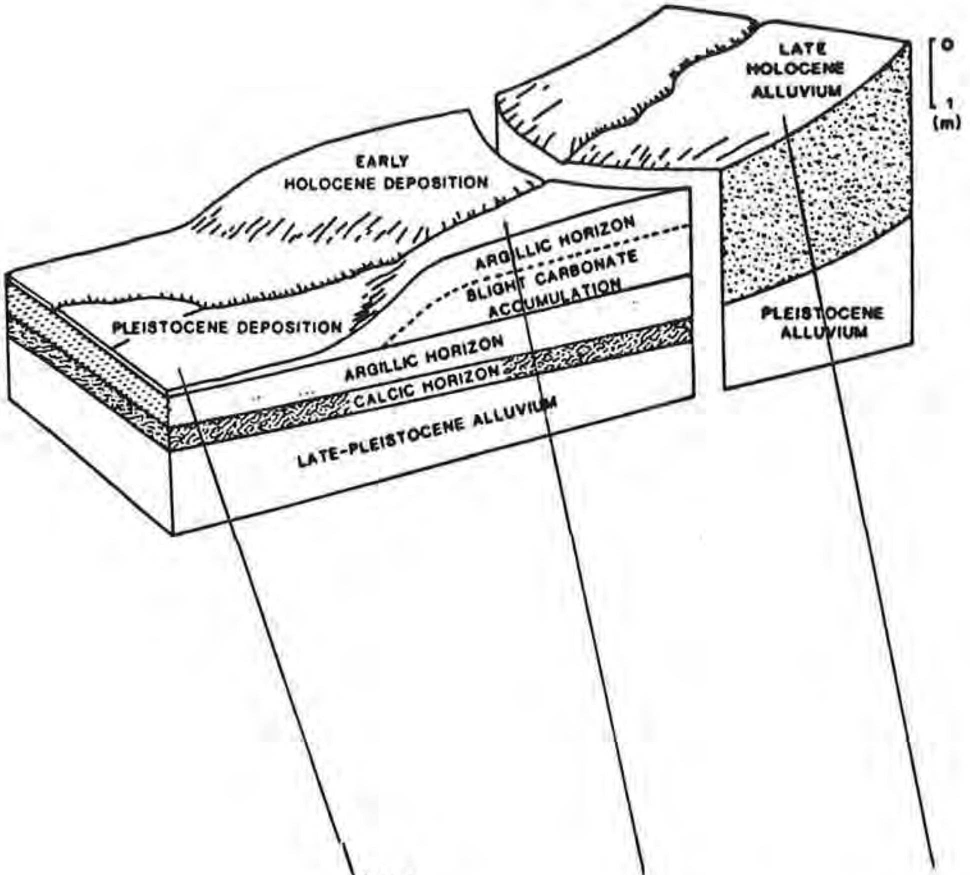
The 25,900-ha NMSU College Ranch is adjacent to the 78,266-ha Jornada Experimental Range, creating a block of 104,166 ha wholly devoted to research (Fig. 21). Both properties are located about 37 km northeast of Las Cruces, New Mexico. The NMSU College Ranch is owned by the University and administered by the Science and Education Administration - Agricultural Research. The College Ranch was established in 1927, and has been the site of much research by both the Department of Animal and Range Science and other departments on the NMSU campus since then.

The Jornada Experimental Range was established in 1912 under the jurisdiction of the Bureau of Plant Industry, and transferred to the Forest Service in 1915. Climatic and vegetation records have been maintained since that time. In 1954, the Range was transferred to the Agricultural Research Service. The Jornada Experimental Range is one of 3 Biosphere Reserves in the Chihuahuan Desert designated by the UNESCO Man and the Biosphere Program (MAB). Both the College Ranch and the Experimental Range have been the sites of much ecological research by local and federal researchers. Two validation sites (for the Desert and the Grassland biomes) for the International Biological Programme (IBP) were located here. Grazing systems, livestock management, and ecological research have been the focus of efforts on both units; both have well-documented records of land use and experimental history, and there are exclosures of various ages as well as other sites of known history available for study or experimentation. The location of nearly all anthropogenic features of the landscape was validated in October 1992, using a Global Position System (GPS) to survey the research area.

Climate

The climate is characterized by abundant sunshine, wide diurnal ranges of temperature, low relative humidity (mean evaporation rate 229 cm per year), and extremely variable precipitation. The average maximum temperature (June) is 36^{oC}; temperatures are coldest in January, with an average maximum of 13^{oC}. The effective growing season, with favorable precipitation and temperature, is generally July through September. Winter precipitation is derived from Pacific frontal storms, with low-intensity rainfall covering wide areas; total winter precipitation can vary dramatically between years. Summer precipitation occurs as intense, brief convective thunderstorms that are highly localized; however, on a regional basis late summer precipitation is more predictable than winter.

Daily rainfall records have been kept at the Jornada Experimental Range headquarters (a Class A weather station) since 1915, and monthly rainfall has been collected at other sites on the Range for varying lengths of record. Mean annual



Site		Playa	Shrubland	Grassland
Dominant vegetation		*Panicum obtusum*	*Larrea tridentata*	*Bouteloua eriopoda*
Soil classification		Typic Torrerts[a]	Typic Haplargid*	Ustollic Haplargid*
Surface soil characteristics				
Physical	% sand[a]	10	80	76
	% clay[a]	57	8	7
	% $CaCO_3$[b]	3.36	1.06	0.68
	% organic C[b]	2.91	0.19	0.48
Chemical	pH (in 10 m$\underline{M}$$CaCl_2$)[b]	7.57	7.69	7.02
	NH_4-N (mg kg^{-1})[c]	10.24	2.15	1.13
	NO_3-N (mg kg^{-1})[c]	6.75	0.61	0.57
Moisture (% of fresh mass)[c]		5.65	1.06	0.95

---

* Lajtha and Schlesinger (1988)

[a] Wierenga et al. (1987), 0-30 cm depth

[b] W.T. Peterjohn, unpublished Ph.D. thesis, Duke University (1990), 0-5 cm depth

[c] This study on 20 June 1988, 0-15 cm depth

Figure 2a. A generalized model of soil development and soil horizon formation on piedmont slopes at the Jornada Experimental Range. (From Lajtha and Schlesinger 1988).

precipitation is 23 cm, with 52% of the annual total occurring between July 1 and September 30. Droughts are a recurrent phenomenon; severe droughts occurred in 1916-1918, 1921-1926, 1934, 1951-57, and a moderate drought in 1970-71. The 50's drought is believed to have been the most severe in the past 350 years; perennial vegetation in the southwest is still recovering.

The Jornada Experimental Range has 23 rain gauge stations with long-term records; there are 57 stations (43 with recording rain gauges) that have been operating since 1974. The College Ranch has 8 stations with long term records; 10 more have been added since 1977.

Geology and Soils

The Jornada del Muerto basin, with the College Ranch and the Experimental Range at its southern end, exemplifies the basin and range topography of the American Southwest. The property extends from the Rio Grande floodplain (elevation 1186 m) to the crest of the San Andres mountains (2833 m). Rocks in the San Andres Mountains are derived from Paleozoic marine sediments; in contrast, the Dona Ana Mountains are largely intrusive igneous rocks. Materials carried by the ancestral Rio Grande form the Jornada Plain, the floor of the intermountain basin. Most of the basin is closed, with no exterior drainage, and water collects in scattered playas. Coarse sediments are found on bajada slopes near the foothills, and silts and clay are concentrated in the lowest areas (Fig. 22). Both water and wind are still actively eroding and moving sediments.

The Jornada Basin was the site of "The Desert Project," a 2-decade field research program sponsored by the Soil Conservation Service to understand the relationship between geomorphology and soil development in desert environments. The results of the project are described in the "Desert Project Soil Monograph" (USDA/SCS, 1979), and in a summary report coauthored by the principal investigators (L.H. Gile, J.W. Hawley and R.B. Grossman. 1981. *Soils and Geomorphology in the Basin and Range Area of Southern New Mexico--Guidebook to the Desert Project.* New Mexico Bureau of Mines and Mineral Resources, Memoir # 39, Socorro, New Mexico). These reports contain soil survey maps at a scales of 1:15,840 and 1:62,400 for a large portion of Dona Ana County (NM). The Desert Project Monograph contains pedon descriptions for several hundred soil profiles that were excavated in the Jornada Basin, analyzed for soil properties by the SCS laboratory in Lincoln, Nebraska, and classified in the 7th approximation system. Some of these samples remain archived at the Lincoln lab.

Although the area of the Jornada LTER site extends beyond the boundaries of the Desert Project, the entire region has also been mapped by a standard county SCS survey (1972) at a scale of 1:48,000. With the aid of two undergraduate students supported by

REU supplements from NSF to the Jornada LTER, Dr. Curtis Monger (NMSU, Agronomy) is currently refining the mapping and delineation of soils on the Mount Summerford bajada, which is the location of many of the current LTER studies. Other published work on the soils and soil development in this region is included in recent papers by Wierenga et al. (1987), Lajtha and Schlesinger (1988) and Nash and Daugherty (1990). The various information on soils, including a digital elevation model for the entire Jornada Basin (Fig. 12) has been entered in the Geographic Information System for the Jornada LTER at a scale of 1:25,000.

Flora:

The vegetation of the proposed study site is representative of that found throughout the Chihuahuan Desert. The flora is rich in species of higher plants. Early collections confined to the Jornada Experimental Range identified 524 species. Twenty-one additional species have been collected in recent years.

On the Jornada Plain, the major grass species on sandy soils are black grama (*Bouteloua eriopoda*), mesa dropseed (*Sporobolus flexuosus*) and red threeawn (*Aristida longiseta*). Shrubs or shrub-like plants on sandy soils include honey mesquite (*Prosopis glandulosa*), fourwing saltbush (*Atriplex canescens*), soaptree yucca (*Yucca elata*) and broom snakeweed (*Xanthocephalum sarothrae*). Extensive dunes have developed where mesquite has invaded sandy soils. Low-lying areas with heavy soils, silts and clays, and which receive water from surface run-off, are dominated by tobosa (*Hilaria mutica*) and burrograss (*Scleropogon brevifolius*). A few of the wetter playas are covered with vine mesquite (*Panicum obtusum*). Some heavy soils are dominated by alkali sacaton (*Sporobolus arioides*) and the Rio Grande floodplain supports stands of saltgrass (*Distichlis spicata*). Gypsum soils support a depauperate flora with a dropseed (*Sporobolus nealleyi*) being most abundant. Tarbush (*Flourensia cernua*) is a frequent invader on heavy soils. Creosote bush (*Larrea tridentata*) dominates on the gravelly soils of the bajada slopes leading up to the mountains and dominates much former grassland.

Within the mountains there are a wide variety of shrub types dominated by honey mesquite, creosote bush, sotol (*Dasylirion wheeleri*), ocotillo (*Fouquieria splendens*); and mescat acacia (*Acacia constricta*). Small areas of scrub woodland occur which are dominated by oneseed juniper (*Juniperus monosperma*) and Mexican pinyon pine (*Pinus cembroides*). Mountain grasslands are usually dominated by *Bouteloua* spp. or by *Stipa* spp.

Extensive vegetation changes have occurred since the turn of the century. The earliest vegetation records were made during a land survey conducted in 1858. These records, plus vegetative surveys made on 58,492 ha of the Jornada Plain in 1915, 1928, and

1963, show that grass cover had decreased from 90 percent in 1858 to only 25 percent in 1963 (Buffington and Herbel 1965). A large proportion of the shrub increase has occurred since 1928. Periodic droughts, selective grazing of grasses by livestock, and shrub seed dispersal by man, livestock, and rodents have all contributed to the spread of shrubs. Extensive grasslands still exist on the NMSU college Ranch and the Jornada Experimental Range largely because brush control programs have been carried out for many years. The vegetation surveys mentioned above, plus aerial photographs made in 1938, 1942, 1973, and 1977, provide good documentation of the vegetation through time (Gibbens and Beck 1988).

Fauna

The fauna of the Jornada Experimental Range is the most completely studied fauna of any arid area in the world. The well studied mammalian fauna includes heteromyid rodents (*Dipodomys* spp. and *Perognathus* spp.), ground squirrels (*Spermophilis spilosoma*), wood rats (*Neotoma* spp.) and a variety of other mice and rats (*Onychomys* spp., *Peromyscus* spp., *Reithrodontomys* and *Sigmodon*). Black-tailed jackrabbits (*Lepus californicus*) are widespread and abundant and desert cotton-tail rabbits are numerous in dense riparian vegetation. Large native herbivores, antelope (*Antilocapra americana*) and mule deer (*Odocoileus hemionus*), occur at low densities and in limited habitats. The most abundant predators are coyotes (*Canis latrans*) and badgers (*Taxidea taxus*).

The reptiles and amphibian faunas have been the subject of numerous studies. The most widespread reptiles are whiptail lizards (*Cnemidophorus* spp.), sideblotched lizards (*Uta stansburiana*) and horned lizards (*Phrynosoma* spp.), prairie rattlesnakes (*Crotalus viridis*), western rattlesnakes (*Crotalus atrox*), bull snakes (*Pituophis melanoleucus*) and whip snakes (*Masticophis* spp.). Numerous other species of lizards and snakes are restricted in habitat and/or not as abundant.

Amphibians are limited in activity to rainy periods when depressions are water filled. Spadefoot toads (*Scaphiopus* spp.) and toads (*Bufo* spp.) are abundant in and around flooded areas.

The arthropod fauna is dominated by social insects, ants and termites. The numerically dominant and widespread ants include liquid feeding honey pot ants (*Myrmecocystus* spp.), seed harvesting ants (*Pogonomyrmex* spp. and *Pheidole* spp.) plus omnivorous species (*Novomessor* spp.). Wolf spiders (*Lycosa* spp. and *Geolycosa* spp.) are abundant in many habitats. Tarantula hawks (*Pepsis* spp.) are among the more notable parasitoid wasps. The shrub arthropod fauna is dominated by sucking insects, primarily Homopterans and Hemipterans.(mirids, psyllids).

Grasshoppers are an abundant, diverse, and conspicuous group of herbivorous insects at the Jornada. Three major life-form groups or guilds occur at the Jornada: 1) ground dwelling (terricoles), 2) grass dwelling (graminicoles), and 3) shrub dwelling (arbusticoles). These life-form guilds are morphologically, behaviorally, and trophically distinct from each other. Fourteen species belong to the ground dwelling guild, the most common of which are *Trimerotropos pallidipennis*, *Derotmema laticinctum*, and *Cibolacris parviceps*. Ground dwelling species live on the soil surface, are generalist feeders, and tend to specialize on specific soil types associated with different geomorphic surfaces. Nine species belong to the grass dwelling guild, the most common of which are *Paropomala pallida*, *Opeia obscura*, and *Orphuella pelidua*. Grass dwelling species live and feed on grass, but are not host species specific. Six species belong to the shrub dwelling guild, the most common of which are *Bootettix argentatus*, *Ligurotettix planum*, *Hesperotettix viridis*, and *Campylacantha olivacea*. Shrub dwelling species live and feed on shrubs, and are host specific to particular shrub species. In general, the species composition and densities of Jornada grasshopper assemblages vary considerably among different landscape units, depending upon soil conditions and the taxonomic and physical structural attributes of vegetation.

The soil arthropod fauna is dominated by prostigmatid mites. Nanorchestid and tydeid mites are widespread. Cryptostigmatid mites are abundant only in areas of dense litter accumulations. Collembolans and psocopterans are abundant in most areas where litter accumulates. The rhizospheres of grasses are characterized by high densities of pygmephorid mites and isotomid collembolans.

The breeding bird fauna is limited to a few species and is characterized by low densities of those species (Naranjo and Raitt 1993). Quail (*Callipepla* spp.), doves (*Zenaidua* spp.), roadrunners (*Geococcyx californicus*) and black-throated sparrows (*Amphispiza bilineata*) are common year-round residents. Migrants that breed on the Jornada include Swainson's Hawk (*Buteo swainsoni*), western king birds, ash-throated flycatcher, say's phoebe, Chihuahuan Raven, cactus wren, northern mockingbird, Crissal thrasher, Scott's oriole, lesser nighthawk, American Kestrel and burrowing owl. The winter bird fauna is dominated by mixed species and flocks of sparrows and finches, harriers, golden eagles, red-tailed hawks and Cooper's hawks.

Appendix VII. Sample Forms for Data Management

NEW MEXICO STATE UNIVERSITY
NSF/LTER -- JORNADA SITE -- DATA SET DOCUMENTATION FORM

All Jornada Desert Site NSF/LTER data sets must be documented on the following form. This applies to any data set intended for permanent archiving. It is assumed that all raw data collected under the auspices of the Jornada NSF/LTER program will be described by the following standardized form. Information that is not available at this time, must be included when available. See the Data Manager for any questions.

RESEARCH PROJECT NAME (general project name under which specific data set was collected):
Animal Transects

DATE THIS FORM COMPLETED: DAY: 18 MONTH: 4 YEAR: 89

SUGGESTED FILE I.D. (An 8-character alphanumeric file identification name):

ASSIGNED FILE I.D. (Leave blank; Data Manager will assign):

ANMLTRAN

BRIEF DESCRIPTIVE TITLE (for the file name suggested above):

LTERII animal transect data

INFORMATIVE ABSTRACT (describe data set completely):

Data for rabbits, birds, and lizards recorded from the LTER II animal transects. Data consists of species names, numbers of individuals, and distances observed from transects. Data is collected from each transect once every two weeks.

KEYWORDS (keywords that describe data set; maximum of 10):

Birds, rabbits, lizards, animals, consumers, populations

MAINFRAME COMPUTER ACCOUNT # (s)(where data will be analyzed or stored):
BIO030

RESPONSIBLE INVESTIGATOR (s): W. G. Whitford, D. C. Lightfoot

P.I.(s) FUNDING THE RESEARCH: Jornada LTER II

RESEARCHERS (list all personnel who will be obtaining data and who would need to be contacted directly if there was a problem in the raw data, with their initials following in " "):

D.Lightfoot "DL", W. Whitford "WW", C. Sandell "CS"

SITE INFORMATION: (e.g. Jornada LTER Creosotebush Plots, etc.):

One 1 km transect is located in each vegetation zone near C-CALI, G-IBPE, M-NORT, P-COLL, and T-EAST.

METHODOLOGY (provide sufficient detail such that an unaware reader could repeat the described data collection procedures, attach additional sheets if necessary):

One observer walks each transect from segment 1 to 20. The observer records all birds, rabbits, and lizards seen. The distance of each animal from the transect line is also estimated and recorded. Transects are walked in the morning hours only, once every two weeks. The Emlen method (Emlen 1971) will be used to estimate densities of each animal species at each site.

KEY LITERATURE (citations that describe sampling procedures, i.e. reference of a published paper, thesis, etc.):

Emlen, J. T. 1971. Population densities of birds derived from transect counts. Auk 88:323-342.

Raitt, R. J. and S. L. Pimm. 1976. Dynamics of bird communities in the Chihuahuan Desert, New Mexico. The Condor 78:427-442.

TREATMENT OF DATA: e.g. SAS analysis (SAS programs should be appended and stored with this form):

Field data is entered using D.A.V.E. data entry and verification program.

ATTRIBUTES MEASURED (variable name used on data sheets, variable code used in computer program, units of measure, brief description if not obvious by name):

VARIABLE NAME	VARIABLE CODE	MEAS. UNIT	ATTRIBUTE DESCRIPTION
date	DAY	MM/DD/YY	sample date
zone	ZONE	alpha code	vegetation community C = creosotebush G = grassland M = mesquite dune P = playa T = tarbush

time	TIME	alpha code	portion of day sampled DN = dawn MN = midmorning MD = midday AF = afternoon SS = sunset
sky	SKY	alpha code	condition of sky CL = clear OC = overcast
wind	WIND	alpha code	wind conditions CA = calm WD = windy VW = very windy
species	SPECIES	alpha code	species code (see list)
number	NUMBER	integer	number of individuals
distance	DIST	meters	distance from transect
segment	SEG	integer	transect segment number (1-20)
code	CODE	integer	animal code: 1 = Bird 2 = Rabbit 3 = Lizard 4 = Mammal 5 = Snake 6 = Turtle

DATE DATA STRING COMMENCED: DAY: 8 MONTH: 3 YEAR: 89

DATE DATA STRING TERMINATED: DAY: MONTH: YEAR:

FREQUENCY OF MEASUREMENT: every 2 weeks

EXPECTED DURATION OF STUDY: duration of LTER II

METHODS OF RECORDING (field data sheets, instrumental, etc.):

Field data sheets or tape recorder. Taped data is transcribed to data sheets.

COMMENTS (include any comments here that more fully describe this data set; *attach additional sheets if necessary*):

See DATAENT.DOC for data entry procedure.

The animal code is added, after the data is entered using the LOTUS add-in D.A.V.E, by a Quattro Pro spreadsheet macro by comparing the species name in the data to those within the species list included in the macro file. Updates to species list should also be made to macro species list. Macro file = ANMLCODE.WQ1. Instructions are included at beginning of macro code with additional instructions provided as macro executes.

Appendix VIII Network Participation by Jornada LTER Investigators, 1989-1993

National LTER Activities:

Meetings:

October 1989	Schlesinger was co-organizer of, and Reynolds, Whitford, and Jarrell attended a workshop on Global Change in Arid Lands, held in Boulder, Colorado under the auspices of the Office of Interdisciplinary Earth Studies (OIES) of UCAR
March 1990	LTER Workshop on woody plant mortality Andrews LTER, Corvallis, Oregon (Huenneke)
May 1990	Spring LTER Coordinating Committee Meeting, San Juan, Puerto Rico (Schlesinger)
July 1990	LTER Executive Committee, Washington, D.C. (Schlesinger)
September 1990	LTER All Scientist's Meeting in Estes Park, Colorado. Schlesinger presented a plenary paper; other Jornada LTER scientists presented several posters.
May 1991	Spring LTER Coordinating Committee, Seattle, Washington. (Schlesinger)
June 1991	Bureau of Land Management (BLM), Workshop on Global Change (Schlesinger, Plenary paper)
September 1991	Schlesinger organized and attended a meeting to explore the potential development of a soil warming experiment within the LTER network and at other research sites in the US and Canada.
February 1992	LTER Coordinating Committee Meeting, Trout Lake, Wisconsin (Schlesinger)
April 1992	USGS/PACLIM Meeting on Climate Variability Asilomar, California (Virginia)
June 1992	LTER/USGS Watershed Modeling Workshop, Denver Colorado (Ward)
August 1992	LTER Coordinating Committee Meeting, Alaska (Jarrell)
August 1992	LTER Data Managers Meeting, Honolulu, HI (Nolen)
August 1992	U.S. Geological Survey (USGS) Meeting on Global Climate Change in Arid Lands, Flagstaff, AZ (Schlesinger)
September 1992:	Intersite Trace Gas Workshop, Fort Collins, CO (Schlesinger/Hartley)
November 1992:	Network workshop with NASA to explore the potential for future cooperation, Albuquerque New Mexico (Nolen, Hope)
March 1993:	Joint Meeting of LTER and NASA/MODIS Scientists, NASA Goddard Space Flight Center, Goddard, Maryland (Nolen)

April 1993: Jornada hosted the spring LTER-CC meeting in Las Cruces

May 1993: Conference on Environmental Information Management and Analysis: Ecosystem to Global Scales, Albuquerque, N.M. (Nolen)

September 1993: LTER All Scientist's Meeting in Estes Park, Colorado. Schlesinger presented the Jornada "Site-bite" and Huenneke participated in a number of workshops to plan future LTER network activities. They represented the Jornada at the Coordinating Committee meeting, and one of Schlesinger's graduate students, Anne Hartley, served on the Graduate Student Coordinating Committee.

Membership on LTER National Committees:
Coordinating: Schlesinger
Data Management: Nolen
Scientific and Long-term Planning: Virginia

Participation in Ongoing Network Projects:

1. The Jornada is a collaborator in the NSF-funded project "Cross site assessment of climatic change on ecosystem dynamics," organized by Bill Parton and Dennis Ojima of CPER
2. The Jornada is a collaborating participant in the ongoing intersite decomposition experiment (LIDET), coordinated by Mark Harmon of the Andrews LTER.
3. The Jornada is a collaborator in the LTER Supplement awarded to Colorado State University to examine vegetation structure-soil process interactions at the Central Plains Experimental Range, Sevilleta and Jornada LTER sites. This project is coordinated by Debra Coffin of CCSU.
4. The Jornada is a core site in the national network established under USDA funding to monitor uv-B radiation in the continental U.S. This program is being coordinated by Jim Gibson of Colorado State University.

International Networking Activities:

May 1989	Huenneke, Anderson and Havstad attended a meeting of the Chihuahuan Desert Man and the Biosphere (MAB) Reserves, Lajitas, Texas
November 1989	Cunningham and Anderson attended a meeting of the Chihuahuan Desert (MAB) Reserves, Mapimi, Mexico.
November 1990	Whitford, Ward, Lightfoot, Anderson and Havstad hosted a meeting of the Chihuahuan Desert MAB Reserves, at the Jornada Experimental Range.
October 1991	Whitford organized and coordinated the Joint U.S./Chilean Workshop on Desertification in Santiago, Chile.
April 1992	Scientists from the Chinese Ecology Research Network (CERN) visited the Jornada LTER site.

Appendix IX. Human Resource Contributions

Students Completing Degrees on the basis of field work or significant funding derived from the Jornada LTER, 1989-1993

1989
Kay, I.S. (M.S., San Diego State University)
Stephens, G. A. (M.S., New Mexico State University)
Van Vactor, S.S. (M.S., New Mexico State University)
Muldavin, D. (M.S., New Mexico State University)
Silva, S.I. (Ph.D., New Mexico State University)

1990
Peterjohn, W.T. (Ph.D., Duke University)

In addition, an NSF Research Experience for Undergraduates (REU) supplement supported two white female students and one Hispanic male student for field research during summer 1990.

1991
Lightfoot, K.S. (M.S., New Mexico State University)
Kelley, M.S. (M.A., New Mexico State University)
Eve, M.D. (M.A., New Mexico State University)
Duncan, J.A. (M.S., San Diego State University)
Turner, D.L. (M.S., San Diego State University)
DeLira, G. (M.S., New Mexico State University)
Bolton, S.M. (Ph.D., New Mexico State University)
Jorat, S.M. (Ph.D., New Mexico State University)

In addition, an NSF Research Experience for Undergraduates (REU) supplement supported one white male and two white female students for field research during summer 1991.

1992
Martinez-Turanzas, G. (M.S., New Mexico State University).
Hyder, P. (M.S., New Mexico State University).
Mason, J.B. (M.A., New Mexico State University)
Bash, D.W. (M.A., New Mexico State University)
Daggett, K.C. (M.S., New Mexico State University)

In addition, an NSF Research Experience for Undergraduates (REU) supplement supported one white male, one Hispanic female, and one Hispanic male for field research during summer 1992.

1993
Cork, S. (M.S., San Diego State University)
Darby, M. (M.S., San Diego State University)
Thomas, P.J. (Ph.D.,San Diego State University)
Tiszler, J. (M.S.,San Diego State University)
Beres, L. (M.S., New Mexico State University)

In addition, an NSF Research Experience for Undergraduates (REU) supplement supported three students during summer 1993.

Appendix X 1993 Friends of the Jornada Symposium

THIRD ANNUAL FRIENDS OF THE JORNADA SYMPOSIUM

Sponsored by USDA/ARS Jornada Experimental Range and the Jornada Long-Term Ecological Research Site
Thursday, May 20, 1993
Foster Hall 201

8:00 AM	Welcome - Kris Havstad and Laura Huenneke
8:15 AM	Introductory Remarks - Bill Schlesinger and Kris Havstad
8:30 AM	Daryl Moorhead, Texas Tech - "Litter Decay in the Desert: Same Processes, Different Emphases"
8:45 AM	Ted Floyd, Penn State - "Top-Down and Bottom-Up Impacts on Creosotebush Arthropods at the Jornada LTER Site"
9:00 AM	Walt Whitford, EPA - "Desert Grassland Ants Diversity and Functional Role as Soil Organisms"
9:15 AM	Keith Yarborough, Big Bend NPS - "Research Opportunities and Needs for Resource Management at Big Bend National Park, Texas"
9:30 AM	Rick Miller, NMSU - "Demographic Variation in *Larrea Tridentata*"
BREAK	
10:15 AM	Curtis Monger, NMSU - "Did increasing Atmosphere CO_2 Levels Contribute to the Decline of C_4Grasses in the Early Holocene?"
10:30 AM	Rex Pieper, NMSU - "Black-Tailed Jackrabbit Diets in the Northern Chihuahuan Desert"
10:45 AM	Jim McCormick, BLM - "Fourty Years of Vegetation Trend in Southwestern New Mexico"
11:00 AM	Neal Ackerly, NMSU - "Playa Age and Persistence as Factors Affecting Prehistoric Settlement"
11:15 AM	Ed Fredrickson, ARS - "Examination of a Local Feature Within a Complex System: Tarbush Phytochemistry by Environmental Interactions"
11:30 AM	Ross Virginia, Dartmouth - "Shrub Resource Islands - Their Role in Stability of Desert Ecosystems"
LUNCH	
1:15 PM	John Zak, Texas Tech - "Is Enzyme Activity and Decomposition Linked to Forage Dynamics in Desert Ecosystems?"
1:30 PM	Mary Abrams, Oregon Graduate Institute - "Soil Spatial Heterogeneity Across A Mesquite Dune Chronosequence"
1:45 PM	Vince Gutschick, NSF - "Preliminary Studies of Transpiration Control of Desert Shrubs"
2:00 PM	Keith Sheets, New Mexico Tech - "Soil Moisture Measurement With Electromagnetic Induction"
2:15 PM	Brad Musick, UNM - "Vegetation Canopy Structure and Wind Erosion"
2:30 PM	Mike Coombs, NMSU, and John LaBry, Silicon Graphics - "Visualizing Strategic Decisions in Managing Deserts"
BREAK	
3:30 PM	Dave Richman, NMSU - "Preliminary Data on the Spider Fauna of the Jornada"
3:45 PM	Peter Herman, NMSU - "Is there a Rhizosphere Effect in Desert Grass Root Zones?"
4:00 PM	Al Peters, NMSU - Satellite Imagery: "A Dynamic Image Stratification Technique" and "Evaluation of Soil Effects on Satellite Based Indices"
4:15 PM	Anne Hartley, Duke - "Nutrient Controls of Nitrogen Fixation by Free-living Microbial Communities in Jornada Soils"
4:30 PM	End Session
6:00 PM	Social at Jornada Experimental Range Headquarters (map on back side)
7:00 PM	Dinner