

LTER-II PROPOSAL

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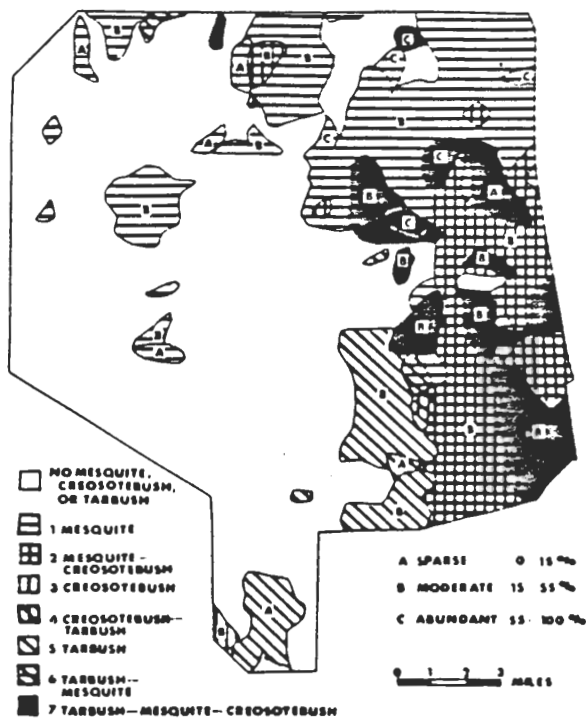
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**DESERTIFICATION: RESPONSES OF ARID LANDSCAPES AND  
ECOSYSTEMS TO RESOURCE REDISTRIBUTION.  
JORNADA LTER II.**

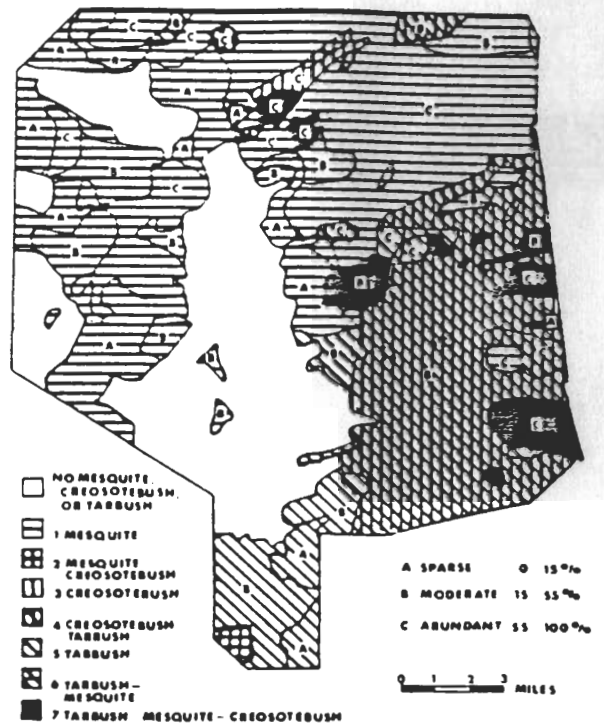
**I. INTRODUCTION**

This proposal outlines a plan for long-term ecological research investigating processes leading to desertification of semi-arid grasslands in the Jornada basin of southern New Mexico and changes in ecosystem properties that accompany desertification. During the last 100 years, large areas of black grama (*Bouteloua eriopoda*) grassland have been replaced by communities dominated by shrubs, especially *Larrea tridentata* and *Prosopis glandulosa* (Buffington and Herbel 1965; see Fig. 1). Similar changes have been observed in other areas of the Southwestern U.S. (e.g., Glendening 1952, Dzurec et al. 1985, Jeffries and Klopatek 1987) and in deserts on other continents (United Nations 1977, Biswas and Biswas 1980) (Fig. 2). This transition appears to be driven by both natural and human-induced environmental changes, which we do not fully understand and has resulted in fundamental changes in various ecosystem processes, including net primary production, water flux, and nitrogen cycling. The consequences of such changes are poorly understood, but they are significant to the socio-economic disruptions that often accompany desertification and to changes in biospheric properties observed at the global level. The proposed research will address both the causes and consequences of desertification through a cooperative program among investigators at four institutions and the USDA - ARS.

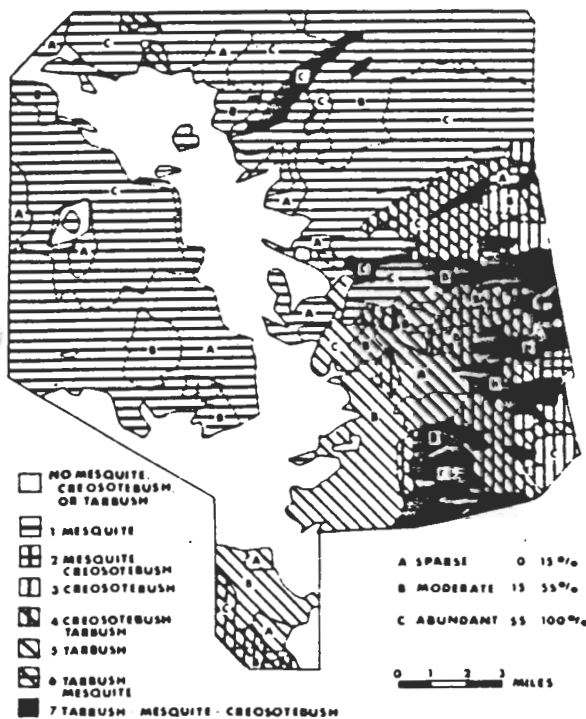
Previous work from the IBP and LTER programs on Jornada desert ecosystems shows that net primary production is limited by both water and nitrogen availability, which vary both temporally and spatially in the mosaic of ecosystems that form the landscapes of the northern Chihuahuan Desert. This work has contributed to the development of the general hypothesis of this proposal that *desertification has altered a previous, relatively uniform distribution of water and nitrogen by increasing their spatial and temporal heterogeneity, leading to changes in community composition and biogeochemical processes in these arid ecosystems*. A major emphasis of the proposed research is to compare the long-term patterns of water and nitrogen availability among a series of ecosystems that



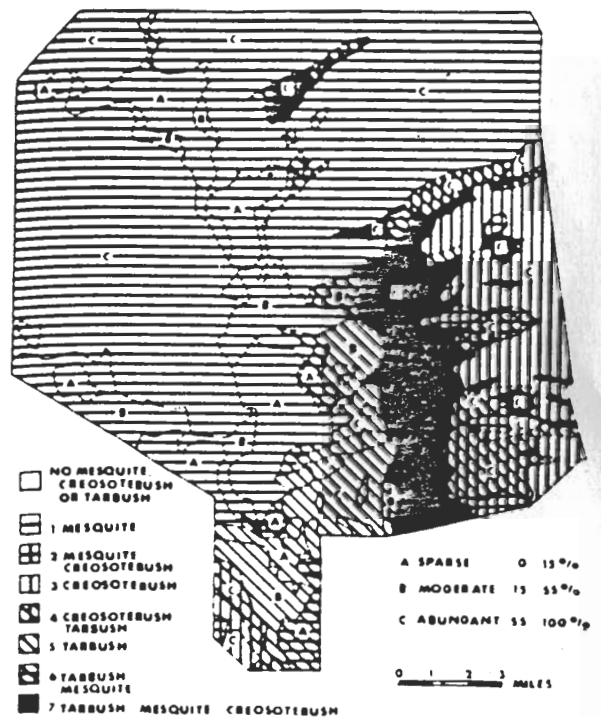
1858



1915



1928



1963

Fig. 1. Vegetation distribution on the Jornada between 1858 and 1963 showing the increase in shrub coverage (shaded areas of the map). From Buffington and Herbel (1965).

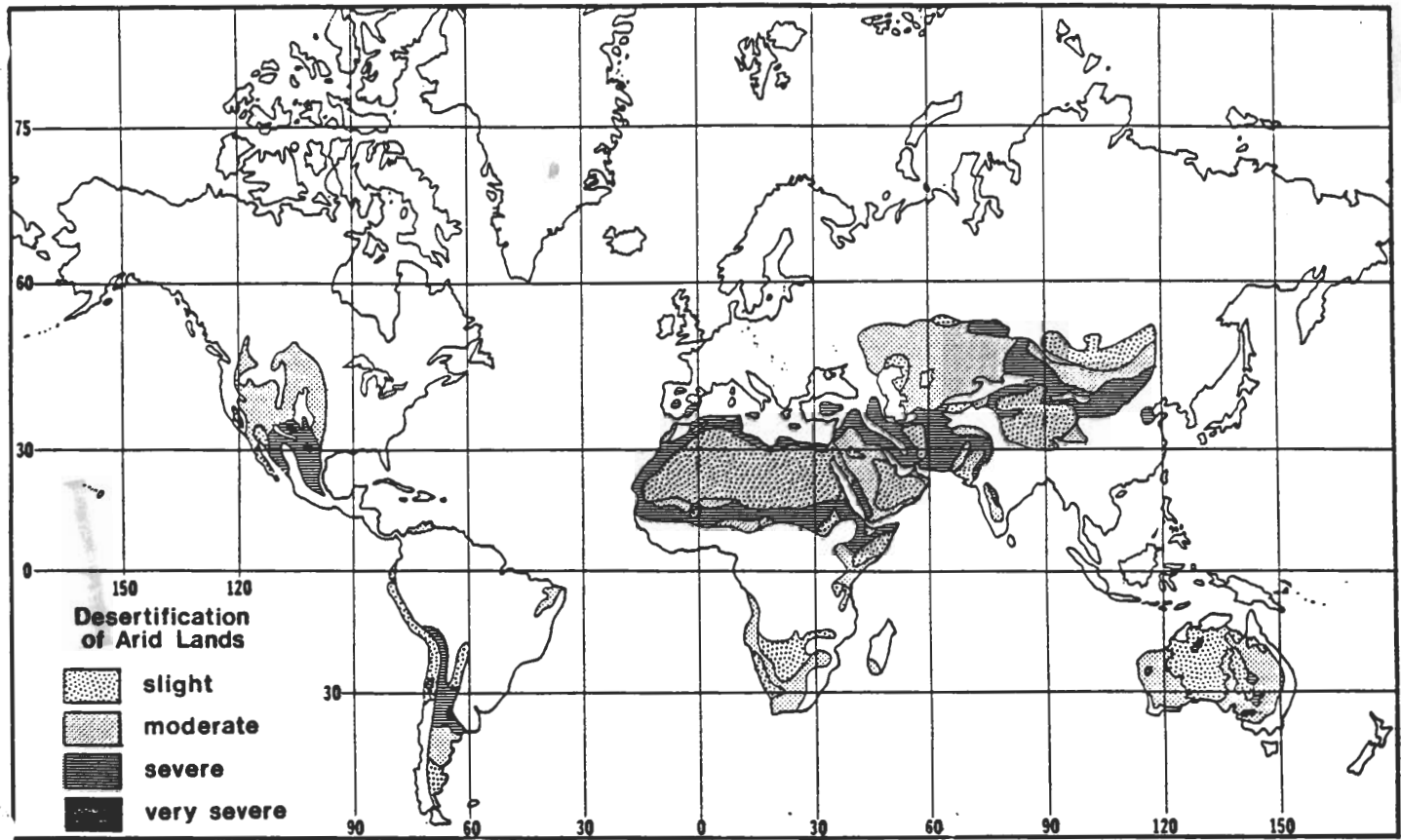


Fig. 2. Desertification of arid lands (from Dregne 1985)

are the products of differing degrees of desertification and that exhibit a spectrum of linkages with one another, via the movement of water and/or materials.

We propose to examine this hypothesis by 3 levels of study: (1) comparative process studies within representative grassland and shrub ecosystems; (2) studies of transport (runoff, runoff, and wind) and the relative linkage among these ecosystems, and (3) landscape-level studies involving remote sensing of regional gaseous flux, spectral vegetation indices from satellite imagery, and a computerized geographical information system (GIS) for the analysis of spatial data. In order to obtain the requisite data on productivity, nutrient and water availability, organic matter processing, consumer populations, and system responses to disturbance, we propose to utilize field experiments and several new technologies. These include stable isotope ratios of C and N, LIDAR measurements

of atmospheric ammonia, mini-rhizotron studies of root dynamics, remote sensing of plant production, and the development of dynamic GIS simulation models of desert landscapes.

The Jornada LTER will be located on the NMSU Research Ranch, 40 km north of Las Cruces, NM, which consists of 104,166 ha encompassing 2 mountain ranges and a large internal drainage basin (see Appendix A). This property is a unique site for long-term ecological research because virtually all of the ecosystems of the Chihuahuan desert are represented on the Jornada. These ecosystems range from reasonably intact, black grama (*Bouteloua eripoda*) grasslands to extremely degraded mesquite (*Prosopis glandulosa*) dunes, creosote bush (*Larrea tridentata*) hillslopes, and tarbush (*Flourensia cernua*) flats. The Jornada has a number of exclosures, some of which have not been grazed since 1927, and a network of 43 recording rain gauges. Both the Desert Biome and Grassland Biome programs of the US/IBP had research sites on this property.

Each member of the Jornada LTER research team currently has projects on one or more of the ecosystems proposed for study and is currently or recently funded by the Ecosystems Studies Program of NSF: Walt Whitford (decomposition and nitrogen mineralization processes); Gary Cunningham (spatial and temporal patterns in plant communities); Laura Huenneke (perennial plant dynamics and demography); Wesley Jarrell (soil processes and plant nutrition); James Reynolds (modeling of plant production and rhizosphere dynamics); William Schlesinger (denitrification processes and caliche deposition) and Ross Virginia (nitrogen fixation and rhizosphere processes). Collaborating scientists include Alan Hope and Doug Stow (remote sensing and geographical information systems); Dennis Killinger (LIDAR remote sensing of atmospheric gases); and Tim Ward (hydrology and hydrological modeling). All of the Jornada PIs have experience working in multi-investigator, interdisciplinary research programs and are committed to long-term research in arid ecosystems.

#### **A. Deserts on a Changing Globe**

Limited or seasonally unavailable rainfall causes the low plant productivity that characterizes desert ecosystems on all continents of the Earth. Although the total area of deserts has changed with climatic cycles, true deserts (rainfall < 25 cm/yr) have occupied about 12% of the Earth's land surface

throughout most of human history (United Nations 1977). Semi-arid grasslands and woodlands occupy an even larger area, so the total extent of dryland ecosystems is about 1/3 of the Earth's land surface (UNESCO 1979). Increasing human exploitation of arid and semi-arid systems has led to the recent conversion of some marginal areas to desert - a process known as desertification. However, changes in the distribution of desert vegetation have also occurred as a result of natural oscillations in global climate (Wells 1983, Van Devender and Spaulding 1979), and recent changes from grassland to desert shrubland have been recorded in areas of the Jornada Basin that have not been subject to grazing (Glendening 1952, Hennessy et al. 1983). Arid and semi-arid regions are dynamic landscapes, and the study of changes in ecosystem properties at the sensitive margin between arid and semi-arid lands offers an opportunity to observe the extent of global change induced by humans.

We suggest that the Chihuahuan Desert and other sub-tropical deserts differ functionally from temperate ecosystems as a result of physiological and behavioral differences in "key" species. Tropical and subtropical ecosystems may be less resistant to disturbance and also less resilient in response to disturbance. This appears to be especially true of semi-arid sub-tropical ecosystems around the world which are affected by desertification at an accelerating rate (Dregne 1985).

The presence of large areas of arid and semi-arid land on the Earth's surface endows these ecosystems with an importance that is likely to have been underestimated in past assessments of global biogeochemical processes. A cursory view might suggest that deserts contribute little to the collective biotic influence over the global ecosystem since low leaf area results in minimal plant production per unit of land area and a small contribution to the total net primary production (Whittaker and Likens 1973), biomass (Olson et al. 1983), and soil organic matter (Schlesinger 1977) on the Earth. However, Bowden (1986) suggests that emissions of gaseous nitrogen (e.g.,  $N_2O$ ,  $NH_3$ ) from desert soils during denitrification and ammonia volatilization may represent a major terrestrial input of these gases to the atmosphere. Wind erosion produces vast quantities of dust from the world's deserts (Goudie 1978, Schutz 1980), potentially affecting global albedo (Courel et al. 1984, Idso and Brazel 1977), rain chemistry (Loye-Pilot et al. 1986, Schlesinger and Peterjohn 1988), soil development (Litaor 1987) and ocean productivity in downwind areas (Graham and Duce 1979).

## B. Conceptual Basis for Desertification

Although it is commonly used, the term desertification is poorly defined and often ambiguous (Verstraete 1986). Desertification is assumed to involve lowered net primary productivity induced by human exploitation of semi-arid ecosystems. The degradation of the semi-arid woodlands of the Sub-Saharan Sahel is well documented (Bremen and de Wit 1983), and the resulting socio-economic disruption is linked to lower vegetative production (Sinclair and Fryxell 1985). However, such changes may not characterize all desertification events. In the landscapes comprising the Jornada Basin, net primary productivity is similar among vegetation types that include both invasive shrublands and grassland communities (Ludwig 1986). Thus, we propose a broader concept of desertification, which is based on changes in the level of resource distribution and use in space and time:

**The overall hypothesis for Long-Term Ecological Research at the Jornada is that desertification has altered a previous, relatively uniform distribution of water and nitrogen by increasing their temporal and spatial heterogeneity, leading to changes in community composition and biogeochemical processes in these arid ecosystems.**

This hypothesis is central to understanding desertification and is an integral part of a conceptual Jornada Model shown in Fig. 3, on which our long-term studies are based. In formulating this model we recognize that the original black grama grassland was shallow-rooted, with seasonal patterns of photosynthesis closely coupled to the availability of soil moisture (Cable 1969, 1975). Infiltration of incident rainfall is enhanced under black grama, since complete canopy cover lowers the effective energy of raindrops (Bach et al. 1986). A large percentage of the incident rainfall enters the soil, and horizontal transport of water and nutrients in runoff are infrequent events (Wood et al. 1987). Although soil moisture varies with rainfall, high infiltration to the soil is thought to result in a uniform availability of moisture in space and time (Paulsen 1953). Uptake and transpiration losses of soil moisture by black grama are closely coupled to input (Cable 1975, 1980), so that the soil profile rarely wets at great depth, confining most biotic processes to the upper soil layers (Herbel et al. 1972). Thus, mineralization and uptake of nitrogen primarily occur in the upper 30-cm of the soil profile (Fisher et al. 1987, Lajtha and Schlesinger 1988).



# THE JORNADA DESERTIFICATION MODEL

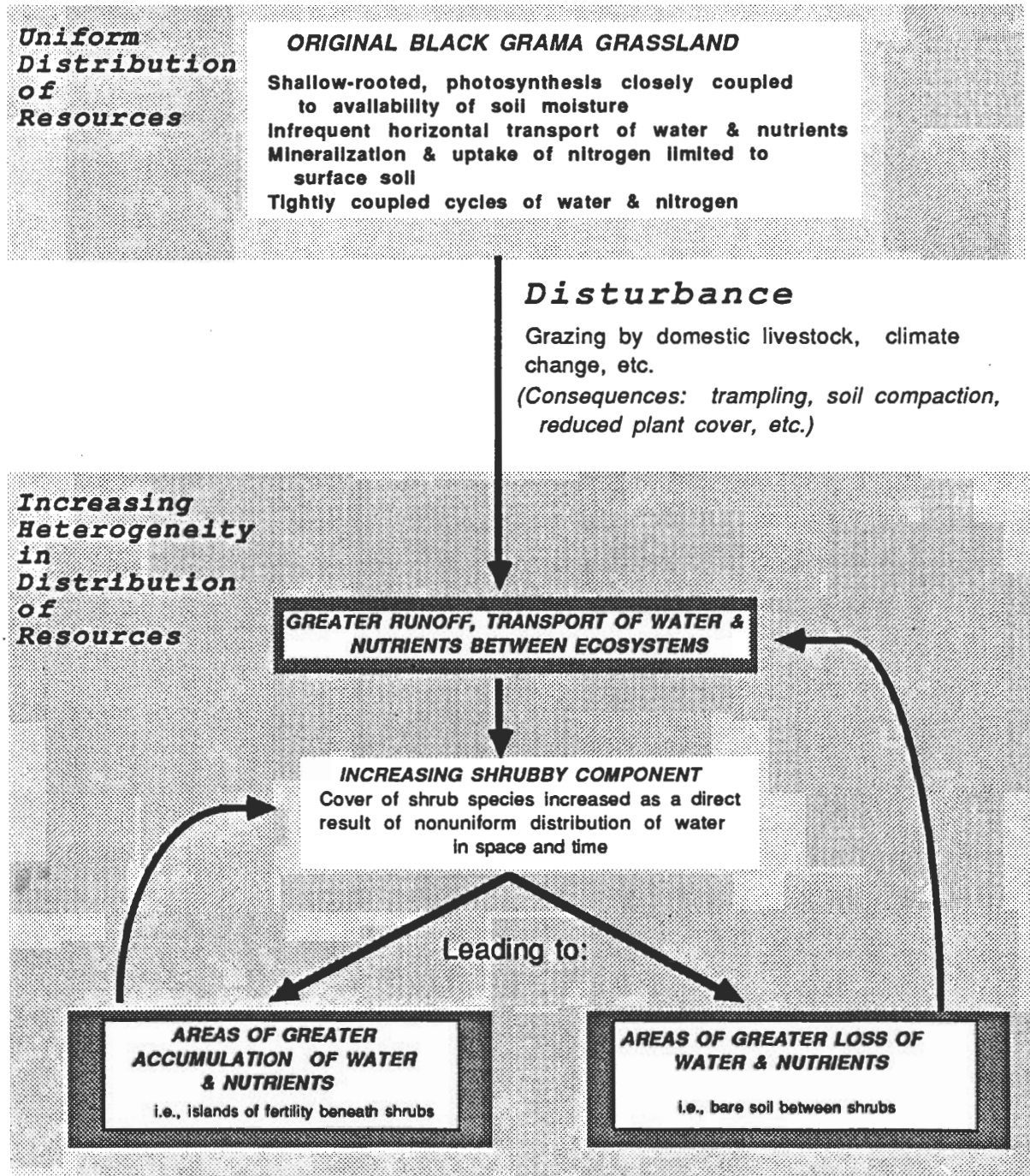


Figure 3. The Jornada Model of desertification -- Jornada LTER II

The introduction of large herds of domestic livestock disrupted this tight connection of soil and plant processes. Heavy grazing during the short summer wet season contributed to loss of grass cover during moderate drought and lowered the competitive potential of black grama. Trampling compacted the soil and reduced infiltration rates (Abdel-Magid et al. 1987, Pluhar et al. 1987). Greater runoff resulted in transport of materials between geomorphic units in the basin. The net effect was to reduce the availability and uniform distribution of soil moisture and nutrients (Paulsen 1953).

In the Jornada Model, we suggest that the cover of shrub species increased as a direct result of non-uniform distributions of water in space and time (Fig. 3). The timing of shrub growth may be relatively independent of moisture inputs; shrubs can tolerate extended periods of dormancy induced by drought. Deep-rooted shrubs may exploit soil moisture resulting from unusual events that recharge the soil profile at great depth (Cunningham and Burk 1973, Fonteyn et al. 1987). Under shrub vegetation, greater redistribution of moisture within the basin by horizontal transport in overland flow may have resulted in heterogeneity in the regional distribution of soil moisture and further increased shrub cover in downslope areas. Even today, when runoff is diverted, shrub biomass declines and the cover of perennial grasses increases (Schlesinger and Jones 1984).

These processes not only altered the distribution of moisture within the basin, but also created local heterogeneity in soil properties, since effective infiltration of rainfall was confined to the area under shrub canopies (Elkins et al. 1986, Lyford and Oashu 1969). Intrasytem cycling of nutrients, largely controlled by biotic processes in any ecosystem, was also progressively confined to the zone beneath shrubs, leading to the well-known "islands of fertility" that characterize desert shrublands (Charley and West 1975, 1977, Parker et al. 1982, Virginia and Jarrell 1983, Lajtha and Schlesinger 1986). Initially these islands may not have represented local accumulations of nutrients as much as remnants of the original homogeneous and fertile soil of the grassland ecosystem.

Increasing local heterogeneity of resources may have produced several feedbacks (Fig. 3). Islands of fertility are favored sites for shrub regeneration (Goldberg and Turner 1986), yielding the self-augmenting levels of local fertility. Meanwhile, intershrub spaces are subject to erosion and

further reductions in moisture input and nutrient availability. Thus, a landscape with a previous relatively uniform distribution of resources became heterogeneous at the local scale.

Such changes not only have altered the local distribution of resources, but also the extent and location of ecosystem processes within the basin as a whole. Erosion of soil from intershrub areas results in greater horizontal transport of nutrients in runoff and may result in higher rates of denitrification and ammonia volatilization in the fine textured, carbon and nitrogen rich soils that accumulate in basin depressions (playas). Nitrogen inputs from recently established areas of  $N_2$ -fixing mesquite might now be transported to sites where nitrogen is lost by the production of reduced gases. Thus, nitrogen losses from the basin may have increased in response to desertification.

## **II. DESERT ECOSYSTEMS: STRUCTURE AND FUNCTION**

The Jornada LTER site is located in the northern part of the Chihuahuan Desert (Fig. 4) which lies in the subtropical convergence zone where converging air masses maintain high atmosphere pressure reducing rainfall over the region. The deserts of North Africa, the Middle East and Eastern Asia are in the same latitudinal belt (see Fig. 2). The Chihuahuan Desert differs from the other subtropical North American Deserts by receiving less than 30% of the annual rainfall during the winter, compared to 40-90% winter precipitation in the Sonoran and Mojave Deserts (MacMahon and Wagner 1985). Summer rainfall is predominantly from localized, intense, short duration convective storms. In addition, most of the Chihuahuan Desert is at elevations greater than 1000 m, which reduces both summer and winter temperatures in comparison to the other N. A. deserts. Most areas of the Chihuahuan Desert regularly experience temperatures below 0° during November through February, while temperatures below freezing are infrequent in the Sonoran and Mojave Deserts. Despite the lower temperatures, some plants grow during all months of the year when water is available. Based on rainfall and temperature it is possible to characterize the Chihuahuan Desert climate into three seasons: (1) hot-dry: May-July (2) hot-moist: July-October (3) cool-dry: November-April (Appendix A).

The present day Chihuahuan Desert is a mosaic of shrubland and remnant grasslands that are

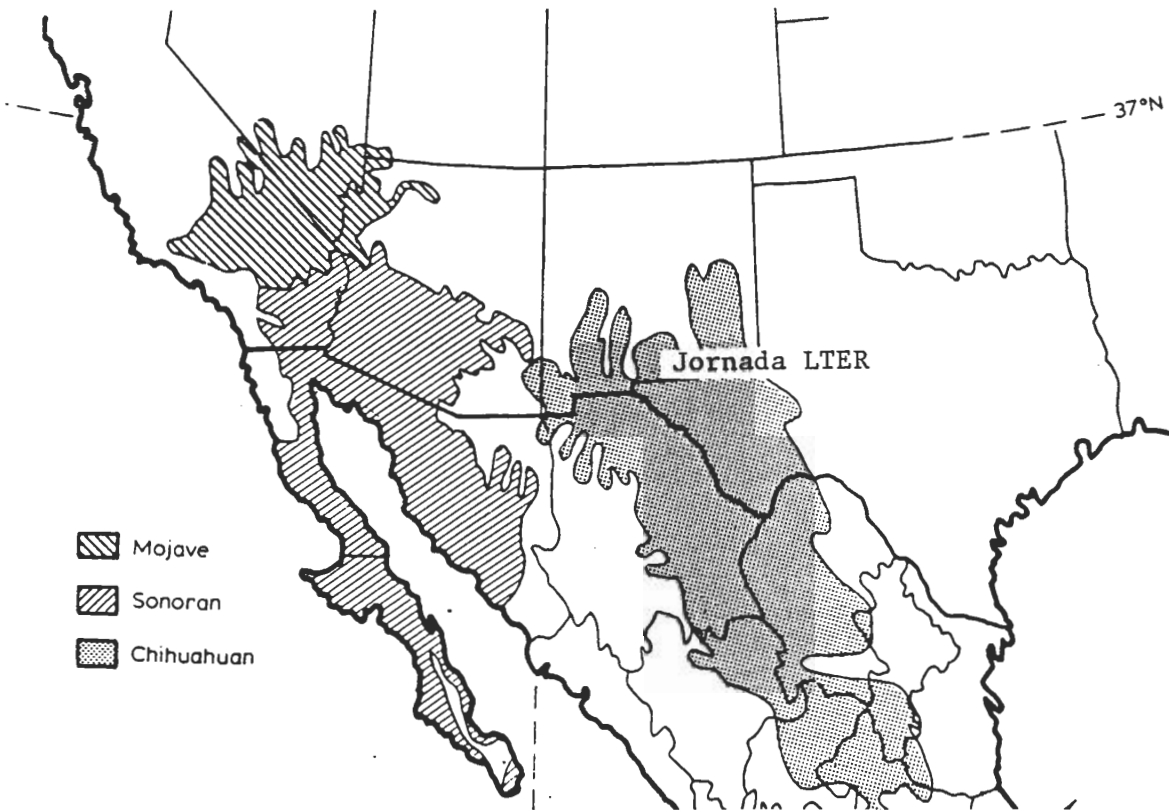


Fig. 4. Location of the Jornada LTER Site and extent of Mojave, Sonoran and Chihuahuan Deserts (from MacMahon and Wagner, 1985).

well represented on the Jornada (Plates 1-6). The Chihuahuan Desert shares many similarities with the other "hot" deserts of the world by virtue of being sub-tropical. It is important to emphasize that the tropical affinities of the flora and fauna and the evolutionary history of sub-tropical deserts impose functional differences on these areas in comparison to temperate "dry" areas. We should therefore expect greater functional differences between short grass steppe ecosystems and the Chihuahuan Desert, which are separated by a few hundred kilometers, than between the Chihuahuan and the African, Middle Eastern or Australian deserts that are thousands of kilometers distant. While there are limited data on these functional similarities, there are data that support this view of the Chihuahuan desert and comparisons of functional similarities and differences are important foci for the Jornada intersite synthesis activities in the LTER network.

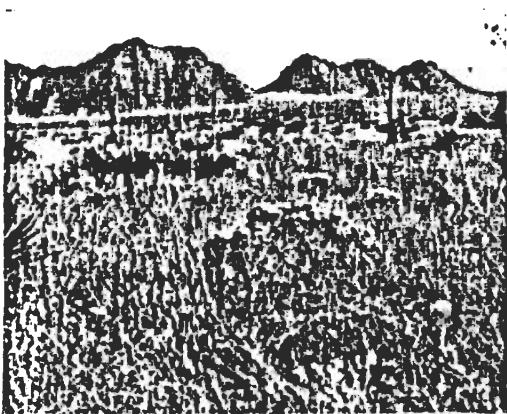


PLATE 1 - Remnant black gramma grassland, formerly widespread on Jornada in the 1870's.



PLATE 2 - Desertified grassland on clay soils in low elevation areas, dominated by tarbush.



PLATE 3 - Creosotebush shrubland on shallow soils of the upper bajada of LTER I transect.

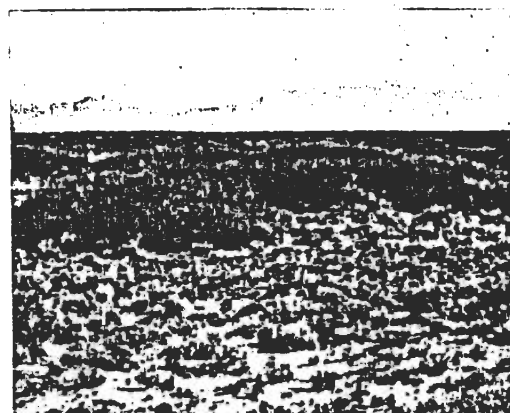


PLATE 4 - Mesquite dunes on highly wind eroded sites.

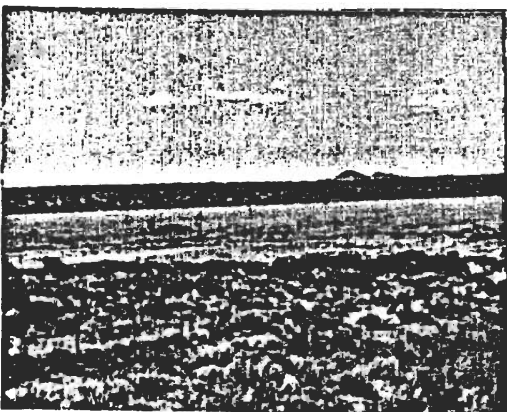


PLATE 5 - Large playa (dry lake bed) on the Jornada basin dominated by mixed grasses

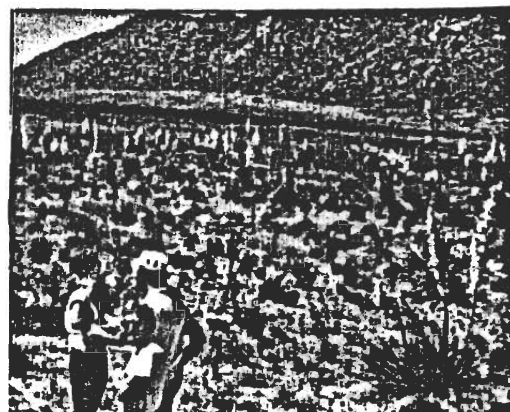


PLATE 6 - LTER I watershed transversed by 3 km long Reference and N-fertilized transects.

## A. Controls on Production

**Water:** The most obvious environmental factor regulating system function in deserts is the supply of water. The low mean values of annual aboveground net primary production (AGNPP) regularly cited to substantiate this generalization obscure a great deal of year-to-year and place-to-place variation in primary production that occurs in many desert landscapes (Noy-Meir 1985). Ludwig (1986, 1987) concluded that there is greater variability in AGNPP among different communities within a desert than among deserts and that there is considerable but asynchronous variability in AGNPP within desert ecosystems over time. Annual above ground net primary production (AGNPP) at the Jornada lies within the range of values for other deserts:  $30 \text{ g}\cdot\text{m}^{-2}\cdot\text{y}^{-1}$  to  $600 \text{ g}\cdot\text{m}^{-2}\cdot\text{y}^{-1}$  (Ludwig 1986), but in some years is near the lower limit of values for temperate forests (Ludwig 1987). This variation in AGNPP can only partly be attributed to water availability. Nitrogen availability is nearly as important as water (Floret et al. 1982, Penning-de Vries and Dijteye 1982, Gutierrez and Whitford 1987, Fisher et al. 1987).

**Nitrogen:** Why should dry ecosystems be nitrogen limited? Related to low nitrogen availability is the low soil organic matter in deserts. Organic matter accumulations occur primarily under shrubs and in soils receiving substantial run-on of organic materials. Soils of intershrub spaces on desert plains and on low slopes tend to have soil organic matter contents of less than 1% (Whitford, unpublished). Low population densities of soil microflora and low concentrations of energy and nutrients for microbial activity are direct consequences of low soil organic matter (Santos et al. 1978, Steinberger et al. 1984).

**Decomposition:** One important difference between temperate and sub-tropical ecosystems is the replacement of earthworms by termites as the dominant soil animals in the tropical systems (Lee and Wood 1971). Unlike earthworms, termites consume dead vegetation, which is then intensely degraded in the termite gut. The excretory products of termites are similar to residual humic substances, which contain little material that is available to microflora and may actually depress microbial activity (Lee and Wood 1971). In addition, subterranean termites deposit feces in chambers well below the root zone of many plants (Whitford, pers. obs.). In the northern Chihuahuan Desert

subterranean termites consume between 50% and 80% of the organic production including roots of annual plants and grasses (Johnson and Whitford 1978, Whitford et al. 1982, Whitford et al. 1987). Other hot deserts have a diverse and abundant termite fauna that undoubtedly consumes most of the dead vegetation and animal feces (Krishna and Weesner 1969). The result of termite activity is that the bulk of material that would potentially contribute to soil organic matter is essentially lost from the system by the respiration of these soil animals. Since the harvesting termites are sub-tropical or tropical in their geographic distribution, these animals may indirectly be responsible for major functional differences between sub-tropical deserts and temperate semi-arid ecosystems.

## **B. Spatial and Temporal Variations**

A high degree of spatial and temporal variability has been observed in desert biota, particularly for species and populations that rely on episodic, rich resources rather than reliable, but low level resources (Shmida et al. 1985). Although other ecosystems are also characterized by spatial and temporal variation, deserts may be unique in the extent to which system-level responses are controlled by spatial variation, and the extent to which spatial variability compensates for temporal variation to maintain ecosystem integrity. In dry years better habitats can provide a refuge for plants and animals that allow survival and potential for expansion during wetter years. Spatial variation in the concentration and availability of resources may reduce biological fluctuations (Shmida et al. 1985). This is essentially a restatement of the overall hypothesis that has guided the work to date on the Jornada LTER project.

There are several sources of spatial variation across a desert landscape, some that result in spatial patterns that are persistent over long time periods and some that are more ephemeral. Geological and geomorphological heterogeneity are among the more persistent features. This geomorphological heterogeneity is particularly important in the basin and range province of the southwestern United States and is a major determinant of vegetation patterns of the Jornada (Wierenga et al. 1986, Wondzell et al. 1987). Rainfall patchiness has a more ephemeral and unpredictable effect on spatial variation. Spatial variation also results from biologically induced patchiness. Micro-climatic and micro-edaphic habitats are created by plants, detritus heaps, animal



burrows and other animal created soil disturbances. These smaller scale more ephemeral spatial patterns are distinct features of the Chihuahuan desert (Steinberger and Whitford 1983, Whitford 1988, Moorhead et al. 1988).

The mountain-piedmont slope-basin floor landscape that forms the watersheds of basin and range deserts is a complex mosaic of exposed geomorphic surfaces, soil types, vegetative communities and slopes (Gile et al. 1981, Peterson 1981, Wondzell et al. 1987). The extent to which the elements of these complex landscapes are linked in terms of water and nutrient transfer depends upon the magnitude, timing and spatial patterns of run-off, transport, run-on relationships between the component elements. Runoff, the driving force determining material linkage, depends on many factors such as rainfall intensity and duration, soil physical and chemical properties, soil temperature, slope, and, perhaps most importantly, vegetative cover.

Desert shrub communities have been described as "islands of fertility" in a sea of low fertility soils (Garcia-Moya and McKell 1970, Charley and Cowling 1968, Lajtha and Schlesinger 1986, Virginia and Jarrell 1983). Shrubs affect not only nutrients but also water infiltration (Elkins et al. 1986), with the result that much of the productivity of herbaceous plants is concentrated under and immediately adjacent to shrub canopies (Parker et al. 1982, Muller 1953). One consequence of this insular pattern of nutrients and organic matter is the concentration of soil organisms in these islands (Santos et al. 1978, Freckman and Mankau 1977, Kamill et al. 1985) as well as the concentration of activities of larger animals in these areas (Steinberger and Whitford 1983, Johnson and Whitford 1978, Peterson and Whitford 1987). Variation in the nitrogen availability to shrubs affects the population densities of canopy arthropods (Lightfoot and Whitford 1987). The relative richness of shrub islands is a function of shrub morphology (Whitford, unpublished data) and presence or absence of symbiotic N<sub>2</sub>-fixers on the roots of the shrub (Lajtha and Schlesinger 1986, Jenkins et al. in review).

### **C. Deserts: Contribution to Global Climate Change**

**Dust and Albedo:** Ecosystem processes in deserts affect global properties and the functioning of other ecosystems at great distances from desert regions. Schutz (1980) concludes that



desertic aerosols are a major contribution to oceanic sedimentation and may have important climatic implications. Loyer-Pilot (1986) showed that Saharan dust significantly increased the pH of rain water on Corsica and suggested that  $\text{CaCO}_3$ -rich dust may counteract the effects of acid rain. The deposition-rate of dust on Japan is influenced by meteorological conditions of the arid and semi-arid regions of China and Mongolia (Inoue and Naruse, 1987). Dust from the Chihuahuan Desert could be a significant portion of the bulk precipitation at LTER sites in the eastern U.S.

Decreased vegetative cover and/or increased patchiness of vegetation and the associated increase in bare ground patches can lead to higher surface albedo. Charney (1977) has proposed a biogeophysical feedback mechanism whereby increased albedo poleward of the Intertropical Convergence Zone (i.e. the location of the subtropical arid zones) would lead to decreased rainfall and an equatorward movement of the arid zone.

**Trace Gases:** Considering the abundance of termites in the Chihuahuan Desert (Johnson and Whitford, 1978) and quantities of organic matter consumed by these animals (Whitford et al. 1982), it is possible that these animals may be contributing significantly to global methane and other trace atmospheric gases which may contribute to global warming through the "greenhouse effect" (Fraser et al. 1986, Zimmerman et al. 1982, Zimmerman and Greenberg 1983, Collins and Wood 1984).

Desertification is likely to have increased the amounts of  $\text{NH}_3$  and  $\text{N}_2\text{O}$  volatilized into the atmosphere through a variety of processes. Desert soils have a full complement of soil flora and fauna necessary for the rapid production of  $\text{N}_2$ ,  $\text{N}_2\text{O}$  and  $\text{NH}_4$  from soil organic matter when environmental conditions are appropriate. Shallow rooted perennial grasses are able to respond to small rain events which also initiate nitrogen mineralization of the surface and near surface organic matter (Sala and Lauenroth 1982). The replacement of perennial grasses with shrubs and annuals has disrupted the tight temporal and spatial coupling of  $\text{NH}_4$  and  $\text{NO}_3$  availability with plant uptake (Whitford et al. 1987). The transport of surface soil organic matter to runoff locations may also remove the source of mineralizable nitrogen from the soils associated with plant roots. All of these factors would lead to an increased flux of nitrogen gases to the atmosphere.

Ammonia volatilization is likely to be important in the transfer of nitrogen to the atmosphere because of environmental conditions extant in desert ecosystems (French et al. 1983). High soil pH, coarse textured soils, high soil temperatures, low soil organic matter, high calcium carbonate, and high wind will all promote high volatilization rates. In addition high levels of grazing can also promote nitrogen loss since up to 80% of the N in urine may be lost by volatilization (Woodmansee et al. 1981). The loss of tight spatial and temporal coupling of nitrogen mineralization and uptake also implies that volatilization is occurring at times and places where plants are not photosynthetically active.

### **III. MODELING APPROACHES**

The complexity of factors influencing productivity and ecosystem dynamics in the arid systems that make up the Chihuahuan Desert landscape calls for an integrated research plan that is best obtained by coupling field observation and experiment with a simulation modeling program. The complex processes within ecosystems are directly affected by transfers of materials across system boundaries which vary temporally with climate and in response to disturbance; this spatial and temporal variability requires scaling up of information to the landscape level which may be feasible using modelling. Within this context, modeling is an important tool that can be useful for: studying the interactions of specific processes and perturbations in desert ecosystems; directing experimental research in areas of insufficient understanding; organizing the results and findings of the various studies; and as a complex and comprehensive bookkeeping facility of known relationships and processes as new understandings evolve.

#### **A. General Modeling Goals**

Modeling will play an important role in Jornada LTER II to develop a predictive understanding of potential ecosystem responses to simultaneous changes in resource availabilities as depicted by the Jornada Model (Fig. 3). Our modeling goals are to examine relationships between intra- and intersite processes to gain an understanding of the mechanisms underlying these responses. The large body of knowledge derived from the proposed studies will profitably be supplemented with simulation models that can be subjected to near-infinite combinations of conditions.

Three major tasks will be addressed by our modeling efforts: (1) describing processes which occur at specific locations on the landscape; (2) characterizing transport of energy and materials between locations; and (3) interfacing local and transport processes in a landscape framework. Our approach will employ a hierarchy of models, using different levels of time and space scales to simulate ecosystem and landscape dynamics.

## **B. Scales of Spatial Hierarchy**

The desert landscape of the Jornada comprises a heterogeneous mixture of soil types, topography, and vegetation (Plates 1-6). Understanding spatial and temporal scales of ecological interactions within this mosaic is fundamental to the objectives of Jornada LTER II and is the cornerstone of the emerging science of landscape ecology (Risser et al. 1984, Urban et al. 1987). Our conceptual model of landscape "dimensions" is given in Fig. 5, illustrating the structural and transport linkages within the Jornada basin. This scheme serves as a hierarchical framework for developing an integrated modeling and experimentation strategy in LTER II:

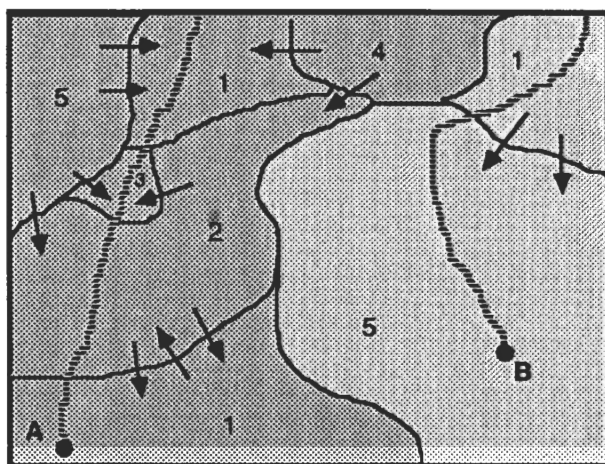
Dimension I: *Source areas* represent parcels of land that have similar responses to energy and water inputs, regardless of their spatial location. These physically homogeneous areas may be identified on the basis of similar soil, vegetation, slope and aspect. Source areas are similar in concept to "hydrologic response units," which are land areas that respond similarly throughout when subjected to a given precipitation event (Li et al. 1977), and to "patches" or "points" which are ecosystems defined on the basis of a biotic community that resides on some distinct soil or sediment type (typically expressed in units of an average square meter or hectare) (Woodmansee 1987).





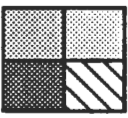
Dimension II: Interactions between adjacent source areas occur by way of *flowpaths* (Woodmansee 1987). Typically, water and wind are the vectors of transport of material and energy between source areas. Field studies at the level of flowpaths correspond to examining the degree of linkage between communities.

Dimension III: *Distribution flow lines* may be regarded as linear collectors of outputs from a series of source areas. Outputs concentrate in these flow lines which generally correspond to drainage lines or channels. These flow lines may be a mechanism for removing mass out of the system.

Dimension IV: *Integrated flow systems (IFSs)* are an assemblage of Dimensions I-III that may deliver mass (by gravitational processes) to a defined point on a distribution flow line (i.e., an effective sink for the system). An IFS is analogous to a drainage basin associated with a river gauging station. In Fig. 5, two IFSs are depicted using reference points A and B

Dimension V: The *regional* level of study includes the mix of integrated flow systems that constitute the Jornada study area.



<i>Dimension:</i>	<i>Identifier:</i>	<i>Description:</i>	<i>Models:</i>
I Point	Numerals 1-5	Source Areas	Process
II Vector		Flowpaths	Ecosystem
III Vector		Distribution Flow Lines (Channels)	
IV Area	 Drainage A  Drainage B	Integrated Flow Systems	
V Area		Region	Landscape

*Figure 5. Conceptual scheme for landscape dimensions.*

This landscape scheme is clearly most applicable to mechanisms and processes associated with flows related to gravity, particularly at the distribution flow line and integrated flow system dimensions. However, aeolian transfers may also be applicable since the integrated flow systems will provide a basis for overall mass balance studies. This hierarchical arrangement lends itself to the integration of simulation modeling and the use of the ARC/INFO GIS (Section IV-D) since the latter is designed to handle parcels, networks, and flows.

### C. Model Hierarchy

Three types of models - process models, ecosystem models, and a dynamic landscape model - will be developed, corresponding to the hierarchy illustrated in Fig. 5. Our approach is to build a suite of models that will allow us to address questions at distinct time and space scales since activities at lower levels (e.g., Dimension I) operate at faster time and smaller spatial scales than activities at higher levels (e.g., Dimension V) (Reynolds and Acock 1985a,b).

**Process Models:** Models that purport to be based on underlying mechanisms that give rise to the observed responses are termed "bottom-up" or *process* models. These models require extensive data and are difficult to develop but predictions can be made outside the range of the experimental data on which they are based.

Our current NSF Ecosystems supported modeling work for the Jornada has focused on constructing various process models of biotic and abiotic controls on carbon, nitrogen, and water flux (Bachelet et al. 1987, Moorhead et al. 1986, 1987a,b,c, 1988, Moorhead and Reynolds in review). For Jornada LTER II, similar "bottom-up" models will be developed for a variety of phenomena related to the Jornada Model (Fig 3), including, for example, plant growth, decomposition, nutrient uptake, mineralization, and water and nutrient flux in the soil. These process models will contribute to our basic understanding of the rates, directions, and magnitudes of important fundamental processes controlling ecosystem response to changing resource availabilities.

**Ecosystem Model:** An ecosystem model - coined GALs (General AridLands Simulator) - will be developed during Jornada LTER II. GALs will be a "patch" model, defined on the basis of a biotic community that resides in a average square meter of major ecosystem types in the Jornada (i.e., Dimension I, Section III-B). GALs will simulate, for example, the dynamics of plant productivity (and LAI), competitive interactions, and nutrient fluxes.

The IBP ecosystem models developed during the early 1970's tended to be monolithic and complex (Watt 1975). These very complex models (composed of numerous coupled process models) lacked robustness and were frequently hypersensitive to slight changes in parameters (Allen and Starr 1982). While these models were often quite successful in simulating specific short-term processes,

they were not well suited for long-term simulations (Allen and Starr 1982). Also, large models such as these are difficult to maintain and verify, are often unstable, and may not be amenable to modification for new situations (Rexstad and Innis 1985, Loehle 1987).

In our efforts to build a model such as GALS to predict ecosystem response to simultaneous changes in resource availabilities (e.g., nutrients and water) it is clear that empirical correlative models have limited utility. Only process models will afford us the opportunity to extrapolate beyond our data with any degree of confidence. However, to avoid the problems associated with building complex, "bottom-up" ecosystem models, we will use various simplification and aggregation schemes to build phenomenological "top-down" models.

A phenomenological equation is limited to observable quantities, preferably has a theoretical justification, but does not attempt to deal with unnecessary complexities (Spanner 1964). Consequently, a phenomenological model is representative of a general phenomenon and not a complex description of underlying mechanisms. One clear advantage of a phenomenological approach is that empirical data are used but they are combined with information about the fundamental elements that control the rates and directions of various ecosystem processes (Landsberg 1986).

The GALS ecosystem modeling effort will employ both "bottom-up" process and phenomenological "top-down" models. While extant process level models will serve as valuable building blocks for the development of GALS, these process models will be summarized in simpler phenomenological formulations for use in GALS. This exercise of simplification itself will yield meaningful insights (Rexstad and Innis 1985).

**Dynamic Landscape Model:** Logically, we should be able to combine patch with flowpath and distribution flow line information into a phenomenological description of landscape dynamics. Our proposed scheme is illustrated in Fig. 6. While the IBP ecosystem models were *point* models in that spatial heterogeneity was largely ignored (Woodmansee 1987), recent advances in computerized geographical information systems (GIS) (Burrough 1986) now make it possible to readily include spatial variability in ecosystem models.

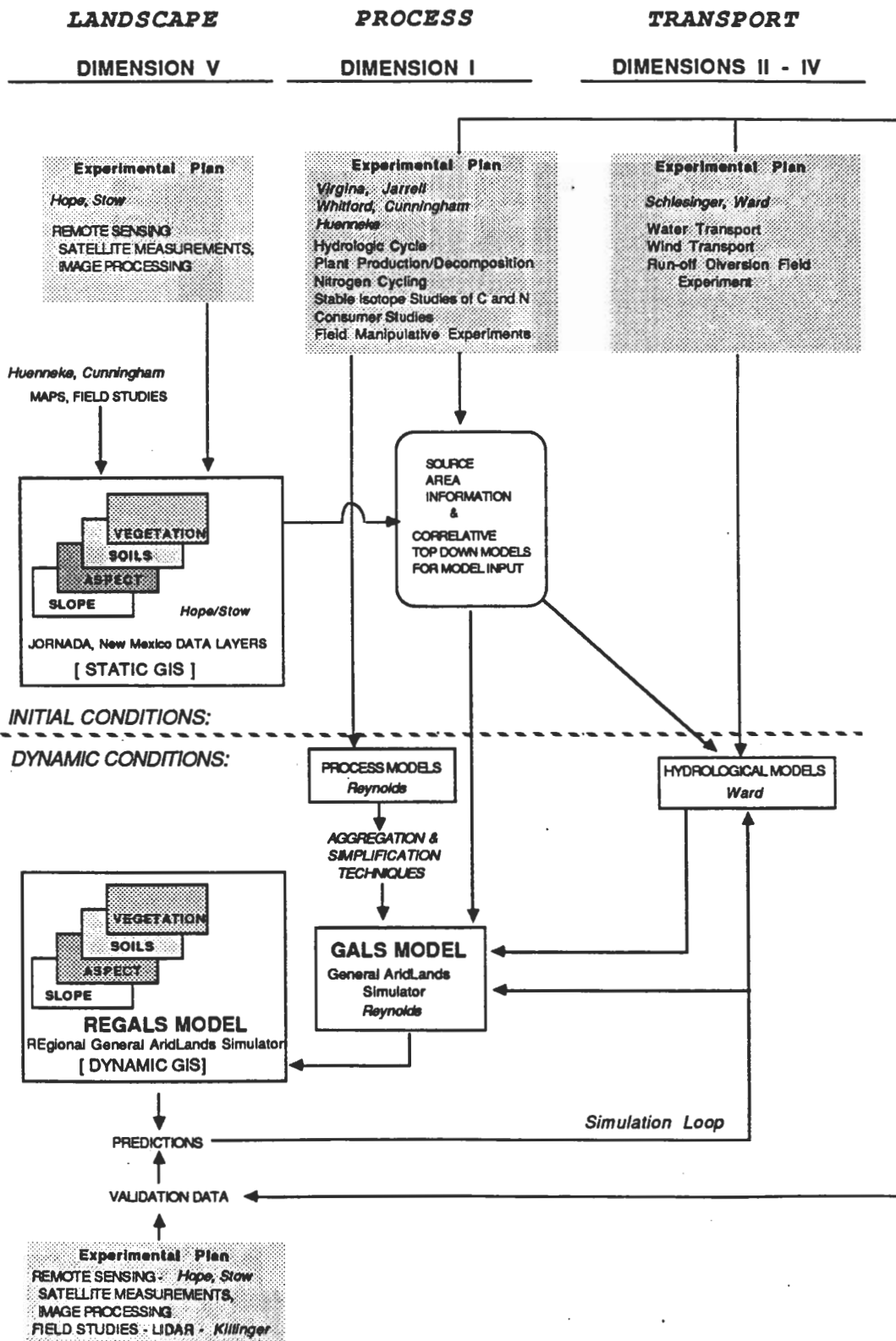


Figure 6. Proposed scheme for integrating spatial landscape dimensions and models. The GALS model is coupled to a GIS to form the REGALS models. Dimensions correspond to those shown in Figure 5. Landscape, Process, and Transport correspond to levels of study defined in proposal. Researchers with major responsibility for projects listed.

GALS will be coupled to a GIS to simulate transport dynamics, including sedimentation, erosion, and water dynamics (at Dimensions II-IV, Fig. 6). We have successfully coupled several hydrology models to GIS schemes at San Diego State and are actively refining this capability.

The GIS may also provide important initial conditions for our models (percent cover of various plant groups, number of water channels, etc. - see Fig. 6) (Curran and Williamson 1987). Through the use of established correlative relations between remotely sensed radiation values and selected biophysical quantities (e.g., biomass, LAI, etc.) it will be possible to provide regional validation data for testing the extrapolation potential of our models across the landscape (Fig. 6). Also, a GIS provides rapid manipulation of many layers of spatial information obtained over large areas of land and can be used to identify source areas (e.g., Dimension I, Fig. 6).

It is possible to interface ecosystem simulation models with GIS models to accomplish a dynamic GIS (Coulson et al. 1987). This coupled model, termed REGALS (REgional GEneral AridLands Simulator), will permit us to explore various questions concerning the spatial and temporal distribution of resources at the Jornada. Our proposed scheme for LTER II, illustrated in Fig. 6, effectively combines the data analyses and manipulation functions of GIS with the powerful extrapolation capability of phenomenological ecosystem models to accomplish a regional landscape model.

REGALS will serve as our quantitative formulation of known and hypothesized relations in the Jornada Model. REGALS will be parameterized to represent our best estimate of range conditions existing in the Jornada in 1858 and run to the present to see if the known changes in vegetative cover from 1858 to the present (e.g., Buffington and Herbel 1965) can be accurately reconstructed (Fig. 1). REGALS will serve as a "what if..." tool for evaluating the contribution of a number of disturbance scenarios to desertification (Jornada Model, Fig. 3), for example, the impact of various levels of cattle grazing and trampling on various flowpath dynamics and distribution flow line processes, the effects of alterations in water and nutrient budgets at the study area, changes in plant cover, changes in the number of drainage streams, changes in sedimentation and erosion, climate changes, etc.



## IV. EXPERIMENTAL PLAN

### A. Current Jornada LTER

*Review of Research to Date:* Jornada LTER I (1982-1987) focused on studies of ecosystem response to spatial and temporal heterogeneity. We hypothesized that spatial differences in water and nutrient availabilities would impose lags in system responses (e.g., plant production) and that these lags would not necessarily be equal, nor synchronous, spatially. The experimental design centered on two 3-km transects, extending from the middle of a dry lake bed to the base of a mountain. The transects traversed 7 perennial plant vegetation zones (Wierenga et al. 1987), encompassing many of the plant communities that make up Chihuahuan Desert landscapes. One transect was fertilized (with 10 kg. ha<sup>-1</sup> of NH<sub>4</sub>NO<sub>3</sub>) once each year during the rainy season; this fertilization was imposed to homogenize a previously patchy and limiting resource. A variety of short-term studies were conducted that evolved from questions or hypotheses generated from the long-term transect studies (see list of publications -Prior NSF Support).

The transect studies demonstrated that some ecological processes (e.g., plant production, N mineralization) and populations (e.g., soil arthropods, ants) vary greatly, exhibiting sharp transitions over short distances, while others vary gradually (Cepeda 1986, Wierenga et al. 1987, Cornelius et al. 1987, Wondzell et al. 1987, Whitford et al. 1987). The complex interactions between rainfall, N availability, soil, and geomorphic position and their effects on plant production and decomposition have been examined by a series of experimental studies on small plots using irrigation and fertilization (Whitford et al. 1986, Parker et al. 1982, Gutierrez and Whitford 1987a,b, Gutierrez et al. 1987, Fisher et al. 1987, Ludwig et al. 1988, MacKay et al. 1987).

The LTER II Jornada Model (Fig. 3) predicts that homogenization of a potentially limiting resource, such as N, will lead to an increase in plant cover and a decrease in plant diversity. Results of the first 5 years of N amendments in LTER I indicate that these predicted responses are occurring for the annual plant species --N amendments resulted in increased annual plant cover and decreased diversity. With time, we anticipate finding similar responses in the perennial vegetation (Cornelius and Cunningham 1987).

Several experiments examined relationships between water inputs and nutrients and mass losses from dead organic matter. Whitford et al. (1986, 1987) found little effect of irrigation on mass losses from litter on the soil surface or from dead roots. Over a period of 2 or more years, total mass losses among irrigation treatments were not statistically discernible (Whitford 1986). The exception was that mass loss from surface litter was accelerated by simulated rain events during an extended rainless period (Whitford et al. 1986). This pattern was confirmed by parallel studies in the southern Negev, Israel, where simulated rain events accelerated mass loss *only* during the summer rainless period (Whitford unpub data). Adding nutrients (S and N) also had no effect on mass losses, except where S repressed termite activity (Mackay et al. 1987).

Studies of mass losses from surface litter using mercuric chloride to eliminate biological activity demonstrated that 15% of the mass loss in summer was the result of abiotic processes such as photo-oxidation. Pauli (1964) was the first to suggest that the intense UV light and high surface temperatures would combine to decompose organic materials in sub-tropical and tropical deserts. We hypothesize that the high 35% to 70% mass losses from surface litter (Schaefer et al. 1985) are due to fragmentation by sunlight and that fragments are transported into the soil by rainfalls. This interpretation is not consistent with conventional wisdom that decomposition rates in deserts are low and occur for brief periods following rains (Noy-Meir 1973). These experimental studies also demonstrated that populations of soil biota are limited by substrate availability and *not* by water (Parker et al. 1985, Steinberger et al. 1985, Whitford et al. 1986, Freckman et al. 1987).

The interpretation of ecosystem responses to water inputs is made more complex by examining the effects on N mineralization. Fisher et al. (1987) reported that extended drying tended to increase N availability and that frequent small rain events depressed N mineralization more than equal sized, infrequent events. Fisher et al. (1987) hypothesized that increased moisture availability eventually leads to losses of mineralizable N due to its conversion to inorganic forms. These N mineralization patterns are consistent with observed patterns of primary production on irrigated plots. Gutierrez and Whitford (1987) reported an order of magnitude lower biomass production of annual

plants during a second year of continuous irrigation. Fisher et al. (1987) found that productivity of creosote bush *Larrea tridentata* was little affected by irrigation but greatly enhanced by N fertilization.

The findings summarized above have clearly demonstrated the importance and link between water and N availability as driving variables in Chihuahuan Desert shrub ecosystems. These studies have raised questions pertaining to the applicability of these results to desert grasslands and how these processes may have changed during the desertification process.

**Ongoing Studies:** The research described in the preceding section represents activities associated with Jornada LTER I. Our intention in Jornada LTER II is to continue collecting some long-term data sets initiated by LTER I that are relevant to our current research proposal. We will continue to fertilize the N-amended transect and to collect the following data on both transects: annual plant cover (twice a year), perennial plant cover (once a year), establishment and death of ant colonies, and soil water contents. Other LTER I data sets will be continued, but with modifications in order to utilize techniques that will be applied to other study areas included in LTER II; these include plant biomass production, decomposition of roots, soil N, censusing and activity of termites, rabbit populations, and organic matter transport.

We will continue to collect weather data from the present meteorological station located near the center of the study transects. These data include rainfall amount and intensity; solar and net radiation; air and soil temperature; wet and dry deposition; wind speed and direction; pan evaporation; and atmospheric moisture contents. These data will be supplemented by the USDA rain gauge networks and comparable meteorological measurements being made at the Jornada Ranch Headquarters.

## **B. Process - Level Studies**

**Hydrologic Cycle:** The central hypothesis in LTER II is that the distribution of resources, particularly water, varies in the 5 ecosystems shown in Plates 1-5. This variation is a primary cause of the shift from grassland to shrubland, and is further exacerbated by the nature of the shrubs themselves.

We suspect that soil moisture availability varies across the landscape and *increases* in the following order: grassland, creosote bush, tarbush, and mesquite dune. Variability results from

differences in the quantity of water entering the soil, at the scale of plant canopy sizes (e.g., 1m). The routine hydrologic measurements will involve monitoring of soil water content (neutron probe - Graecen 1981) and soil water potential (soil psychrometers - Fonteyn et al. 1987). The water content measurements will be used primarily for water balance, while the psychrometer measurements can be used for water balance and to describe the availability of water to vegetation. Fonteyn et al. (1987) describe the successful application of soil hygrometers to the study of plant uptake and soil water balance on the Jornada. The soil moisture monitoring plots will be installed adjacent to the runoff plots (Section IV C) to allow direct comparison of the data.

In the black grama grassland, a set of 12 randomly distributed neutron access tubes over an area of approximately 0.25 ha should characterize soil water relations. In the shrub communities, a more systematic distribution of neutron tubes will be required. Six pairs of tubes will be installed: in each pair, one will be located under the canopy, the other midway between shrubs to represent maximum and minimum extremes of evaporation and transpirational water in these systems. All tubes will be inserted to 4 m where possible. Measurements, at monthly intervals, will be made at depths of 25, 50, 100, 150, 200, 250, 300, 350, and 400 cm

We hypothesize that evaporative water losses *increase* in the following order: grassland, creosote bush, tarbush, and mesquite dune. To determine rates of water loss from the soil surface, moisture dynamics in the surface soil must be followed after rainfall events. Because neutron probe readings are often inaccurate near the soil surface, the surface plate method (Gardner 1985) will be used to circumvent this problem. To obtain accurate estimates of surface soil water potential and soil temperature, soil psychrometers will be placed 5 and 20 cm below the soil surface under and between 3 shrubs at each site. In addition, the perimeter of three 1-m<sup>2</sup> plots will be trenched and lined with plastic sheeting to provide data on evaporation, since roots have excluded from the plots. One set of psychrometers will be placed within each trenched plot (Fonteyn et al. 1987). Measurements will be taken on the same days as the neutron probes are read, thus, water gain or loss each 2-week period can be computed by comparison with the previous sampling point. Using this information, the variability across the systems can be assessed and hydrologic dynamics elucidated.

The short-term pattern of soil drying immediately following a light storm event can be followed more efficiently with shallow psychrometers than with other measurement devices. Twice during each season, short-term drying patterns (on the order of days) will be measured immediately after light showers to obtain estimates of the duration of water availability following these light storms.

***Plant Production and Decomposition:*** We hypothesize that the patterns of total plant production are synchronous in the ecosystems of the Jornada landscape, i.e., high and low production occurs in the same years in all systems. Plant biomass and production data are necessary for both the development and validation of the ecosystem and landscape models. In addition, these data will be coupled with measurements of plant nutrient concentration to estimate element uptake in the various ecosystems. Since, no single method can provide information on plant production at all spatial scales of interest, we will use methodologies ranging from hand-held radiometers and satellite remote sensing of canopy reflectance to direct harvesting.

**Aboveground Production - Spectral Vegetation Indices (SVIs):** Recent studies in biophysical remote sensing have demonstrated relationships between spectral vegetation indices (SVIs) and biophysical quantities such as biomass, leaf water content, leaf area index (LAI), intercepted photosynthetically active radiation, canopy resistance, and net primary productivity (Hatfield et al. 1984, Hope et al. 1986, Sellers 1985). The small canopy cover to bare soil ratio characteristic of the Jornada is likely to affect the nature or integrity of many of these relationships. The following research design addresses the potential difficulties associated with the Jornada conditions.

Spectral Vegetation Indices have been developed to reduce multispectral reflectance data to single values that relate directly to specified biophysical quantities. Most SVIs include combinations of red and near infrared reflectance with their formulation, depending on the specific application. Two of the most widely used SVIs are the simple ratio (GR) and normalized difference (ND) indices:

$$GR = NIR/R \quad \text{and} \quad ND = (NIR - R)/(NIR + R)$$

where R and NIR are reflectances in the red and near infrared portions, respectively, of the electromagnetic spectrum. Initially, these 2 indices will be used for the Jornada since ND generally

has a non-linear relationship and GR a linear relationship with biomass or LAI. Furthermore, ND is more sensitive to changes in biomass where vegetation is sparse.

The principal aim of developing the vegetation index is to determine the most suitable SVIs for predicting area averaged standing biomass and production. Since production is ultimately tied to leaf area and photosynthetic activity, we anticipate that a measure of plant leaf area should be a reliable index of total plant production on the Jornada. The following procedure will be used: (1) SPOT or other satellite images (e.g., Landsat/TM or NOAA/AVHRR) of the Jornada Basin will be obtained, (2) a sample of target sites will be selected that represent the major vegetation cover conditions, (3) field estimates of biomass at the end of the growing season will be made, (4) target areas in the satellite scenes will be isolated and the associated radiance data will be extracted, (5) SVIs will be computed, (6) these SVIs will be related to field estimates of leaf area, and (7) the appropriate indices will be applied to the entire study area to determine spatial patterns of leaf area and, ultimately, biomass and productivity.

Additional methodology intended to normalize the SVIs for the effects of soil background radiant emittance will be used. First, hand-held radiometers will be used to characterize the reflectance properties of soils at each of the target sites. Since radiometers record radiant emittance in the same spectral bands as SPOT (optics may be changed for other sensor systems), the soils reflectance data may be used in combination with the satellite data to enhance variations in reflectance attributable to vegetation.

A second strategy that will be tested is to compare sequential satellite data sets and relate the observed differences to ground estimates of biomass change. It is hypothesized that this multi-temporal approach will serve to normalize the soil background since it will be relatively constant (in terms of reflectance) from overpass to overpass.

The research focusing on the vegetation indices will be integrated with the baseline satellite data studies and will be dependent upon accurate geometric registration of the imagery. It should also be noted that the study may be extended to include data from other satellite systems. For example, the

Thematic Mapper (TM) system includes more spectral bands than the SPOT system and, if necessary, the bands could be investigated in terms of their suitability for a spectral vegetation index.

Aboveground Production - Clipping Estimates: It is extremely difficult to measure total AGNPP for desert shrubs if stem production is included. Hence, most studies of shrub and tree production in deserts are based on estimates obtained from clippings of leaves, reproductive tissues, and new stems (Ludwig 1987, Sharifi et al. 1982). Previous work on woody shrubs on the Jornada during the IBP Program established basic allometric relationships for shrub canopy parameters and shrub biomass and production based on clippings (Ludwig et al. 1975). The existence of these data somewhat simplifies estimation of shrub production in the current project.

We will measure production of the dominant woody species by clipping at each site. Marked branches will be harvested at peak aboveground biomass and the mass of leaves, reproductive tissues, and new twigs will be determined. Regression relationships between leaf weight and area will be determined to provide an estimate of LAI for each system. Harvest estimates of LAI will be compared with comparable estimates derived from the analysis of remotely sensed data. Primary production will also be determined on the grassland site by total harvest of marked plots at the beginning and end of the growing season.

Subsamples of each tissue type from the various study sites will be retained for nutrient analysis. Plant nutrient uptake will be calculated from the production and nutrient concentration data. Production and nutrient uptake data will be extrapolated to a per area basis by using equations relating clipping production to shrub canopy dimensions derived from IBP and LTER I studies. These estimates will be compared with production estimates derived from remote sensing of the same vegetation units.

Belowground Production - Root Studies: Rooting depths, root morphologies, and root phenologies are expected to differ greatly among the 5 ecosystems. This variation may reflect the degree of coupling between temporal and spatial patterns in water and nutrient availability, and plant growth response. Rooting patterns at various sites are expected to vary due to inherent differences in plant rooting characteristics, soil properties, and water distribution patterns.

We hypothesize that the root phenology of the shrub systems will vary less with season of the year than grasslands. Mini-rhizotrons root viewing tubes (Upchurch and Ritchie 1983, 1984) will be installed in each of the 5 ecosystems. Six tubes (clear plastic, 5 cm diameter, 2 m long) will be distributed in a 2 X 3 grid in the grassland. In the shrub systems, 3 tubes will be inserted at a 30° from the vertical, starting at the edge of the shrub canopy and angling toward the base of the shrub; 3 tubes will likewise be inserted midway between shrubs. Where possible, tubes will be installed where the dominant roots will be those of the shrub under study.

Once each month, a Circon color video camera (available from UC Riverside) will be inserted into the tubes. The number of root intersections with the upper surface of the tube will be recorded by depth, with visual discrimination between living and dead roots. Every 3 months, a cassette recording will be made of the entire exposure face. Also each month, neutron probe readings will be made in these tubes at 20 cm increments.

These readings will provide the phenological patterns of the root system, as well as the depth distribution and relative quantities of roots under and between plants. Measurements of soil water content will provide information of the distribution of root activity as affected by water availability. While the relative quantities of root biomass in each plant community may be compared, absolute quantification using this technique has proven to be difficult, even in agricultural monocultures (Upchurch and Ritchie 1984). Rough estimates of root biomass production can be made for comparative purposes by estimating root lengths and average diameters.

Decomposition: As discussed previously, our previous work has established that much of the decomposition of materials on the soil surface is controlled by abiotic influences. Studies by Cepeda (1986) during Jornada LTER I demonstrated that variances in mass losses of litter on the soil surface were large and showed no consistent spatial patterns. Whitford et al. (1987) have argued that decomposition and N mineralization / immobilization of annual plant roots are keys to understanding N availability and the linkage between rainfall and primary production. We are currently engaged in an extensive study of root decomposition on the transects that is providing some interesting data for comparison to the studies of Whitford et al. (1987). In LTER II, we propose to study decomposition



of annual plant roots across the 5 ecosystems in order to test the hypotheses that (1) rates of mass loss will be the same across all ecosystems and (2) that initial rates of N immobilization (first 6 months of decomposition) will be the same across all habitats, followed by comparable rates of mineralization across all habitats.

We propose to study decomposition of tethered roots of the herbaceous annual *Baileya multiradiata* that occurs in all of the study sites. We will bury 20 sets of roots in each habitat in May each year, the approximate time that pulses of dead annual plant roots enter the systems following the death of winter-spring annuals. Ten sets will be removed at the end of October, the end of the hot-wet season. The remaining 10 sets will be removed the following May. The roots will be carefully brushed clean, dried, weighed and analyzed for C and N contents (Whitford et al. 1987). A new set will be enplaced each year in May.

**Nitrogen Cycling:** Nitrogen limitations to AGNPP in deserts have been described by numerous researchers (e.g., West and Skujins 1978, Ettershank et al. 1978, Ludwig 1987). The AGNPP of creosote bush and fluff grass on the Jornada increased by 27% and 102%, respectively, after the addition of  $10 \text{ g N m}^{-2}$  in a year with average rainfall (Ettershank et al. 1978). These results indicate that the amount and the timing of N availability play a critical role in determining patterns of AGNPP across this desert landscape. This leads to the hypothesis that during desertification, major changes occur in the distribution of limiting nutrients (e.g., N), resulting in an increase in their spatial heterogeneity. This is associated with increasing shrub dominance.

**Soil Nitrogen Distribution:** We will test the above hypothesis by determining the distribution of soil nutrients to a depth of 4 m in each of the 5 ecosystems. Samples will be collected relative to shrub canopies for shrub-dominated sites and from a grid system at the grassland (in conjunction with installation of the neutron access tubes). Five cores will be collected under shrub canopies and 5 cores will be collected from the shrub interspace at all sites except the grassland. In grassland, 10 cores will be collected from a grid. We will determine the following parameters for each sample depth increment (0-10, 10-20, 20-50, 50-100, 100-200, 200-300, 300-400 cm): saturation paste pH,  $\text{CaCO}_3$ , organic C,  $\text{NaHCO}_3$ -extractable P, KCl-extractable  $\text{NH}_4$  and  $\text{NO}_3$ , total Kjeldahl N,

exchangeable cations, and DPTA-extractable micronutrients. These data will provide baseline information on the total quantity of and variability in the distribution of nutrient reserves in each system.

Nitrogen Mineralization: Ongoing studies of Jornada LTER I are examining the amount of potentially mineralizable soil N in various plant communities and the effects of supplemental water, N fertilization, and drying-wetting episodes on mineralization (Fisher et al. 1987). Much of this work has been concentrated on the *Larrea*-dominated bajada ecosystem. To fully characterize N dynamics on the additional sites in LTER II, it will be necessary to determine the mineralization potential of these soils using comparable methods. Temporal patterns of mineralization as well as estimation of field mineralization rates will be measured as part of the resin bag study described below. Mineralized  $\text{NH}_4$  and  $\text{NO}_3$  will be eluted from the exchange resins exposed to field soil.

Nitrogen Uptake by Plants: Plant N uptake will be estimated for the dominant plant(s) in each of the 5 ecosystems by multiplying clipping production values by tissue nutrient concentrations. This will provide a relative estimate of the uptake of N and other elements by ecosystem type. This will enable us to test the hypothesis that N uptake is greatest for systems dominated by  $\text{N}_2$ -fixing plants (i.e., mesquite) and is lower for systems dominated by plants which have no rhizobial symbionts.

Nitrogen Gains - Precipitation and Dryfall: Nitrogen inputs from precipitation and in dryfall will be determined from bulk precipitation collectors placed at each site and one automated wet-fall, dry-fall collector at the central weather station. Precipitation chemistry will be monitored including pH, EC,  $\text{NO}_3$ ,  $\text{NH}_4$ ,  $\text{SO}_4$ , and major cations and anions.

Nitrogen Gains - Symbiotic  $\text{N}_2$  Fixation : The abundance of mesquite on the Jornada has increased as grass cover has declined (Buffington and Herbel 1965). Since mesquite is capable of symbiotic  $\text{N}_2$ -fixation, inputs of fixed N to the Jornada may have increased dramatically over the past 100 years. There are 2 major hypotheses related to symbiotic  $\text{N}_2$ -fixation that we intend to test: (1) Inputs of symbiotically fixed  $\text{N}_2$  have increased during desertification as a result of increased concentration of water into localized areas (runon) and the creation of high infiltration systems (such as sand dunes) and (2)  $\text{N}_2$ -fixation by dune and grassland mesquite is directly related to total

precipitation, while  $N_2$ -fixation by playa mesquite is directly related to the occurrence of large rain events causing runoff into arroyo channels and flow into the playa.

Conventional methods for assessing symbiotic  $N_2$ -fixation (acetylene reduction assay) are poorly suited for deep rooting perennials. In such instances measurements of stable N isotopes at natural abundance levels have been <sup>used</sup> to estimate symbiotic  $N_2$ -fixation by deep rooted desert plants (Shearer et al. 1983, Virginia et al. 1988). The natural  $^{15}N$  abundance of mesquite at the playa, arroyo, dune and grassland mesquite systems on the Jornada indicate active fixation by mesquite at all sites except the playa (Virginia, Jarrell and Whitford unpubl. data). However, root nodules have been recovered as deep as 7 m from roots of playa mesquite (Jenkins et al. in review). This indicates either current  $N_2$ -fixation rates at the playa are low or that high spatial and depth variation in the abundance of  $^{15}N$  in the soil profile at the playa may mask the isotope signal from  $N_2$ -fixation.

We hypothesize that the fractional contribution of fixed N to mesquite ( $FN_{dfa}$ , or "fixed N derived from atmosphere") will be directly related to total annual precipitation for sites that do not collect significant amounts of runoff (i.e., grassland and dune mesquite). The  $FN_{dfa}$  for water collecting systems such as the playa will be low except in years when there has been deep recharge of the soil profile from flooding. We will collect leaf tissues from mesquite and non-  $N_2$ -fixing control species at times corresponding to peak leaf biomass (May) and at the end of the summer rains (September). Approximately 5-10 mesquite and 10-15 control samples will be collected at each site at each sampling time. The natural abundance of  $^{15}N$  in these tissues will be analyzed at SDSU using a Micromass 602D dual collecting isotope ratio mass spectrometer.  $FN_{dfa}$  will be calculated from an isotope dilution expression,  $FN_{dfa} = (\delta^{15}N_o - \delta^{15}N_t) / (\delta^{15}N_a)$ ; where  $\delta^{15}N_o$  is the  $^{15}N$  abundance of a suitable non-fixing control plant;  $\delta^{15}N_t$  is the  $^{15}N$  abundance of the  $N_2$ -fixing plant; and  $\delta N_a$  is the  $^{15}N$  abundance of fixed N after it has been incorporated into plant tissue (Virginia et al. 1988)

Ecosystem level inputs of symbiotically fixed  $N_2$  will be estimated from information on the fraction of plant N derived from  $N_2$ -fixation combined with data on plant production and N uptake for each mesquite system.

Nitrogen Losses: Relatively new techniques for quantifying concentrations of trace atmospheric gases over broad areas of the landscape are available (e.g., LIDAR) and will be used. A description of the studies of ammonia volatilization and denitrification is provided with the landscape level studies (Section IV C).

*Stable Isotopes: Temporal Variation in Carbon and Nitrogen Cycling:* The total N fraction of most soils has a higher  $^{15}\text{N}$  abundance than atmospheric  $\text{N}_2$ . Variation has also been noted in the isotopic ratio of soil  $\text{NH}_4$  and  $\text{NO}_3$  pools, although this has not been found for all soils studied (Black and Waring 1977, Ledgard et al. 1984). This variation results from kinetic isotope fractionations favoring the lighter  $^{14}\text{N}$  isotope during N transformations such as ammonification, nitrification, and denitrification. This leads to the hypothesis that annual variation in the  $^{15}\text{N}$  abundance of plants will reflect changes in soil N cycling on the sites; directional shifts in plant  $^{15}\text{N}$  abundance will indicate a major disturbance in the cycling of organic matter and N in the soil.

Long-term studies of variation in plant  $^{15}\text{N}$  abundance (an indicator of the N isotope composition of the available soil N) have not been made. We hypothesize that directional changes in N cycling processes may be accompanied by distinctive shifts in the isotope abundance of the soil N pools. For example, a prolonged period of above normal precipitation might lead to increased rates of denitrification. Since there is a large isotopic fractionation effect associated with this biological reaction an enrichment in the  $^{15}\text{N}$  content of the residual inorganic  $\text{NO}_3$  is expected. This change in soil N cycling might be detected by a pattern of increasing plant  $^{15}\text{N}$  abundance through time.

We will determine the  $^{15}\text{N}$  abundance of dominant non- $\text{N}_2$ -fixing species at each site to provide information on changing soil  $^{15}\text{N}$  abundance. Samples of perennial shrubs will be collected at the end of the summer rains prior to leaf senescence. Samples will also be collected from summer and winter annuals to determine if differences exist in the N sources available to these plants.

We are also interested in testing the hypothesis that vegetation changes from grassland to shrubland have altered the  $^{13}\text{C}/^{12}\text{C}$  ratio of soil organic matter. The overall shift in vegetation on the Jornada has been from dominance by  $\text{C}_4$  grasses to  $\text{C}_3$  shrubs. This change in vegetation from a

grassland to a mosaic of shrub-dominated ecosystems is expected to have caused major changes in the nature of the soil organic matter pool and the cycling of nutrients in the soil system. C<sub>3</sub> and C<sub>4</sub> plants have distinctive <sup>13</sup>C/<sup>12</sup>C ratios (δ<sup>13</sup>C values). Typically, C<sub>3</sub> plants range between -23 and -34 δ<sup>13</sup>C with a mean of -26, while C<sub>4</sub> plants have δ<sup>13</sup>C values of -9 to -17 with a mean of -12 (Smith and Epstein 1971). Measurements of the <sup>13</sup>C/<sup>12</sup>C ratio (δ<sup>13</sup>C) of soil organic matter have been used to assess plant community changes (Dzurec et al. 1985, Krishnamurthy et al. 1982) since the δ<sup>13</sup>C of soil organic matter should reflect the relative contribution of C<sub>3</sub> and C<sub>4</sub> vegetation types.

The long-term data record of vegetation change on the Jornada provides an opportunity to examine changes in the nature of the soil organic matter pool as a function of time since conversion from a C<sub>4</sub> to a C<sub>3</sub>-dominated vegetation. We will determine the δ<sup>13</sup>C of recently accumulated soil organic matter (0-2.5 cm) and organic matter from deeper soil (presumed to represent organic matter accumulated under grass cover) at sites of varying ages since conversion from grass to shrubland. We will also make the same measurements for soils collected from the 5 main ecosystems under study. These data will provide important information about changes in the soil organic matter pool that have occurred in response to vegetation changes on the Jornada.

**Other Elements:** Elements of special concern (in addition to N) in this ecosystem may include phosphorus (P) and the micronutrients, especially the metal cations zinc (Zn), copper (Cu), iron (Fe) and manganese (Mn). Because all of the Jornada soils are calcareous to a greater or lesser extent (Marion et al. 1988), the availability of these elements to plants may be low, and the primary productivity of the ecosystem may be limited as a result. Studies of mesquite ecosystems on the Jornada indicate very low soil levels of Zn and Cu (Jarrell, Virginia and Whitford unpubl.). The response of the Jornada plant species to micronutrient deficiencies is unknown. Very little is known about the seasonal dynamics of micronutrients in soils; this is particularly true for calcareous, non-agricultural systems. A detailed study of P fractions in soils along the original transect suggested that soil P availability was moderate, and the N/P ratio varied little with soil age (Lajtha and Schlesinger 1988). However, bicarbonate-extractable soil P concentrations in the mesquite dune systems are lower than those along the transect (Jenkins et al. in review). In addition, seasonal patterns suggest

that soil microbes may effectively compete for P during periods of peak microbial activity. Because of its importance to symbiotic  $N_2$ -fixation, patterns of P availability need to be monitored.

A number of papers have reported the use of anion exchange resins to measure soil P availability in the laboratory and the field (Amer et al. 1955, Lajtha and Schlesinger 1988). Investigators have also used ion exchange resins to measure micronutrient extractability (e.g., Mo, Bhella and Dawson 1972) in the laboratory and have correlated it with plant uptake (Jarrell and Dawson 1978). More recently, exchange resins have been buried in bags in the field and recovered; sorbed nutrients are displaced and analyzed (Binckley and Matson 1983). Although problems have been noted in interpreting results, monitoring elemental solubility in this manner can increase our understanding of the seasonal and long-term dynamics of plant nutrients in field soils.

A fundamental hypothesis of LTER II is that available soil nutrients will vary over time as a function of seasonal soil water content. The quantities of nutrients taken up by the plants will be determined through analysis of the tissue collected in plant productivity determinations. Plant tissue types collected at maximum biomass accumulation will be separated at harvest, ground, and analyzed for total N, P, S, K, Ca, Mg, Fe, Mn, Zn, Cu, and Mo using colorimetry, flame emission and atomic absorption spectroscopy, inductively-coupled plasma spectroscopy, and ion chromatography.

Yearly dynamics of soil nutrient ion activity will be monitored through the use of synthetic ion exchange resins (Gibson et al. 1985). Exchange sites on anion and cation exchange resins (Dowex 1-X8 and Dowex 50-X8, respectively) will be saturated with sodium bicarbonate. Five to ten g of moist resin will be placed in flat, rectangular decomposition-resistant terylene mesh bags and placed 10 and 30 cm below the surface. Sample bags will be placed under the canopy, and midway between, six individual plants in the shrub communities. In the grassland, twelve sets of bags will be distributed in a grid pattern throughout the community.

Bags will be collected and replaced in July and December, just before and just after the normal wet season. Sorbed ions will be eluted from the resin with HCL. In the eluate,  $NH_4$ ,  $NO_3$ ,  $PO_4$ ,  $SO_4$ , K, Ca, Mg, Fe, Mn, Zn, and Cu will be determined. These measurements will allow us to infer

the comparative nutrient availability status in all ecosystems at two depths in the soil profile in situ through time and in relation to soil water content.

**Consumer Studies:** The autecological hypothesis of Noy-Meir (1979) predicts that desert animal populations fluctuate in time and space as a function of water availability. That hypothesis also predicts no feedback effects of animal (consumer) activities on rates of primary production, nutrient cycling and secondary production of other species. Our data suggest that the autecological hypothesis is not applicable to northern Chihuahuan Desert ecosystems. Indeed, we view consumers as key elements regulating rates of ecosystem processes, affecting the patch dynamics of component ecosystems in the landscape and modifying water and nutrient availability across the landscape. The animal populations selected for study by the Jornada LTER are species or groups of species that we have found to affect plant production - both directly and indirectly - and/or to affect the re-distribution of water and nutrients.

Populations of desert cottontail rabbits, black-tailed jackrabbits, ants, and termites will be studied. The activities of these organisms (e.g., burrowing, digging, transport of organic matter) contribute to increased patchiness in water and nutrient availability and, hence, contribute to the desertification process. In addition, many of these taxa may benefit by some degree of desertification; that is, desertification may result in increases in resources that limit the population size of some of the animals.

Rabbits: Rabbits affect a number of ecosystem properties and processes and are the major (largest biomass) native herbivore within the Chihuahuan Desert. These species utilize herbaceous plants during the warm months of the year but switch to browse on woody stems during the dry, cool months (Steinberger and Whitford 1983). Browsing is limited to shrubs with higher stem water content and affects virtually all stems of the selected shrubs (Steinberger and Whitford 1983). Rabbits indirectly affect soil processes by excavating "forms" under shrubs. These "forms" account for a large quantity of disturbed soil that is readily eroded (Whitford unpublished data).

We hypothesize that areas adjacent to shrub habitats and shrub habitats will support higher densities of lagamorphs than distant non-shrub habitats, because of the dependence of these animals

on deep rooted shrubs as a source of moisture during the dry winter periods. Jackrabbits may exhibit seasonal movement from grass habitats to shrub habitats.

Densities of cotton-tailed and black-tailed jackrabbits will be estimated on a monthly basis by the flush transect technique (Overton 1971) on permanent transects established in each of the ecosystem types. Annual surveys for rabbit-browsed shrubs and deposition and transport of rabbit feces will be made on permanent 10 m x 10 m plots established in each area.

Ants: Ants are among the most abundant animals in all deserts. The ant fauna of the Jornada is well known (Whitford 1978) and includes a variety of trophic groups: granivores, omnivores, fungus-culturing detritivores, liquid feeders and predators. Diversities of ants vary among habitats and both densities and diversities are affected by desertification (Wisdom and Whitford 1981). Studies of the ant fauna during Jornada LTER I suggested that the demography of ant colonies may be affected by site fertility (M. Conley, unpublished data). Other studies have demonstrated that ant colonies affect both water and nutrient distribution on the small patch scale (Whitford 1987, S. Carlson unpub. data, R. DiMarco unpub. data). Soil translocated to the surface by ants during nest maintenance and construction may account for considerable soil turnover and may contribute to both aeolian and fluvial eroded materials.

We intend to test the following two major hypotheses: (1) The rate of turnover of ant colonies differs among landscape units and is independent of the degree of desertification and (2) the quantities of soil translocated to the surface by ants varies as a function of rainfall pattern among the 5 ecosystems.

We will continue to follow the fate of marked colonies of ants along the LTER I transects. Transects will also be established at the black grama, mesquite dune and tarbush sites, and colonies identified with permanent metal tags on aluminum spikes. A series of plots will be established in those habitats and in the creosote bush and basin slope areas for measurement of soil transport by ants. We will sample during the active season for ants (Whitford et al. 1978) and collect the freshly transported ant mound material from each plot (Whitford 1987). This material will be compared with



the physical characteristics of non-affected surface soils. Soil transport by ants should vary by species as a function of nest depth and volume and life span of colonies.

Termites: The importance of termites as consumers of dead plant material, producers of soil macropores, effectors of soil organic matter and soil N, agents of soil turnover and effectors of AGNPP in the northern Chihuahuan Desert is well documented (Johnson and Whitford 1975, Parker et al. 1982, Whitford et al. 1982, Elkins et al. 1986, Gutierrez and Whitford 1987, Schaefer and Whitford 1981, MacKay et al. 1987, Silva et al. 1986, Whitford et al. 1987). The magnitude of direct and indirect effects of termites on ecosystem processes suggests that these organisms act as "key" species in hot semi-arid ecosystems (Elkins et al. 1986).

The preferred sources of energy for Chihuahuan Desert subterranean termites (predominantly *Gnathamitermes tubiformans*) are dead leaves, stems, and roots of annual plants and grasses. Data in Johnson and Whitford (1975) and unpublished data from Jornada LTER I show that aerial extent, numbers, and activity of surface foragers is higher in habitats where these plants are abundant than in shrub habitats. These observations suggest the following two hypotheses: (1) Surface foraging, aerial extent and numbers of foraging termites decrease as degree of desertification increases and (2) termite activity will exhibit greater temporal variation in shrub (desertified) habitats than in grassland habitats.

There are no direct means of censusing these small insects because nest chambers extend to depths of 10 m in the soil. Consequently, we rely on several indirect measures of population size by estimating numbers or activity of the foraging portion of the colonies. We will use two measures of termite activity on a series of plots in each major vegetation type: (1) consumption from termite baits (Johnson and Whitford 1975) and (2) production of gallery carton (Whitford et al. 1982). We will establish two 5 X 5 grids of termite baits (toilet paper rolls); removal of paper by termites is an indirect measure of abundance and activity. Aboveground foraging galleries are constructed after heavy rains. We will establish 5 permanent 1-m<sup>2</sup> plots in each vegetation type and will collect gallery carton (at regular intervals after soaking rain events) to estimate the volume and characteristics of the soil material moved by termites.

**Field Manipulative Experiments:** The following studies are designed to provide field tests of the Jornada Model (Fig. 3). These tests include water augmentation and nutrient manipulations.

Water Augmentation: We have conducted extensive studies dealing with irrigation applications to simulate increased rainfall in the Jornada (see Gutierrez and Whitford 1987a,b; Whitford et al. 1986, Fisher et al. 1987). Water additions to *Larrea* - dominated systems have been made to investigate changes in soil fauna, decomposition rates, mineralization, and plant growth (op. cit.). In situations where water distribution patterns have been disrupted by grazing we hypothesize that shrub establishment is likely. This can be tested by artificially increasing the heterogeneity of water distribution in a grassland system. We propose to apply water as a point source in a widely-spaced grid to create local patches of increased water availability within the grassland matrix.

Twelve 4 m<sup>2</sup> plots will be centered at 6 m intervals along a line of 14 mm polyethylene tubing. Each set of 2 plots along the line will constitute a block. One plot will be randomly designated as watered, the other as unwatered. A single vortex drip emitter (4L/hr) will be placed in the middle of each watered plot and neutron access tubes will be inserted in each of the watered and unwatered plots to follow water storage and water use in the patches. Vegetation changes within each 4 m<sup>2</sup> plot will be regularly monitored.

Increased Homogeneity of Water and Nutrient Availability: The transect study of LTER I provides data relevant to address various hypotheses stemming from the conceptual Jornada Model (Fig. 3). The spatial and temporal heterogeneity in the availability of soil N was decreased by aerial application of N fertilizer to the transect. Grass cover increased along the transect where natural heterogeneity in N resource availability was decreased (Cunningham and Whitford, unpub. data).

Our central hypothesis suggest that restoration of homogeneity in water and nutrient availability in former shrub-dominated systems should result in reinvasion by grasses. We will bulldoze established mesquite dunes to effectively redistribute the "islands of fertility" contained in these dunes to the nutrient-poor shrub inter-spaces; this should increase the homogeneity of soil nutrients and water infiltration. Twelve 30 X 30 m plots will be established in the mesquite dune

ecosystem. Six blocks of 2 plots each will be marked and 1 randomly selected plot within each block will be bulldozed, while the other plot will serve as a reference. The mesquite shrubs on the treated plots will be herbicided during the spring of the first year of the project. This is necessary since mesquite is a vigorous resprouter and we wish to follow re-establishment of seedlings. We will redistribute the sand contained in the dunes during the following summer when soil moisture is high enough to limit wind erosion from the denuded plots.

The distribution of soil N and P prior to and after the soil disturbance treatment will be determined. Permanent line transects and/or plots will be established within the disturbed and control plots, the species identified, and the cover of dominant species establishing in the plots will be followed each year. Neutron access tubes will be installed in the center of mesquite dunes and in the intershrub area of control plots and in a random fashion in the treated plots. There will be a total of 12 access tubes among the treated plots and 12 access tubes among the reference plots to monitor changes in soil moisture storage. Soil movement and the potential re-establishment of dunes around newly established plants on the disturbed plots will be followed by routine measurement of exposure or burial of erosion pins driven into the soil.

### C. Transport Studies

Changes in the processes that link ecosystems along drainage basins are central to our model of desertification (Fig. 3). We suggest that as a result of increased runoff, there is a greater linkage among ecosystem types. This linkage has altered the extent and location of ecosystem processes in the basin. This section presents hypotheses and proposed field studies to examine these aspects of ecosystem function.

**Water transport:** In the black grama grassland, *Larrea tridentata* shrubland, and *Flourensia* shrubland, we will establish nine runoff plots located in three blocks (27 total), similar to plots used in past work by Whitford in LTER I. These plots are designed to catch the runoff produced on a 2 x 2 m area, which will be located randomly in each community. Each plot is defined by metal edging that diverts runoff from adjacent and upslope areas. The runoff from the defined area is diverted into a trough on the downslope side, where it collects in a graduated set of containers. Following each

rainfall event that produces overland flow, the content of the containers will be measured for runoff volume and sediment yield. A subsample of the dissolved and particulate content will be analyzed for N, P, K and Ca in organic and inorganic forms. Since there are relatively few rain events producing runoff in any given year, these studies must be continued for long-term collections. Thus, these studies will commence the long-term collection of runoff data that has proven so useful in understanding ecosystem function in sites such as the Hubbard Brook Experimental Forest.

Secondly, we will capitalize on a field experiment established by USDA researchers in 1983 and currently monitored only for runoff volume and sediment yield. These workers established a series of 3.7 X 22 m plots in which control, *Larrea*- removal, and *Larrea*-removal/grass seeding treatments were established with 4 replicates each. Their data suggest consistently greater infiltration (lesser runoff) on the grass-seeded plots. Their studies will continue for the duration of our proposed work, but we will begin to analyze their collections for the runoff losses of nutrient elements. Differences in the transport of  $\text{NH}_4$  and  $\text{NO}_3$  among these treatments will indicate whether the potential for changes in the extent and location of ecosystem processes such as denitrification and ammonia volatilization has been enhanced by the widespread invasion of shrubs in former grassland communities. Karl Wood (USDA) has agreed to our cooperative use of these plots and to share the data he is accumulating on runoff and sediment yield.

Although long-term runoff plots are essential to understanding hydrologic processes in desert ecosystems, rainfall simulations can provide additional data, spanning a range of known rainfall amounts, intensities, durations, and antecedent moisture conditions. Recent work at the Jornada (Bolin and Ward 1987) has allowed the development of a preliminary model in which rain energy plays a critical role in determining runoff and sediment yield. LTER II will include rainfall simulation experiments in plots adjacent to the natural runoff plots described above. These simulations will be conducted over 1 x 1 m plots during the three seasons of the Chihuahuan desert climate. In addition, a larger Swanson rotating boom rainfall simulator is available from Los Alamos to this project (see letter from E. Springer, Appendix B). Comparisons of runoff, nutrient and sediment yield between the grassland community and those areas dominated by *Larrea* and *Flourensia* shrublands will allow a

further test of the Jornada model of desertification and important data for parameterizing the GIS model of the Jornada Basin.

**Wind transport:** Transport of organic matter and soil by wind is an important part of the linkage among ecosystems and soil losses by aeolian erosion contribute to soil degradation and desertification. We propose two approaches for measuring aeolian transport. First, in each of the 2 x 2 m plots described above, a grid of erosion spikes will be established to record the initial height of the soil material. To the extent that sediment yield is less (or greater) than total apparent losses of soil material, losses (or gains) by aeolian movements will be indicated. We anticipate that aeolian movement will be greatest in the downslope areas (e.g., *Flourensia* shrublands) which have fine-textured soils. Long-term comparisons of these processes between communities will allow a test of this hypothesis.

In a separate set of experiments, 25 x 25 cm plots containing fluorescent-marked sand/silt/clay-sized particles will be established in all five ecosystem types. These plots will be placed randomly in each ecosystem and the marked soil materials placed on the soil surface without disturbing any natural vegetation. Runoff will be diverted from these plots using metal edging upslope, and their small size precludes significant generation of runoff *in situ*. Thus, movement and loss of these materials from the field plots will be indicative of the comparative potential for aeolian losses in each site. Differences between ecosystems will falsify the hypothesis and support our model suggesting a greater lateral transport of materials in desert regions undergoing desertification.

Ancillary studies of wind erosion and the transport of atmospheric particulates are currently under way at the Jornada under the auspices of Dr. Carol Breed of the US Geological Survey (Flagstaff, Arizona). Her work seeks to compare the atmospheric burden of dust particles among various desert ecosystems of the southwestern U.S. We anticipate a mutually beneficial cooperation with her. Another potential collaboration may be developed with Dr. Don Doehring at Colorado State University to compare the ambient levels of dust among various arid and semi-arid LTER sites.

**Gaseous Losses:** We hypothesize that rates of denitrification in the playa (dry lake) are controlled by the availability of  $\text{NO}_3$ . This hypothesis suggests that the rate of denitrification in areas

receiving runoff have been significantly enhanced by a greater delivery of  $\text{NO}_3$ , a potentially limiting substrate, from upslope areas. Since nitrification is exceptionally rapid in these desert soils (Lajtha and Schlesinger 1986, Fisher et al. 1987), most available nitrogen will be moving as  $\text{NO}_3$ . Nitrate is a likely limiting substrate in playa soils, which have exceptionally high levels of organic carbon (Whitford, pers. obs.). Tests of this hypothesis are currently under way (Schlesinger and Peterjohn).

We hypothesize that rates of ammonia volatilization are similar in the surface soils of various communities in the basin. In soils with pH above 8.0, significant amounts of ammonia can be lost through the abiotic conversion of  $\text{NH}_4$  to  $\text{NH}_3$  (Nelson 1982). These losses are well known in the application of urea in arid lands (Aggarwal et al. 1987), and during the mineralization of animal-derived urea in grassland soils (Schimel et al. 1986). Rapid rates of nitrification may limit the potential for ammonia volatilization under most conditions in desert soils; however, the potential for such losses exists whenever organic matter is mineralized under high pH. Soil erosion during desertification may have increased the rates of ammonia volatilization by exposing pedogenic carbonate at the surface; in such soils equilibrium solution pH should be ca. 8.3 (Marion et al. 1988). The proposed work examines the possibility that ammonia volatilization losses have increased in areas of the Jornada Basin that have undergone erosion during the transition to shrubland communities. Site-specific rates of ammonia volatilization will be determined under dry and simulated rainfall conditions using sulfuric acid traps. These rates will be determined in the 5 reference ecosystems to test the hypothesis.

**Field Experiment-Runoff Diversion:** Studies in the Mojave Desert (Schlesinger and Jones 1984) suggest that downslope hydrologic movements allow a greater development of shrub biomass on desert piedmonts (bajadas) receiving runoff. Greater runoff during the decline of black grama grassland cover may have created a positive feedback, leading to increases in shrub cover in downslope areas. We will establish areas from which the runoff is diverted from its natural downslope pathway. This will create downslope, experimental plots in which the vegetation must depend solely upon incident rainfall. These, and adjacent control areas, will be monitored for soil moisture content (thermocouple hygrometers) and for changes in vegetation cover on an annual basis.

We envision that each diversion will be 10 m in length; 5 replicates will be established in areas of black grama grassland and *Larrea tridentata*. We anticipate little change in the black grama grassland sites, but the cover and productivity of *Larrea tridentata* should decline in areas of runoff diversion.

#### D. Landscape-Level Studies

**Ammonia Volatilization/LIDAR:** Laser remote sensing (LIDAR) involves projecting a short laser pulse through the atmosphere followed by reception of a portion of the radiation reflected from a distant target or from atmospheric constituents. The backscattered radiation is altered in intensity and wavelength according to the strength of the interaction and the concentration of the interacting species (Killinger and Menyuk 1987). Consequently, sensitive single-ended measurements of the composition of trace gasses in the atmosphere can be made. Such measurements depend upon the availability of lasers at the wavelengths where the atmospheric molecular species interacts strongly, the presence of an atmospheric transmission window at this wavelength, and the lack of interfering signals which will limit the sensitivity of the measurement.

We propose to use a CO<sub>2</sub> laser as a Differential-Absorption Lidar (DIAL) system for the detection and measurement of atmospheric ammonia (Force et al. 1985). DIAL measurements of atmospheric ammonia have been made previously using two CO<sub>2</sub> lasers tuned to the absorption line of NH<sub>3</sub> near 9.217  $\mu$ m. These measurements established a sensitivity limit of approximately 3 ppb for a LIDAR path length of 2.7 km (related to the 10% error in the detection of the average DIAL signal). The ambient level of atmospheric NH<sub>3</sub> was found to vary between 0 and 20 ppb, and was inversely dependent upon the relative humidity, possibly due to the solubility of NH<sub>3</sub> on the surface of water vapor aerosols.

For the Jornada we propose to use a similar CO<sub>2</sub> LIDAR system for the remote detection of atmospheric ammonia. The DIAL system will consist of a small, compact CW (continuous wave) CO<sub>2</sub> laser system (laser / transmitter / telescope / detector) housed at a central site from which the laser beam will be directed toward small optical retroreflectors or hard targets located at strategic points radially from the central site at ranges of up to several km away. Path-averaged measurements of the ammonia concentration will be made with an estimated sensitivity of better than 0.51 ppb due to the

use of a stable, cw laser as opposed to a pulsed laser as in previous measurements. The location and number of the retro's will be chosen to maximize the ability to provide a pseudo-range resolved ("grid-pattern") measurements. A site visit by Killinger in Nov. 1987 identified potential locations for a LIDAR system to allow measurement of  $\text{NH}_3$  concentrations above several different Jornada ecosystems. The beam steering apparatus of the central site LIDAR will be computer controlled in order to allow rapid, automated measurements of each path. It should be noted that true "range-resolved" DIAL measurements would utilize backscatter from natural occurring dust and aerosols in the atmosphere and would require laser pulse energies several orders of magnitude higher than proposed and the use of heterodyne detection at a significant increase in cost. It is anticipated that the DIAL system, laser beam paths, and measurements will be modified after the initial measurements. The climatological data at the central site will be used to calculate gas flux dynamics. Our initial measurements will be made in the summer months: May-September. We expect no detectable or slight ammonia volatilization during the dry months of May, June, and early July and large fluxes with the onset of summer rains. The proposed measurements are for the summer season only. We expect to build and test the LIDAR system in year 1 and to obtain usable data in year 2 and beyond.

**Baseline Satellite Data:** Desertification has resulted in changes in plant community patterns and distributions throughout the entire Jornada basin. To address these landscape-level changes, remote sensing will be used to (1) provide information for estimating plant cover and production and (2) provide long-term records of vegetation change.

The location of the Jornada will allow acquisition of visible and infrared satellite imagery. Except during dust storms, the relatively clear atmosphere over the study area minimizes atmospheric effects on satellite images and, when present, they can be more easily removed from spectral data. The proximity of the study area to White Sands Missile Range is advantageous for purposes of sensor calibration. Initial efforts will be to assess the ability to resolve vegetative signals from the Jornada ecosystems from digital image data recorded by operational satellites, such as SPOT, Landsat, and NOAA. Particular attention will be paid to how the varying spatial, spectral and radiometric resolution of these satellite systems influences our ability to determine types and abundance of



vegetation. SPOT multispectral (MS) image data will be emphasized at first, since its higher spatial resolution and comparable radiometric resolution should make it most amenable to resolving vegetation signals. An additional advantage of SPOT is its pointability, which means that the study area can be framed and contained within a single scene allowing for stereoscopic imaging. It is anticipated that three SPOT/MS and one Landsat/TM scenes will be acquired the first year. A similar number of scenes from the satellite deemed most effective at imaging vegetation distributions will be acquired in subsequent years.

Desert ecosystems pose unique problems for remote sensing studies. The sparse vegetative cover results in a limited reflected vegetation signal. This signal can be difficult to detect remotely when a bright soil or rock background dominates the reflected radiance received by a remote sensor. Because of this, we will retain a fair degree of flexibility in the research design. While initial investigations will utilize SPOT satellite data because of its detailed resolution (20 m), we will investigate the potential of using other systems (e.g., Landsat/TM or NOAA/AVHRR) which have different radiometric, spatial resolution and orbital characteristics.

The other major effort in this baseline study will be in the digital processing of satellite image data, in an attempt to restore its fidelity. This will involve both geometric and radiometric restoration processing. Geometric processing will entail rectification of systematic distortions and precision georeferencing of the image data to an earth coordinate system. High order geometric transformations will be applied, with the possible limitation of sparse ground control. Once an initial geometrically accurate base image is produced, subsequent images will be spatially registered to it. Radiometric processing will mostly involve removal of atmospheric radiance and corrections for off-nadir imaging. Assistance in radiometric processing will be provided by the USDA Water Conservation Laboratory in Phoenix.

***Geographic Information Systems (GIS):*** Geographic information systems (GIS) provide the means for integrating remotely sensed data into process studies at different spatial scales. The GIS capabilities will be utilized for the management, analysis, and modeling of spatial data. Both raster (grid cell) and vector (polygon) systems may be used (see Appendix A, part M)

The GIS capabilities of the Center for Earth Spatial Analysis Research (CESAR) at San Diego State University will be utilized for Jornada LTER II in two broad areas. First, a general GIS will be developed for the entire study area by digitizing soils and vegetation data layers. Elevation data will be obtained from USGA digital elevation tapes or by digitizing contour maps and slope and aspect maps of the area will be derived by computer from the elevation layer. This general GIS will serve as a management tool and will also be used to examine the interrelationships between the spatial data layers (e.g., soils and vegetation). Furthermore, the GIS will be the basis for establishing uniform source areas, flow lines, and integrated flow systems (Fig. 5). Processed data entered into the GIS are spatially referenced to an earth coordinate system and may then be related to other data layers, retained for temporal comparisons and analyzed statistically.

The second application of GIS technology relates directly to the simulation modeling efforts. Research will be initiated to integrate the GALS model into the structure of the ARC/INFO GIS system. This will enable the models to utilize the resident data layers to generate simulated layers, which then constitute an input layer for the next simulation period (i.e., the REGALS model - a dynamic GIS, Fig. 6).

The GIS for LTER II will be developed using ARC/INFO and ERDAS GIS. ARC/INFO, a commercial GIS developed by the Environmental Systems Research Institute (ESRI) stores and retrieves geographic data using topological- or vector-coding scheme. This means that data are represented as points, arc or polygons. The ERDAS GIS is a raster grid-base system, which interfaces well with the raster structure of image data. ESRI and ERDAS are beginning to market an interface between their systems, which will be implemented at SDSU within the next year.

## **V. PERSONNEL AND PROJECT MANAGEMENT**

The LTER II PIs have worked together for the past 5-6 years and have on-going research programs on the Jornada which depend upon coordinated field work by the PIs, technicians and students at New Mexico State University (NMSU). The research techniques to be used, solutions to problems encountered in the field, communication of important observations, etc., are the subjects for telephone discussions and research meetings. NMSU's Biology Department maintains

two house trailers close to the NMSU campus that are rented at cost for extended visits by the PIs and collaborating scientists. We will coordinate working visits in the summer to allow intensive interactions of the PIs in the field. The PIs will meet in San Diego at regular intervals for modeling workshops. This has worked well for the process modeling to date and will continue for the dynamic landscape GIS model development. In summary, based on the long-term professional and personal relationships of the PIs we are confident that our group will interact as effectively (or perhaps more effectively) than a group located at one place by scheduling quality time for our meetings.

**Personnel and Project Administration.** The Jornada LTER PIs are ecosystem ecologists with the sub-disciplinary breadth necessary to adequately address the complexity of desertification processes. All of the PIs are currently engaged in research programs on the Jornada and have considerable experience with desert systems in North America and elsewhere. Publications by the Jornada PIs range from animal population studies, animal and community structure, factors affecting primary productivity, nutrient cycling, regulation of decomposition, global nutrient budgets, soil processes, soil-plant relationships, and modeling (see vitae).

The research breadth and expertise of the Jornada LTER PIs not only allows for complete coverage of the five LTER core areas, but also brings considerable technological expertise. The Jornada LTER PIs and their areas of expertise are:

Walter Whitford (PI)	-	Animal effects on ecosystems, biogeochemistry
Gary L. Cunningham	-	Plant physiological ecology, landscape ecology
Laura Huenneke	-	Plant community ecology, animal effects on ecosystems
Wesley Jarrell	-	Soil physics and chemistry, plant- soil relationships, biogeochemistry
James Reynolds	-	Modeling, GIS-modeling interface
William Schlesinger	-	Biogeochemistry, soil processes
Ross Virginia	-	Natural abundance isotope ratios, biogeochemistry, plant physiological ecology

The investigators based at New Mexico State University have primary responsibility for the field work, data management and limited analytical work. The laboratories at San Diego State

University and Duke University will take on the responsibility for most of the analytical work (e.g. elemental analysis, isotope abundance). The modeling and GIS efforts are centered at San Diego State University. Our experience to date with both modelling and field/laboratory experiments and studies demonstrate the feasibility and procedures that allow for effective collaboration within our group.

In addition to the PIs there are other collaborating scientists who may or may not receive funding directly from the Jornada LTER program, but who conduct research that is essential to the LTER and/or benefit from the LTER. Jornada LTER funded collaborators include Tim Ward (hydrology), Dennis Killinger (LIDAR), and Doug Stow and Allen Hope (GIS) (see vitae). Additional collaborators associated with LTER research are Marsha Conely (population ecology), Fred Fisher (biogeochemistry), Diana Freckman (soil ecology), Barbara Hemmingsen (microbial ecology), Tom Kieft (microbial ecology), Kate Lajtha (biogeochemistry), Steve Loring (arthropod ecology), Peter Wierenga (soil physics), and John Zak (microbial ecology).

**Relationship of Jornada LTER to the USDA/SEA-AR Jornada Program** The Jornada LTER program makes every effort to support and compliment the program of the USDA/ARS research program. In turn, the USDA/ARS under the direction of Carlton Herbel has been fully supportive of the research efforts outlined in this proposal (see Appendix C for letter from Herbel). The Jornada USDA/ARS has made and will continue to make the records from their extensive network of rain gauges available to us. We are assisting Herbel's group with analysis of some of their long-term data sets. We have organized collaboration with Karl Wood on erosion and runoff chemistry studies (see description in proposal text.) We have organized a Jornada seminar series in order to facilitate communication among all scientists working on the Jornada. That series has been well attended and has generated enthusiastic discussion of a variety of the ideas presented. We intend to continue that effort. USDA scientists who have a close relationship with the Jornada LTER are Dean Anderson (large herbivore behavior), Robert Gibbens (plant ecology), Carlton Herbel (range ecology), and Karl Wood (rangeland hydrology).

**Intersite Activities- LTER Network** The Jornada PIs are currently involved in several intersite activities and will continue a high level of intersite activities in the future. We are currently involved in intersite research on: (1) dead wood turnover on the Jornada and South Caroling coastal plain with North Inlet LTER scientist E. Blood, (2) a synthesis focusing on the functional transition between shortgrass steppe and desert with W. Lauenroth of the CPER, and (3) an examination of temporal and spatial variance in ecosystem parameters, a project led by J. Magnusson of the Northern Lakes LTER. Our group has had discussions with other LTER scientists and propose to lead a synthesis on "animals as agents redistributing materials within and among ecosystems". We expect to contribute significantly to the following intersite activities described in the LTER Coordination and Synthesis Program Proposal submitted to the NSF in December, 1987: (1) data management, (2) stable isotope initiative (R. Virginia), (3) productivity along life form gradients, nutrient limitations across regional and latitudinal gradients, and sustainable productivity in arid environments (Jornada LTER team), (4) modeling disturbance (Reynolds), (5) scaling up to landscape, regional and global levels (Jornada LTER Group). We have discussed future intersite efforts with the proposed LTER research teams at the University of New Mexico, Utah State University, and San Diego State University. Collaborative efforts will include but will not be limited to reciprocal transplant gardens, LIDAR and FTIR measurements, and exchanges of remote sensing data.

In order to participate fully in network synthesis efforts we anticipate that each PI will devote up to 40% of their time allocated to LTER in intersite activity and we have budgeted 40% of the travel budget to support these intersite synthesis activities.

**LTER Advisors** We will meet with an advisory group annually to review our program. The following scientists have agreed to serve in this capacity: Robert Woodmansee (Colorado State), Pamela Matson (NASA, Ames), Nancy Stanton (Univ of Wyoming), and Peter Sharpe (Texas A&M).

**Data Management** The overall responsibility for data management lies with the Data Manager who is located at New Mexico St. University. The Jornada LTER has developed an

efficient, operational data management system that has effectively served our needs over the last 5 years.

Data Input Procedure: Data are entered and archived in the Jornada LTER data base following a standardized data documentation form (see Appendix D). Raw data are entered onto a Zenith PC/AT microcomputer using a spread sheet (LOTUS 1-2-3) and plotted to check for obvious errors. When verified by the typist, a printout of the data set is given to the responsible investigator for verification. These data are copied to 2 other discs as backups - one is returned to the researcher along with a final data printout. Documentation for each data set is stored on computer discs and updated as additional data are entered. Original data sheets are retained by responsible PIs; xerox copies are retained by the data manager.

Data storage procedure. A computer disc library contains all original and backup discs used in data entry. When a particular study or experiment is completed, these data are downloaded to the mainframe and permanently stored. Using a computerized search system, names of all files are available in an alphabetical list, using brief descriptions of the files and the names of the investigators. To simplify data searches, a keyword list (up to 10) is available. Computer printouts of data sets and accompanying documentation are available upon request.

Data set transfers: Data sets can be transferred by to any of the PIs via BITNET or phone modem. The data manager has IBM compatible and Apple MacIntosh systems available for data transfers.

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## **APPENDIX A.**

### **Description of Jornada Study Area and Research Facilities Available to the Jornada LTER**

#### **A. Land Ownership and Administration**

The 25,900 ha New Mexico State University (NMSU) College Ranch is contiguous to the 78,266 ha Jornada Experimental Range, creating a block of 104,166 ha wholly devoted to research. Both properties are located about 37 kilometers N of Las Cruces, New Mexico (Fig. 4). The NMSU College Ranch is owned by the University and administered by the Science and Education Administration-Agricultural Research (SEA-AR, formerly Agricultural Research Service). The NMSU Ranch and the Jornada Experimental Range have been designated as Ecological Reserves by the Institute of Ecology and the Jornada Experimental Range has been designated as a Biosphere Reserve under the UNESCO Man and the Biosphere Program. The Jornada Experimental Range is a Biosphere Reserve where manipulative research is permitted and is paired with Big Bend National Park which is a preservation-type Biosphere Reserve in the Chihuahuan biotic province.

The eastern one-third of the Jornada Experimental Range is included in a buffer zone for the White Sands Missile Range, U. S. Army. This area is available for research use but access is denied the general public. The San Andres National Wildlife Refuge, administered by the U. S. Fish and Wildlife Service also overlaps the Jornada Experimental Range, at the crest of the San Andres Mountains. Mineral rights on both properties are under the jurisdiction of the Bureau of Land Management (BLM). Leases for gas, oil and geothermal exploration contain stringent clauses which protect research sites from disturbance. On the east and north, the properties are bordered by military or BLM lands; only on the west and south do private lands adjoin the research areas.

The Jornada Experimental Range was established in 1912 under the jurisdiction of the Bureau of Plant Industry. In 1915 it was transferred to the Forest Service and research activities began. Climatic and vegetation records have been maintained since that time. The Forest Service maintained an active research program until 1954 when the Experimental Range was transferred to the Agricultural Research Service (ARS). The ARS continued ongoing research programs and, with recent staff increases, has expanded into new research areas.

The NMSU College Ranch was established in 1927. Since that time it has been the site of much of the research carried out by the Department of Animal and Range Science as well as projects initiated by other University departments. Many joint projects involving both University and Federal researchers have been and are being carried out on this site. During the recent IBP program a validation site for the Desert Biome was located on the NMSU College Ranch. A validation site for the Grassland Biome was located on the Jornada Experimental Range. Both the NMSU Ranch and the Jornada Experimental Range have been used primarily for livestock breeding, nutrition and grazing research. Over the years this has led to the construction of many interior fences. Not all of the area is grazed by livestock. On the NMSU College Ranch an 872 ha pasture has not been grazed since 1968. About 48 ha are included in small enclosures, some of which have not been grazed since 1927. On the Jornada Experimental Range, three large enclosures totaling 488 ha were established in the early 1930's. Smaller enclosures total about 26 ha, some having existed since 1915. In addition, the 16,671 ha area called the mountain pasture on the east side of the Jornada has not been grazed since 1946.

On the NMSU College Ranch all livestock are owned by the University. The Jornada Experimental Range leases grazing rights to a private cooperator. However, the SEA-AR has complete control over livestock placed on the Experimental Range and hires the herdsman who tend the livestock.



## B. Climate

The climate of the area is characterized by an abundance of sunshine, a wide range between day and night temperatures, low relative humidity, an evaporation rate averaging 229 cm per year, and extremely variable precipitation. The average maximum temperature is highest in June at 36 °C; the temperature is lowest in January when the average maximum is 13.3 °C. The effective growing season, when both precipitation and temperature are favorable, is normally July through September.

Winter precipitation is derived from frontal storms of Pacific origin and is characterized by low-intensity rainfall covering wide areas. The summer precipitation is derived from air masses moving up from the Gulf of Mexico and occurs as intense, convective thunderstorms that are highly localized and of short duration.

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 equal or shorter timespans. The average annual precipitation is 230 mm with 52 percent of the annual rainfall occurring between July 1 and September 30. Droughts, or periods of low rainfall that seriously injure vegetation, are a recurrent climatic phenomenon. Severe droughts occurred in 1916-1918, 1921-26, 1934, 1951-57, and a moderate drought in 1970-71. The 1951-57 drought is believed to be the most severe in the past 350 years.

The importance of precipitation to plant growth, and the highly localized nature of summer rains has led to a recent increase in the number of rain gauges used on the Jornada Experimental Range and the NMSU College Ranch. The Jornada Experimental Range has 23 stations with long-term records. Since 1974 the number of stations has been increased to 57 stations and 43 of these are now equipped with recording rain gauges. The NMSU College Ranch has 8 stations with long term records, and 10 stations with standard gauges have been added since 1977.

## C. Geology and Soils

Geologically, the combined properties present a representative cross section of the basin and range topography characteristic of the Southwestern United States. The properties extend from the flood plains of the Rio Grande at an elevation of 1,186 m to the crest of the San Andres Mountains at an elevation 2,833 m. The San Andres Mountains are formed by a west-dipping fault block and have moderate to steep slopes on the west and precipitous slopes on the east. Rocks in the San Andres Mountains are derived from marine sediments deposited in the Paleozoic. In contrast, the Dona Ana Mountains are composed of extruded igneous rocks. Mt. Summerford in the Dona Ana Mts. is 1,760 m and forms the source of the watershed that was intensively studied by the US/IBP Desert Biome program and is the location of the intensive Jornada LTER I studies 1982-1987.

Materials carried in by the ancestral Rio Grande and washed from the surrounding mountains have formed the Jornada Plain, which occupies the level-to-gently-undulating floor of the intermountain basin. Most of the basin is closed, with no exterior drainage, and water occasionally collects in scattered playas. Coarser sediments are found near the foothills and the silts and clays are concentrated in the lowest areas. Both water and wind erosion processes are still active and microrelief changes are continuous.

The unconsolidated materials comprising the Jornada Plain are approximately 100 m in depth. The water table occurs below the fill materials at depths of 100 to 130 m. The area is geothermically active and many exploratory wells have been drilled on the western part of the NMSU College Ranch.

Soils of the Jornada Experimental Range were first surveyed in 1918, and a more detailed survey of some portions of the Range was made by the Soil Conservation Service (SCS) in 1963 and 1971. From 1958 until the early 1970's the Jornada Basin was the site of the USDA Desert Project of the SCS. This large effort sought to understand the general processes of soil development in desert areas, especially soil formation in various alluvial situations. During the Project a large number of soils were classified and mapped. Although the work did not extend to

the Experimental Range, per se, a number of the soil groups are coincident with those in the LTER study area. The Desert Project has been extensively published, most recently in the summary volume by Gile et al. (1981).

Soils on the NMSU College Ranch have been identified along the LTER I transect (Wierenga et al. 1987), and processes of soil development in that area are described by Lajtha and Schlesinger (1988). All soils in this area fall into subgroups of Haplargids, although local areas of Mollisols occur in the black grama grassland near mountain fronts. All soils have a caliche layer at depth, but the degree and depth of its occurrence varies depending upon site position and soil age.

#### D. 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. A complete plant species list has never been compiled for the NMSU Ranch but many species occur in the Dona Ana Mountains and on the Rio Grande flood plain which are not found on the Jornada Experimental Range.

On the Jornada Plain, the major grass species on sandy soils are black grama (*Bouteloua eripoda*), 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 runoff, 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 airoides*) 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 (*Dasyllirion wheeleri*), ocotillo (*Fouquieria splendens*); and mesquit 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. 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 a good documentation of the vegetation through time.

#### E. 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., *Forelius* spp. and *Conomyrma* spp.). *Gnathamitermes tubiformans* is the most abundant termite and is found in all locations except areas of deep clay soils. Tenebrionid beetles (*Eleodes* spp.) are often associated with seed harvesting ants. Wolf spiders (*Lycosa* spp. and *Geolycosa*) 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*, *Trimerotropos californicus*, *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 *Boottettix 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. Quail (*Callipepla* spp.), doves (*Zenaidura* spp.), roadrunners (*Geococcyx californicus*) and black-throated sparrows (*Amphispiza bilineata*) are common year-round residents. Migrants that breed on the Jornada include Swainsons hawks (*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.

## F. Control and Security

The study site is secured and controlled by the USDA Science and Education Administration and New Mexico State University. Administrators of the site have formally acknowledged the management implications of this project and are cognizant of their related

responsibilities. The land included in these entities is legally deeded and claimed by the USDA and New Mexico State University as permanent holdings.

Considerable research is ongoing on both ranches, and ranch personnel and researchers have developed a protective ethic (and strict rules) that has resulted in very little damage to the environment. It is the combined experience the co-principal investigators on this project who have been studying the Jornada for many years, that equipment and research sites have never been disturbed. The president of New Mexico State University is fully aware of the implications of this project, and fully supports the intent of the NSF for Long Term Ecological Research sites (see Appendix E).

## **G. Herbarium**

The NMSU Biology Department Herbarium was founded in 1888 and now houses 50,000 specimens. Its present emphasis is to build a good collection representative of the floras of New Mexico, the Chihuahuan Desert, and northern Mexico. The representation of plants from the vicinity of Las Cruces is excellent. The collection is well curated and an active loan and identification program continues. There is one curator, Richard Spellenberg, and a work-study assistant during the academic year.

## **H. Museums**

The NMSU Museum of Entomology in the Department of Biology has approximately 50,000 specimens in its collection. Of those about half have been identified. The material so far accumulated occupies about 3/4 of the 532 drawers available. The space for cabinets is large enough to hold double the present number of cabinets. The holdings are best represented with material from New Mexico and the Chihuahuan Desert region. The taxonomic groups best represented are those families which 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 specimens came into the collection at the turn of the century and provide a good basis for comparison of faunas.

Numerous paratypes, but no holotypes or allotypes are in the collection. Considerable effort is being made to obtain proper identifications in groups which are sparsely represented. Exchanges of specimens are frequently made with other institutions - both regional and national.

NMSU Biology Department Vertebrate Museum. The vertebrate collections of the Department of Biology include approximately 10,000 specimens of mammals, 2,000 of birds, and 6,000 of reptiles. They are housed in a separate portion of the Biology building in standard cases or other appropriate containers, with ample space for expansion. Specimens include study skins, skeletal materials, and spirit specimens. Specimens are catalogued by accession number, taxonomic classification, and geographic locality. Geographical representation stresses the southwestern U.S. Curatorial supervision is provided by three permanent curators, with routine tasks performed by student employees and volunteers. An indication of the quality of storage and curation is the fact that the mammal collection was included in the American Society of Mammalogists listing of collections meeting accepted standards (J. Mamm., 59:911-914, 1978).

## **I. Jornada Experimental Range**

Access to the Jornada Experimental Range is via an all-weather gravel road. Telephone communications to Las Cruces is via underground cable. Radio base stations are located at the Jornada Experimental Range headquarters and at SEA-AR's Range Science Building located on the New Mexico State University campus.

Heavy equipment located at the Jornada Experimental Range headquarters and available for research activities include a D-8 Caterpillar with bulldozer blade and 9-ft. rootplow, two Model 12

roadgraders, a Model 3020 John Deere tractor with frontend loader and backhoe, a 15-ton truck-tractor with semi-trailer tank and flatbed, and a Giddings drilling and soil coring rig.

## **J. NMSU College Ranch Facilities**

The primary facilities are found at ranch headquarters. Two houses are present for full time employees. Accessory buildings include storage facilities - 200 m<sup>2</sup>, tool shop - 30 m<sup>2</sup>. Wells for water source and power line for 120/240 volts are accessible.

## **K. Libraries**

**Holdings.** The New Mexico State University library is adequate to support the proposed research with holdings in excess of 612,000 books and bound periodicals (the library maintains over 61,000 periodical subscriptions) and 429,000 microfilm items. The NMSU library has been a U.S. Federal Depository since the establishment of the University and Houses 350,000 Federal documents.

**Services.** The library maintains equipment and personnel to access all of the commercially available on-line bibliographic data bases. It maintains an on-line OCLC bibliographic data base which interconnects over 1,500 libraries including most of the major universities. The library is open 96.5 hours/week and maintains a TWX service for world-wide telegraphic messages.

## **L. Analytical Facilities**

**1. NMSU Laboratories:** The biology department has four laboratories (2400 sq ft) dedicated to ecological research which would be available in part for research associated with this program. These laboratories are equipped with drying ovens, balances and analytical equipment. The department has two equipment trailers on the NMSU ranch and maintains a standard weather station as part of Dr. Whitford's research program. The department has three vans which are used for field research and classes and two pick-ups used only for field research.

The following major equipment is available for ancillary research: scintillation counter, growth chambers, four 15' x 30' green houses, scanning and transmission electron microscopes, I-R gas analyzer, wind tunnel and standard laboratories for animal and plant physiology.

**2. San Diego State University:** The LTER project will have access to the wet chemistry laboratories of R. Virginia (500 square feet) and the Systems Ecology Research Group Core Analytical Laboratory (850 square feet). These laboratories are well equipped for elemental and stable isotope analysis of plant, soil and water samples. Equipment available for LTER include: (1) Inductively Coupled Plasma Emission Spectrometer (Perkin-Elmer Model 6500) with flame atomic absorption and a equipped with a computer controller and data management workstation for elemental analysis of plant, soil and water samples; (2) Dual collecting stable isotope ratio mass spectrometer (VG MicroMass 602 D) for determination of C and N isotope abundance of plant and soil samples; (3) Auto analyzers (2 Technicon units) for determination of N and P in plant and soil digests and extracts; and (4) Necessary equipment to prepare samples for analysis on above instruments including: Technicon BD-40 block digester, Kjeldahl distillation units, grinding mills, analytical balances, perchloric acid fume hood, pH meters, conductivity meters, high vacuum pumps.

**3. Duke University:** The laboratory of W. Schlesinger conducts routine analysis of soil and water samples from arid regions. The laboratory contains soil sampling, sieving, and splitting equipment, drying ovens, analytical balances, and muffle furnace. For analysis the lab contains a Perkin-Elmer Model 370 atomic absorption spectrophotometer, a Dionex 2010i ion chromatograph, and an Orion 701 pH meter with Ross Combination and NH<sub>4</sub> sensing electrodes. A Varian 3700 gas chromatograph is available for denitrification studies. The Botany and Forestry Schools joint access to a block digestion system and Scientific Instruments Autoanalyzer.

## **M. Computing and GIS Facilities**

**1. New Mexico State University Statistics Center:** The long-term ecological monitoring proposed here will require the services of the New Mexico State University Statistics Center, which was organized in 1970 to promote excellence in research at our University. The center primarily serves the research faculty and graduate students, but other groups within the university and the state are also served. The professional and support staff of the center are highly qualified and dedicated individuals. The center will be fully available to the needs of proposed research described here.

The university computer center houses an AMDAHL 470/V5 computing processor with eight channels and four megabytes of main memory. An IBM 4341 increases the capabilities of the above unit by approximately 40 percent. Peripherals provide an additional 922 megabytes of disc storage and the usual printers (two IBM 1403 units), card readers (IBM 2540 and 2501), and a newly acquired plotter.

**2. San Diego State University:** The Systems Ecology Research Group Core Computing Facility will support the LTER modeling efforts. It consists of of Token-Ring network with six Apollo DOMAIN nodes having 19 mb of RAM available for distributed processing. Five workstations (DOMAIN 3000's), four with 4 megabytes (mb) of RAM and one with 2 mb, two of them with 15 inch high resolution color monitors are in the network. The sixth node is a device server with 1 mb of RAM which supports a magnetic tape drive and laser printer. These nodes are multi-tasking machines which utilize the 68020 32-bit processor. Two 155 mb and one 72 mb hard disks are in the network. Additional microcomputers are available including 4-XT compatible machines and several Macintosh plus computers. Three operating systems are available for the Apollo network (DOMAIN Aegis, Berkeley 4.2 UNIX, and AT&T System 5 UNIX). A variety of graphics, statistical, and publishing software packages are available for these systems.

The SDSU Center for Earth Systems Analysis Research (CESAR) located in the Geography Department is part of the Systems Ecology Core Analytical Facility. The purpose of this center is to focus state of the art technology in remote sensing, geographic information systems and automated cartography on problems with a spatial dimension. The pertinent hardware and software include: (1) ERDAS image processing/GIS systems on IBM PC/AT supported by cipher 1600 BPI tape drive, Cuho video digitizer, matrix QCR digital color film recorder, Calcomp 1044 coordinate digitizer; (2) ARC/INFO GIS on VAX 11/750 with 5 Tektronix graphics terminals, TIN topographic data module, and NETWORK systems routing module; (3) TAE/VICAR on VAX 11/750, Raster Technology Model One/25 image display system; and (4) field radiometry equipment such as 2 Exotech 4 band radiometers, Everest Interscience thermal infrared radiometer and polycorder data logger. SDSU will purchase a microcomputer, image display device and a fiber optics communication link to meet the hardware needs for the ERDAS workstation and the ERDAS-ARC/INFO interface. A color video camera, recorder and frame grabber will also be purchased for CESAR before the start of this project.