Central Arizona - Phoenix LTER
Arizona State University
Land-Use Change and Ecological Processes
in an Urban Ecosystem of the Sonoran Desert

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PROJECT SUMMARY

The Project Summary should include a statement of objectives, methods to be employed, and the significance of the proposed activity to the advancement of knowledge or education. Avoid use of first person to complete this summary.
DO NOT EXCEED ONE PAGE. (Some Programs may impose more stringent limits.)

Summary

This project is a long-term study of the Phoenix metropolitan area and fringing regions of central Arizona into which Phoenix is rapidly expanding. Objectives of the Central Arizona-Phoenix (CAP) LTER project include (1) generation and testing general ecological theory in an urban environment, (2) enhanced understanding of the ecology of cities, (3) identification of feedback between ecological and socioeconomic factors, and (4) involvement of students at all levels (especially K-12) in the enterprise of scientific discovery.

Phoenix is one of the largest and most rapidly growing young cities of the arid and semi-arid American West. Because Phoenix is young, urban redevelopment is minor compared to expansive growth at the city's edges, where agricultural lands and natural desert habitats are being rapidly converted to suburbia. Historic patterns of growth will be reconstructed using maps, planning documents, aerial photgraphs and satellite imagery to generate a GIS-based record of urban change. Modeling will be centered on a hierarchical, spatially-explicit, patch-dynamic approach, based on land-use patches including parks, open space, remnant native vegetation, residential, commercial, and industrial categories. At intermediate scales, landscape models will be developed to determine configuration effects of multiple patches. A regional simulation model of the entire area will be developed to predict (and then test) the ecological consequences of alternative patterns of future development.

Patch-specific ecological characteristics will be monitored in five core categories: primary production, natural population and community characteristics, storage and dynamics of organic matter, movement of materials (including water), and patterns of disturbance by redevelopment, fire, and flood. A successional model will guide this work; both short-term ecological trends associated with land-use change at the patch level and long term change as patches "mature" will be followed. Of special interest is ecological change within a given patch type on the city-center to suburban-edge gradient.

Socioeconomic factors are included in this study as feedbacks between land-use decisions and ecological characteristics. That is, how do ecological features shape land-use decisions and how, in return, do ecological consequences modify future land use policy? Research will determine the importance of ecological factors to individual perceptions of quality of life. In addition, objective analyses of change in property values and shifting demographic patterns within the urban landscape will be assessed as an indicator of ecological and other values. These efforts will be enriched by multiple partnerships with agencies and municipalities.

This research effort includes a substantial commitment to K-12 education by involving teachers and students as hands-on research partners, through interaction with developing urban-science curricula, and by providing a real time electronic interface with research discoveries via the internet. This component of the project is enhanced by a strong interface with the Phoenix Urban Systemic Initiative and numerous other educational partners.

OVERVIEW

We propose a long-term ecological study of metropolitan Phoenix, Arizona — a young, rapidly growing city of the arid Southwest. We will determine the ecological changes associated with human settlement from its initial establishment to the current and future urban/suburban states. An understanding of the reciprocal linkage between urban development and ecological pattern and process will be gained in part through development of a GIS-based, hierarchical, patch-dynamic simulation model which will in turn be used to generate and test hypotheses about future ecological states. The study we propose incorporates socioeconomic variables as drivers of land-use pattern and ecology as an important feedback on land use. The study region (Fig. 1) (Central Arizona-Phoenix=**CAP**) will encompass the city of Phoenix, surrounding suburbs, and associated agriculture embedded in an undeveloped, expansive, and natural (by comparison) environment of desert, chaparral, and forest.

OBJECTIVES

A set of four primary objectives guides this multifaceted research program:

1. To advance ecological understanding through development of ecological theory. The urban environment provides many unique opportunities to develop and test general theory by virtue of its heterogeneity, patchiness, distinct patch edges, lateral growth, mix of native and introduced species, and rapid change. The urban ecosystem has been largely neglected as a research laboratory for basic ecological research in the United States. We will embrace it as such.

2. To understand the structure and function of the urban ecosystem. By comparison of ecosystem dynamics in urban and other ecosystem types (e.g., other LTER sites and nearby desert research sites) a better understanding of ecosystem ecology in general can be derived.

3. To make ecological predictions that can be used to guide future development of human-dominated environments while sustaining ecological values. Because ecological understanding of urban environments is limited, urban growth has been largely guided by engineering and socioeconomic criteria. We intend to fill that gap.

4. To involve the public in the research effort through dissemination of information via the media, public outreach, and educational initiatives, especially at the K-12 level. To the fullest extent possible we plan to include the public as research partners, to foster an understanding of science as a process, and to enhance scientific (ecological) literacy among the citizenry at all levels.

URBAN ECOLOGY: BACKGROUND AND TRADITIONS

Human interest in the environment of cities is, of course, as old as cities themselves. City planning has a long history stemming from the Greek city states of the first millenium B.C. which were designed to separate humans from nature (Cunningham and Saigo 1997). Later models included nature by design. Saarinen (1965) likened the structure of cities to biological structures with form and connectance. Doxiadis (1968) saw cities as consisting of four elements, man, *nature*, society, and buildings. Today, open space and green belts are highly valued components of city design (Carter 1995) and awareness of environmental problems inherent in urban areas has heightened. Early studies of natural wildlife populations in cities were largely European. Fitter's (1945) book on London's natural history was probably the first. Recent studies of the fauna of Warsaw (Kubicka et al. 1986), birds of Budapest (Sasuri 1990), and forest vegetation of Berlin (Seidling 1990) continue that tradition. Kieran's (1959) natural history of New York City and Gill's (1966) work in Los Angeles initiated a focus on U.S. urban ecology. Gill and Bonnett (1973) incorporated economic value in assessments of natural areas and associated wildlife in their studies of Los Angeles and London.

In the past three decades, a more holistic ecological view of urban environments as ecosystems has been developed (Bornkamm et al. 1982, Stearns and Montag 1974). Learmouth (1977) developed an ecosystem compartment model of Calcutta, depicting flows of energy and movement of materials; however, this model lacked spatial detail. The science of landscape ecology added a spatially explicit element to urban ecosystem studies (Forman and Godron 1986, Naveh 1982) which is central to the modeling effort we propose here (Clarke et al 1996). A variation on this theme is the urban gradient approach proposed by McDonnell and Pickett (1990) to organize studies of both ecological communities and nutrient cycling in urban environments (White and McDonnell 1988).

E.P. Odum (1997) has used a host-parasite analogy to describe the relationship between the heterotrophic urban area and the productive agricultural and "natural" landscape elements in which it is embedded. While this is a somewhat jaundiced view, it motivates us to enhance ecological understanding of urban ecological relationships in the interest of managing a more sustainable whole. McDonnell and Pickett (1990) state "the study of a metropolis as an ecosystem would be a radical expansion for ecology". We are eager to participate in this effort.

PHOENIX AS A RESEARCH SITE

At the end of the Civil War in 1865, Phoenix did not exist. The city arose as an agricultural community based on abandoned, irrigation-providing canals originally established by the Hohokam peoples some 1000 years earlier. Archaeological evidence suggests the Hohokam population reached 50,000-100,000 at its peak, then disappeared mysteriously, presumably because of an unknown ecological limitation (Redman 1992). Phoenix did not reach 50,000 again until after World War II. Today, 2.4 million people—half of the population of the state of Arizona—live in the greater Phoenix metropolitan area. The population of Phoenix has doubled twice in the past 35 years, making Phoenix one of the fastest growing cities in the country—now adding 50,000 individuals every year.

Several characteristics of Phoenix make it an ideal site for ecological study. The metropolitan area is **rapidly growing** in population and in areal extent (Fig. 2). Growth occurs by spatial expansion at its edges into either never-developed "natural" desert environments characterized by a native palo verde-saguaro (*Cercidium-Carnegiea*) community or into areas previously used for irrigated agriculture (cotton, citrus, alfalfa). Because the city is **young**, turnover within its boundaries (e.g., by urban renewal) is low and land-use change occurs primarily as peripheral expansion. Greater Phoenix has **distinct boundaries** separating it from an extensive natural environment of Sonoran desertscrub vegetation that has never been developed by humans (Fig. 3). The "Valley of the Sun" is an extensive plain of sedimentary deposits derived from the catchments of the Salt, Verde, and Gila Rivers which converge near Phoenix. The city is of relatively low relief (elevation = 274-335 m), thus an important ecological variable is held constant. The valley is surrounded by mountain remnants composed of metamorphosed sedimentary and volcanic rocks or of intrusive granitic rocks. Several remnants composed of those rocks and 17 million-year-old brown-red sands and gravels (with palm tree fossils) exist in the metropolitan area and have never been developed.

The **prehistory** of what is now Phoenix is **well documented** thanks to a concerted archaeological effort (Crown and Judge 1991, Gumerman 1991). An excellent opportunity exists to compare ecological conditions inherent in two large but quite different civilizations that have occupied this same site. All of the growth of modern Phoenix post-dates photography and much of it is accompanied by recent environmental and socioeconomic databases.

Phoenix is hot and dry (summer mean daily maximum temperature = 40EC; mean annual precipitation = mean 18 cm). Selection of an urban research site in an arid environment is not a mere novelty. Much of the western United States and fully one-third of the earth's surface is in drylands and these areas are seeing rapid population growth worldwide. Thus, our research results should be broadly applicable. Temperature in Phoenix is increasing due to a heat island effect (Brazel 1987). Ecological limitation is overridingly by one ecological resource: **water**. Water is supplied by surface flow of the Salt, Verde, and Gila Rivers and by groundwater. While water supply is judged ample for the next two decades (Welsh 1985), we anticipate potentially severe limitation as demand grows, supply fluctuates, and groundwater quality deteriorates. Water use at present is luxuriant and prices are artificially low (Welsh 1985). Water inputs and outputs occur at distinct points, enabling construction of a water and transported materials mass balance for the city and for sub-units of the CAP region that may reveal water quality consequences of different land uses.

The **natural diversity of biota is high**. There is a great variety of native birds, arthropods, small mammals, and plants in the southwestern USA (Brown 1994). Because of its favorable climate, many introduced species, especially plants, have been established throughout the city and into the surrounding natural environment. The existence of the Phoenix metropolitan area has undoubtedly *increased* species richness in the region. Opportunities for research in community ecology are unprecedented as native and introduced biotas interact.

Greater Phoenix is surveyed with a **mile square, township and range grid system** with north-south orientation. In most municipalities, zoning is regularized by this structure with central residential areas surrounded by circumferential commercial strips. This greatly facilitates GIS-based spatial modeling. Superimposed on this uniform grid are municipal centers (Mesa, Tempe, Scottsdale, Glendale, Chandler) which were once discrete, but are now parts of a coalesced whole. These communities add an intermediate-scale hierarchical element to spatial pattern and provide a challenge to coordinated land-use policy in the region as a whole.

Finally, **Arizona State University**, with three campuses in the Phoenix metropolitan area, has an established commitment to both urban issues and environmental science and will match NSF funds nearly 1:1 with new faculty lines, post-doctoral support, technical personnel, has strong community partnerships, and graduate RA's (see budget).

GENERAL RESEARCH PHILOSOPHY AND APPROACH

A. APPROACH

We propose a research program that is, at its heart, **ecological** in a broad sense. As we will show in this proposal, this is impossible without considering a distinct underlying fabric of social, political, and economic drivers and feedbacks (Fig. 4). However, we maintain an ecological focus in the interest of comparative ecology and integration of our research findings with other sites of the LTER network. Surely, we could propose a study of Phoenix centered on socioeconomic variables and include ecological factors in a suite of multiple independent and dependent variables, but such studies already exist and often ecological factors are poorly resolved. Given our ecological focus, the overarching ecological question is: **How does the pattern of development of the city alter ecological conditions of the city and its surrounding environment, and vice versa?** The *city* will be described using a GIS-based hierarchical, patch-dynamic, spatially explicit model. The *surrounding environment* consists of agricultural and never-developed "natural" habitat patches. Patchiness is likely to be heavily influenced by land use, thus we will begin our study using land-use maps supplemented with remotely sensed images. *Pattern of development* refers to both changes in the patch structure within current boundaries and development of a patch structure in accreted edges. Future states will be monitored by satellite and fixed-wing aircraft. Past states will be reconstructed from archived land-use maps and planning documents. **Because of the youth of Phoenix, we believe we can reconstruct its entire land-use history reliably.** *Ecological conditions* will be described with a host of variables; for example, plant distribution and diversity, bird populations, and nutrient cycling. These are specified in the five LTER ecological core research elements presented in detail below. Ecological conditions will be measured on a land-use, patch-specific (including corridors), GIS-organized basis. Our **working hypothesis** at the outset of the study is that the ecological condition of any patch is related to five factors, namely (1) land use, (2) patch location, (3) land-use history, (4) patch age, and (5) proximity to other patches. GIS data layers for this analysis will include variables beyond those described for the LTER ecological core; for example, underlying geology, climate, air quality, and precipitation chemistry (Fig. 5). Spatial patterns of these factors are unlikely to be determined at the land-use patch scale. These factors, however, are important in that they constrain processes at the land-use patch scale.

B. SCIENTIFIC METHOD

Our goal is to develop an understanding of the reciprocal link of causation between pattern and process; that is, to deduce the processes generating spatial and temporal pattern and the consequences of these patterns for higher-level processes (Fig. 4). For many project elements, patterns are unknown and substantial description will be required at the outset. In other cases, patterns are established and alternative hypotheses can be generated and their predictions tested to determine the processes that generated these patterns. While we would prefer to do hypothetico-deductive hypothesis testing using experimental manipulations in the field, this is possible in only a small subset of the research areas we have identified. Our goal is to increase the proportion of our research amenable to this approach as the project progresses. At the outset, we have organized all research elements to be *question driven*, although answers are as often descriptive as explanatory. Core elements are organized in this manner. Exemplary questions addressing larger themes are listed below.

C. SUBSIDIARY ORGANIZING ECOLOGICAL QUESTIONS

Question 1: What ecological conditions are associated with the range of current land uses? A landscape map can be easily generated, but how do ecological features map on this surface?

Question 2: For any given land use, how does ecological condition change as a function of distance from the urban center(s)? This question is predicated on the concept of urban gradients (McDonnell and Pickett 1990).

Question 3: What ecological changes are associated with land-use change? Do patches of the same land use differ as a function of their different histories? What are the sequences of ecological change that occur *within* a given land-use state over time? This is essentially a study of urban succession at the patch level.

Question 4: Other factors being equal, how are ecological changes modified by adjacent or nearby patches? Answers to this question will emerge from an analysis of a landscape which include many patches.

Question 5: How do edges between patches facilitate or inhibit the spread of influence (organisms, disturbance, water) from patch to patch? The answer to this question explains interactions among adjacent patches.

Question 6: At what scales are various ecological parameters controlled? For example, scorpions may be controlled at the "backyard" scale by pesticide-use decisions; air quality at the regional scale by transportation policy.

Question 7: What are the likely ecological consequences of alternative land-use patterns associated with future development? Alternative futures are possible. The simulation component of our modeling effort will link those decisions with ecological consequences.

D. SOCIOECONOMIC FACTORS

Socioeconomic factors will be represented by multiple data layers in our modeling (Fig. 5) and all the questions we ask can be answered for these variables as well. At the outset, however, we will focus on socioeconomic factors in two ways. First, what processes guide the generation of land-use pattern in the first place? Second, how do ecological consequences feed back on future land-use decisions? Assessment of these questions has to do with individual and community values, perceived quality of life, economic incentives for development, and development of land-use policy codified in law. These considerations reduce to the question: **What "natural" ecological and socioeconomic processes interact to generate spatial pattern (e.g., land use patch mosaic) and how do ecological consequences of development feed back on future decisions?**

E. DIVERSITY OF APPROACH

The central spatial model is a powerful tool with an embedded method for answering many of the questions we have posed. However, the model is large, will be initially unwieldy, and will require some time before it is operational. Therefore we will use several approaches independent of this effort in order to gain early answers to more tractable questions. For example, *before-after* studies will be used to document change at sites already identified for change (e.g., highway extensions, golf-course construction). *Urban gradients* freed from the land-use based sampling system will be used early on to identify spatial trends (e.g., precipitation chemistry, rattlesnake distribution) and to describe spatial pattern in a single patch type (e.g., occurrence of native vegetation in residential areas). Studies of patch types of special interest, such as desert remnants and suburban yards, will be initiated immediately.

F. DATA

As for other cities, environmental and socioeconomic data for Phoenix are overabundant, thanks largely to the efforts of a variety of governmental agencies. We will invest a considerable effort in gathering and filtering these data and incorporating them in our GIS. Some research elements will use existing data extensively (Core 4); however, meaningful ecological data in several broad areas do not exist and a substantial effort will be directed toward collecting new data to answer new questions.

MODELING APPROACH

The modeling effort in this project is organized around a hierarchical patch-dynamics conceptual framework (Wu and Levin 1994, Wu and Loucks 1995, Forman 1995). To guide empirical investigations and to make mechanistic predictions, a series of related models will be constructed, each of which addresses different questions at distinct spatial scales. These models can be grouped into three categories: *patch models*, *landscape models*, and *regional models*. At the local scale, homogeneous **patch models** will relate patch characteristics such as size, shape, and boundary conditions to ecological variables (e.g., plant species diversity, soil metabolism). These models will apply to single patch types such as parks, residential areas, or industrial areas (see Fig. 5). The models may be as simple as statistical relationships or input-output models, but are important for understanding fine-scale effects of urban development. They will be used to provide information for constructing and parameterizing coarser scale models. At the **landscape** scale, we will build models for distinctive landscapes consisting of multiple patch types. These models will explicitly consider spatial heterogeneity and interactions among patches of different types. At the **regional** scale (Phoenix metro area), we will develop a hierarchically structured, patch dynamic, urban landscape model. This is the most comprehensive and complex of all the models to be developed in the project. It explicitly considers the spatial heterogeneity of processes across different scales of space and time. This model follows the basic principles used by several models of urban development and land mosaics (Clarke et al. 1996, Kirtland et al. 1994, Costanza et al. 1990, Sklar and Costanza 1991, Forman 1995). Boundaries for the regional model will be placed well beyond the current limits of metropolitan Phoenix (Fig. 6) in order to incorporate anticipated expansion for three decades.

The regional model is spatially explicit and will use both grid-based, remotely sensed data and integrated ecological measurements made on the ground. GIS will be used to store, manipulate, and analyze spatial data as well as to assist the modeling process. The model will include rule-based land-use transition probabilities that depend on history, neighboring cells, and long-distance effects reflecting physical, ecological and socioeconomic influences (Fig. 7.). These functions will change in time in both model and reality and will be estimated by comparing time series data (photographs and remote sensing information) , which essentially assumes urban development occurs as a Markovian process. Simulation modeling will be based on this framework using C or C++ language and will be linked with GIS (AVENUE with Arc View 3).

On the ground sampling defined by LTER Core research will initially be stratified because of our working hypothesis that land use is a significant driving variable. However, we will simultaneously develop a tessellation-stratified sampling framework using hexagon-based grids superimposed on the metropolitan landscape to enhance objectivity and to remove the land-use bias (Stehman and Overton 1995).

Remotely sensed data will be acquired from a wide range of sensors including visible, thermal, and radar to determine land use at high spatial scales. These data can then be used to create regional land use thematic maps that depict different processes; for example, urban versus native materials, permeable versus impermeable surfaces, and transportation systems (Fig. 8). Classification algorithms and methods have been developed in a pilot program between ASU, the City of Scottsdale, and NASA that are applicable to this project. P. Christensen is a team member of the NASA Mission to Planet Earth ASTER Investigation and can schedule ASTER images of the Phoenix region at 16-day intervals to provide a long-term set of land use data beginning in mid-1998. Further information on remote sensing data is provided in section F, below.

RESEARCH PLAN: LTER CORE AREAS

This section describes the exemplary research we propose under the five LTER ecological core areas plus two socioeconomic core elements. In each section, "long-term research" refers to data that will be collected in a GIS format for the regional spatial model effort. "Experiments" refers to other proposed studies that are separate from the regional model. These research elements may in fact be descriptive, pattern-seeking studies or manipulative experiments. Some experiments will be done once while others will be repeated at intervals to reveal temporal trends.

A. PATTERN AND CONTROL OF PRIMARY PRODUCTION

Primary production is the rate of generation of organic compounds by the natural processes of photosynthesis and chemosynthesis. This project will focus on primary production of by vascular plants. Phoenix is superimposed on Sonoran desertscrub vegetation originally dominated by *Larrea tridentata* (creosote bush) to the west and a *Cercidium-Carnegiea* (palo verde-saguaro cactus) association to the east variously transected by a *Populus-Salix* (cottonwood-willow) riparian network (Fig. 9). Much of the region, especially flat areas dominated by creosote bush, was converted to irrigated agriculture (cotton, citrus, alfalfa) near the turn of the century. Urban development is moving rapidly into these three vegetation types. Riparian communities of the valley have been severely reduced due to water table decline and dewatering of the Salt River. While only remnants of natural communities exist, these are distributed throughout the greater metropolitan area, largely as parks and refuges. Urban and suburban areas are now replete with exotic plants derived from Asian, Australian, American and African stocks that are suited to the local arid climate.

Long-Term Research

We are interested in the rates of net primary production exhibited by vegetation associated with various land-use patches of the region and how rates at larger scales depend upon patch size, shape, location, and configuration. In particular, **Q: what changes in primary productivity are characteristic of 1) conversion of natural vegetation and agriculture to first suburban, then urban uses, 2) supplementation of water availability via irrigation, and 3) at the largest scale, long-term trends in land use pattern?** By reconstructing regional land use over the past 50 years, we can determine trends in total productivity and resulting gas exchanges with the atmosphere. We hypothesize these trends to be parabolic, with highest rates associated with peaks in agricultural productivity. To explain these trends, we will develop relationships between water use and production to evaluate the alternative hypotheses that total production is controlled by a) water availability, b) land area loss by human structures (buildings, roads, airports) and/or c) economic and social factors, such as decisions to replace agriculture with golf-course centered development or to alter irrigation technology.

<u>Approach</u>: The first step in this analysis is to develop a vegetation type and density map for the region using GIS data derived from satellite and aerial imagery. Reconstruction of past configuration will be derived from agricultural- and land-use records archived by federal and local agencies and the irrigation district (Salt River Project, SRP). An archive of historic photographs is available for "ground truthing" of land-use patterns. Once a vegetation map is developed, patch specific rates of net primary productivity will be assessed based first on literature estimates. We anticipate that patch to patch variance will be high in the urban environment; however, ground truthing of selected patches will be used to differentiate rates characteristic of similar patches.

Patch specific measurements of primary production will be made in two ways. Tree productivity will be derived for major native and non-native species by age and growth measurements derived from coring combined with empirical regressions relating age and dry mass of plant parts. Dendrochronological studies have the advantage of relating growth to past climate and to determine climatic response as a function of location within the urban complex. Dating by tree cores will be supplemented with serial photographic techniques and survey of homeowners and land managers. Litter production studies will further supplement this approach. Emphasis will be on 1) palo verde (C*ercidium microphyllum*), a native tree species widely used as an ornamental in broad range of patch types, 2) grapefruit (*Citrus paradisi*), a remnant of citrus agriculture popular in suburban and urban landscaping, and 3) shamel ash (*Fraxinus uhdei*), a rapidly growing shade tree of Central American origin used predominantly for suburban yards.

Productivity of grasses and shrubs will be estimated from studies of energy flow in suburban yards (described later) and in cooperation with landscaping services charged with maintaining suburban parks and golf courses (grass clippings per unit area as an estimate of above-ground net production). Soil organic matter storage studies (section C below) will be used to estimate belowground accumulation and decomposition rates as an index of subsurface production.

Experiments

Two opportunities for experimental work emerge from this LTER core element; water-climate-productivity feedback studies and arbuscular mycorrhizal (AM) relationships with primary production. While patch specific quantification based on remotely sensed images combined with ground truthing is necessary for the GIS-based modeling effort, these data are mostly sensitive to land use change. More detailed studies are required to detect diel and seasonal patterns of variation and to investigate short-term feedback relationships. While our initial focus is on water relations, nutrients may also play an important role. Since nutrient uptake is closely related to AM quality and quantity, a study of mycorrhizal dynamics is also proposed. The emphasis of these studies is on process, thus we will investigate a limited number of species at a limited number of sites.

1. FEEDBACKS BETWEEN PRODUCTION, WATER USE AND MICROCLIMATE.

Water loss rates (ET) influence productivity by controlling water availability and by feedbacks on temperature via latent heat transfer (evaporative cooling). Because of the strong linkage between CO_2 assimilation and ET, the latter should be measured in conjunction with productivity measurements. Simultaneous measurement of CO_2 and water flux allow computation of water-use efficiency. In particular, we are interested in whether water-use efficiency varies among patches, plant species, and, especially, location on the urban gradient. Initial studies will focus on two patch types: native remnant patches (creosote bush and cactus) and grasses of urban greenbelts. Site-specific measurements will be made on a diel basis with a portable infrared gas analsyis system using a whole plant/canopy chamber. Measurements will be made seasonally. Measurements will also be made on bare ground to assess soil fluxes (see section C below). Microclimate will be determined with small, portable weather stations consisting of 5-10 sensors and a datalogger. Because of their limited scope in space and species measured, results will not be scalable. However, these physiological relationships will provide an index of plant water-use relationships that can be followed in the long term by repeating these studies at regular intervals (e.g., 2-3 years).

2. PLANT-MYCORRHIZAL RELATIONSHIPS.

Primary productivity of above- and belowground plant parts in urban ecosystems is affected by associated symbionts. The most important root symbiont in arid and semi-arid regions is arbuscular mycorrhizae (AM). The diversity of indigenous AM fungal communities decreases when natural ecosystems are disturbed by human activities (Giovannetti and Gianinazzi-Pearson 1994). An on-going survey of AM in deserts of North America (C. Martin and J. Stutz, ASU Botany) will be expanded to describe the biodiversity of AM in the greater Phoenix land-use patches described for this study. Trap culture techniques will be used to concentrate and isolate AM species. Soils from these patches will be collected on an urban-centered gradient, described in terms of mycorrhizal flora, then used in an experiment to measure plant growth (citrus) under greenhouse conditions. Emphasis will be on patches that were originally agricultural. but have since been subjected to clearing and suburban development. Results of this study will reveal the extent to which soil characteristics limit primary production and thus require greater fertilizer application, water use, or both, to foster healthy plant growth.

Research Opportunities

In addition to the research described above, several research opportunities in this core area will be developed as associated funding and personnel become available. Two are of high priority. Land values and development decisions are often strongly dependent services provided by healthy ecosystems (e.g., Daily 1997). However, ecological data are not available upon which to base these decisions.

Aquatic primary productivity in an extensive array of urban, suburban, and golf course lakes could be measured by whole system oxygen techniques to establish a spatial pattern that would then be pursued by partitioning variation between chemistry and origin of source water (urban runoff, treated wastes, municipal water). A spectrum of lake ages from recent to 30 years is available in the Phoenix area, from which lake development patterns can be assessed (Amalfi and Sommerfeld 1987). Surface water is a highly valued amenity in arid Phoenix and the value of lakes is reflected in property values of lakeside development. Deteriorating quality is, on the other hand, a detriment to perceived environmental value and, in extreme cases, human health.

Productivity consequences of alternative residential water use options. In the Phoenix area, three major types of water use for landscaping exist: flood irrigation with untreated water, use of treated water via sprinklers, and xeriscapes using desert vegetation. With expanded funding, we will initiate a study of the ecological consequences of these three strategies. While data exist on water use associated with each scheme, little is known about consequences for primary productivity. Such a study will be coordinated with broader ecological studies of households which include variables such as plant, insect, and bird biodiversity, soil characteristics, and microclimatic implications.

B. DYNAMICS OF POPULATIONS SELECTED TO REPRESENT TROPHIC STRUCTURE

Organisms, populations, communities and resources are typically distributed in patches of widely varying size and quality (Kolasa and Pickett 1991, Levin 1992). Human activities in urban settings have greatly altered the frequency, quality, distribution, and life span of these patches. All of these factors can influence local population, metapopulation, and community dynamics through impacts on trophic structure (Kareiva 1990, Kareiva and Wennergren 1995) and local extinction rates (Simberloff 1995). In turn, we expect changes in population and community dynamics of native or exotic biotas to feedback on human populations through economic, sociological, and biological channels.

Long-Term Research

We will focus our long term monitoring efforts on the spatiotemporal characteristics of organisms in four species groups: humans, arthropods (specifically butterflies, pest insects, and arachnids), birds, and plants. We have chosen these species groups for monitoring because they span the range of habitat preferences, dispersal characteristics, trophic position, and life history features exemplified by species in Phoenix's urban ecosystem. We aim to identify the spatiotemporal scales at which different populations are controlled and how populations and communities change as functions of urbanization.

On a patch-specific basis, we will monitor arthropods using a combination of sweep nets, sticky traps, pitfall traps, and soil samples extracted by Berlese funnel. Additionally, we will sample fixed length urban transects using nets attached to moving vehicles. Birds will be surveyed in cooperation with state and Audubon Society efforts. Large plants (e.g., palo verde, mesquite, saguaro) will be assayed by ground-truthed aerial photography and satellite imagery, whereas smaller plants (e.g., grasses, shrubs, cacti) will be surveyed in permanent quadrats. Human populations will be monitored using existing census data.

These population and community monitoring efforts will add many data layers to our hierarchical GIS model. This research component, however, is primarily designed to help resolve urban configuration effects on critical ecological variables and to seek scale relationships among taxa. This component of the LTER Core is eminently amenable to K-12 student involvement both through directed field work and questionnaire-style neighborhood surveys (e.g., to document raptor, rattlesnake, or coyote sightings, shade tree plantings, and gardening practices). We also plan feedback to schools through curricular modules and presentation of long term trends via the Internet. To take advantage of existing, unique strengths, we will supplement our primary long-term monitoring efforts with two additional projects.

1: LONG TERM CHANGE IN PLANT COMMUNITIES.

Q: On a decadal scale, how do plant communities in natural remnants change as urban environments encroach? Fortunately, plant communities of natural desert environments near Phoenix were censused and characterized 20-30 years ago when the sites were much more remote from a smaller urban area. The city has now approached and/or enveloped these sites. We will resurvey these sites over the next 5 years to identify species or functional groups that are particularly sensitive to urban encroachment. Sites targeted for resurvey include the Sierra Estrella, White Tank, McDowell, and Usery Mountains; Lake Pleasant; and South Mountain Park. Future efforts will identify the mechanisms behind changes in plant community composition; candidate mechanisms include changes in air quality, escape from cultivation, release from competition or herbivory, loss of pollinators or seed dispersers, and selective human harvest.

2: LONG TERM CHANGE IN LICHEN DISTRIBUTIONS.

Q: To what extent do lichen assemblages portend ecological change by teleconnection with the urban environment? Lichens of the Southwest are diverse, widespread, slow growing, long-lived, and sensitive to air quality and atmospheric deposition. ASU maintains an extensive herbarium collection of lichens aimed at understanding air quality-lichen interactions in the region (Nash 1975). We will survey lichen communities on an extended urban gradient (city center to 30 km beyond the current fringe) to identify spatial patterns in lichen community structure that may be used as an early warning system for changes in air quality. After assembling these baseline data, sensitive sites will be resurveyed for lichens at 5-10 year intervals.

Experiments

We will conduct at least three experiments that link patch characteristics of the urban ecosystem to population and community dynamics.

1. ECOLOGICAL DIVERSITY IN REMNANT PATCHES.

Q: For remnant patches of native vegetation, how do patch size and surroundings affect the maintenance of ecological diversity? Rapid development in the Phoenix metro area allows us to take creative advantage of a "natural experiment" for investigating the impacts of patch size and surroundings on ecological diversity. Our basic strategy is akin to that employed in studies of Amazonian deforestation (Lovejoy et al. 1986, Bierregaard et al. 1992): we will use *a priori* information on where development will take place in the Phoenix area to guide our sampling efforts. As development extends further into the Sonoran Desert or historically agricultural areas, new park areas ranging in size from 1 ha playgrounds to < 5 km^2 "city" parks to the 40 km^2 South Mountain Park (the largest metropolitan park in the world) are being designated and set aside to satisfy developmental guidelines and push home values higher. These islands of native desert habitat or former agricultural land provide refuge for species escaping urban sprawl and serve as sources of aesthetic and recreational enjoyment for the valley's human population.

We will collect baseline pre-development data on incidence of key indicator species spanning a range of dispersal and reproductive abilities, trophic positions, and environmental tolerance in soon-to-be isolated remnants of varying sizes. Surveys and small scale experiments to investigate patterns and mechanisms of species disappearance will continue as development proceeds and park areas are cut off from surrounding habitats. We will compare species richness and community composition in recently isolated remnants with areas of comparable size isolated years ago for which species lists exist or could be compiled easily. This "natural" experiment affords us an excellent opportunity to examine the biotic consequences of patch formation and isolation along urban-agriculture-desert interfaces. Obtaining these data will allow land management experts to more accurately identify the biological uniqueness of different parcels of land and target undeveloped regions rich in isolation-sensitive species with adequately sized preserves.

2. MULTI-TROPHIC DYNAMICS.

Q: How similar are multi-trophic dynamics among different types of habitat patches in the urban ecosystem? We have identified groups of species at three trophic levels (e.g., grasses, herbivorous arthropods [aphids, mirids], and predatory arthropods [ladybugs, spiders]) that occur across our range of habitat types (e.g., industrial waysides, suburban backyards, agricultural fields, and desert parks). Using replicated, controlled cage experiments, we will manipulate species densities and resource regimes to test for trophic cascades or bottom-up control. We ask, how similar are patterns of plant damage, herbivore outbreaks, herbivore control by predators, and seasonal tropho-dynamics among habitat types? We will attempt to identify patch type characteristics driving the dynamical differences. Ultimately, we will combine our experimental results with a patch dynamic model to better understand how inter-patch differences in tropho-dynamics impact regional fluctuations in plants, herbivores and predators. We will link these experiments to other LTER core areas by quantifying changes in ecosystem function (e.g., productivity, P/R ratios, organic matter accumulation) as functions of trophic complexity and patch type.

3. PATCHINESS AND SPECIES INVASIONS.

Q: How does patchiness of the urban landscape contribute to species invasions across habitat boundaries? One consequence of increasing patchiness in the CAP ecosystem is that vastly disparate community types are brought in close proximity to each other. The profound contrasts in water dependency and other characteristics between native desert and anthropogenic habitats may place crucial limits on species invasions across patch boundaries. Paradoxically, eco-conscious legislation demanding xeriscaping in suburban areas may contribute to cross-boundary species invasions. For example, several non-native, desert landscaping plants (e.g., monk's pepper tree [*Schinus terebinthifolius*], Chilean mesquite [*Prosopis chilensis*]) have escaped cultivation into the Sonoran Desert. The ecological impacts of these invasive species are essentially unknown.

Baseline survey data will identify non-native plants, arthropods, and birds that have successfully invaded desert habitats. To identify the impacts of invasive species, we will 1) conduct seed germination and competition experiments (invader vs. "endemic"), 2) perform manipulative cage experiments examining the impacts of invasive pest herbivores (e.g. white flies) on native desert plants, and 3) conduct manipulative cage experiments investigating the impacts of nonnative predatory arthropods (e.g., praying mantids) on native desert arthropod fauna. Key aims of this experimental research are to tie invasions by nonnative species to observed shifts in abundance of native species and to identify, at a mechanistic level, patterns of resource availability and patch characteristics that facilitate cross boundary invasions.

C. PATTERN AND CONTROL OF ORGANIC MATTER ACCUMULATION IN SURFACE LAYERS AND SEDIMENTS

In natural ecosystems, a substantial fraction of organic matter is stored as detritus in dead wood and in litter and below ground soil horizons. Natural desert soils are largely composed of weathered rock materials and the products of that weathering, and soluble materials such as calcium carbonate concentrated by infiltration and evaporation. Thus, soils represent a small fraction of total organic matter storage (compared to living biomass). Agricultural and urban turf ecosystems (parks, golf courses, residential lawns) depart from this natural baseline however, especially after long periods of managed use. Thus we expect a wide variation in natural soil organic carbon storage among land-use patches within the urban complex. At intermediate (landscape) scales, patterns of organic matter storage may be driven by water policy. For example, xeriscaped Scottsdale is likely to store less and different kinds of soil organic matter than adjacent Tempe, where residential flood irrigation is widespread.

Long-Term Research

1. SOIL ORGANIC MATTER.

As part of our patch dynamic model, soil characteristics will be measured to describe organic matter storage and a host of other soil features: texture, porosity, exchangeable cations, extractable nitrogen, and metals. Because soil development is a slow process, we anticipate that this survey will be done initially and repeated at ten-year intervals (fig. 10).

Research will answer the questions **Q: What long-term trends in organic matter storage occur in different land use patches? In particular, Q: how do long-term trends change when land use is altered and at what rates? And Q: by what mechanisms does organic matter accrual or loss occur?** While these are largely descriptive questions, we hypothesize that organic matter accrual occurs during agricultural phases and diminishes following transitions from agricultural to residential use. On the other hand, desert upland to residential transformations are followed by organic matter increase due to enhanced primary production and import of mulch.

2. SOIL METABOLISM AND GAS FLUX.

Change in storage of soil organic matter is a function of the difference in supply and loss rates. While supply of organic matter is by primary production and import (especially deliberate human import), loss of organic matter can be measured directly as CO_2 evolution, using a variety of techniques. We will measure patch-specific CO_2 evolution of soils to document the pattern and rate of organic matter change. Initially we will focus on a few patches identified as significant to the preliminary spatial model, and sampling will be expanded based on model results. **Q: what are the temporal trajectories of patch-specific soil respiration and trace gas emission? Q: How does water use influence CO2 evolution? Q: What metabolic changes are associated with land use change?**

Approach: We will use a combination of methods to measure soil metabolism. The soil profile method (De Jong et al. 1979) and direct measurement of CO_2 concentrations inside the headspace of temporarily sealed PVC cylinders (Rochette et al. 1991) will be used at representative sites. The measurement of soil pCO_2 in the soil profile allows for the calculation of gaseous fluxes (Johnson et al. 1994). Additional samples of extracted gases will also be assayed for NO, N_2O and CH_4 to determine emission rates of these important trace gases.

Experiments

1. DECOMPOSITION IN SOILS.

Decomposition of surface organic materials is a measure of a variety of soil characteristics including microbial and invertebrate communities and is the major input into the soil organic matter pool. In a given patch type, both nutrients and water can control decomposition rate. **Q: How does rate of decomposition of natural organic particulates vary in water-subsidized, agricultural, and remnant native-vegetation patches along the urban gradient?**

Approach: We propose a long-term decomposition study following Harmon and Melillo (1990). Litter types will include mesquite (*Prosopis juliflora*) and creosote bush (*Larrea tridentata*) leaves, Bermuda grass (*Cynodon dactylon*) roots, and wooden dowels. A companion study will use the buried bag method (David et al. 1990) to measure changes in organic matter and nitrogen in local soils enclosed in nylon bags and buried in surface horizons. Bags will be retrieved at yearly intervals for five years and analyzed for C and N changes. Precipitation and soil moisture at experimental sites will be monitored periodically. Results of these two studies will provide insight into mechanisms involved in long-term soil OM trends measured at a wider array of locations throughout the urban complex.

Research Opportunities

Soil storage of organic matter and decomposition dynamics represent only a part of a more integrated description of whole system metabolism (energy budgets) that links primary production and aboveground storage to below ground processes. Primary production data derived from element A will be combined with this element to provide this picture for all patches. Detailed studies of residential patch energy flow on a spectrum of water use strategies (Section A) will collect similar but more extensive data on both above and below ground components. Ultimately, we wish to link these patch studies with a larger scale study of regional sources and sinks incorporating landfills. We suspect that patch-specific energy budgets will reveal a substantial export vector in the form of lawn and shrubbery clippings and inputs of organic fertilizers and commercial mulch. The importance of these cross boundary transfers and their consequences for the metabolism of the larger urban unit is a research opportunity we are eager to initiate with auxiliary funding.

D. PATTERNS OF INPUT AND MOVEMENT OF NUTRIENTS THROUGH ECOSYSTEM COMPONENTS

Biogeochemical processes are summarized for whole ecosystems by estimates of material mass balance. While mass balance cannot provide detailed information on mechanisms of chemical retention and transformation, the technique allows inference about sources, sinks, and overall ecosystem functioning (retention or release of materials as a function of ecosystem structure [e.g., Likens et al., 1977, Stoddard, 1994]). Although chemical mass balances have been used to evaluate sources of non-point source pollutants in many cities, we have very little knowledge about whole-ecosystem material balances for urban ecosystems. Monitoring of material movement and retention will focus on long-term, whole-system mass balances (capitalizing on the definable water-born inputs and outputs of this arid-land city and its extensive monitoring database), spatial and temporal variability of exports, groundwater nitrogen balance (using an existing MODFLOW model for Phoenix [Putnam et al. 1996]), and short-term material transport during storms. In addition, several experiments and future research opportunities are identified that will be conducted in the context of the long-term monitoring.

Long-Term Research

Our monitoring plan is designed to permit computation of whole-system budgets for salts, nitrogen, and DOC/POC for the entire study area, in varying degree of detail (salts > N > C). With this information, plus additional data on exports, we can begin to answer questions about how material transport and retention change with increased urbanization.

<u>Overview of Approach</u>: For construction of mass balances, the ecosystem is defined hydrologically (Fig. 11), and storage of materials is defined in the context of the patch dynamics model outlined earlier. We will measure (or synthesize from existing [and ongoing] data collection efforts): **inputs—**surface water inputs (Fig. 12), atmospheric deposition, and anthropogenic inputs (e.g., fertilizer, fuel, food and materials, livestock, and livestock feed—estimated from federal/state agency data); **outputs—**surface water outflows and anthropogenic outputs (estimated as for inputs and from wastewater effluent); and **changes in storage—**by difference, and in groundwater, using MODFLOW, pumping data, and chemical monitoring of samples from an extensive well network ; in soils, via patch-specific analyses of nutrient content; in sediments, periodic (infrequent) sampling and synthesis of existing data. By interleaving LTER monitoring with existing monitoring programs,

the program, such as the USGS NAWQA Program, will be extremely cost-effective while at the same time greatly expand our ability to understand the flow of materials through the ecosystem.

1. SPATIAL AND TEMPORAL VARIABILITY IN EXPORTS FROM URBAN AND DESERT WATERSHEDS.

Background: Arid-land climate and hydrology are characterized by extreme interannual variability (Graf 1988, Grimm 1993). Correspondingly, C and N exports from desert watersheds exhibit dramatic temporal variability (Jones et al. 1995, Grimm 1992). Many human activities (e.g., flow regulation, large reservoirs, on-site retention of stormwater) are intended to reduce this variability. There also is spatial variability in the relative contributions of different landscape patches to material export from these watersheds, although this is only recently beginning to be quantified (Fisher and Grimm NSF; Parks and Baker in press; Baker et al. in review). Parks and Baker (in press) concluded that reservoirs are a major source of DOC, with areal production rates ~ 200x upstream watershed exports. Little is known about the export of carbon from *urban or agricultural areas* in desert ecosystems; yet analysis of urban stormwater in Phoenix shows that DOC levels in pulsed outputs can be extremely high (>50 mg/L; Lopes et al. 1995; Lohse et al. 1994).

POC and DOC play an important role in aquatic ecosystem metabolism, especially in streams and rivers (Fisher and Likens 1973, Findlay et al. 1993). DOC forms aqueous metal complexes, participates in various redox reactions and, when sorbed to particles (as POC), alters the partitioning of hydrophobic organic compounds (reviewed by Thurman, 1985). In the past decade, the role of DOC as a precursor to disinfection by-products has received intensive study. Nitrogen is a limiting element to terrestrial and aquatic productivity, but also can be a significant groundwater pollutant (as nitrate). Finally, trace contaminants including lead, zinc, and copper are ubiquitous in the urban environment. Traces of DDT and substantial amounts of total petroleum hydrocarbons (TPHC) exist in runoff from the Phoenix metropolitan area (Sommerfeld and Amalfi 1991, Lohse et al. 1994). We anticipate that export of lead and DDT will decline over time, as they have in national trend studies (Smith et al., 1987). This study will compare exports of C, N, and contaminants in desert and urban watersheds (entire Phoenix system and component watersheds).

We propose that temporal variability (annual-decadal scales) in exports of materials is controlled primarily by hydrologic variability, and further hypothesize that spatial variability in export rates are caused largely by heterogeneity in land use. For the desert/urban contrast, then: **Q. Are nutrient (C, N) export rates *and interannual variability in nutrient export rates* from the urban area greater or less than those from the surrounding desert? How will nutrient export and its variability change with continued urbanization?** We predict that the overall export of materials will change to reflect urbanization of land that was previously in desert scrub or agriculture. What are the "hot spots" of nutrient and contaminant storage and contribution to export in the city vs. the desert? We predict that temporal variability in exports will be less in urban than in desert watersheds, but we suspect that spatial variability may be higher in cities relative to surrounding desert watersheds due to greater heterogeneity in storage of materials and in surface infiltration capacity.

Approach: Long-term temporal trends in concentration and export rates for N, DOC, POC, and contaminants will be determined for the entire ecosystem and for major land-use types. Comparison with nearby desert watersheds will rely on data from ongoing studies (e.g., see "Results from Prior NSF Support"). Source area contributions at finer spatial scales will be determined in studies focusing on exports during discrete storms for which we can calculate total loads. Monitoring of soil (or other surface materials) storage of nutrients and contaminants (according to the patch-specific, GIS-based design outlined earlier) will permit estimation of the potential contribution of different patches to the total load exported during single events.

To test predictions on temporal variability, we will compare coefficients of variation for total export over a number of years. Spatial variability in transport and contributions of landscape patches to export of materials will be assessed using a variety of spatial statistical techniques. Since this work involves thorough sampling of single events, we will be able to analyze storm export over space and time for discrete urban watersheds, to determine how urban spread influences spatial variability in material transport. For example, export from a typical *urbanized watershed* can be determined by monitoring an urban canal, which transports urban stormwater.

2. NITRATE ACCUMULATION IN GROUNDWATER.

Background. Nitrogen inputs to the earth surface have increased dramatically (Prospero et al. 1996), such that combined inputs in fertilizer, N deposition from fossil fuel combustion, and enhancement of N fixation due to leguminous crops now exceed biological N fixation on a global basis (Vitousek 1994). This has resulted in nitrogen saturation in forest ecosystems (Aber et al. 1989; Stoddard 1994), increased riverine transport of N (Peierls et al. 1991, Howarth et al. 1996), and eutrophication of streams and rivers (Haycock et al. 1993) and coastal marine ecosystems (Giblin and Gaines 1990, Lajtha et al. 1995). The Phoenix metropolitan ecosystem, growing out of old agricultural land in a desert setting, has many characteristics that are blamed for increased N loading: fertilizer use, human waste production, and extensive automobile pollution. In addition, concentrations of transported N (primarily nitrate) during floods can be exceptionally high in desert streams (>5 mg/L; Grimm 1992); the fate of this transported N is currently under study, but much of it may end up in groundwater through mountain-front recharge. Through this proposed research, we hope to understand which of these factors is most critical to groundwater N dynamics in the urban environment.

A preliminary N mass balance (D. Anning, USGS, personal communication) suggests that the largest N inputs to the Salt River valley are human waste (40%), fertilizer (31%), and animal wastes (14%). Surface water inputs and precipitation account for only 4% of input N; N fixation by alfalfa accounts for the remaining 11% of N input. Sixty-five percent of the N input is retained within the system and the remainder is exported. No attempts have yet been made to quantify the upper basin desert contribution to groundwater N, yet this preliminary analysis suggests that nitrogen *must* be accumulating in soils or groundwater in the Phoenix metropolitan ecosystem. Groundwater contamination by nitrate is widespread in this urban environment; the majority of wells exceed 10 mg/L NO_3-N. Spatial analysis and preliminary stable isotope analyses suggest that agricultural land use is the major source of this contamination (Wolfe 1996).

Questions to be addressed in these studies are: **Q: Which sources of N are most important in contributing to groundwater N accumulation?** and **Q: How will the rate of groundwater N accumulation (and the relative importance of these sources) change with expanding urban development?** At this stage, the answers to these questions will require additional monitoring and refinement of estimates of inputs. The preliminary mass balance cited above is a starting point (hypothesis) from which this work will expand. We expect changes in the rate of groundwater N accumulation as agricultural land use is converted to urban (residential) land use.

Approach: Inputs of nitrogen to the groundwater system from the urban ecosystem cannot be determined directly and will therefore be estimated by difference in the groundwater N mass balance. Measured terms will include change in accumulation (integration of water storage and nitrate concentrations), aquifer pumping, and system inputs and outputs (by groundwater modeling). This effort will be closely coordinated with ADWR, the USGS, and SRP (see "Ongoing projects"). Additional inferences regarding sources of nitrogen to the groundwater system will be based on spatial analysis and stable isotopes of N. We anticipate that most N inputs are localized in the vicinity of feedlots and agricultural fields. If so, groundwater nitrate concentrations in the uppermost aquifer should be correlated with fertilizer and animal waste inputs. In addition, we propose to analyze stable N isotopes in groundwater nitrate and several sources (atmospheric deposition, mountain-front recharge, fertilizer leachate, septic tank leachate, soil leachate), and to employ a mixing model to evaluate relative contributions of these sources (see, e.g., Valiela et al. 1992).

3. SALINIZATION OF SOILS AND AQUIFERS.

Background: Many prehistoric agricultural communities (see, e.g, Fig. 13) became unsustainable as a result of salinization (Gelburd 1985, Redman 1992). Concentration of salts occurs because most of the water used during irrigation is lost by evaporation. This leads to one or more consequences: (a) high salinity in water exported from the system, (b) saline groundwater, and/or (c) salt accumulation in soils. Of greatest concern in the Phoenix area is increased salinity of groundwater (TDS > 2000 mg/L is not uncommon; Sabol et al. 1987; Miller and Johnson 1996). Some agricultural land on the lower Gila River has been taken out of production due to salinization.

Land in the Phoenix ecosystem is rapidly being converted from agricultural use to urban (mostly residential) use. This conversion will change irrigation practices. **How will salinization of soils and groundwater change as land use changes?** On one hand, we expect the amount of irrigated land to decrease, since impervious surfaces, xeriscaped landscapes, and other parts of the urban landscape are irrigated little, if at all. On the other hand, homeowners are less likely to be less concerned (or even aware) about salinization and are thus unlikely to manage soil salinization. On balance, we hypothesize **H: The rate of accumulation of salts in the Phoenix ecosystem's soils and aquifers will decline over time as agricultural land is converted to urban land.**

Approach: The rate of salt accumulation in the Phoenix ecosystem can be determined by compiling a salt balance. The proposed LTER input/output salt balance will be sufficient to quantify the net retention of salts in the watershed and, with a higher degree of uncertainty, the rate of buildup of salts in aquifers. Accumulation of salt in soils can be determined by difference. Accumulation of salts in surficial soils also will be measured directly by analyzing the salt content of soils in permanent plots on a patch-specific basis consistent with the GIS-based model, allowing an independent assessment of the "by difference" estimate.

Experiments and Research Opportunities

1. MATERIAL TRANSPORT IN SMALL WATERSHEDS DURING STORMS: A DESERT-URBAN COMPARISON.

In addition to the coarse-scale mass balance for the metropolitan system described above, we propose a more detailed comparison of sources and fates of materials (especially C and N) transported during storm events between relatively undisturbed Sonoran Desert watersheds and paired urban watersheds. Pairing will be based upon watershed size, average slope, and other landscape features. Tentatively, the first comparison will be between one of the lower tributaries of Sycamore Creek (flood transport study funded by NSF LTREB) and Indian Bend Wash (in conjunction with USGS monitoring). Each watershed will be instrumented with atmospheric deposition collectors and samplers that collect runoff from different landscape elements or patches, defined by topographic position, vegetation, slope, and extent of upstream influence. Build-up of C and N on vegetation, soils and streets. will be analyzed for N and C components. Intensive sampling by automated samplers augmented by grab samples will be collected during a series of storms. Flow paths will be measured or (at least for the urban watershed) modeled using standard hydrologic models Water and mass balances for each storm will be computed for various segments of the watersheds. Because much of the urban watershed has been modified to enhance water retention, we expect it to retain nutrients more effectively than the desert catchment.

2. EFFECTS ON RECIPIENT SYSTEMS.

The net result of material retention and transformation during transit of water through the urban system is material export. Most evidence clearly shows that outputs of nutrients vastly exceed inputs. Thus, the city is a source patch (for nutrients, carbon, contaminants, salts) in the larger landscape. Likely consequences of this net export of materials for downstream or recipient ecosystems include toxicity, eutrophication, and alteration of carbon quality. For example, fish in the lower Gila River have very high levels of DDT, reflecting widespread use of this pesticide in the 1950s-1960s. Stormwater runoff from several urban drainages in Phoenix commonly exhibits short-term toxicity (Amalfi et al. 1990, Lopes et al. 1995). Nitrogen export (surface water output is about 3x input from upstream watersheds) is likely to alter aquatic productivity along the length of the Gila River and perhaps beyond (i.e., the Gulf of California). Groundwater (see above) and urban lakes also are recipient systems for sub-watersheds within the metropolitan area. With information on long-term changes in export, we propose to examine parallel changes in 1) riverine and riparian productivity along the lower Gila River, 2) aquatic invertebrate community composition and secondary production, and 3) carbon quality for sediment respiration (bioavailability assays coupled with chemical characterization; Aiken & Leenheer 1993, McKnight et al. in press). Each of these will consist of a one-year study, conducted in the lower Gila River system and slated for repetition in each subsequent LTER funding cycle.

E. PATTERNS AND FREQUENCY OF DISTURBANCE TO THE RESEARCH SITE

We will adopt Sousa's (1984) definition of disturbance as a punctuated event that changes the ratio of resources to organisms. Three types of disturbance will be studied: fire, flood, and urban development. For each of these agents, we will describe the disturbance itself in terms of intensity, size, location, spatial distribution, anthropogenic mitigation and enhancement, and rotation time. Response of the ecosystem will be described in terms of resistance and resilience. Resistance is the before-after difference in ecosystem state caused by the disturbance event. Resilience is the rate of return to pre-disturbance conditions. Both contribute to system stability but the definitions of each require modification for the three disturbance types we will consider.

Several questions motivate research on disturbance described here. Some of these will be addressed descriptively with our GIS-based patch-dynamic model while others will be answered by discrete research projects. Collectively these questions deal with the nature and consequences of disturbance and how these relationships change during long term development and expansion of the city. **Q: What is the relative importance of different agents of disturbance in the greater urban environment? Q: How does the system respond to disturbance at multiple scales? Q: How does a single disturbance type operate differently among patch types? Q: How do the variables describing both disturbance and recovery from disturbance vary as a function of location on the urban development gradient in space and time?**

1. URBAN DEVELOPMENT AS DISTURBANCE.

Urban growth occurs by change in patch type. This may occur in the form of new construction on previously undeveloped patches (mostly at the urban periphery) and redevelopment involving a change from one type of built environment to another (e.g., urban renewal, characteristic of the center city). Both of these events are relatively discrete in time and both potentially change the ecological characteristics of the patch and larger scale elements which include the patch. In this context, the change in ecological factors associated with the development event (razing and/or construction) is analogous to *resistance* — a short-term response. Once patch type is changed, more gradual and prolonged ecological change may follow. This analogue of *resilience* in natural systems is associated with slow change on the site after disturbance, such as immigration of birds, maturation of trees, increase in plant species richness associated with landscaping and gardening, and accretion of soil organic matter associated with lawns. While resilience is used here to describe post disturbance change, this application is not strictly analogous to resilience in natural systems where the endpoint is the pre-disturbance state. In urban environments, the probability of transition from the built environment to the natural state is likely to be zero.

Approach: Land use data are available from ground and aerial photographs, municipal records of ownership, property transfer records, and zoning maps (Fig. 14). A temporal series of GIS-based maps will be used to identify location and dates of land use change (see research core area F). These data will allow us to describe spatial and temporal characteristics of disturbance; that is, what is the size frequency of various patch type transitions? Where in the urban landscape do these transition types occur? What is the rotation time by disturbance type? (Rotation time is the time required for the entire system to be totally replaced). These descriptive elements will be used to identify trends in disturbance pattern and to identify an array of patch types of different kind and age for study of the resilience response (for example, cotton agriculture to residential transitions of ages 5, 10, and 50 years). Ecological characteristics of these different age (but same type) patches will be used to construct successional gradients. Ecological gradients during succession have been described for many natural ecosystems and are typically asymptotic or parabolic. We hypothesize that urban systems exhibit parabolic trajectories of ecological characteristics following disturbance. While concepts of urban decay capture this trend, ecological factors are not usually implied. By analysis of data layers describing socioeconomic features of these same patches, we can seek correlations and generate testable inferences linking ecological change with social drivers (or vice versa).

A second, more straightforward approach to urban patch transition as a disturbance is to identify exemplary transitions before they occur using planning agency data. In this way, more detailed before-after studies can be initiated and followed over the long term (decades). This research element must be strongly integrated with the GIS-based studies of human impact on land use change, which are described in detail below.

Experiments

1. FIRE

Fire is a common agent of disturbance in natural systems. In desert scrub, fires are large scale, low intensity events followed by rapid recovery (high resilience). In urban areas fires are intense, small scale events. Response is typically one of high resistance (fire prevention). Fire data are maintained by the US Forest service in surrounding "natural" areas while municipal fire departments maintain records for urban areas. Rural Metro fire department maintains records of fires in less developed and unincorporated areas. Much has been written about fire policy in forest and rangeland and alternative approaches to fire management (Pyne 1997); however, the application of resulting theory and concepts stops at the urban fringe. In arid lands, wildfire is a serious threat to development at the urban periphery and fire prevention dictates residential management with ecological implications, e.g. fire breaks, control of size and location of shrubbery, selection of building materials. Inside the urban area, fire risk is largely associated with structures rather than natural vegetation. An exception exists at the boundaries of residential and native remnant parks or fallow agricultural fields. We will develop an analysis of risk, policy, spatial characteristics, ecological consequences, and economic exigencies of fire disturbance on the urban gradient from the city center to natural vegetation building on concepts derived from fire dynamics in wildlands.

2. FLOOD

In natural areas, floods are common events. Response of natural communities occurs through high resistance (riparian trees) or high resilience (aquatic biota). Urban environments are structured to localize flood disturbance and to control damage by managed land use. Floods in urban areas may exhibit threshold responses. Large levels of damage occur above a certain threshold intensity or patch size. Low intensity or limited scale events are incorporated ecologically by land use decisions (floodways, dikes and levees, building codes). We plan an initial comparative study to answer the question: **how do natural and urban landscapes respond to flood disturbance?** As with fire, this research component will borrow concepts and terminology from the study of natural systems for application to urban catchments. For example, how resistant is the urban riparian zone to floods of annual magnitude? How rapidly do eroded banks revegetate? What connections exist between streams and floodplains? How does flooding influence transport of materials (see section D, Long term research 1)?. We will approach these questions by comparing Sycamore Creek, located east of the suburban fringe, with Indian Bend Wash, a human-engineered parkland-floodway surrounded by the city of Scottsdale. Sycamore Creek is a site of a long-term, NSF-sponsored (LTREB) study of flood effects in a natural desert drainage.

F. HUMAN IMPACT ON LAND USE AND LAND-COVER CHANGE AND ECOSYSTEM DYNAMICS

Urban areas represent a complex pattern of human-environmental systems open to continuing change at a geographic scale unprecedented in human history. The rapidity and scale of land use associated land cover changes presents a unique opportunity to investigate interrelationships between urban land-use processes and ecosystem dynamics in a dryland setting. Land use involves both the manner in which the biophysical attributes of the land are manipulated and the intent underlying that manipulation — the purpose for which the land is used (Turner et al. 1995). Land use processes, which are driven by socioeconomic, institutional, and cultural factors, influence natural ecosystem dynamics through events and activities that can be identified, monitored, and predicted (Fig. 15).

Human activities are expressed through a system of urban land uses. Our research will incorporate five salient aspects of land use that offer the most potential for investigating human-ecological interactions. At its most basic level, land use can be classified by *type and density.* Activity types (agricultural, residential, commercial, industrial, transportation and open space) can be described by variations in density. Higher densities are associated with more desirable locations and higher land values. Second, *land use succession* provides a way to address the phenomenon of increased intensity of urban use as the urban area grows. Residential uses may displace irrigated agriculture or open space, while commercial land uses outbid residential users for highly desirable, prestigious locations. Third, *scale* is a powerful indicator of ecological disturbance. Post-industrial land development occurs at a larger scale than what occurred previously in the sense that it involves larger parcels of homogeneous land uses. Fourth, *location* is a unifying characteristic. We might expect, for example, a park surrounded by residential land use to have different ecological processes than one surrounded by commercial land uses or other open space. Finally, the *pattern* of development describes variations in the clustering or dispersed siting of structures and their associated roads. Current planning strategies favor high-density clustered development interspersed with open space. Traditional development involves a more even system of development where each home has its own one-half acre.

Long-Term Research

The continuing decentralization and the expanding physical extent of Phoenix has created identifiable patterns in local, internal, urban structure. Our monitoring will focus on four basic transitions in land use and their formulation into alternative successional trajectories: (1) outward decentralization and expansion, such as peripheral growth, (2) physical restructuring and modification including land use change and redevelopment in existing urban and agricultural areas, (3) shifting social and demographic characteristics such as income changes, residential mobility, aging, and racial transitions within the same location, and (4) creation or presentation of "open spaces" through either the non-development and restoration of existing desert areas, or the creation of "green spaces;' such as golf courses, parks, or common lands. Our central task is to construct a series of alternative land-use successional trajectories (see Fig. 7), and then to ask **Q: What are the ways in which social and economic forces drive land-use change in each setting?**

Experiments

1. RETROSPECTIVE ANALYSIS

Archaeological and geological investigations offer unique perspectives of long temporal and broad spatial scales of observation. By comparing modern results with those from the archaeological or geological record we can determine the significance of a human-induced change, such as incision of drainage systems, deforestation of riparian areas, or diversion of stream flow— all of which occurred in prehistoric times, yet resulted in what many scientists consider the pristine environment of the last century. **Q: What patterns of downcutting and filling of the basin were associated with development of irrigation in the valley?** Geological processes of downcutting and filling will be traced through time (Pewe 1987, Bull 1991, Pearthree 1991). **Q: What was the previous extent of the built environment and scope of agricultural systems?** (Masse 1991). The Hohokam experience demonstrates the potential for long term, sustained use of this desert basin (Fish and Fish 1992). Finally, **Q: How did these prehistoric changes, both human-caused and natural, affect paleoecosystems?** Paleoecological conditions of this region can be characterized for various periods in its past using samples collected from archaeological deposits, pack rat middens, and pollen cores (Fall et al. 1981).

2. MONITORING PAST AND PREDICTING FUTURE LAND-USE CHANGE

An early task of our project will be the clarification and detailed modeling of actual trajectories of land-use change in the form of recent historical reconstruction, current records and future transition probabilities (Fig. 16). The probabilities of particular land use changes are affected by numerous human factors. Rich sources of information on prior probabilities include public agency records of development proposals, building permits, well drilling permits, and changed planning policy. Field observation in selected parcels of the maintenance or abandonment of structures and landscaping, expansion of local infrastructure such as roads or sewers, or actual transformations as they begin to occur will supplement existing urban planning documents and predictions based on agency records. In this manner, we will monitor real-time changes and collect data that allow us **to predict, with reasonable probability, the direction of future changes, thereby permitting us to initiate biological (see cores areas A-E) and social monitoring before, during, and after the actual change and allowing for unprecedented experimental control**.

3. LAND USE CHANGE NEAR NEW TRANSPORTATION ROUTES

Of particular interest in terms of human-environmental interactions will be an examination of transportation networks and their impact on human population dynamics, including continuing decentralization, and ecological conditions. Metropolitan Phoenix is in the midst of what could best be called an "unplanned travel growth experiment." **Q**: **How will the construction of planned peripheral urban freeways over the next 10 years affect the character of the nearby land use? and Q: How will these changes affect local ecosystem dynamics?** Rapid population growth in metropolitan Phoenix is being exceeded by growth in the number of workers and in the number of work trips by single-occupant vehicles (Pisarsky 1987, 1996). These characteristics suggest increasing pressures to develop peripheral settings with resulting changes in ecological conditions. Remote sensing monitoring combined with GIS interpretation will allow monthly evaluation of these trends. Currently, several members of the LTER team are working on a nested arid-climate pollution-dispersion urban-airshed model with funding from EPA Region VI. The model and data we will collect will help to develop a better understanding of the relationship between air quality, meteorological conditions and various pollutant sources. Ecological core area studies will begin to provide answers to the second question posed above, but our analysis will provide important information to those teams on the siting of long-term study plots within the context of the patch dynamics approach.

4. DEVELOPMENT PATTERN

At local, landscape, and regional scales, peripheral residential development choices may have an impact on air pollution, land values, and related land uses. One pattern we see developing in peripheral neighborhoods is **increasing unit size** of new residential developments. This pattern leads us to ask, **Q: Does increasing unit size allow outer neighborhoods to incorporate local ecological priorities not possible in city center development, such as desert wash preservation and wildlife habitat protection? How does this affect regional air quality via its impact on travel patterns? In what ways does larger unit size affect ecosystem dynamics?** We will answer these questions by comparing neighborhood design and travel patterns in a series of neighborhoods along the gradient outward from the city center(s) that are also being monitored in the five ecology core groups. Data on the daily work travel patterns for residents of selected peripheral neighborhoods will be derived from annual Maricopa County employee surveys using procedures developed by Burns (1992, 1995).

G. MONITORING APPROACH FOR SOCIOECONOMIC AND ECOSYSTEM DATA

Traditional LTER monitoring provides information on long-term changes in ecosystem structure and dynamics that is purposefully as distant from human influences as possible. In contrast, CAP-LTER monitoring will integrate human decisions and activities, providing both a technical basis for urban ecological investigations and a solid foundation for improved future decision making. Our database will be an on-going resource to inform the actions and decisions of key agents of land use change — including public elected and appointed officials, public and private owners of land, and individuals.

Recognizing the complexity of human activities within an urban center and the limitations on financial resources of the LTER, we will incorporate extant databases and utilize synthetic approaches developed by our partners, to the extent they are relevant. The decennial U.S. census provides the most comprehensive source for monitoring a wide range of demographic, economic, and social trends. A special mid-decade (1995) census exists for our region that will allow our baseline information to be as current as possible. MAG has conducted an in-depth analysis of this information that will be extremely useful to us and save enormous costs to the project. They are using a series of models (DRAM/EMPAL) to incorporate location-specific data with region-wide trends in transportation, employment, social trends, economic measures, demography, and others (MAG 1996). We will work to coordinate our GIS approaches, remote sensing, patch definitions, and locations of experimental studies with the MAG systems in order to expand our data sources and to make our results more immediately accessible by regional planners and government officials.

Long-Term Research

We will use an approach that combines the latest in remote sensing technologies, patch specific ground truth monitoring, data enrichment experiments, and incorporation of extant survey data.

Remote sensing and on-the-ground experimental data will be overlayed with information on ecosystem conditions derived from ecological core studies and will also be integrated with regional planning data based on census and other information assembled by our partners: the Maricopa Association of Governments, Salt River Project, and Arizona State Lands Department. GIS analysis affords the opportunity to measure within one-, five-, or ten-mile radii the context for a given parcel of land and to assess the effect of that context on ecosystem dynamics.

Approach: In order to understand the observed land-use changes it is necessary to examine the drivers — both institutional and individual — behind human decision making (Sanderson 1994). Primary among those is the **economic environment**, comprised of production and consumption activities and their various interactions and feedback that provide values to alternative land uses (Fig. 17). The **political environment** of decision making is composed of local and regional institutions, each with distinct constituencies, taxing capabilities, and enforcement of regulatory environmental standards. And finally, the **cognitive environment** of human perception of potential rewards, risks, and quality-of-life values strongly influences decision making by community leaders and individuals.

Experiments

1. QUALITY-OF-LIFE DECISIONS

The Morrison Institute for Public Policy at ASU, one of our partners, is engaged in a valley-wide study that has devised a series of objective, regional **quality-of-life** indicators and protocols for use by community leaders to make decisions that affect land values, and ultimately decisions to change land use. Our own analysis will focus the next stage of this inquiry on regions we are monitoring ecologically in order to answer **Q: What are the relative values given various environmental variables? and What economic tradeoff will people make to improve ecosystem dynamics?** We will distribute questionnaires with an expanded environmental section to residents in geographical areas that are representative of our patch model.

2. ENVIRONMENTAL EQUITY

An important, yet often overlooked, aspect of how values are assigned to land is that of environmental equity. Siting of industrial and waste treatment facilities, highway corridors, parklands, and dense housing all affect the quality of life for local residents. There are questions of spatial equity--to what degree are environmental risks or environmental benefits, such as parkland, spatially concentrated. **Q: In sum, what are the tradeoffs among cost, risk, and equity objectives?**

At ASU, we have developed GIS models and multiobjective optimization models with numerical measures of both risk and equity (Wyman and Kuby 1996). These models have already been applied to hazardous waste transport and processing in the metropolitan Phoenix area and can be expanded to include pollutant-transport models and other data layers we are adding to our GIS-based analysis. We have also initiated an environmental equity study of South Phoenix. South Phoenix has large concentrations of low-income and minority residents where land use is dominated by heavy industry, agriculture, and the largest urban park in the country. We will supplement the ongoing study by locating some of our new biological monitoring activities in this area as well as conducting surveys of local residents to determine their views on environmentally related quality of life measures. This expanded study will allow us to examine the interface of extreme values for both biological and social variables in a context where government agencies and local groups are seeking radical changes.

H. SPECIAL OPPORTUNITIES FOR INTERACTION WITH K-12 EDUCATION

The process of science provides an intellectual framework for understanding the existing physical and social environment as well as preparing students to be knowledgeable and active adult citizens. The K-12 and outreach philosophy of the CAP-LTER is to provide systemic K-12 and public science educational opportunities by building upon existing linkages and programs in the metro Phoenix area.

These efforts span the geographic and socioeconomic boundaries of the region while supporting reform efforts that range from pre-service teacher training through individual student projects. The Phoenix area has already invested heavily in systemic reform and our programs will not be designed to create a new curriculum, but rather through partnerships to provide opportunities and services that will enhance efforts already underway (Fig. 18; see also "Results from Prior NSF Support". Our primary partner in this endeavor is the Phoenix Urban Systemic Initiative (USI), which includes eight elementary school districts and the Phoenix Union High School District, with 80% Latino students. The involvement of students' families and peers in informal settings serves to build upon the knowledge base established in the classroom. Our informal education partners (see Fig. 18) will present information on CAP-LTER activities.

Our plan is to have the Education Team work with the project's science education coordinator to develop modules based on the experiments being carried on by the project scientists. These modules would be aimed at core concepts and inquiry skills already being taught in the schools at each grade level. The role of the education specialist would be to work with our partner organizations to help create and "package" these modules and act as a matchmaker between core scientists and the schools and teachers that would use the modules. Activities might range from collecting and analyzing biological samples (see examples in ecological core areas), making social science observations, and monitoring changing demographic patterning**S** all in a real-time interactive framework. The most exciting aspect is that the teachers and students who collect their own data will be part of a much larger scientific investigation that is seeking to better understand the human impact on the structure and function of the ecosystem of which they are part. Water testing, insect identification, bird counts, air quality monitoring, transportation surveys, and even residential ecology modeling all could be done by students and integrated in the CAP-LTER database, thereby vastly expanding the coverage of our project. Team members will train teachers through workshops and academies and also make presentations in classes and have students visit field sites and laboratories. In the summer of 1997, ASU's Research Office will initiate a new magazine, *Chain Reaction,* that will be widely distributed to school teachers and students in this region and across the country. Successful LTER modules and scientist-student interaction will be regularly featured, providing a mechanism to disseminate some of our programming.

By providing a rich series of research participation opportunities to students and community members at various levels and in numerous venues, we hope to further the goals of the National Science Education Standards (NRC 1996). It will be the task of the Education Research Team, under the experienced guidance of Alfredo G. de los Santos, Jr., to assess the impact of our activities and how effectively we are reaching the diverse audiences in our community and to prepare an evaluation after the third and sixth year of the grant. It is our plan to have a report of our activities and most successful modules for distribution to other LTER's and USI's across the country.

RESEARCH TACTICS AND PRODUCTS

The proposed research plan will be implemented in stages throughout the six-year funding period. We recognize that much of the GIS-based modeling work, the nutrient budget approach, and the models of human feedbacks to land use adopted herein will hinge on rapid acquisition and entry of existing data from municipalities, agencies, and individual research programs. Therefore, a large portion of effort and resources in the first year will be devoted to data management activities. Further, a hierarchical patch-dynamic, GIS-based model for the entire Central Arizona-Phoenix (CAP) study area is our ultimate goal, but because the area is large and complex, we propose to develop a pilot model first. This smaller pilot model, to be completed by the end of year two, will be based on a subunit of the CAP study area (e.g., the city of Tempe) that includes agricultural and desert fringe. The purpose of the pilot model is 1) to assess the variance associated with GIS ecological data layers in order to design a statistically sound sampling program for the entire CAP study area, and 2) to anticipate and remedy problems associated with model development, enabling construction of the larger CAP model by the end of year five. We propose to bring the water chemistry database and material mass balance models into use by year two. Thereafter we will update import-export data annually. Finally, we will devote a substantial portion of years one and two to development of research protocols that are appropriate for the urban environment and can, in some cases, be accomplished by educational partners (school teachers and pupils), and that are consistent with methods in use at other LTER sites. Experiments and special monitoring projects that are done once per $\geq$ five years will be staggered through the final four years of the project.

We realize that the research we propose is extremely broad and we have intentionally chosen to emphasize foci that match the talent and experience already in place at ASU and in the Phoenix community (Table 2). A major effort during the first funding period will be directed toward filling gaps in expertise through faculty- and post-doctoral-level hiring made possible by a generous institutional match. We aspire to orchestrate a research effort that is genuinely collaborative by deliberately adding colleagues with strong interactive skills and predilections.