Urban Ecosystems, 7: 199–213, 2004

Approaches to the study of urban ecosystems: The case of Central Arizona—Phoenix

NANCY B. GRIMM nbgrimm@asu.edu
School of Life Sciences, Arizona State University, Tempe, AZ 85287, USA

CHARLES L. REDMAN
The Center for Environmental Studies, Arizona State University, Tempe, AZ 85287, USA

Abstract. CAP LTER focuses on an arid-land ecosystem profoundly influenced, even defined, by the presence and activities of humans and is one of only two LTER sites that specifically studies the ecology of an urban system. In this large-scale project, biological, physical, and social scientists are working together to study the structure and function of the urban ecosystem, to assess the effects of urban development on surrounding agricultural and desert lands, and to study the relationship and feedbacks between human decisions and ecological processes.

Our interdisciplinary investigations into the relationship between land-use decisions and ecological consequences in the rapidly growing urban environment of Phoenix are of broad relevance for the study of social ecological systems and cites in particular. Refinements in our conceptual model of social ecological systems focuses our attention on recognizing the scales and periodicities of ecological and human phenomena, understanding the means and impacts of human control of variability in space and time, and finally an evaluation of the resilience of various aspects of socio-ecological systems especially their vulnerabilities and their potential for adaptive learning.

Keywords: long-term studies, data mining, nutrient cycling, diversity, ecological footprint, urban climate, socioecosystem, resilience, urban landscape, urbanization

Introduction

Ecological theory developed over the past century with limited reference to the massive and pervasive alterations of natural ecosystems made by *Homo sapiens.* In the past decade, however, a renewed interest in human-dominated ecosystems in the USA coupled with the critical need to find solutions to environmental problems where they are most severe, led the US National Science Foundation to augment the funding of two of its extant Long-Term Ecological Research (LTER) sites to include social science research, and to create two new sites devoted to the study of urban ecological systems. Since then, urban ecology has flourished in the USA, perhaps owing in part to that investment. This article provides a summary and case history for the Central Arizona–Phoenix (CAP) region, based on the first six years of study under the LTER program. We first will highlight research from the CAP LTER that illustrates work at several scales involving data mining, monitoring, experiments, and synthesis activities, then we will describe new directions in which our experiences have led our team, culminating in exposition of the conceptual themes that emerge from our preliminary attempts at synthesis of research to date on this complex, human-dominated ecosystem.

Research on the CAP LTER has been directed at answering an overarching research question that still guides us today:

> How do the patterns and processes of urbanization alter the ecological conditions of the city and its surrounding environment, and how do ecological consequences of these developments feed back to the social system to generate future changes?

This question focuses our thinking on the interaction between the ecological and human domains in the context of an extremely fast-growing metropolis. Population growth and land consumption in the Phoenix metropolitan area are consistently among the highest in the USA; changes in ecological conditions accompany extensive and continuous modification of the land surface, the micro-climatic and biogeochemical environment, and biodiversity patterns, and a rate of land conversion (largely from desert to residential or farmland to residential land uses) exceeding an acre per hour. Although change is thus a strong element of our approach, we are also concerned with relatively stable patterns and aspects of the system that do not change. Finally, we have long recognized that virtually every change is accompanied by some sort of response, both social and ecological, which yields a complex set of feedbacks that drive further change (Grimm *et al.*, 2000). In the past six years, dozens of researchers have devoted themselves to illuminating these issues, yet it is fair to say that we are only a fraction of the way to our goal. We have a good start at identifying and monitoring the ecological consequences of urbanization, but are only beginning to understand how those consequences feed back to the social system and generate future changes.

Our research question must also be asked at a variety of scales, with the focal scale being the Phoenix metropolitan area (ca. 4000 km^2), but with interesting questions asked both at lower and higher levels of a time-space scale hierarchy (figure 1). In some cases, the

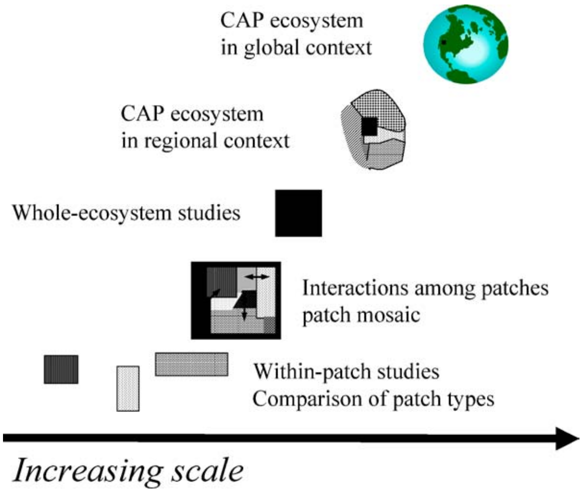

Figure 1. A framework for considering scales of investigation in urban ecological studies.

feedbacks may occur at scales different than the primary scale addressed by the research. In describing our research findings, we refer to the following scales: (1) *Individual land-use patch types*, such as land-use or land-cover patches, or even units within those (i.e., households/lots, parks, etc.). At this scale, our research has primarily characterized ecological and social patterns. (2) *Mosaics of patches.* Here the focus is on the relationships AMONG these individual patches. (3) *Phoenix metro.* Several efforts have been made to describe ecological condition without reference to the heterogeneity within the urban ecosystem, but by treating the system as a "black box". (4) *The CAP ecosystem in a regional context.* The ecosystem interacts with its surroundings in ways that can be quantified. For example, the city can be seen as a source or sink for elements. (5) *Urbanizing central Arizona in a global context.* Can lessons learned in CAP be transferred to other dry land regions internationally? Is the global importance of urban areas predictable from their per-area impact, or does a higher order "global landscape of cities" come into play?

Research findings from the CAP LTER

Study site description

The Phoenix metropolis, comprising >20 municipalities, is situated in a broad, flat, alluvial basin dotted with eroded volcanic outcrops at the confluence of the Salt and Gila Rivers. The basin once supported a vast expanse of lowland Sonoran desert and riparian vegetation, consisting of a saguaro-paloverde desertscrub association in the uplands and pediments, creosotebush and salt bush in the lowlands, and cottonwood-willow gallery forest along the river margins. The CAP study area (6400 km^2) includes the rapidly expanding Phoenix metro area, including four of the five largest cities in Arizona, along with surrounding agricultural and desert land. Human population in the region has increased by 47% since 1990 to >3.5 million people (US Census Bureau, 2000). Growth and expansion of Phoenix has occurred mostly in the second half of the 20th century. While earlier land conversion was predominantly from farmland to residential areas, the newest housing has been established mostly on desert land, leading to spatial variation in extant vegetation and structure of residential landscapes.

Urban expansion in this arid region (annual rainfall = 180 mm) has been supported by water-supply projects involving the construction of local reservoirs and the Central Arizona Project canal (Kupel, 2003), and was spurred by the development of air conditioning and the "suburban lifestyle", including widespread use of motor vehicles, after WWII. Owing largely to irrigation for agriculture and urban landscapes, managed landscapes with their exotic plants contrast sharply with the undeveloped desert with its native vegetation (Hope *et al.*, 2003).

Overview of methods

Each of the CAP LTER research strategies can be conceived of as belonging to one of "four legs of a table" of LTER research (Carpenter, 1998): long-term research (monitoring), experiments, comparative ecology, and models or theory. In this paper, we will consider

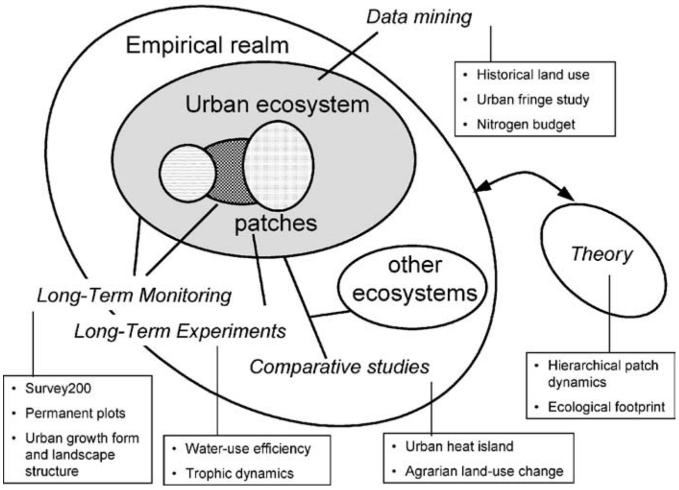

Figure 2. Diagram showing relationships among the different approaches to long-term study of urban ecosystems employed by CAP LTER. Small, boxed text lists specific CAP LTER projects discussed in the text.

comparative studies and theory/modeling as complementary means of achieving synthesis, lumping them under this heading. We add to these strategies our own view, so apt for the urban environment, that data mining can provide an essential means of testing hypotheses and understanding ecological change. Because the CAP LTER is a new project without local precedents, there are few previous ecological projects in the urban portion of our study area. However, because it is an urban area, there have been numerous agencies collecting data in great detail, albeit not under an ecological paradigm. This wealth of background data is tremendously important and much of our early work has been mining these sources of information and putting them into a format and conceptual framework that make them amenable to our own analyses. In the narrative that follows, we present results from the CAP LTER organized according to these research strategies, using examples from a range of scales and subject matter (figure 2).

Research findings

Data mining activity provided the basis for our Historic Land Use project. Drawing on aerial photography, satellite imagery, municipal and county records from 1912, 1934, 1955, 1975, and 1995, we developed maps of broad land-use categories that provided a context within which many of our subsequent studies have proceeded. Another important background pattern, a mass balance of nitrogen within the urban ecosystem has been assembled by mining county, state, and other records for data on sources and sinks of nitrogen.

Our analysis of historic land use revealed that one aspect of the pattern of development, the predominant transition, has changed over the past century. Phoenix and neighboring municipalities began as farming communities after the Civil War, and the amount of land in agricultural use increased from 1912–1934, was constant (although moving outward from the urban cores) from 1934–1975, and declined from 1975–1995. Most of the newest developments (since 1980) have occurred on former desert lands, whereas many of the earlier urban residential areas developed on former farmland (Knowles-Yánez *et al.*, 1999; Gammage, 1999). The history of a given parcel of land has important consequences for ecological variables; for example, whether a site was farmed in the past century is a strong determinant of present-day soil nitrate concentration (Hope *et al.*, in review). Nitrate is the predominant form of N in soils of the region, and N is an important plant nutrient which, given sufficient water, may limit primary productivity. This backbone of mined data has given us the opportunity to develop expectations of the ecological conditions in similar modern land-use patches with different histories.

CAP LTER researchers also mined county records to trace in detail the appearance of residential neighborhoods on former desert or agricultural lands. This resulted in a preliminary understanding of one of the key processes of urbanization in our region: the establishment, and outward migration, of an urban fringe. Gober and Burns (2002) describe the urban fringe as a "wave of advance" that migrates into the outlying desert and agricultural lands, preceded by predictable changes in types of businesses and microclimate and progresses through stages of development. Particularly in the past 20 years, this fringe takes the form of a checkerboard because development often hops the established urban edge in a sort of "leap-frog" pattern. At a more local scale, this morphology of the urban fringe can be modeled as a colonization process (Fagan *et al.*, 2001). Such basic models can be used as null hypotheses for the pattern of development that, in the current phase of research, are being refined to incorporate the effects of individual or group decisions by human inhabitants, the composition of the population along the fringe, and the effects of external, triggering events.

One of the most fruitful early data-mining exercises was the construction of a whole-ecosystem nitrogen (N) budget for the CAP region. Data were gathered entirely from existing records of federal, state, county, and municipal agencies to quantify all of the inputs, storage terms, and outputs of N (Baker *et al.*, 2001). Three features of the urban N budget are noteworthy (figure 3): (1) inputs of N on an areal basis exceed inputs to surrounding native desert ecosystems by a factor of 7–8; (2) over 90% of these inputs are human-mediated (although not all of the human-mediated inputs are intentional); and (3) inputs exceed outputs by an amount of N that is greater than inputs to most ecosystems. Many aspects of the N budget suggest research questions to be answered in the years to come; for example, where is the excess N stored or removed within the ecosystem? The answer to this question will be found by understanding the workings of individual patches and the interactions of mosaics of those patches (e.g., through hydrologic connectivity). Another intriguing question is, what is the fate of the NO_x (N oxides from atmospheric N_2 that are by-product of fossil-fuel combustion) produced as a consequence of the automobile-driven lifestyle of Phoenicians? Is it deposited to the land surface, where it acts as a fertilizer, or, as an ozone precursor, does it exacerbate already severe air pollution problems? If NO_x is deposited, is it first transported outside the city, representing an impact at the regional scale as was found for ozone deposition in the rural surroundings of New York City (Gregg *et al.*, 2003)?

Long-term research, or continuous monitoring, is a fundamental aspect of the LTER approach and has taken two forms at the CAP LTER; the 200-point survey and a series of

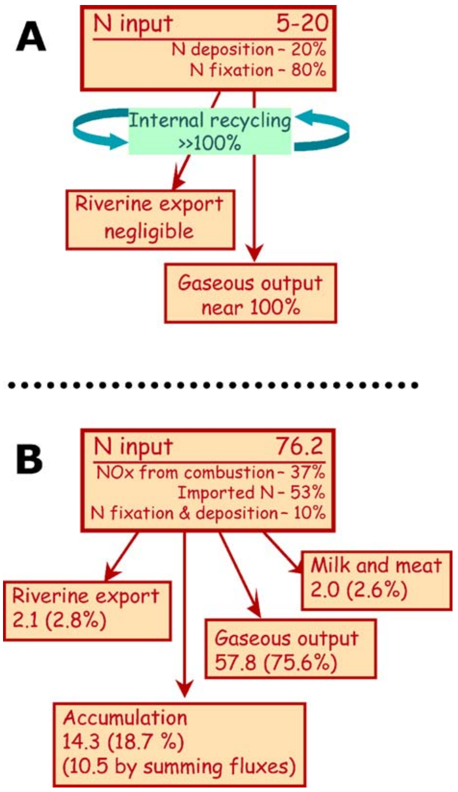

Figure 3. Comparison of nitrogen budgets for (A) a desert ecosystem and (B) an urban ecosystem (CAP). Values for the desert ecosystem are approximations based on literature values (West and Skujins, 1978; Cleveland *et al.*, 1999); values for the urban ecosystem are from Baker *et al.* (2001).

permanent monitoring plots. Because CAP is a new site, our "long-term" research extends just six years, except in situations where data mining allows us to extend the sequence back in time.

Given the broad expanse of the CAP ecosystem (6400 km^2) and its spatial heterogeneity (Luck and Wu, 2002), we used a dual-density, tessellation-stratified random sampling design to characterize it (figure 4). This design, which established 204 sampling points, each randomly selected within a grid cell of 5 × 5 km (with outlying points established in every third grid cell, hence the dual density), allows us to measure several environmental variables (Table 1) in a 900-m^2 plot, with measurements repeated in springtime every five years. In addition, because the entire dataset is geo-referenced, we can superimpose social data (from the census, our Historical Land Use project, and other available information) on this extensive "snapshot" of the CAP ecosystem. The survey permits examination of slowly changing variables over a broad expanse in space at a low sampling frequency, yielding a coarse-grained characterization that is unable to resolve dynamics on shorter time frames. Moreover, although it is possible to separately characterize different land-cover and

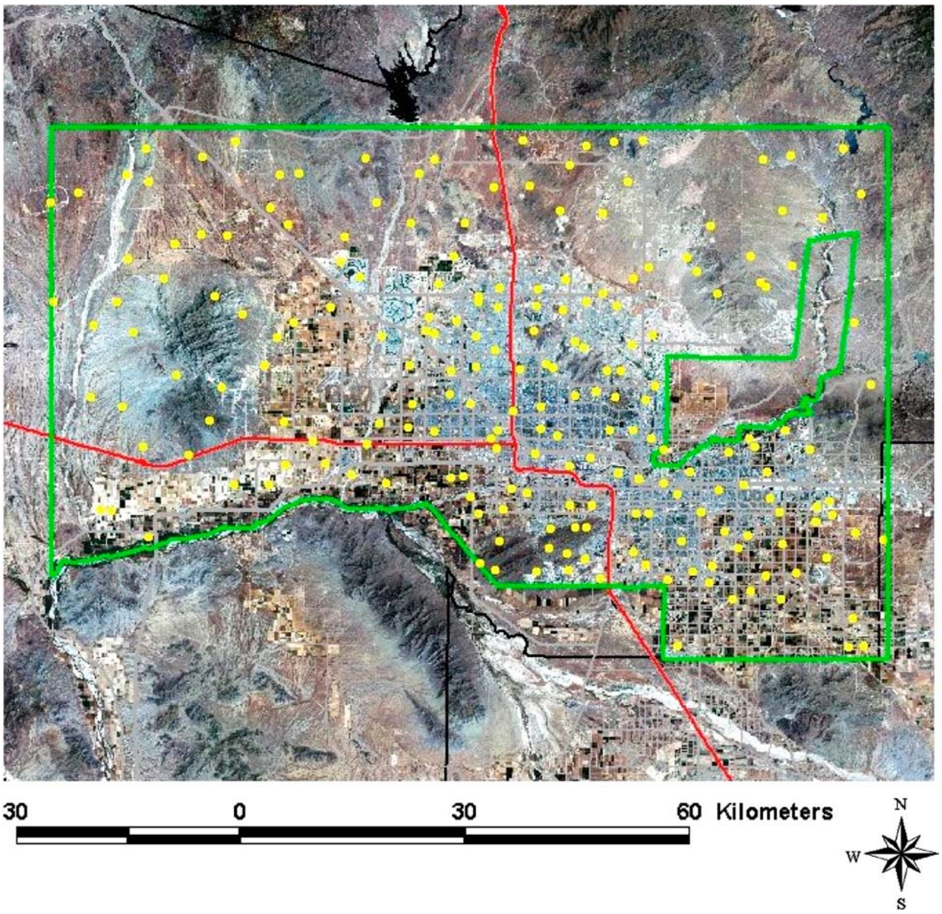

Figure 4. Satellite image of the central Arizona-Phoenix ecosystem, showing the study area boundary (green lines) major freeways (red lines), and 204 sampling points (yellow dots). Also evident in the image are the area's mostly dry rivers, a reservoir (black, top center), and the undeveloped desert (brown shades) surrounding the urban area (blue-gray shades) with its fringing agricultural lands (black, brown and white areas with a checkered appearance near center of image and at lower right).

land-use types, this approach is also well suited to gaining an understanding of the whole from viewing the mosaic of patches (figure 1). We can ask, for example, whether desert plots embedded in urbanized surroundings differ from those on the periphery of the study area.

Data analysis from our first (spring, 2000) application of the 200-point survey design reveals a difference in potential driving and controlling variables between the urban plots and the desert plots. The generic richness of woody vegetation, a measure of plant diversity, is positively correlated with median family income for the urban plots (Hope *et al.*, 2003). Although this intriguing pattern is a correlation and cannot imply causation, the finding leads us to new research questions in an effort to understand the mechanisms by which humans control their environment. Another finding from our survey is that while soil nitrate

Table 1. Variables measured in the 200-point survey of the Central Arizona-Phoenix ecosystem. All samples and measurements are geo-referenced

Photos from plot center
Local weather (air temperature, wind speed, . . .)
Built structure
Ground cover: impervious surface, vegetation, soil
Soil physical properties
Soil biota: mycorrhizae, microbial populations (??)
Soil chemistry: organic matter, total C and N, organic C, nitrate, ammonium
Soil processes*: net nitrification, net mineralization, denitrification potential
Vegetation: vegetation cover
Vegetation: plant identification (usually to genus or species)
Vegetation: canopy cover and biovolume
Arthropods: vegetation-associated arthropods
Arthropods*: ground-dwelling
Birds*: point counts
Humans: activity surveys

*These measurements done at a subset of the 204 points.

concentration is spatially autocorrelated in the desert plots, no such spatial relationship exists for the urban plots (Hope *et al.*, in review). We interpret this difference to reflect the extent to which human manipulation and management has introduced heterogeneity in soil chemical properties at a scale much lower than that found in deserts.

Mechanisms that explain the patterns we find at this broad extent and coarse grain will likely be identified by more intensive examination of permanent plots. Our permanent plots, established to date in a few residential, urban commons, and desert sites, are used for investigations of variables that change more rapidly (e.g., seasonally) and potentially show the direct and indirect effects of human action. Permanent plot monitoring has focused on plants, primary productivity, water use efficiency, and arthropod communities. Studies of water use in the yardscape designs typical of Phoenix metropolitan residential areas show that monthly water volumes applied to xeric designs remain relatively constant throughout the year, whereas irrigation practices for mesic vegetation tend to follow rates of monthly evapotranspiration with higher summer than winter application rates (Martin and Stabler, 2002). Thus, overall water use does not differ significantly between the two types of yard design, indicating that water conservation lies to a greater extent in the habits of residents than in their choices of plants. These findings illustrate the close interaction of ecological (water use efficiency) and social (irrigation practices) variables at the scale of individual homeowner lots.

Experimentation has been used in CAP LTER to further explore the ecological and social processes that underlie the patterns we observe in the urban ecosystem. In the case of water use, Martin and his colleagues (C.A. Martin, Arizona State University, personal communication) directly manipulated replicated experimental yardscapes with 3 vegetation-pruning treatments and two watering regimes. Oleander and Texas sage grown at low irrigation rates had lower WUE left non-pruned (3.0 and 0.9, respectively) relative to those sheared every six weeks (1.0 and 0.6, respectively). These results show the importance of drip irrigation and pruning practices in controlling primary production and WUE of landscape shrubs in the landscape in arid climates (Stabler and Martin, 2004). The researchers hope these experiments will help uncover the effects of common management practices by homeowners on plant growth, carbon sequestration, and soil processes. Another direct, manipulative experiment is a crossed predator exclusion-watering experiment to determine the impact of predation and plant growth rate on herbivore populations (S.H. Faeth, Arizona State University, personal communication).

Synthesis of our many lines of study to enhance understanding of urban ecosystem function in general, and to focus in particular on the feedbacks outlined in the original research question, is a central goal of the CAP LTER. Syntheses are being undertaken from a number of perspectives and at a number of scales (and across scales). Modeling and comparative studies are key strategies being used to accomplish our integrative approaches.

The hierarchical, patch-dynamics model developed for CAP (Wu and David, 2002) provides a framework for integrating different kinds of models (e.g., population dynamics, ecosystem processes, land-use and land-cover change) across different spatial scales (from local land-cover type to the regional landscape). Such an approach is necessary because both ecological and socioeconomic patterns and processes in any urban landscape occur on a variety of scales, and hierarchical linkages among scales often significantly affect the dynamics and stability of urban development. The patch-dynamics approach focuses not only on the spatial pattern of heterogeneity at a given time, but also on how and why the pattern changes over time, and how that pattern affects ecological and social processes. Because cities are both expanding and changing within their boundaries, the dynamic aspect of this approach is crucial to a complete understanding of urban ecological systems.

Another synthesis activity, dealing with the impact of the consumption and production activities in an urban area on surrounding or even distant ecosystems, borrows from ecological footprint concept (Rees and Wackernagle, 1994; Rees, 1996). Using a spatially explicit algorithm, Phoenix-metro and the 19 other largest US cities were compared in terms of their footprints of water use, food supply, and assimilation of carbon dioxide waste (Luck *et al.*, 2001). This analysis considers urban ecosystems in their regional contexts (e.g., figure 1), and reveals that natural heterogeneity in resource distribution (at the continental scale) strongly determines the size of cities' ecological footprints for water, food, and CO_2 assimilation. However, technological innovations increasingly break down regional differences in ecological constraint—for example, low food production rates in Arizona are of little consequence in a modern era where food is so often imported from elsewhere. On the other hand, the water footprint may be truly regional, and spatial limitations in the availability of water may offer a potential to restrain the rampant growth of central Arizona, if indeed the era of major water projects has ended (Gammage, 1999; Kupel, 2003). The assimilation of CO_2, in contrast, is an ecosystem service that is probably best considered in a global context; indeed, the CO_2 assimilation footprint for the 20 largest US cities exceeds the land area of continental USA (Luck *et al.*, 2001). This very large footprint is precisely the reason that we see continuous increase in the global concentration of atmospheric CO_2.

The urban heat island is one of the best-documented phenomena associated with urbanization worldwide (Oke, 1982). In Phoenix, clear evidence for an urbanization-driven

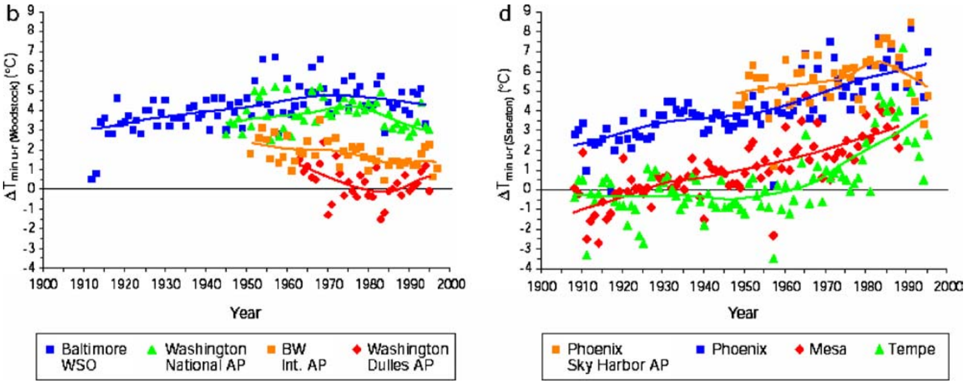

Figure 5. Temporal trends in the 20th century in minimum air temperature for four urban sites in the Baltimore Ecosystem Study (left) and Central Arizona-Phoenix (right) LTER sites. From Brazel *et al.*, 2000 (used with permission).

climate change over the 20th century was detected and compared to changes over the same time period in Baltimore, our sister LTER city (Brazel *et al.*, 2000). The signal in Phoenix is much more dramatic than other world city sites at 10 times the global change trend, owing to the stable air and clear days of this desert city. Minimum temperatures in the Phoenix summertime have increased by 10°C over the last 50 years (figure 5); whereas in Baltimore, these temperatures peaked by the 1950s in concert with maximum city-core growth. Daytime temperatures in Phoenix in many places are actually cooler than surrounding desert lands and show no temporal trend in the 20th century. In Baltimore, daytime temperatures have significantly increased in the city, since the surrounding rural lands are forested and have remained cool. The months of early summer show maximum heat islands in Phoenix, whereas in mid-late summer, these features are most predominant in Baltimore. A group of CAP LTER researchers have recently considered the secondary feedbacks of the urban climate changes on several ecosystem processes (Baker *et al.*, 2002).

A view to the future: Lessons learned and new approaches for CAP

With the insights gained from six years of research on the urban ecosystem, we are now embarking on the second phase of our project. Our early focus was on establishing the "four legs of the table" for urban LTER research dealing with the traditional core areas of inquiry (figure 2); however, we were soon faced with the realization that simply starting along a research path that had been tread before was unlikely to yield new insight and was particularly ineffective at getting at the feedback that is central to our core question. We experimented with ways to work together across disciplines and to devise effective research strategies in this new study domain. Although we have not yet solved the problems inherent in interdisciplinary integration, we have worked with others to more fully develop the range of social science core topics (Redman *et al.*, 2004) that should be included in long-term investigations of coupled social-ecological systems, and we have paid close attention to the training of the next generation of interdisciplinary scientists through an Integrative

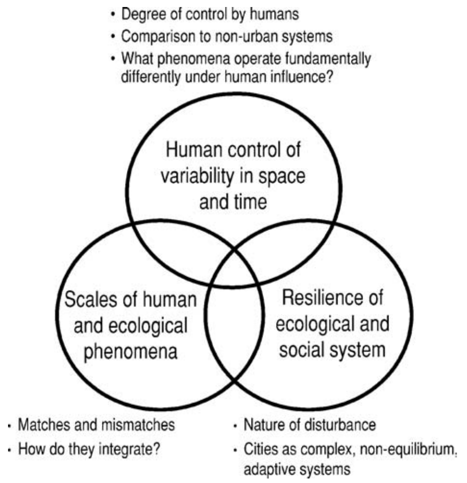

Figure 6. Conceptual themes to be emphasized in Phase II of the Central Arizona-Phoenix LTER program. These themes will link field projects to the central research question involving the feedbacks among patterns of urbanization, ecological consequences, and human responses. Questions outside the Venn diagram illustrate several new areas of focus for this urban ecosystem study.

Graduate Education and Research Training (IGERT) program in urban ecology. Interaction with physical/earth scientists, with environmental engineers, and with social and economic scientists is essential for expanding and fully developing the field of urban ecology. Further, it is only armed with the tools of the many impinging disciplines that we will contribute to the enhancement of broader ecological (and social science) theory.

On a practical level, we have learned that interdisciplinary work requires certain practices that might seem rigid or forced, but without which natural tendencies to group with one's "own kind" (i.e., ecologist, anthropologist, geophysicist, civil engineer) would prevail. Questions asked should be broad enough to be of interest to social scientists, earth scientists, and life scientists alike. No "dogma" from any single discipline can be imposed on the others. Experiments and monitoring must be co-located to the greatest extent possible. Projects must be interdisciplinary from the outset, as it is difficult if not impossible to attract other perspectives if the questions to ask and methods to use have already been decided.

On a more theoretical level, we identify three general conceptual themes that will cast our empirical research into a generalizeable context (figure 6). These interpretive themes will link field projects to the CAP LTER's initial research question involving the feedbacks among patterns of urbanization, ecological consequences, and human responses.

Scales and periodicities of ecological and human phenomena

Biological and physical processes occur at multiple scales that are intrinsic to the organism or to the geophysical context. Humans operate at varying scales as well, due to their physiology, social organization, and culture. The scales and periodicities of ecological and human phenomena sometimes match well and integrate easily, and sometimes they are mismatched. These mismatches may introduce risk of breakdown into the system, or may in fact offer opportunities for growth or change.

Human impact and control of variability in space and time

In addition to their direct control of ecological and social phenomena in the urban milieu, humans also often act to control the *variability* of these phenomena—either to keep this variability within limits acceptable to them or to gain advantage from the management of variability. In what ways and to what extent does human control transform the operation of the socio-ecological system? For example, replacing dead plants, adding fertilizer, and irrigation all buffer the plant community against climatic pressure, creating a socio-ecological system that would not survive without human intervention. If the matches and mismatches between the ecological and human systems are a key force in driving the system, then in what ways do human efforts at controlling the variability act to create or mitigate crises and/or opportunities? We must identify phenomena that operate fundamentally differently under human influence. In our study area, all of the surface flow of the Salt River is removed from its channel upstream from the city and redistributed to residential and commercial uses far from the channel. Hence, the riverbanks now support gravel-mining operations instead of riparian vegetation. The water, now redistributed throughout the metropolis, supports vegetation spread over a much larger area. Patterns of groundwater also change radically, with depth to groundwater increasing near the river channel and decreasing in irrigated areas. If new patterns or processes unique to urban ecosystems can be identified, how and why do they arise?

Resilience of socio-ecological systems

Cities have been said to be complex, non-equilibrium, and adaptive systems (e.g., Wu and David, 2002). In what ways do urban ecosystems exhibit the properties of complex adaptive systems? Are these human-dominated ecosystems resilient? What are the threats to them, and what are their vulnerabilities? What qualities do we want to maintain, what aspects are we willing or anxious to eliminate? Do these systems sacrifice resilience at one scale to preserve it at another? Can we help build institutions that will protect urban socio-ecological systems from dramatic, undesirable changes at all scales and also promote qualities and functions deemed to be positive?

Integrative research

Finally, we have rearranged, merged, and created new *integrative project areas* that are, from the outset, as purposefully interdisciplinary as we can make them. Along with the use of the three conceptual themes (figure 6) to link our field projects to more general issues, we view these integrative project areas as having interpretive value that can help refine goals for individual projects, thereby enriching their results. We describe three of the six integrative project areas here; the remaining areas are (1) biogeochemical linkages of air, land, water, and groundwater; (2) nature and interactions between ecosystem health and human health; and (3) local climate change and socio-ecosystem response.

Land transformations

Fundamental to unraveling urban ecosystem dynamics is an understanding of past, current, and future land-cover and land-use transformations. To the extent that humans have a role in these changes, perception of the current patterns and of the implications of alternate choices is crucial to action taken. These actions result from human decision-making that occurs in the context of social institutions and is influenced by factors ranging from economics and traditions to expected ecological benefit. It is essential to recognize that the range of alternate changes to land cover and land use are constrained and sometimes guided by ecological and human legacies that set the stage and often limit the choices. Thus, current soil properties may derive more from historic than from present land use, as is the case with soil nitrate concentration in urban residential sites being higher if the site was ever farmed. Other legacies may be centuries old: the manipulation of floodwater and diversion of river water practiced by the pre-historic Hohokam civilization (800–1400 AD) still can be seen in modern landforms; to what extent the legacies have significant ecological consequences is still to be measured.

Human management and control of biodiversity

Among topics of great current interest in ecology is the loss of biodiversity worldwide. It is widely assumed that cities have reduced species diversity, but a thoughtful consideration of this question indicates that reduction in diversity is not always the case (Kinzig and Grove, 2001). In this project area, we ask: what is the impact of human activities on biodiversity in urban areas? The human presence and their built environment may alter biodiversity by fragmenting habitat, changing available food and water, and introducing pesticides or competitors into the environment. Humans often degrade conditions for native species through these actions, but they also enhance conditions for both native and introduced species by enhancing water availability, providing new sources of food, and adding nutrients. Members of our team have argued that human impacts on biodiversity can be divided into those that are intentional, such as removal of noxious species or use of bird feeders, those that are indirect, such as landscaping preferences, and those that are incidental, such as zoning decisions or locating industrial centers (Kinzig, in preparation). Sometimes the human drivers are implicit as in the effects of socio-cultural differences between individuals or groups or even entire nations or cultures. At other times human intervention is more explicit and comes from top-down administrative decisions or is the accumulation of a series of bottom-up choices of individuals. We discussed earlier how plant generic diversity in CAP was found to correlate with wealth (Hope *et al.*, 2003). While one mechanism that could produce this pattern is that families with greater disposable income will spend more on plants (an intentional effect, at the level of individual homes), another is that wealthier families live on *bajadas* (slopes from volcanic outcrops), the soils of which are better drained and support higher diversity (an incidental effect), or that wealthy families live in neighborhoods with a greater number of covenants, codes, and restrictions (Martin *et al.*, 2003) that ‘enforce’ higher plant diversity—an intentional effect, but at a higher level of social organization.

Ecological, economic, social, and political aspects of urban water systems
Given that central Arizona is among the most arid environments in North America and that Phoenix historic (and prehistoric) growth was initiated by highly successful farming communities, the *control of water* is at the core of the operation of the urban ecosystem. Factors that govern water availability and patterns of use are at the intersection of climate, geography, economy, energy, aesthetics, and political power (Kupel, 2003; Gammage, 1999). Each of these factors has its own drivers and operates at various scales of space and time. During the past century people in central Arizona have chosen to re-engineer 100% of the surface water flow through the Salt and Gila river valleys, extract groundwater, and import water from the Colorado River drainage. Issues of sufficient water being available for farming, municipal and industrial consumption, riparian vegetation, residential landscaping, and groundwater replenishment grow increasingly contentious and are fundamental to economic and political issues. But we do not know the extent to which an urban ecosystem in the desert is rendered vulnerable when its water is so contentiously allocated and reallocated. How resilient are various components of the social system to prolonged drought? What are the hidden consequences of 66 years of no baseflow, for river function and for ecosystem services derived from a "healthy" river ecosystem? What will be the impact and resilience to the inevitable 500-year flood?

Our recent consideration of these and other integrative questions, i.e., questions that derive from a conscious inclusion of social and ecological variables in our studies, have brought many of us to ask a more fundamental question about our science. To what extent and in what ways do patterns and processes in human-dominated systems require qualitative *changes to ecological theory* as it has been traditionally portrayed? Up to this point most ecologists working in cities have relied on traditional ecological theory by viewing humans as disturbing forces and cities as extreme (and undesirable) environments. Assigning to human variables the residual variance from traditional analyses appears to work, up to a point, just as the Ptolomeic explanation of the solar system could be elaborated to fit empirical observations. However, at some point it is more effective to reconceptualize the theory to better explain the patterns. We suggest that we try this strategy by considering the integration of new elements into ecological theory. Certainly not all ecological theory must be refined, nor will all changes be radical, but we do believe that given the pervasive presence and impact of humans on all global environments, not just urban ecosystems, our minds must be open to change. Urban ecosystems, because of the clearly dominant influence of people, institutions, and the built environment offer the best laboratory for examining possible refinements.

References

Baker, Baker, L.A., Hope, D., Xu, Y., Edmonds, J. and Lauver, L. (2001) Nitrogen balance for the central Arizona-Phoenix (CAP) ecosystem. *Ecosystems* **4**, 582–602.

Baker, L.A., Brazel, T., Selovar, N., Martin, C.A., Steiner, F., McIntyre, N.E., Nelson, A. and Musacchio, L. (2003) Local warming: Feedbacks from the urban heat island. *Urban Ecosystems* **6**, 183–203.

Brazel, A., Selover, N., Vose, R. and Heisler, G. (2000) The tale of two climates—Baltimore and Phoenix urban LTER sites. *Clim. Res.* **15**, 123–135.

Carpenter, S.R. (1998) The need for large-scale experiments to assess and predict the response of ecosystems to perturbation. In *Successes, Limitations, and Frontiers in Ecosystem Science* (M.L. Pace and P.M. Groffman eds.), pp. 287–312. Springer-Verlag, New York.

Cleveland, C.C., Townsend, A.R., Schimel, D.S., Fisher, H., Howarth, R.W., Hedin, L.O., Perakis, S.S., Latty, E.F., VonFischer, J.C., Elseroad, A. and Wasson, M.F. (1999) Global patterns of terrestrial biological nitrogen (N_2) fixation in natural ecosystems. *Global Biogeochem. Cycles* **13**, 623–645.

Fagan, W.F., Meir, E., Carroll, S.S. and Wu, J.G. (2001) The ecology of urban landscapes: Modeling housing starts as a density-dependent colonization process. *Landsc. Ecol.* **16**, 33–39.

Gammage, G., Jr. (1999) *Phoenix in Perspective: Reflection on Developing the Desert.* Herberger Center for Design Excellence, College of Architecture and Environmental Design, Arizona State University, Tempe.

Gober, P. and Burns, E.K. (2002) The size and shape of Phoenix's urban fringe. *J. Plan. Educ. Res.* **21**, 379–390.

Gregg, J.W., Jones, C.G. and Dawson, T.E. (2003) Urbanization effects on tree growth in the vicinity of New York City. *Nature* **424**, 183–187.

Grimm, N.B., Grove, J.M., Pickett, S.T.A. and Redman, C.L. (2000) Integrated approaches to long-term studies of urban ecological systems. *Bioscience* **50**, 571–584.

Hope, D., Gries, C., Zhu, W., Fagan, W.F., Redman, C.L., Grimm, N.B., Nelson, A., Martin, C. and Kinzig, A. (2003) Socio-economics drive urban plant diversity. *PNAS* **100**, 8788–8792.

Hope, D., Zhu, W., Gries, C., Oleson, J., Kaye, J., Grimm, N.B. and Baker, B. (In review) Spatial variation in soil inorganic nitrogen across an arid urban ecosystem. *Urban Ecosystems.*

Kinzig, A.P. and Grove, J. (2001) Urban-suburban ecology. *Encyclopedia of Biodiversity* **5**, 733–745.

Kinzig, A.P., Warren, P., Hope, D., Katti, M. and Martin, C. (In preparation for Conservation Ecology) Understanding patterns of urban biodiversity. *Conservation Ecology*.

Knowles-Yanez, K., Moritz, C., Fry, J., Redman, C.L., Bucchin, M. and McCartney, P.H. (1999) Historic land use: Phase 1 report on generalized land use Center for Environmental Studies, Arizona State University, Tempe, p. 21.

Kupel, D.E. (2003) *Fuel for Growth: Water and Arizona's Urban Environment.* The University of Arizona Press, Tucson.

Luck, M.A., Jenerette, G.D., Wu, J.G. and Grimm, N.B. (2001) The urban funnel model and the spatially heterogeneous ecological footprint. *Ecosystems* **4**, 782–796.

Luck, M. and Wu, J.G. (2002) A gradient analysis of urban landscape pattern: A case study from the Phoenix metropolitan region, Arizona, USA. *Landsc. Ecol.* **17**, 327–339.

Martin, C.A. and Stabler, L.B. (2002) Plant gas exchange and water status in urban desert landscapes. *J. Arid. Environ.* **51**, 235–254.

Martin, C.A., Peterson, K.A. and Stabler, L.B. (2003) Residential landscaping in Phoenix, Arizona: Practices, preferences and covenants codes and restrictions (CC&Rs). *Journal of Arboriculture* **29**, 9–17.

Oke, T.R. (1982) The Energetic Basis of the Urban Heat-Island. *Q.J.R. Meteorol. Soc.* **108**, 1–24.

Redman, C.L. (1999) Human dimensions of ecosystem studies. *Ecosystems* **2**, 269–298.

Redman, C.L., Grove, J.M. and Kuby, L.H. (2004) Integrating social science into the Long-Term Ecological Research (LTER) Network: Social dimensions of ecological change and ecological dimensions of social change. *Ecosystems*. Online First: http://0-www.springerlink.com.library.lib.asu.edu:80/link.asp?id=xre6r5q9f0bnf50p

Rees, W.E. and Wackernagle, M. (1994) Ecological footprints and appropriate carrying capacity: Measuring the natural capital requirements of the human economy. In *Investing in Natural Capital: The Ecological Economics Approach to Sustainability* (A.M. Jansson, M. Hammer, C. Folke and R. Costanza, eds.) pp. 362–390. Island Press, Washington DC.

Rees, L.W. (1996) *Our Ecology Footprint: Reducing Human Impact on Earth.* New Society Publication, Philadelphia.

Stabler, L.B. and Martin, C.A. (2004) Irrigation and pruning affect growth and water use efficiency of two desert_adapted shrubs. *Acta Horticulturae* **638**, 255–258.

U.S. Census Bureau. (2000) Census 2000. (http://www.census.gov/main/www/cen2000.html).

West, N.E. and Skujins, J. (1978) *Nitrogen in Desert Ecosystems.* Dowden, Hutchinson & Ross, Inc., Stroudsburg.

Wu, J.G. and David, J.L. (2002) A spatially explicit hierarchical approach to modeling complex ecological systems: Theory and applications. *Ecol. Model.* **153**, 7–26.