Integrated Approaches to Long-Term Studies of Urban Ecological Systems*

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> *In 1935, Arthur Tansley wrote:*
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> *We cannot confine ourselves to the so-called "natural" entities and ignore the processes and expressions of vegetation now so abundantly provided by man. Such a course is not scientifically sound, because scientific analysis must penetrate beneath the forms of the "natural" entities, and it is not practically useful because ecology must be applied to conditions brought about by human activity. The "natural" entities and the anthropogenic derivates alike must be analyzed in terms of the most appropriate concepts we can find.*
> *(Tansley 1935, p. 304)*

Keywords: long term ecological research · Phoenix, Baltimore · Watershed dynamics · patch dynamics · scale · land cover · hydrology · human social system · ecosystem

This quote captures the spirit of the new urban emphasis in the US Long-Term Ecological Research (LTER) network. We know now that Earth abounds with both subtle and pronounced evidence of the influence of people on natural ecosystems (Russell 1993, Turner and Meyer 1993). Arguably, cities are the most human dominated of all ecosystems. Recent calls for studies on "human-dominated ecosystems" (Vitousek et al. 1997) finally have been heeded, over 60 years after Tansley penned his warning, with the addition of two metropolises (Phoenix and Baltimore) to the LTER network.

In this article, we describe an emerging approach to understanding the ecology of urban areas by contrasting these two metropolises, and we present a call to action for ecologists to integrate their science with that of social scientists to achieve a more realistic and useful understanding of the natural world in general and its ecology in particular (Pickett and McDonnell 1993, Ehrlich 1997). We begin by framing a conceptual basis for the study of urban ecological systems: the rationale, contrasting approaches, and special considerations for including human interactions at different scales and in a spatial context. We then discuss the application of our conceptual approach by comparing site conditions and initial research results in Baltimore and Phoenix. We conclude with a summary and synthesis of implications for the integration of social and ecological sciences.

The Conceptual Basis for Studying Urban Ecological Systems

Why has the study of urban ecological systems attracted so much recent interest? The rationale for the study of human-dominated systems is three-pronged. First, humans dominate Earth's ecosystems (Groffman and Likens 1994, Botsford et al. 1997, Chapin et al. 1997, Matson et al. 1997, Noble and

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* Urban ecological systems present multiple challenges to ecologists—pervasive human impact and extreme heterogeneity of cities, and the need to integrate social and ecological approaches, concepts, and theory

Originally Published in 2000 in BioScience 50:571–584
J.M. Marzluff et al., *Urban Ecology,*

Dirzo 1997, Vitousek et al. 1997); therefore, humans must be integrated into models for a complete understanding of extant ecological systems. Second, development of these more realistic models for ecological systems will lead to greater success in finding solutions to environmental problems (Grossmann 1993). Third, although the study of ecological phenomena in urban environments is not a new area of science, the concept of city as ecosystem is relatively new for the field of ecology. Studying cities as ecosystems within new paradigms of ecosystem science (Pickett et al. 1992, Wu and Loucks 1995, Flores et al. 1997) will both raise the collective consciousness of ecologists regarding urban ecosystems and contribute to the further development of concepts that apply to all ecosystems.

Evidence that human influence on the environment has been pervasive for thousands of years has been accumulating from anthropological and archaeological research (Turner et al. 1990, Redman 1999). Major human impacts on the environment probably go back as far as 12,000–15,000 years ago, when Siberian hunters first entered the Americas. These hunters may have played an important role in the extinction of many species of large mammals (Morgan 1993, MacLeish 1994, Stringer and McKie 1996). The introduction of agriculture transformed human–environmental relations in virtually all parts of the world, leading to, in addition to the obvious benefits, localized but intense episodes of deforestation, soil erosion, disease, and regionwide degradation of vegetative cover long before the modern era (for the Mediterranean, Butzer 1996; for Central America, Rice 1996). Among the more severe human-induced environmental impacts are those associated with ancient urban societies, whose dense populations, rising rates of consumption, and agricultural intensification led to regional degradation so extreme that cities were abandoned and the productive potential of entire civilizations was undermined to the point of ruin. Archaeology has documented repeated examples of such impacts, including the salinization of southern Mesopotamia 4000 years ago (Redman 1992), valleywide erosion in ancient Greece (van Andel et al. 1990), and almost complete depopulation of large tracts of Guatemala (Rice 1996) and highland Mexico (O'Hara et al. 1993) from 1000 AD to 1400 AD. Clearly, human actions dramatically alter the functioning of ecosystems of which humans are a part, and, equally clearly, humans are a part of virtually all ecosystems and have been so for millennia. Nowhere has this human participation been more intense than in cities, suburbs, and exurbs and in the supporting hinterlands.

Today, urbanization is a dominant demographic trend and an important component of land-transformation processes worldwide. Slightly less than half of the world's population now resides in cities, but this proportion is projected to rise to 61% in the next 30 years (UN 1997a). The developed nations have more highly urbanized populations; for example, close to 80% of the US population is urban. However, projections for the twenty-first century indicate that the largest cities, and the largest growth in city size, will occur in developing nations. Between 1980 and 2030, the percentage of the urban population on the African continent will double from 27% to 54% (UN 1997a). Urbanization trends of the past century also show a dramatic rise in the size of cities: Over 300 cities have more than 1 million inhabitants, and 16 "megacities" have populations exceeding 10 million (UN 1997b). Urbanization interacts with global change in important ways. For example, although urban areas account for only 2% of Earth's land surface, they produce 78% of greenhouse gases, thus contributing to global climate change. Cities also play a central role in alteration of global biogeochemical cycles, changes in biodiversity due to habitat fragmentation and exotic species, and changes in land use and cover far beyond the city's boundaries (i.e., within the urban "footprint").

The growing impact of urban areas on the face of the earth is reason enough to study them. An even more compelling argument for understanding how cities work in an ecological sense is the fact that humans live in them and must depend on proper management to maintain an acceptable quality of life for the foreseeable future. Because human societies are an important part of urban ecological systems (and perhaps all ecosystems; McDonnell et al. 1993), ecologists now recognize that "most aspects of the structure and functioning of Earth's ecosystems cannot be understood without accounting for the strong, often dominant influence of humanity" (Vitousek et al. 1997, p. 494).

To understand human actions and influences on ecosystems, it is essential to use approaches developed in the social, behavioral, and economic sciences. Conceptual frameworks that explicitly include humans will be much more likely than those that exclude them to accurately inform environmental problem solving. The reasons for this contention are obvious: Human perception, choice, and action are often the phenomena that drive political, economic, or cultural decisions that lead to or respond to change in ecological systems.

What can the integration of social and ecological sciences as applied to human-dominated ecosystems bring to the field of ecology? One of the main goals of the LTER program is to understand the long-term dynamics of ecosystems. Although approaches, types of ecosystems, and disciplinary expertise often differ among the sites, conceptual similarities in many ways overshadow these differences. In their common commitment to understanding long-term ecological dynamics, for example, most LTERs recognize two classes of variables affecting ecosystems. The first and better-studied class of variables includes patterns and processes of ecosystems, which are constrained by "natural" factors such as geologic setting, climate and its variation, species pools, hydrologic processes, and other biological or geophysical factors. Underlying this first class of variables are the fundamental drivers of ecological systems: the flows of energy and information and the cycling of matter (by the flow of information we refer primarily to evolutionary origins and change; e.g., Reiners 1986). Understanding how these drivers, and the constraints they impose, interact with ecological patterns and processes to produce long-term dynamics has been a major goal of most LTER programs. The second class of variables are those directly associated with human activities, such as land-use change, introduction or domestication of species, consumption of resources, and production of wastes.

The simplified model shown in Fig. 1 defines the intellectual arena within which LTER ecologists typically work. The inclusion of both natural processes and human activities influencing long-term ecosystem dynamics is appropriate because even LTER sites in purportedly pristine areas are subject to human-caused disturbance and change. Patterns and processes of ecosystems, where the five core areas (primary production, populations, organic matter, nutrients, and disturbance) of the LTER program are centered, have been more completely specified than have social patterns and processes. It is clear, however, that several important interactions and feedbacks are missing from this approach. Because many of these missing features are the subject matter of the social sciences, it is through contributions in this area that an understanding of the world's ecosystems can be most enhanced (Ehrlich 1997). At the same time, these interactions and feedbacks should not be pursued in isolation within a self-contained, traditional social-scientific framework, because the human activities that influence ecosystem dynamics are reciprocally influenced both by biogeophysical driving forces and by ecosystem dynamics.

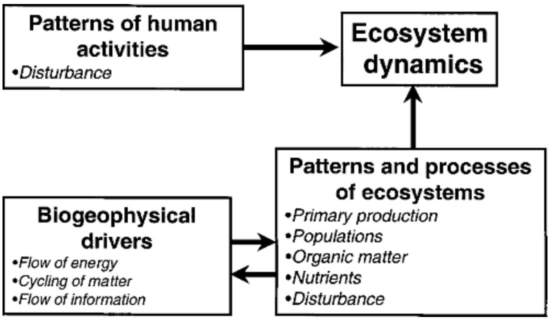

Fig. 1 Two classes of variables that affect ecosystems: patterns and processes of ecosystems and patterns of human activities. Ecologists have mostly studied the former, and have developed theory based on the fundamental biogeophysical drivers that determine ecosystem pattern and process. Items listed under "patterns and processes of ecosystems" are the core areas of long-term ecological research

An example of this reciprocal influence between human activity and ecosystem dynamics is provided by work at the North Temperate Lakes LTER site (Carpenter et al. 1999), one of two LTER programs that have received additional funding to add social science research and regionalization to their programs (the other augmented program is the Coweeta LTER). In Wisconsin, agricultural land uses are linked to eutrophication of the area's lakes, primarily through excess phosphorus inputs. Farmers' use of fertilizers can directly affect soil dynamics, and soil conditions can, in turn, affect a farmer's decision to use fertilizers (see Carpenter et al. 1999). In addition, a wide set of socioeconomic drivers, such as the local or regional economy, can influence human interaction with the natural landscape. In the example of fertilizer use, the market potential of the crops, government subsidies, and even the practices of neighboring farmers can influence a farmer's decision to use fertilizers (see Carpenter et al. 1999). Finally, ecosystem dynamics themselves, as altered by impaired water quality caused by leaching of excess fertilizer-derived nutrients, can influence patterns of socioeconomic activity at a larger scale, including real estate values, industrial relocation, or recreation patterns. Examining these interactions both complicates and enhances the long-term study of an ecosystem.

Without understanding interactions and feedbacks between human and ecological systems, our view of ecosystem dynamics both at local and global scales will be limited—as will be our ability to apply these insights to public policy and land management. Acknowledging the central human component leads to an emphasis on new quantitative methods, new approaches to modeling, new ways to account for risk and value, the need to understand environmental justice, and the importance of working within a globally interacting network (e.g., Grossmann 1993). These added interactions and feedbacks traditionally have been studied by social scientists in isolation from life and earth scientists. Rarely, if ever, has a focused long-term study incorporated all the interactions implicit in Fig. 2. Such integration requires a research team that brings together scientists from the natural, social, and engineering sciences in a unified research endeavor.

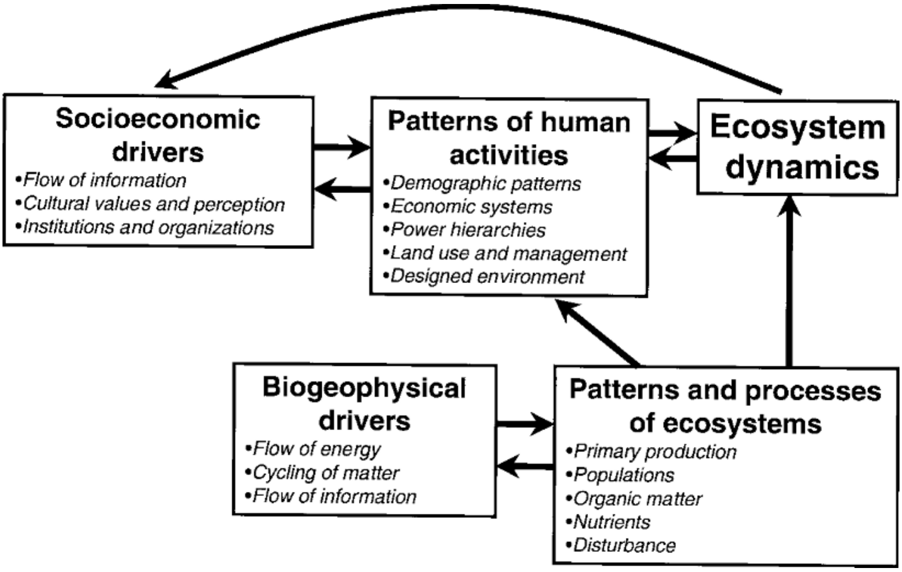

Fig. 2 A more comprehensive view of the drivers, interactions, and feedbacks affecting ecosystem dynamics that recognizes, in addition to biogeophysical drivers, socioeconomic drivers that determine patterns of human activity. Items listed under "patterns of human activities" are suggested core areas of long-term social science research

Ecology in and Ecology of Urban Ecological Systems

The simplest phrase describing the research being done in the Baltimore and Phoenix LTER studies is urban ecology. However, this term is fraught with misunderstanding because it is often applied to research that does not encompass the full suite of concepts we hope to develop. We prefer to distinguish between two different types of research that more accurately describe the projects we envision: ecology in cities and ecology of cities. There are abundant examples in the literature of ecology in cities (e.g., Sukopp and Werner 1982, Sukopp 1990). The basic questions addressed by such studies are, how do ecological patterns and processes differ in cities as compared with other environments? What is the effect of the city (i.e., a concentration of human population and activities) on the ecology of organisms inside and outside of its boundary and influence (e.g., McPherson et al. 1997)? Research topics exemplifying ecology in cities are distribution and abundance of animal and plant populations, air pollution and meteorology, patch-specific ecological pattern and processes, edge effects (because edges are especially pronounced in cities), and exotic–native species interactions. Tools for doing ecology in cities include before–after experiments, which allow the study of effects of rapid changes occurring in the urban environment, and the concept of urban–rural gradients (e.g., McDonnell et al. 1993), which can be a form of space-for-time substitution to detect impacts of urbanization on ecological processes. These examples help illustrate that ecology has been done in cities for a long time. We do not wish to claim that the urban LTERs are the inventors of urban ecological studies! But perhaps much of the uniqueness of the new urban LTER programs lies in their attempt to treat cities as ecosystems, that is, to study the ecology *of* cities.

The concept of ecology of cities has to do with how the aggregated parts sum, that is, how cities process energy or matter relative to their surroundings. Ecologists might take many different routes to understanding the ecology of cities: mass balances of nutrients for the entire system, patch dynamics (wherein all patch types, and the changes in and among them, are considered for the landscape as a whole), ecological effects of land-use change, whole-system metabolism, spatial distribution of resources and populations (e.g., a metapopulation approach), and estimation of the ecological footprint of a city (Rees and Wackernagel 1994, Folke et al. 1997). Tools for studying ecology of cities include the watershed approach, wherein measurement of inputs and outputs is simplified because the system is defined as the area of land drained by a particular stream (e.g., Bormann and Likens 1967, Likens and Bormann 1995); patch dynamics modeling; and monitoring and modeling of land-use change by incorporating remote sensing and GIS (geographic information systems) methodologies. Of course, each approach borrows from the other, and with increasing scale what is viewed as the ecology-of-cities approach may become ecology in an urban patch within the larger region of which the city is part. Our intent is not to advocate one approach over the other, but we do agree with McDonnell and Pickett (1990, p. 1231), who stated nearly a decade ago that "study of the [city] as an ecosystem . . .would be a radical expansion of ecology." Thus, both the Baltimore and Phoenix LTER programs are doing ecology in cities but are framing their work within the context of city as ecosystem.

An ecosystem is a piece of earth of any size that contains interacting biotic and abiotic elements and that interacts with its surroundings. By this definition, and with Tansley's purpose and definition of the term in mind—"the whole *system* (in the sense of physics), including not only the organism-complex, but also the whole complex of physical factors forming what we call the environment of the biome—the habitat factors in the widest sense" (Tansley 1935, p. 299)—a city is most certainly an ecosystem. But few studies have treated cities as such (a notable exception is the study of Hong Kong by Boyden et al. 1981; see also Boyle et al. 1997). Ecosystems have definable structure and function. Structure refers to the component parts of the system: organismal (including human) populations, landscape patches, soils and geologic parent material, and local atmospheric and hydrologic systems. Ecosystem function is a general term referring to the suite of processes, such as primary production, ecosystem respiration, biogeochemical transformations, information transfer, and material transport, that occur within ecosystems and link the structural components. The function of a whole ecosystem or a part of an ecosystem can be thought of as an integrated measure of what that unit does in the context of its surroundings. For example, a component ecosystem in a region contributes stocks of resources or fluxes of materials to that larger region. More specifically, a city might contribute airborne particulates or nitrogenous or sulfurous gases to ecosystems located downwind of it.

In addition to the structure, function, and processes traditionally studied by ecologists in any ecosystem, urban systems also contain the dominant components of social institutions, culture and behavior, and the built environment. An ecology-in-cities study that incorporates these components might consider, for example, how irrigation practices or creation of hydrologic infrastructure (e.g., canals, pipes, or storm drains) influences the distribution of insects on household or neighborhood scales. An ecology-of-cities approach might include models of urban growth and spread that reflect economic and social drivers; for example, the tendency of people to want to live on hillslopes (behavior) or the market value of housing near transportation routes (economics). This type of study must necessarily involve the reconceptualization of human activities, not as disturbances to the ecosystem but as important drivers of and limitations to it (e.g., Padoch 1993). Traditional scholarship of urban systems in the human–social, ecological, geophysical, and civil infrastructural domains has been pursued in relative isolation, with each developing its own disciplines, methodologies, and evaluation tools (Borden 1993). Urban ecosystem studies can bring elements of these disparate approaches together, underscoring the interdependence of these phenomena.

Traditional biological or earth science–based approaches to ecosystem studies are insufficient for urban systems because of the interaction of social systems with biogeophysical systems (Borden 1993). Although some have argued that humans can be treated as just another animal population, albeit an important one (but see Padoch 1993), the suite of social drivers of urban ecosystems—information flow, culture, and institutions—are not easily modeled within a traditional population framework (Padoch 1993, Turner and Meyer 1993). Several modifications of this framework are necessary to successfully integrate human activity into an ecological model. The first is to acknowledge the primary importance of human decision-making in the dynamics of the urban ecosystem. This decision-making operates within a broad context of culture, information, and institutions. This modification puts an appropriate emphasis on the differential creation, flow, and control of information within the human ecosystem. Culture, the learned patterns of behavior for each particular society or group, and institutions, the formal structures that codify patterns of behavior, also are central components of decision-making and thus are key to understanding environmentally relevant decisions.

State variables of urban ecosystems must include more than measures of population size, species diversity, and energy flow. They must also include measures of state as perceived by humans, often referred to as "quality of life." Educational opportunities, cultural resources, recreation, wealth, aesthetics, and community health all are factors that may differ among cities, yet these variables have few parallels in traditional ecosystem studies.

Special Considerations for the Human Component of Urban Ecological Systems

Ecologists must ask whether theories developed for ecological systems in the presumed absence of human influence will be appropriate for systems, like cities, where human dominance is unquestionable We suspect that simple modification of ecological theory will prove unsatisfactory, because the modifications we have just discussed deal with aspects of human social systems that are far from simple. Although incorporation of existing social science models (Pickett et al. 1997) into ecological theory provides a starting point, development of a new integrative ecology that explicitly incorporates human decisions, culture, institutions, and economic systems will ultimately be needed (James Collins, Ann Kinzig, Nancy Grimm, William Fagan, Diane Hope, Jianguo Wu, and Elizabeth Borer, unpublished manuscript). At the same time, it is incumbent upon social scientists who hope for a realistic understanding of the urban system to consider biogeophysical feedbacks and interactions with the ecological system. The suite of social system components that we plan to include in our new models is listed in the box on page 576, although not all of these components may be relevant to any particular model or process.

Social system components

The following are examples of social system components to be incorporated into human–ecological models of urban ecosystems (from Pickett et al. 1997).

Social institutions
- Health
- Justice
- Faith
- Commerce
- Education
- Leisure
- Government

Social dynamics
- Physiological
- Individual
- Organizational
- Institutional
- Environmental

Social order
- Age
- Gender
- Class
- Norms
- Wealth
- Power
- Status
- Knowledge
- Territory

Social resources
- Economic (information, population, labor)
- Cultural (organizations, beliefs, myths)

Within the context of the LTER program, the subject matter for investigation started with a set of five core areas that are common to all LTER research: primary production, populations representing trophic structure, organic matter storage and dynamics, nutrient transport and dynamics, and disturbance. Given, as we have suggested (Figure 1), that three fundamental biogeophysical drivers of ecosystems are the flow of energy, the flow of information, and the cycling of materials, what are the comparable drivers and core areas of social systems? Social scientists working at the augmented (Coweeta and North Temperate Lakes) and urban LTER sites consider individuals to be guided in their activities by the knowledge, beliefs, values, and social resources shared with other members of their social system at different levels of organization (e.g., at family, community, state, and national levels). In this perspective, the three fundamental drivers of human elements in the ecosystem (Figure 2) are:

- Flow of information and knowledge
- Incorporation of culturally based values and perceptions
- Creation and maintenance of institutions and organizations

These drivers condition human activities and decisions (see also Turner and Meyer 1993). Although understanding the nature and interaction of these drivers must be the ultimate goal of most inquiries, actual investigations may more often be oriented toward measuring the patterns of human activity these processes create. Defining the following core topics—each characterized by its activities, structure, and historic trajectory—is key to a comprehensive approach to human ecosystem analysis (Figure 2):

- Demographic pattern
- Economic system
- Power hierarchy
- Land use and management
- Designed environment

Collectively, these core topics serve as guidelines of inquiry analogous to the five ecological core areas identified early in the LTER program's history. On the one hand, they reflect the processes operating within the system; on the other, they are a practical guide for field investigations. The entire LTER network (not just the urban and augmented sites) thus provides an excellent starting point to incorporate social science research that is relevant to, and integrated with, studies of ecosystem change.

A Conceptual Scheme for Understanding Urban Ecological Systems

We have now identified drivers and patterns of activity in both ecological and social systems that must collectively be considered for a full understanding of human-dominated ecosystems. A more specific conceptual scheme or model for how a study of urban ecological systems can be approached is represented by Figure 3. This scheme has been modified, through recent discussions, from schemes presented by the Baltimore and Phoenix LTER groups in grant proposals and various publications (e.g., Grimm 1997, Pickett et al. 1997); indeed, it is still evolving. The diagram includes a set of variables that are linked by interactions and feedbacks.

The two variables in the upper corners—coarse-scale environmental context and societal patterns and processes—can be viewed as constraints, which are the outcome of operation of the fundamental biogeophysical and societal drivers. The coarser-scale environmental context includes climate, geology, history, and biogeographical setting, and societal patterns and processes encompass the socioeconomic system, culture, demography, and social institutions.

The middle two variables are the focus of the new urban LTER research: land use and ecological patterns and processes associated with any given land use. Land use incorporates both the intent and the reality of how a given parcel within a metropolitan boundary is altered by human decisions, whereas ecological patterns and processes—energy flow; nutrient cycling; the hydrologic cycle; species distribution, abundance, and interactions; ecosystem and landscape structure; and disturbance—are those phenomena studied by all LTER teams. Land use and associated ecological conditions are viewed at a single point in time, using a hierarchical, patch mosaic perspective. Land-use change occurs because of development, urban renewal, changes in land management or ownership, or infrastructure development, among other causes.

The last two variables in the lower corners of Figure 3—changes in ecological conditions and changes in human perceptions and attitudes—result from the interaction between land-use change and ecological pattern and process. Changes in ecological conditions represent the next time step of ecological patterns and processes, and changes in human perceptions and attitudes represent the human reaction to either ecological pattern and process or changes therein, as expressed through the filter of human experience.

The interactions and feedbacks depicted in Figure 3 are intended to reflect temporal dynamics to some extent. As an example, land-use decisions are based on the environmental and politico–socioeconomic context, the land use is then perceived as good or bad, and this feedback can lead to

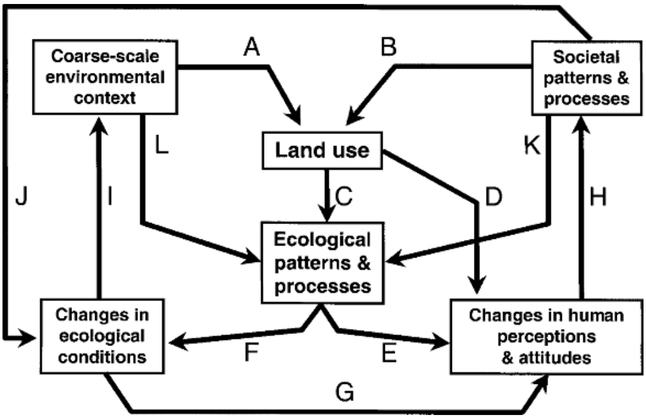

Fig. 3 Conceptual scheme for integrating ecological and social systems in urban environments. Variables are in boxes; interactions and feedbacks are arrows: A, environmental context sets the range of possibilities for land use–land cover; B, societal decisions and human behavior (incorporating their suite of determinants) are the direct drivers of land-use change; C, the pattern of land use (whatever the driver) determines ecological patterns and processes; D, humans perceive and react to land-use change (independent of any ecological effects); E, humans also perceive and react to ecological patterns and processes; F, in this interaction, ecological processes as affected by land-use change result in a change in ecological conditions; G, such changes in ecological conditions may result in changes in attitudes (even if human perception previously ignored ecological pattern and process), and changed ecological conditions are perceived as good or bad by humans; H, changes in perception and attitude feed back to the societal system (patterns and processes of society) to influence decision-making, and this part of the cycle begins anew; I, in some cases, changed ecological conditions can alter the coarse-scale environmental context (example: urban heat island), resulting in a feedback that is relatively independent of human response. J, K: When a societal response to changed ecological conditions is deemed necessary, the society can act directly on the changed conditions (J) or on the underlying ecological patterns and processes producing the problem (K). Finally, the environmental context of course influences ecological patterns independent of land use (L)

different human decisions. This sequence of decisions and changes in land use does not incorporate new ecological information (i.e., the changes in ecological condition that result from the land-use change); such a situation is unstable and seems unlikely to lead to a sustainable urban environment. A sequence of interactions and feedbacks carried out when a change occurs or in response to an environmental problem, however, would incorporate either short-term solutions to those problems or adjustments in management decisions based on a solid ecological foundation.

To illustrate the sequence of changes and feedbacks to further change, consider an example from the Central Arizona–Phoenix LTER site: the establishment of an artificial lake in the once-dry Salt River bed (Figure 4). The initial land-use decision (establishment of the lake) was constrained on the physical–ecological side by the existence of an alluvial channel with no surface water flow (because of upstream impoundments) in a region of North America characterized by a high propensity for flash flooding (Baker 1977). Societal constraints included the economic cost of the project, the perceptions of political and economic benefit, available technology (collapsible dams, recirculating pumps), and the existence of human-created infrastructure (engineered channel, diversion of surface flow into canals). Given these constraints, and based on our best understanding of lake ecology, the ecological conditions associated with the lake when it was filled were likely to be high nutrients with concomitant high algal production, high rates of infiltration, and a high probability of floods. At the next time step, we expected such changes in ecological conditions as eutrophication, losses of water to the groundwater system, and establishment of a robust mosquito population. Preliminary monitoring confirms the predictions of high phytoplankton biomass and insect populations, and a summer flash flood resulted in a brief episode of high phosphorus loading (Amalfi 1999).

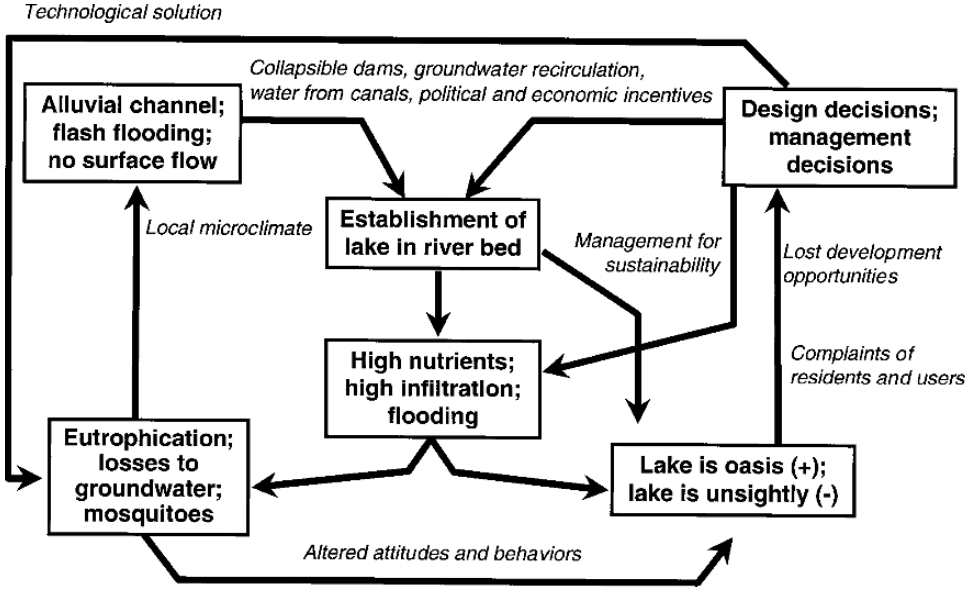

Fig. 4 Conceptual scheme adapted to show the interaction among physical, ecological, engineering, social, and management variables and drivers in the new Tempe Town Lake, Arizona

The predicted sequence of ecological conditions may result in a full range of reactions from the public. Feedbacks to the societal patterns and processes—in this case, the design and management decisions—could lead either to chemical additions to control algal blooms or to more ecologically based management practices, such as control of nutrient inputs. Indeed, complaints from the public about insect populations already have resulted in implementation of a chemical control program (Amalfi 1999), and feedbacks of ecological information and knowledge of the lake's dynamics have helped create and modify a lake management plan. Thus, societal responses can act directly on the changed conditions (arrow J in Fig. 3; e.g., addition of chemical control agents, the technological solution in Fig. 4) or indirectly, via an effect on the underlying ecological patterns and processes producing the problem (arrow K in Figure 3; e.g., diversion of upstream point-source nutrient inputs to the water supply, the arrow labeled management for sustainability in Fig. 4). We believe that this general scheme (Fig. 3) allows us to think about how social and ecological systems interact in urban areas. In addition to addressing fundamental ecological processes, this approach allows one to make predictions that are testable, and it also provides tools that citizens and decision-makers can use to create more ecologically sound policy.

A modeling framework for investigating cities

The conceptual insights of the broad scheme in Figure 3 illustrate in general how processes from the social realm, biological environment, civil infrastructure, and the larger climatic and geological context can be integrated with the specific characteristics of metropolitan Phoenix and metropolitan Baltimore. But the extreme patchiness of urban environments dictates attention to spatial detail, using novel approaches of landscape analysis and modeling. Although the two cities are quite different, integration is furthered by a common approach to spatial analyses: a hierarchical patch dynamics approach (Wu and Loucks 1995, Pickett et al. 1999). Hierarchical patch dynamics models start with ecological processes associated with fundamental units of landscapes at some specific scale, called patches. They then address ecological processes that are associated with the patches. The structure of the patches can be a major determinant of those processes. However, patch structure and arrangement also can change through time. Hence, models must account for such change; that is, they must be dynamic. Furthermore, because patches at a particular scale are often themselves composed of smaller patches, and can be aggregated into larger patches, the models must be hierarchical. By considering patch dynamics simultaneously at multiple scales, with an accompanying hierarchy of models, the complexity of urban systems is rendered more tractable and translation of information across scales is facilitated (Wu 1999).

Special Characteristics that Dictate a Novel Framework

The modern metropolis presents a strikingly heterogeneous pattern for study. For instance, the sharp contrasts between neighborhoods is a familiar characteristic of cities (Clay 1973). Within the span of a city block, which is on the order of 200 or fewer meters, an observer may cross several obvious boundaries. Different kinds of commercial use, shifts between owner-occupied and rental properties, and shifts in socioeconomic resources available to residents are but some of the many contrasts cities present. Such heterogeneity is not unique to dense, central urban districts. In fact, the contemporary suburb is zoned for even more discrete transitions than the traditional mixed use of older cities. Residential streets, feeder streets, commercial streets, strip malls, regional malls, and industrial parks are notable patches in the suburban landscape. Of course, the scale of transition in post–World War II suburbs tends to be coarser than that of older neighborhoods and districts because of the shift to dependence on the automobile. However, spatial patchiness in the social, economic, and infrastructural fabric of metropolitan areas remains their most obvious feature. Social scientists have long been aware of the functional significance of spatial heterogeneity and mixture of uses within urban areas (Jacobs 1962). The ecological significance of such socioeconomic heterogeneity is, however, an open question. Indeed, determining to what extent the well-recognized patchiness of urban areas has ecological dimensions and ecological implications is one of the main motivations of integrated, long-term ecological research in the metropolis.

Whatever its ecological significance, the conspicuous spatial heterogeneity in urban systems is an entry point for integration with social science. The existence of such clearly defined patches as neighborhoods and cityscapes, which combine infrastructural and natural features, is apparent to all researchers who must work together to generate the interdisciplinary synthesis for understanding cities as ecological systems. Hydrologists, ecologists, demographers, economists, engineers, and citizens all can and do recognize the spatial heterogeneity of cities. Neighborhood associations, watershed associations, census tracts, and similar groupings are institutional expressions of this common recognition. Of course, each discipline or constituency may see the boundaries or the most salient features of the patchwork somewhat differently. For example, the civil engineer and the urban recreationist will have different views of the boundaries of a watershed. The first may see a “sewershed”; the second, a visually unified landscape that is engaging on a morning jog. Therefore, new, multidimensional classifications of the heterogeneity of the metropolis are required. Among the principal dimensions of such classifications, however, will be factors that control the flow of materials, energy, and information through and within the metropolis. An emphasis on these kinds of variables suggests that a spatially explicit, ecosystem perspective can emerge from the heterogeneity of the metropolis.

The interdisciplinary integration required to understand the ecological significance of spatial pattern in urban ecosystems must account for several important features of humans and their institutions. Although these features are implied in the social drivers and phenomena we introduced earlier (Figure 2, see box page 129), these features add complexity to ecological studies of the city and, therefore, cannot be ignored. The spatial heterogeneity of urban systems is established by formal institutions, such as zoning regulations, and maintained by other formal institutions, such as public works and the courts. However, less formal institutions, such as families and community associations, also contribute to the spatial structure and its function. Humans, as individuals and groups, are self-aware, capable of learning quickly, and engaged in extensive networks of rapid communication. These features of the human components of urban systems mean that the feedback among the biological, human, infrastructural, and the larger physical contexts can be strong and, in many cases, rapid. This is one reason that education has been incorporated into the structure of urban LTER programs. We hypothesize that learning about the heterogeneity and function of an urban area can be a tool that citizens and institutions can demonstrably use to improve their neighborhoods, city, and region through management, planning, and policy (Grove and Burch 1997).

Patch Dynamics and Hierarchical Approaches

Spatial heterogeneity was independently chosen as a starting point by both the Central Arizona–Phoenix and Baltimore Ecosystem Study LTER teams. In addition to the advantages already laid out, the patch dynamics approach also brings the advantage of hierarchical nesting and aggregation. Such a flexible hierarchical approach is important because the structures, and consequently the processes, that govern the function of the metropolis as an ecological system occur at a variety of scales. For example, just because some social processes occur at the scale of neighborhoods of, say, 15 square blocks, does not mean that the most important ecological impacts occur at the same scale. Similarly, the concentration of resources or wastes in particular patches can be due to decisions made at great distances from the point of concentration. Therefore, patches may be scaled up or down for different functional analyses, and the configuration of patches that are relevant to specific paths along which resources and information flow can be assessed.

As an example, Baltimore can be described in terms of the five-county metropolitan area (Figure 5). Within it are three principal watersheds that extend from the rural hinterlands to the central city. Each of these watersheds can be divided into subcatchments. The 17,000-ha Gwynns Falls catchment contains 16 smaller watersheds that have been used for discussion of management and restoration activities. Still smaller units can be used for mechanistic studies of ecosystem and socioeconomic processes. The fact that different nestings are possible within the larger units means that the scales at which important interactions occur can be captured, and the promulgation of their effects to different scales, whether coarser or finer, can be determined (see Grove and Burch 1997).

A similar nested set of units is being identified in the Central Arizona–Phoenix study area (Fig. 5). At the largest scale, three patches exist along an east–west gradient from primarily commercial–industrial–residential, to primarily agricultural, to primarily desert land use-land cover. The political boundaries of the 24 different municipalities in the Phoenix metropolitan area form another set of smaller patches, and heterogeneity of land use-land cover is evident within these smaller units. Interestingly, patch size, regularity, and connectivity differ within the three broadest patches (Matthew Luck and Jianguo Wu, Arizona State University, personal communication).

The patch dynamics approach focuses explicitly not only on the spatial pattern of heterogeneity at a given time but also on how and why the pattern changes through time and on 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 complete understanding of urban ecological systems. Even within a coarse resolution land-cover type, change occurs over time in the resources available for management of biotic structure and maintenance of civil infrastructure and in the requirements and interests of humans in specific patches. The explosive changes in patch structure at the urban fringe of the rapidly expanding Phoenix metropolis is one example of this phenomenon: formerly desert patches are converted to residential housing develop-

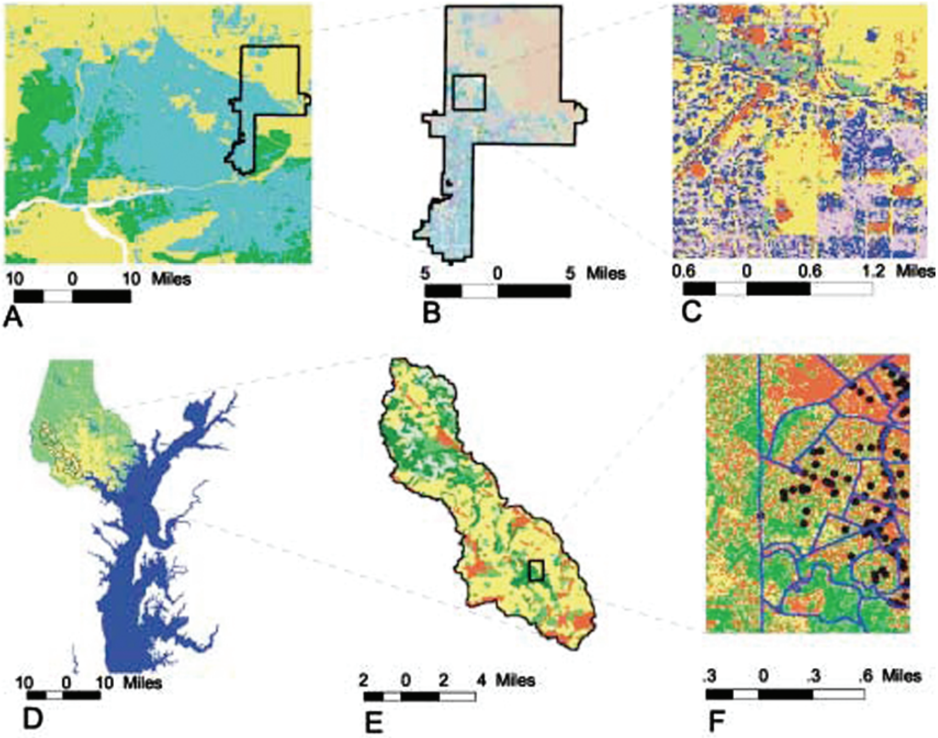

Fig. 5 Examples of hierarchically nested patch structure at three scales in the Central Arizona–Phoenix (CAP; upper panels) and Baltimore Ecosystem Study (BES; lower panels) regions. At the broadest scale (A, D), patches in the CAP study area include desert (mustard), agriculture (green), and urban (blue); for the BES, patches are rural (green), urban (yellow), and aquatic (blue). (B) The municipality of Scottsdale, AZ, showing major areas of urban–residential development (blue, lower portion) and undeveloped open lands (tan, developable; brown, dedicated). (C) Enlargement of rectangle in B showing additional patch structure at a neighborhood scale (green, golf course/park; mustard, undeveloped desert; red, vacant; pink, xeric residential; purple, mesic residential; yellow, asphalt). (E) Gwynn's Falls watershed, MD, with residential (yellow), commercial/industrial (red), agricultural (light green), institutional (medium green), and forest (dark green) patch types. (F) Enlargement of rectangle in E showing additional patch structure at a neighborhood scale (dark green, pervious surface/ canopy cover; light green, pervious surface/no canopy cover; yellow, impervious surface/canopy cover; red, impervious surface/no canopy cover; blue, neighborhood boundaries; black circles, abandoned lots). Panel A courtesy of CAP Historic Land Use Project (caplter.asu.edu/research/contributions/HistoricLandUse_Color.pdf), B and C courtesy of CAP LTER/Geologic Remote Sensing Laboratory (elwood.la.asu.edu/grsl/), D, E, and F courtesy of USDA Forest Service and BES LTER

ments and, with this conversion, demand for amenities of urban life increases sharply. In Baltimore, patch dynamics are conspicuous both at the suburban fringe and in the ever-growing collection of vacant buildings and empty lots within the older, dense urban areas. In both the fringe and core patches, ecological processing of water, nutrients, and the provision of goods and services are not constant in time. The dynamics of patches in and around the city have implications for the ecological processes and status of areas well beyond the city and even beyond the present suburban and exurban areas. The search for open land, development opportunities, and changes in the economics of farming and production forestry all influence and are influenced by urban patch dynamics.

Application of Integration: Comparisons between Baltimore and Phoenix

Having laid out a coarse conceptual scheme for integrating social and ecological principles and a more specific modeling framework that deals with heterogeneity and dynamics of urban ecological systems, we turn next to a consideration of the distinctly different cities chosen for inclusion in the LTER network. In almost every characteristic, Phoenix and Baltimore are dramatically different (Table 1). In terms of the physical environments, Baltimore is an eastern seaboard metropolis straddling the Coastal Plain and Piedmont provinces, whereas Phoenix is an inland city situated in a broad alluvial basin at the confluence of two large desert rivers. Phoenix has a hot, dry climate (receiving less than 200 mm of precipitation annually), whereas Baltimore has a mesic, temperate zone climate (1090 mm of precipitation). Natural hydrological regimes are flashy (rapid rises and falls in flows) in Phoenix, whereas in Baltimore rainfall and runoff are more uniform throughout the year. The transport of water and materials by surface runoff is thus highly episodic in Phoenix, where baseflow exists only in manmade canals and as treated sewage effluent. Baltimore's hydrology and material transport, in contrast, can be studied using standard watershed approaches, although flashiness associated with urbanization dictates a focus on storm flows even there.

Ecological contrasts between Baltimore and Phoenix also are striking: deciduous forest versus desert, high (temperate forest) versus low (desert) biotic diversity, and different disturbances that

Table 1 Contrasting characteristics of Baltimore and Phoenix, two metropolises that are recent additions to the US Long-Term Ecological Research (LTER) network

Characteristic	Baltimore	Phoenix
Climate	Mesic, temperate	Arid, hot
Geographic–geomorphic	Land–sea margin	Alluvial basin
Topography	Coastal plain	Flat, outcrops and buttes, surrounding mountains
Hydrologic characteristics	Seasonal runoff systems	Flashy; episodic surface runoff
Natural vegetation	Eastern deciduous forest	Sonoran desert scrub
Native biotic diversity	High	Low–moderate
Invasibility–impact of exotic biota	Moderate	High
Primary limiting factor (ecological)	Seasonally variable	Water
Natural disturbances	Hurricane	Fire, flash flood
Succession rate	Moderate	Slow
Remnant patches	Forest	Desert
Prehistory	Low density, scattered	Large civilization 1000 years before present
History	Early seaport	Abandoned until 100 years before present
Age of city	300+ years	Less than 100 years
Rate of population growth	Moderate	Rapid
Urban growth mode	Spread and redevelopment	Spread
Urban form	Compact, with core and fringing suburbs	Extreme spread, coalescing cities, interior open space
Limits to expansion	None	Public and Indian land
Interior open space	Abandoned	Never developed or remnant
Economic base	Industrial	Hi-tech, tourism
Ecosystem boundaries of LTER study	Primary Statistical Metropolitan Area	County or regulated portion of watershed
Patch definition	Watershed; socioeconomic patches; ecological patches	Combination of patch age, position, neighbors, land use, land-use history

initiate succession (which probably occurs at very different rates). Water is undoubtedly the primary limiting factor to production in the desert region that Phoenix occupies, although nitrogen limitation also is prevalent in both terrestrial and aquatic ecosystems (Grimm and Fisher 1986). In Baltimore's eastern deciduous forest, limiting factors vary seasonally, but may include low temperatures and frost in winter and soil nutrient limitation and occasional late summer drought during the growing season.

In terms of societal organization, there are important differences as well. Modern Phoenix is a much younger city than Baltimore, having been established only after the Civil War and having experienced a meteoric rise in population just since World War II (and, interestingly, since the invention of air conditioning). Baltimore is more than 300 years old; it was established as a seaport after a long history of scattered habitation of the area (see Foresman et al. 1997 for a detailed analysis of land-use change in the region). The site of Baltimore did not support a large prehistoric urban settlement, but the Hohokam civilization in central Arizona included thousands of inhabitants until its demise (circa 1350 AD).

Because of climatic conditions, the Phoenix area was not actively settled until quite late in prehistory (circa 500 AD), compared with surrounding regions of the Southwest. The limitation was insufficient rainfall for agriculture; hence, any kind of substantial occupation would require knowledge of irrigation techniques and social organization to build and maintain the system. The Hohokam civilization was able to work cooperatively and establish a settlement system centered in the valley, which grew quickly. From prehistoric times to the present, the environmental challenges presented by an arid environment have required cooperative activity by human groups for urban centers in such environments to succeed. Individual farmsteads, such as those that characterized Baltimore's prehistory, would have been at serious risk in an arid environment. In contrast, prehistoric settlement of the Baltimore area succeeded based on small-scale agriculture and harvesting of coastal resources by small social groups. However, for Baltimore to move beyond its small-scale roots, as it has done in historic times, cooperative action was required, this time to build and maintain the harbor and to establish global trading connections. The summons to cooperative action was both environmental (an accessible harbor) and socioeconomic (a market for long-distance exchange of goods). The establishment of a plantation culture both relied on and contributed to global trade because of the perceived need for slave labor.

Finally, present-day contrasts in population growth and characteristics of urban growth and form reflect the distinction between an older city that has undergone economic restructuring (loss of manufacturing jobs and more service jobs) and a newer city with an economic base that has always been primarily in the service sector, with, recently, high-tech manufacturing. The Phoenix metropolitan area is one of the fastest growing in the nation (exceeded only by Las Vegas), with a population that is projected to double within approximately 25 years (Hall et al. 1998) and spreading development that consumes up to 4 square miles of desert or agricultural land per 1000 residents added to the population (Gober et al. 1998). The population of Baltimore city has declined 23% between 1950 and 1990, but growth is high at the county level, reflecting flight from urban to suburban and rural communities (Rusk 1996).

Despite these marked dissimilarities, we see an opportunity for convergence in the realm of urban ecological study. For both projects, the central objective is to understand how land-use change over the long term influences ecological pattern and process, and how this suite of changes feeds back through the social system to drive further change (e.g., Figure 3). Furthermore, although some of the key questions posed for the two systems are necessarily different, there are some common questions and a common approach has been adopted for answering many of them. The guiding principle of the LTER program—that research should, whenever possible, enable comparison between different ecosystems and across sites—dictates attention to ensuring comparability of approach. Some of the research efforts of the Baltimore and Phoenix studies reveal how social and ecological research can be integrated in ways that permit cross-comparison of results.

Baltimore Ecosystem Study: Integration of Physical, Biological, and Social Drivers of Watershed Dynamics

The Baltimore study uses watersheds as fundamental units in which to study the reciprocal interactions of the social, biophysical, and built environments. Over the past 300 years, human settlement and land management have substantially changed the character and productivity of the Chesapeake Bay, the largest and most productive estuarine system in the world (Brush 1994). Hydrologists, ecologists, and social scientists, together with public agencies, nonprofit organizations, and community groups, are working to understand how people at different scales (households, neighborhoods, and municipalities) directly and indirectly affect water quality in the watersheds of the Baltimore metropolitan region. Initial research has shown a significant relationship between concentration of political and economic power in the city and the different levels of public and private investment in green infrastructure among neighborhoods (green, open spaces and trees). Additional research is focusing on the direct ways in which households might affect water quality through irrigation and through the use of fertilizers and pesticides, as well as on how such land-management practices vary with household demographic and socioeconomic characteristics.

This research will provide important information on how people influence urban watersheds at different scales and will result in a hydrological–ecological–social watershed model that policymakers, planners, and managers can use to assess strategies for improving the water quality of the watersheds.

Central Arizona–Phoenix Study: Urban Fringe Dynamics

Phenomenal rates of urban growth and expansion in the Phoenix metropolitan area are being studied with the intention of defining a new framework through which to view the ecosystem (Gober et al. 1998). The doubling of population in each of the last two 30-year periods has led to a rapid spread of the Phoenix urban area into former farmlands and undisturbed desert landscapes. To monitor this growth, researchers are analyzing data on the exact locations of new residences for each year of the past decade. The data reveal that almost all new single-family residences are built along the periphery of the city and that urban sprawl acts as a "wave of advance" that spreads out from several nodes of urban development, as has been observed for other youthful cities (Whyte 1968). The speed of this wave and its geographic dimensions seem to respond to conditions of the local economy and characteristics of the landscape. In turn, the landscape and local ecosystem are transformed by this advance of new housing in several predictable stages—land-surface preparation (removal of vegetation, soil disturbance); infrastructure construction; scattered, "pioneer" housing developments; and fill-in of vacant land with housing. Behind the wave, neighborhoods age, leading to continued transformations in the nature of the human and biotic populations that inhabit those spaces. This analysis provides a locational tool that is more sensitive to the key processes that define the urban phenomenon than the normal grid map of the city.

Summary and Synthesis

If Vitousek et al. (1997) are correct that by excluding humans we cannot possibly understand ecosystems, and if it is critical that the social, behavioral, and economic sciences join in the endeavor to understand ecosystems, then it is essential that ecologists welcome the approaches and models of the social, behavioral, and economic sciences. We have argued that one way to do so is by focusing on five new core topic areas for social science. We have argued as well that the study of cities as ecological systems presents opportunities for theoretical advances in ecology, and that such advances cannot be accomplished without integration of the social sciences.

We believe that the expansion of social science activities within the LTER network will do much to facilitate construction of the concepts most appropriate for understanding change in the world, as will new initiatives in studies of humans as components of ecosystems. With this commitment, ecologists can begin to ask important questions about interdisciplinary research, agree about methodology and measurement, and successfully integrate social and ecological data across scales of time and space. At no time has there been a more compelling need for integration and such a wide diversity of researchers ready to begin.

Acknowledgments This paper evolved from discussions among the authors of concepts and approaches developed in each of the urban LTER proposals. We thank the many investigators from both the Central Arizona–Phoenix and Baltimore Ecosystem Study LTER programs who contributed to the development of those proposals. We particularly wish to thank Stuart Fisher for many helpful discussions of the ideas presented herein. The "commandments" of long-term social science research arose from our discussions at a Coordinating Committee meeting of the LTER network, and were sharpened through the contributions of Steve Carpenter, Ted Gragson, Craig Harris, Tim Kratz, Pete Nowak, and Chris Vanderpool, and by discussions with Diane Hope, Mark Hostetler, Kimberly Knowles-Yanez, and Nancy McIntyre. Figures 1 and 2 are adapted and expanded from diagrams created by Tim Kratz; we thank him for providing a framework in which to place those ideas. Many thanks to Peter McCartney for his assistance in assembling Figure 5. Comments from Rebecca Chasan, Bill Fagan, Jianguo Wu, Weixing Zhu, and two anonymous reviewers greatly improved the manuscript. The Baltimore Ecosystem Study and Central Arizona–Phoenix LTER programs are supported by the National Science Foundation's (NSF) Long-Term Studies Program (grant numbers DEB 9714835 and DEB 9714833, respectively). The Baltimore Ecosystem Study also acknowledges the Environmental Protection Agnecy–NSF joint program in Water and Watersheds, project number GAD R825792, and the USDA Forest Service Northeastern Research Station for site management and in-kind services. Uninterrupted time for manuscript completion was afforded N. B. G. as a visiting scientist at the National Center for Ecological Analysis and Synthesis (a center funded by NSF grant no. DEB-94-2153, the University of California–Santa Barbara, the California Resources Agency, and the California Environmental Protection Agency).

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