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Linking Land-use Change with Ecosystem Processes: A Hierarchical Patch Dynamic Model

by Jianguo Wu, G. Darrel Jenerette, and John L. David

Abstract

Urbanization continues to accelerate and profoundly transform the surface of the earth, resulting in devastating effects on the structure and functioning of ecosystems throughout the world. In the Phoenix metropolitan region, urbanization has dramatically changed the Sonoran Desert landscape in the past several decades. To understand how urban ecosystems work and to achieve ecological sustainability in urban areas, we must be able to quantify and project land use and land cover change and its ecological consequences. In this paper, we present the theoretical basis and general structure of a hierarchical patch dynamics model (HPDM-PHX) that integrates land use change with ecosystem processes in metropolitan Phoenix. The spatial hierarchical model explicitly considers three spatial scales: the local ecosystem, landscape, and region. Urban systems are studied as dynamic patch mosaics in which a variety of ecological and socioeconomic processes take place, and in which nonlinear interactions between pattern and process at different scales lead to emergent properties. Our major research goals are twofold: to develop and test a hierarchical patch dynamics modeling and scaling approach to regional analysis and assessment, and to develop an understanding of how land use change (mainly urbanization) affects ecosystem production and biogeochemical cycling at the local, landscape, and regional scales in the Phoenix metropolitan area. Although HPDM-PHX is developed for a particular urban landscape, the modeling approach should be applicable to other landscapes of different types.

Introduction

Land-use and land-cover change is indicative of the power and will with which humans modify and conquer nature. Anthropogenic activities, such as agriculture and urbanization, have drastically transformed natural landscapes everywhere around the world, inevitably exerting profound effects on the structure and function of ecosystems. In the past 120 years, the world has lost 500 million hectares of forest to land conversion (Houghton et al. 1983, 1987; Ojima et al. 1994), while cultivation of grasslands in the Central Plains of the United States has resulted in losses of 800–2000 g C/m2 since settlement by Euro-American farmers (Burke and Schimel 1990; Burke et al. 1991). In particular, the conversion of natural and agricultural areas to highly artificially modified urban land uses has been taking place at an astonishing rate. According to the United Nations, the world urban population was only a few percent of the global population in the 1800s, but increased to nearly 30 percent in 1950 and reached 50percent in 2000. It has been projected that 60percent of the world population will live in urban areas by 2025. By contrast, urban land in the United States increased by 22 million acres between 1960 and 1980 (Frey 1984), that is, by 1.1 million acres per year. Seventy-four percent of the U.S. population (203 million people) resided in urban areas in 1989, and that number is projected to rise to more than 80 percent in 2025 (Alig and Healy 1987; McDonnell et al. 1997).

Although urban areas represent arguably the most important habitats for humans, they are among the least understood ecosystems of all, and urban ecology has not been considered part of the mainstream ecology worldwide (Collins et al. 2000; Wu 2000). It is true that ecological studies in urban areas have a long history dating back to the early 1900s or earlier (see Harshberger 1923; Breuste et al. 1998). In parallel, much research has been done in spatial pattern and urban dynamics by geographers and social scientists with little or only superficial consideration of ecology in and around cities (e.g., Forrester 1969; Berry and Kasarda 1977; Batty and Longley 1994). However, understanding how urban ecosystems work does not come simply from a large number of botanical, zoological, sociological, or geographic investigations within cities. The urban whole is larger than the sum of its biological and abiotic parts. The ecology of urban systems as integrated wholes needs new and integrative perspectives (Pickett et al. 1997; Grimm et al. 2000; Zipperer et al. 2000).

In this paper, we describe the theoretical basis and the general structure of a hierarchical patch dynamics model for the Phoenix metropolitan region, HPDM-PHX, which integrates land use change with ecosystem processes. The main goal of our modeling project is to develop an understanding of how urbanization affects ecosystem productivity and biogeochemical cycles at local and regional scales. In particular, the model is used to address the following questions: How has the landscape pattern of the Phoenix metropolitan area been transformed by agriculture and urbanization since the early 1900s? How have these land use and land cover changes affected ecosystem production and nutrient cycling (e.g., C and N)? How do primary production and carbon and nitrogen dynamics differ among natural, agricultural, and urban ecosystems along a landscape gradient of urbanization? How do variations in climatic conditions (precipitation and temperature) affect the primary production and C and N dynamics for different land cover types? As the project is still unfolding, this paper focuses primarily on the theoretical basis and general structure of the hierarchical patch dynamics model of the Phoenix metropolitan area.

Land-use Change and Ecosystem Processes

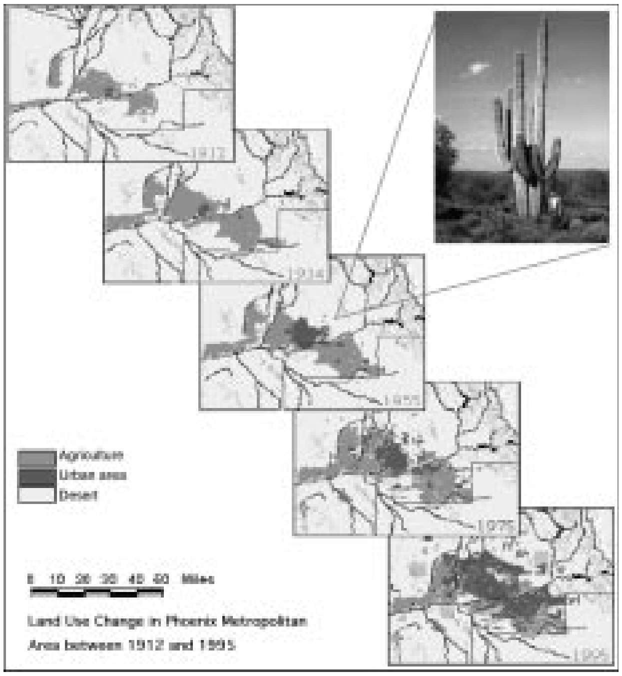
Land-use and land-cover changes may significantly affect the composition of plant communities by fragmenting the landscape, removing and introducing species, and altering water, carbon, and nutrient pathways (Ojima et al. 1994; Vitousek et al. 1997; Vitousek and Mooney 1997; Shugart 1998). These changes may result in modifications of land surface properties, such as surface albedo and latent and sensible heat fluxes (Pielke and Avissar 1990), and also modify the quality and quantity of litter and allocations of carbon and nutrients, further enhancing greenhouse gas feedback to climate systems (Hall et al. 1988; Ojima et al. 1994). Therefore, land use and land cover changes and their influences on ecosystem processes must be incorporated to address large-scale ecological and environmental issues such as urbanization, global climate change, desertification, and resource management. Recent studies in landscape ecology have indicated that understanding the interactions between landscape pattern and ecological processes at broad spatial scales is crucial for properly managing natural and human-dominated ecosystems (Moss 1988; Risser 1990; Ludwig et al. 1997; Dale et al. 2000).

To investigate the ecological consequences of land use and land cover changes, a spatially explicit, landscape ecological approach is essential. On the one hand, land use and land cover change is inherently a spatial process, and simulating land use and land cover change must consider neighborhood effects that represent local-scale interactions as well as top-down constraints imposed from broader scales. On the other hand, studies of ecosystem processes need to incorporate landscape patterns that vary in both space and time. Forman (1990) stated that “for any landscape, or major portion of a landscape, there exists an optimal spatial configuration of ecosystems and land uses to maximize ecological integrity, achievement of human aspirations, or sustainability of an environment.” We speculate that there may be multiple spatial configurations that are equally optimal in complex spatial systems such as urban landscapes, although it would be extremely difficult, if ever possible, to test such hypotheses through field experiments. Nevertheless, empirical studies have demonstrated that the configuration of landscape elements (e.g., natural vegetation remnant patches, parks, golf courses, agricultural fields, and urban blocks) often influences various ecosystem processes, such as net primary productivity, watershed discharge characteristics, and nutrient cycling (Lowrance et al. 1985; McDonnel and Pickett 1990; Risser 1990; Knapp et al. 1993; McDonnel et al. 1997). Recent ecological studies also have suggested that measures of landscape pattern (indices or metrics) may reveal ecological processes operating at different scales (e.g., Krummel et al. 1987; Hoover and Parker 1991; Graham et al. 1991; Hunsaker et al. 1994; Wu et al. 2000). While caution must be carefully taken, landscape structural measures may be used as indicators for monitoring ecosystem changes at regional scales (O’Neill et al. 1994, 1997; Jones et al. 1996). Thus, methods of spatial pattern analysis not only are important for quantifying landscape structure and its change, but for relating landscape pattern to ecological processes as well (Wu and Qi 2000).

Urbanization and Landscape Pattern Change in Phoenix

The Phoenix metropolitan region, Arizona, the United States, is located in the northern part of the Sonoran Desert. Phoenix is the home of the Central Arizona–Phoenix Long-Term Ecological Research (CAPLTER) Project, supported by the U.S. National Science Foundation. The major goal of CAPLTER is to understand the pattern and process of urbanization and their ecological consequences. While the climate of this area is one of the hottest and driest regions in North America, the biodiversity of the Sonoran Desert is among the richest of all deserts in the world. Summer temperatures average 30.8oC while winters are warm with average temperatures of 11.3oC. Average annual precipitation in the Phoenix area is 180 mm, with approximately 50 percent in the form of summer thunderstorms and the remainder associated with winter frontal systems originating in the Pacific Ocean. Native vegetation is characterized by desert scrub communities that are dominated by creosote bush (*Larrea tridentata*), mesquite (*Prosopis glandulosa*), and several other shrub species. The giant cactus, saguaro (*Carnegiea gigantea*), standing tall with multiple arms reaching out, is found throughout the area either as the prominent landscaping plant in human-constructed environments or as the monarch of a variety of cactus plants in the desert. With its magnificent charisma and sacred status, saguaro is undoubtedly the most recognizable symbol of the Sonoran Desert landscape (see photo, Figure 1).

Figure 1. Historical land use change in the Phoenix metropolitan area between 1912 and 1995 (Modified from Knowles-Yanez et al. 1999).



In the southwest United States and the Phoenix metropolitan area in particular, urbanization has rapidly transformed the desert landscape (Figure 1). According to the U.S. Census Bureau, Arizona had a net percent population increase of 30.4 between 1990 and 1999, second only to Nevada, whose population increased by 50.6 percent during the same period. In recent decades, Phoenix has become one of the largest and fastest growing cities in the United States (Figure 2, Table 1), with more than a half of the population of the entire state of Arizona concentrated in the Phoenix metropolitan area. The population of Maricopa County, where the Phoenix metropolitan area is located, was only 5,689 in 1880. It increased to 1.51 million in 1980 and reached 2.72 million in 1997. By contrast, the population of the state of Arizona was 4.55 million in 1997 and 4.67 million in 1998. The rapid population growth in the Phoenix metropolitan area has led to an equally fast expansion of urbanized area. The tight linear correlation between population and urban area (Figure 2; see Jenerette and Wu 2001) suggests that rapid urban sprawl in the Phoenix area will persist at least in the near future as a result of the continued explosive population growth due to the influx of immigrants.

Figure 2. Population growth in Maricopa County of the Phoenix metropolitan area between 1880 and 1997. The population growth is highly correlated with the expansion of urbanized area.

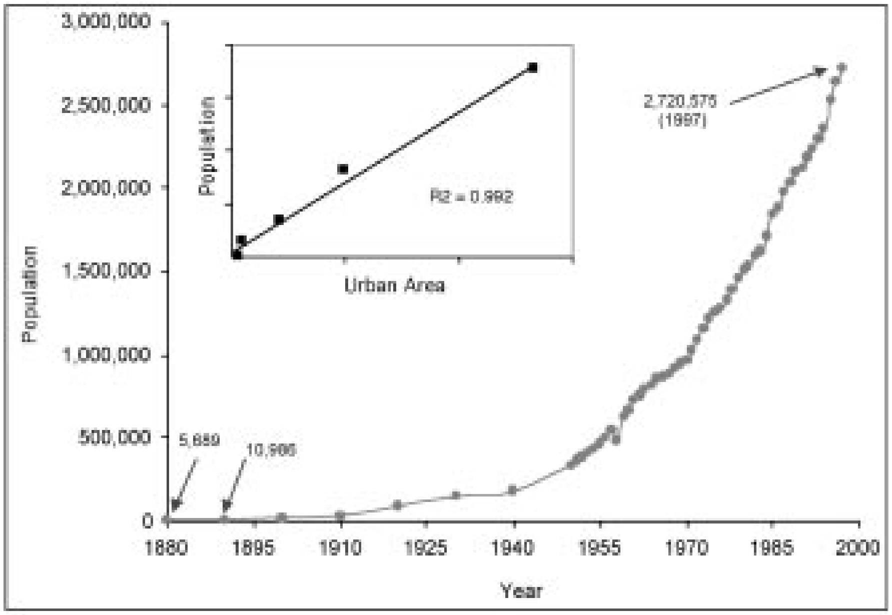


Table 1. The top 10 fastest growing metropolitan areas in the United States between 1990 and 1998 (data source: U.S. Census Bureau http://www.census.gov/).

	Rank by Population Size		Rank by Percent Change
	7/1/98	4/1/90	4/1/90 to 7/1/98
Las Vegas, Nev.	33	51	1
Laredo, Tex.	167	201	2
McAllen-Edinburg-Mission, Tex.	78	95	3
Boise City, Idaho	100	117	4
Naples, Fla.	161	177	5
Phoenix-Mesa, Ariz.	14	19	6
Austin-San Marcos, Tex.	41	52	7
Fayetteville-Springdale-Rogers, Ark.	134	148	8
Wilmington, N.Carolina	151	166	9
Provo-Orem, Utah	117	129	10

Urbanization has resulted in dramatic structural changes of the Sonoran Desert landscape. For example, as urbanization progressed large, contiguous desert patches were broken up (Figure 3A, B), with an increasing number of patch types (land use types) occurring in the landscape. The density of patches of various types and thus the density of edges increased exponentially (Figure 3C, D). The overall patch diversity increased steadily due mainly to the increasingly even proportions of dominant land use types (Figure 3E), whereas the geometric shapes of patches in the landscape as a whole became more and more irregular (Figure 3F). In short, urbanization has made the Phoenix landscape structurally more fragmented and complex. These land use and land cover changes due to urbanization inevitably result in significant alterations of the biological composition and spatial configuration of local ecosystems, which in turn have important effects on water, carbon, and nutrient cycles, and the climatic systems at the landscape and regional scales.

Model Structure of HPDM-PHX

Theoretical basis

Our modeling approach is based on the concepts and principles of the hierarchical patch dynamics paradigm, which integrates hierarchy theory with the theory of patch dynamics (Wu and Levin 1994; Wu and Loucks 1995; Reynolds and Wu 1999; Wu 1999). The complexity of ecological systems stems from the multiplicity of spatial patterns and ecological processes, nonlinear interactions among components, and spatial heterogeneity (O’Neill et al. 1986; Wu 1999). Simon (1962) noted that complexity frequently takes the form of hierarchy, whereby a complex system consists of interrelated subsystems that are in turn composed of their own subsystems, and so on, until the level of elementary or “primitive” components is reached. A major utility of hierarchy theory is to simplify complexity (deriving order out of seeming disorder) and thus facilitating prediction and understanding. In the case of building complex yet stable software systems, computer scientists have developed the object-oriented design, analysis, and programming paradigm following a hierarchical approach (Booch 1994). On the other hand, effective human problem-solving procedures also are hierarchical (Newell and Simon 1972). It has been argued that if a complex system is not hierarchical, we may never be able to adequately describe it; if we could, it would be hardly comprehensible (Simon 1973).

Figure 3. Structural changes of the Phoenix metropolitan landscape between 1912 and 1995. Rapid urbanization has resulted in an accelerating increase in landscape fragmentation and structural complexity.

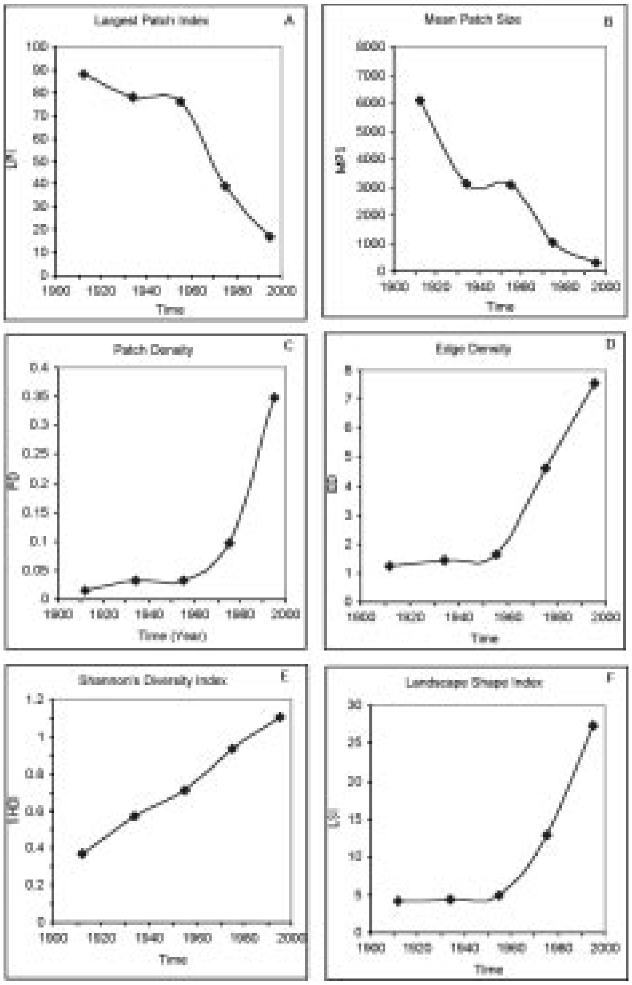


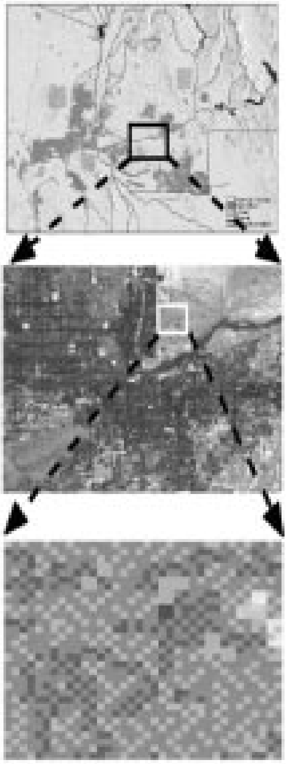
Table 2. Main components of hierarchical patch dynamics paradigm (see Wu and Loucks 1995 and Wu 1999 for details).

- Ecological systems are spatially nested patch hierarchies, in which larger patches are made of smaller patches.
- Dynamics of a given ecological system can be viewed as the composite dynamics of patches at adjacent hierarchical levels.
- Pattern and process interact with each other and their relationship changes with scale.
- Nonequilibrium and stochastic processes are common in ecological systems and can be forces that lead to order or organization at broader scales.
- Persistent ecological systems usually exhibit metastability, which is often achieved through spatial incorporation.

Spatial patchiness is ubiquitous in nature, and patch dynamics are common and essential in many ecological systems. A fundamental flaw in the classic equilibrium paradigm in ecology has been its inability to recognize the importance of heterogeneity and scale linkages of patterns and processes. The recent emphasis transition in ecology, from equilibrium, homogeneity, determinism, and local or single-level phenomena to non-equilibrium, heterogeneity, stochasticity, and hierarchical properties, clearly indicates a paradigm shift in ecology. The hierarchical patch dynamics paradigm explicitly emphasizes the dynamic relationship among pattern, process, and scale in a landscape context (see Table 1). While hierarchy theory provides useful guidelines for “decomposing” complex systems by giving them a “vertical” structure, patch dynamics emphasizes the dynamics of spatial heterogeneity and horizontal interactions between patches in a landscape (Wu and Levin 1994; Wu and Loucks 1995; Wu 1999).

To “decompose” the complexity of the Phoenix metropolitan landscape in terms of its structure and functionality, we adopt the concept of ecosystem functional types (EFTs) (see figure 4), which provides a way of grouping a large number of local ecosystems into a smaller number of categories that each have similar functional properties in terms of biogeochemical cycling (Reynolds et al. 1997; Reynolds and Wu 1999). Thus, EFTs in modeling the functioning of landscapes are similar to trophic levels or guilds in modeling foodweb dynamics. We distinguish three EFTs hierarchically at three distinctive spatial scales: the local ecosystem, landscape, and region (Figure 3). Because the EFT concept emphasizes ecosystem attributes and processes (e.g., primary productivity, biogeochemical cycling, gas fluxes, hydrology), it provides concrete meanings to patches and thus reinforces the less tangible process aspect of the hierarchical patch dynamics paradigm. While these EFTs possess spatial heterogeneity at different spatial and temporal scales, we hypothesize that changes in ecosystem structure and function are much smaller within each patch type than between patch types, and that these changes show detectable scale discontinuities in space (Wu et al. 2000). This hierarchical EFT approach facilitates our understanding of the diversity and distribution of local ecosystems as well as their changes due to urbanization in the region. In addition, it allows us to model similar local ecosystems with the same model structure and similar sets of parameters.

Figure 4. Hierarchical ecosystem functional types for the Phoenix metropolitan area. The EFT hierarchy consists of the local ecosystem, landscape, and region levels, each of which is characterized by a set of distinct features in structure and function.



EFT/Scale
Major Characteristics

Regional EFT (the regional landscape)

- Composed of different types of local landcapes
- Heterogeneous in ecosystem structure and function
- Characterized by the dominant biome and land use type at the regional geographical scale (e.g., an urbanized desert region vs. an agricultural grassland region)

Landscape EFTs (local landscapes)

- Composed of different land use and land cover types
- Heterogeneous in ecosystem structure and function
- Characterized by dominant land use types, such as urban landscapes, rural landscapes, agricultural landscapes, and natural desert landscapes

Local EFTs
(local ecosystems or land cover types)

- Relatively homogeneous vegetation-soil complexes
- Readily detectable from air photos and remote sensing data (e.g., Landsat images)
- Largely corresponds to the categories of the Anderson et al. (1976) level II classification

We define a local EFT (or local ecosystem) as a land use/land cover type with a relatively homogeneous vegetation-soil complex (e.g., an agricultural field, a residential area, a park, a remnant desert fragment). Such local EFTs are readily detectable from air photos and remote sensing data (e.g., Landsat images), and they largely correspond to the categories of the Anderson et al. (1976) level II classification. The landscape EFTs (or local landscapes) are spatial mosaics of a number of local EFTs of different types. They are heterogeneous in ecosystem structure and function, and each dominated by one or a few land use/land cover types. For example, urban landscapes are filled with human constructions, agricultural landscapes are replete with cultivated fields, and natural desert landscapes are dominated by native vegetation. Conceivably, the structure and function of a landscape EFT is a function of both the landscape composition (the variety of patch types and their relative abundance) and the configuration of patches (e.g., patch shape and spatial arrangement). These characteristics are important in determining the behavior of a particular mosaic (e.g., the effect of vegetation on hydrologic flow [Pickup 1985; Turner and Garnder 1991; Wondzell et al. 1996] and exchanges of water, organic matter, propagules, nutrients, sediments, etc. [Sklar and Constanza 1991]. A regional EFT is a mixture of the landscape EFTs or local landscapes, and characterized by the dominant biome and land use type at the regional geographical scale. In our case, the regional EFT is the Phoenix metropolitan region of the Sonoran Desert.

The local, landscape, and regional EFTs provide a hierarchical structure to the system under study and an integrative framework for coupling landscape pattern with ecosystem processes (e.g., biogeochemical cycles). Patch dynamics occur simultaneously over a range of scales at differential rates, and our hierarchical patch dynamics model aims to scale up ecological processes from the local ecosystem to the landscape and then the regional level in the spatially nested hierarchy. Thus, HPDM-PHX has three distinctive hierarchical levels built in its structure: the local ecosystem, the landscape, and the region.

Local ecosystem model

At the local ecosystem level, we use modified versions of two ecosystem process models: CENTURY, a general model of terrestrial biogeochemistry originally developed for the Great Plains grassland ecosystem by Parton et al. (1987, 1988) and PALS, a patch-level arid ecosystem simulator developed by J. F. Reynolds and associates for the Jornada Basin, New Mexico (Reynolds et al. 1993, 1997).

CENTURY simulates the long-term dynamics of carbon, nitrogen, phosphorus, sulfur, and plant production and has been tested for a number of grassland ecosystems worldwide (Parton et al. 1993). The main input data for CENTURY include: monthly average maximum and minimum air temperature, monthly precipitation, lignin content of plant materials, plant C and N, soil texture, atmospheric and soil N inputs, and initial soil C and N levels. Model output includes information on carbon and nitrogen fluxes, net primary production, and soil organic matter. While it contains several submodels, the main governing equations in the CENTURY model are as follows (Parton et al. 1993):

$$\frac{dC_i}{dt} = K_i L_C A C_i \qquad i = 1, 2$$

$$\frac{dC_i}{dt} = K_i A T_m C_i \qquad i = 3$$

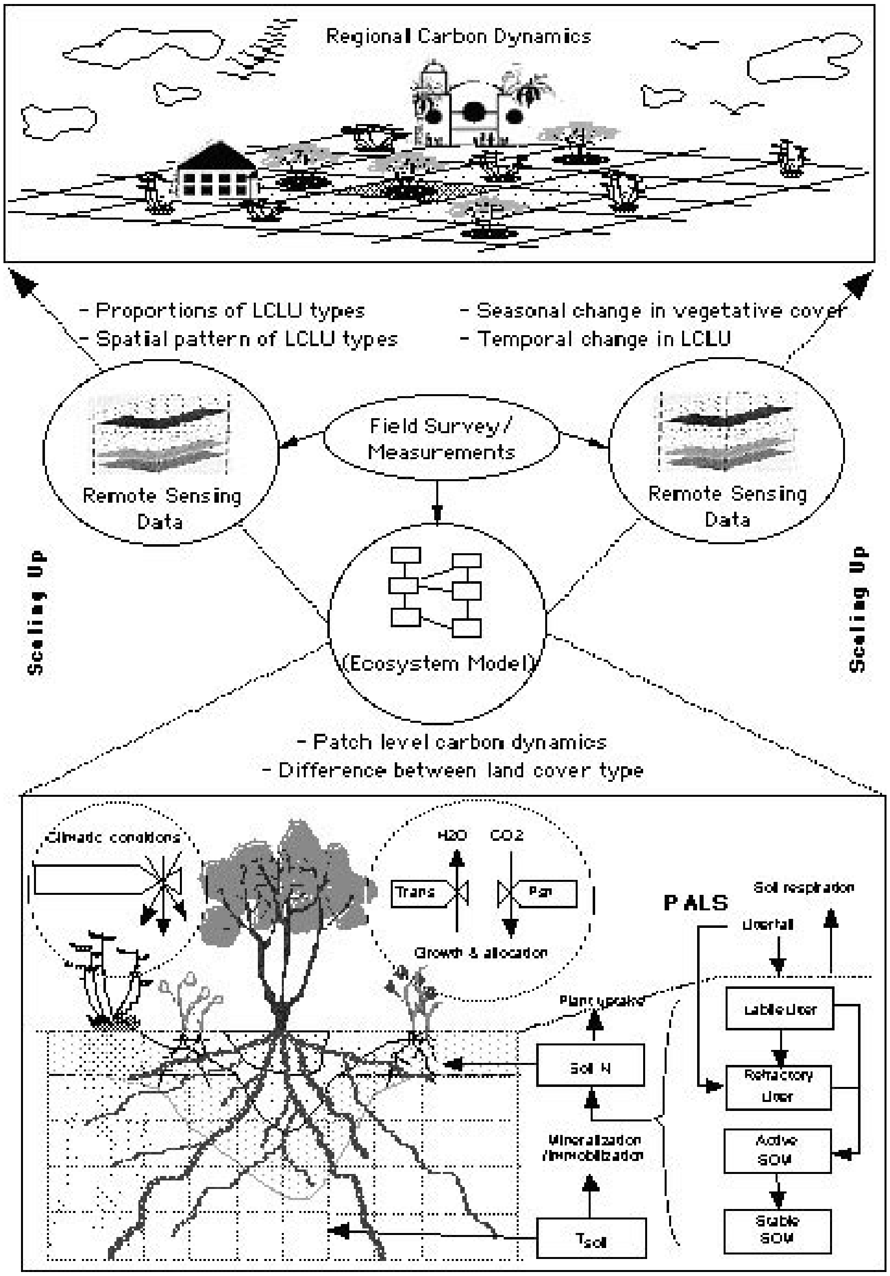
$$\frac{dC_i}{dt} = K_i A C_i \qquad i = 4, 5, 6, 7, 8$$

$$P_p = P_{mx} T_p M_p S_p$$

where C_i is the carbon in the state variable; i =1, 2, 3, 4, 5, 6, 7, 8 denote surface and soil structural material, active soil organic matter, surface microbes, surface and soil metabolic material, slow and passive soil organic matter fractions; K_i is the maximum decomposition rate (year^{-1}) for the ith state variables; A is the combined abiotic impact of soil moisture and soil temperature on decomposition (product of the soil moisture and temperature terms); P_p is the aboveground potential plant production rate ($\text{g m}^{-2}\ \text{month}^{-1}$); P_{mx} is the maximum potential aboveground plant production rate; T_p is the effect of soil temperature on growth; M_p is the effect of moisture on production; and S_p is the effect of plant shading on plant growth.

PALS simulates carbon, water, nitrogen, and phosphorus cycles, and takes into account variations in patch type, plant characteristics, soil resources, and climatic factors (Figure 5). The abiotic components of PALS include micrometeorological conditions (e.g., temperature and moisture within and above the canopy) and soil properties (e.g., water flux, nutrients, temperature). The model PALS is well suited to explore questions related to nutrient cycling and has been parameterized for the Jornada LTER site, California chaparral, and a grassland in Kansas (Reynolds et al. 1997, 1999). Main advantages of using PALS for our project in Phoenix include: (1) it includes the major ecosystem processes in desert systems, (2) the model has been tested on several sites, and (3) the similarity in dominant plant species in the Jornada Basin and the Phoenix area means that model parameterization can be greatly facilitated. We use these two ecosystem models in parallel for the following reasons. CENTURY and PALS represent different levels of mechanistic details in simulating ecosystem processes, and thus comparing them can help us understand what details can be ignored in the process of scaling up from the local ecosystem to the region. Model comparison provides a means for increasing our confidence in estimating ecological variables especially when data are rarely available (Schimel et al. 1997). Moreover, ecosystem models that are tailored for different land cover types encountered in the Phoenix metropolitan area need to be developed based on CENTURY and PALS. We are currently in the process of collecting and compiling input data for running CENTURY and PALS for several major land cover types in the Phoenix metropolitan area. These models will be validated and compared at the local ecosystem level and among different local EFTs before being spatially incorporated into the landscape and regional models.

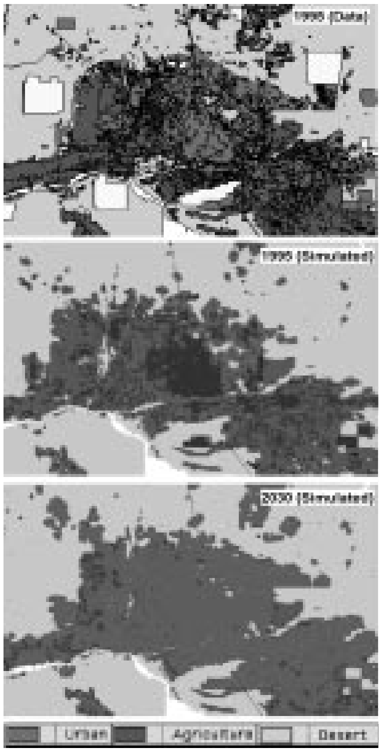
Figure 5. Illustration of the plant functional type based ecosystem model, PALS (Reynolds et al. 1993, 1997), and its role in the scaling up of ecological processes.



Land-use and land-cover change model

The applications of spatial Markovian and cellular automata approaches in modeling vegetation dynamics, land use and land cover change, and urban growth have mushroomed in the past two decades (e.g., Couclelis 1985; Turner 1987; Batty and Xie 1994; Green 1994; Clarke et al. 1997; Wu 1998). The combination of the two approaches is often desirable when stochastic factors are important in determining local transition rules (e.g., Li and Reynolds 1997; Balzter et al. 1998). However, these models usually are not integrated or coupled with ecosystem models. While our land use and land cover (sub)model in HPDM-PHX shares some of the similarities of the Markov–cellular automata approach, it is fully integrated with the ecosystem model. The landscape and regional models conceptually resemble each other, but differ significantly in spatial extent—the landscape model is nested in the regional model. The regional model is the integration, rather than a simple summation, of various component landscapes when horizontal interactions between them are strong and nonlinear.

Figure 6. Land use change in the Phoenix metropolitan area. Top: 1995 land use classification map; middle: simulated land use pattern for 1995; and bottom: projected land use pattern for 2030.



We have developed two land use change models based on the historical land use change data for the Phoenix metropolitan area. The first was a Markov–cellular automata model (Jenerette and Wu 2001), in which parameters and neighborhood rules were obtained both empirically and with a genetic algorithm (GA). The model simulated the change in land use pattern better with the optimized parameter set using GA than with the empirically derived parameter set. While a high degree of accuracy of statistical properties of the simulated results was readily achieved, the spatial structure of land use patterns was only satisfactory at coarse scales. To improve the spatial accuracy, we have developed a hierarchical land use and land cover change model that takes into account both the local neighborhood effects and influences and constraints at broader spatial scales (e.g., ownership and administrative boundaries). The incorporation of information on ownership substantially improved the overall accuracy of the simulated land use pattern (Figure 6; David and Wu 2000). The current version of the model simulates only three land use types. However, to link it with ecosystem process models, we still need to modify the land use change model to represent several important land cover types in the metropolitan area.

The land use and land cover model and ecosystem models are integrated through a framework illustrated in Figures 7 and 8. The land use change model is driven by local rules and top-down constraints which are in turn influenced by socioeconomic processes in the region. Changes in landscape pattern then result in changes in ecosystem processes at both local and regional scales. Although the effects of land use change on ecological processes are often more obvious and dominant than the feedback of changed ecological conditions to land use decisions, the latter does exist and will become more important as urbanization continues to progress. Model validation and applications will involve several steps: 1) to assess the reasonableness of the model structure and the interpretability of functional relationships within HPDM-PHX; 2) to simulate ecosystem processes across a gradient of land cover types; 3) to evaluate the correspondence between model behavior and the expected patterns of model behavior at local ecosystem, landscape, and regional scales; and 4) to conduct a series of sensitivity and uncertainty analysis with HPDM-PHX.

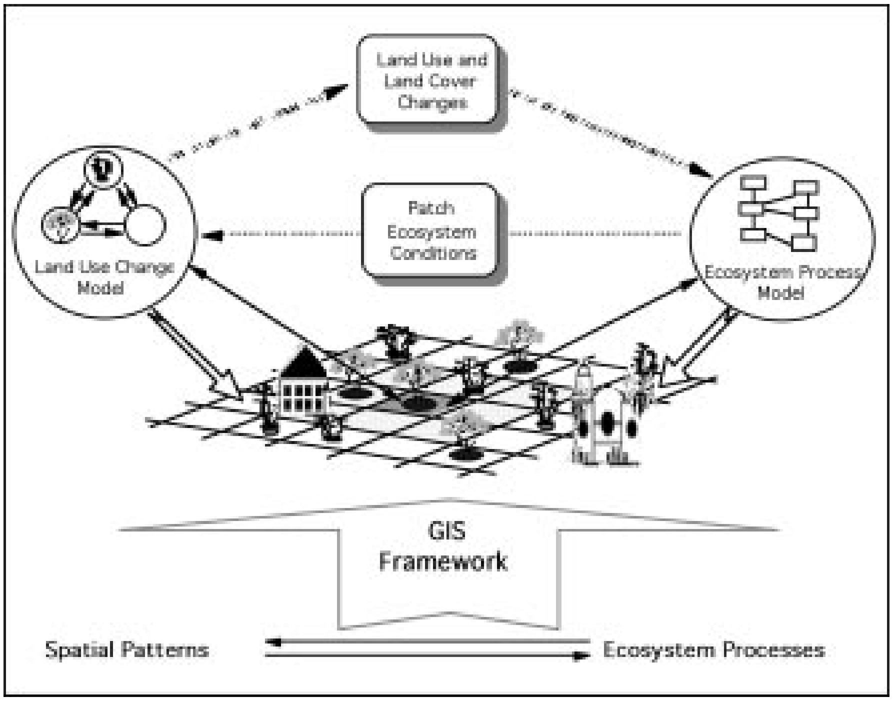


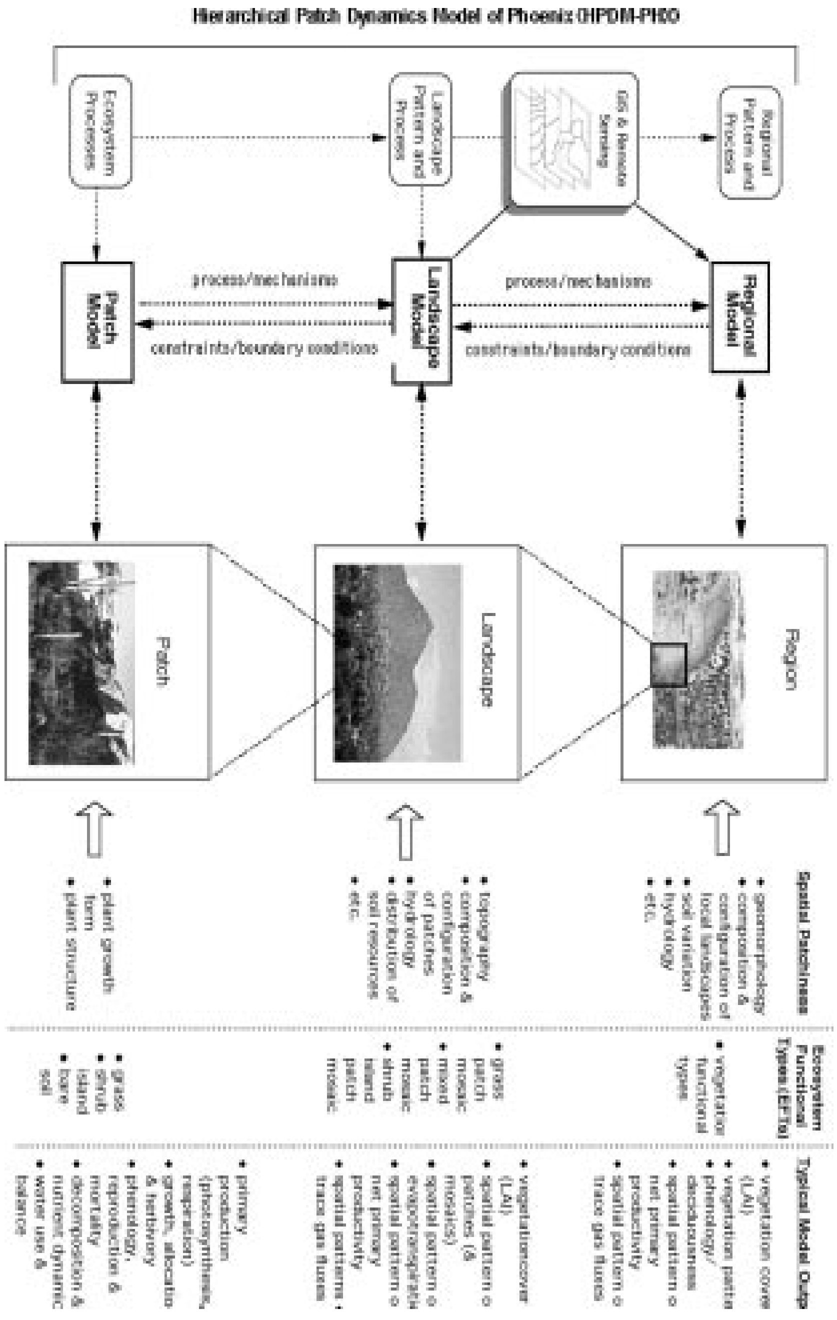
Figure 7. Illustration of the coupling between the ecosystem model and land-use change model within a GIS framework.

Discussion and Conclusions

Land-use change is perhaps the most conspicuous and pervasive human alteration to the surface of the earth. Although the Great Wall of China may look more spectacular from the space, land use change in the forms of urbanization and agriculture has far more profound and widespread ecological consequences. Indeed, habitat destruction is generally identified as the major cause for the loss of biodiversity and habitat destruction occurs mostly in the form of land conversion. There is no other form of land transformation that alters natural environments more radically than urbanization, which is an important global change problem that has received much less attention from either scientists or decision makers as compared to issues of global climate change. It only becomes evident in recent years that land use change is important to regional and global climate change (Houghton 1994; Houghton et al. 1999).

Undoubtedly, rapid global urbanization continues to have significant impacts on the environment as well as on economic, social, and political processes at local,

Figure 8. Schematic representation of the model structure of HPDM-PHX.



regional, and global scales. While the urban environment represents one of the most critical habitats for the survival and civilization of modern humans, they are among the least studied and most poorly understood. One may argue that urban ecology as "ecology in cities" or "human ecology" or "social ecology" in urban areas is as old as ecology itself. But much of the previous research in urban ecology has been more partial than comprehensive, more descriptive than explanatory, and more disciplinarily biased than interdisciplinarily integrated. More comprehensive, integrative perspectives that explicitly consider both ecological and socioeconomic components and their interactions in urban systems are needed. Urban environments exhibit arguably the most conspicuous and complex spatial heterogeneity, which often appears to be hierarchical, and a landscape ecology perspective is thus essential for studying the ecology of cities (Zipperer et al. 2000). We need to understand urban systems as integrative landscapes, i.e., dynamic patch mosaics that are created, modified, maintained, and destroyed by ecological and socioeconomic processes. Undoubtedly, interactions between pattern and process at different scales in urban landscapes may frequently lead to emergent properties that can not be understood by focusing only on individual patches.

Here, we present a hierarchical patch dynamics model, HPDM-PHX, that deals explicitly with spatial heterogeneity, functional complexity, and scale multiplicity in the Phoenix urban landscape. The model is based on the hierarchical patch dynamics paradigm (Wu and Loucks 1995) and the hierarchical scaling ladder approach (Wu 1999). A salient feature of the spatially explicit hierarchical model is that it integrates land use and land cover change with ecosystem processes explicitly at different spatial scales. Although developed for a particular urban landscape, the modeling approach should be applicable to other landscapes of different types. With this model, we hope to effectively address the question: How does urbanization affect the landscape structure and ecosystem processes in the Phoenix metropolitan area?

Solutions to ecological and environmental problems entail understanding and prediction of natural and anthropogenic patterns and processes on broad spatial and temporal scales. However, most ecological studies have been conducted on fine scales and as a consequence our knowledge of our environment also is polarized toward local scales. Thus, a grand challenge for regional scale analysis and assessment is to unravel how spatial heterogeneity at coarse scales affects ecological processes and to develop scaling strategies and rules for extrapolating information from the local ecosystem to the landscape and to the region. We believe that the hierarchical patch dynamics modeling and scaling approach can facilitate the integration between disciplines and across scales in the study of regional patterns and processes.

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