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Modeling the urban ecosystem: a conceptual framework

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Abstract. In this paper I build on current research in urban and ecological simulation modeling to develop a conceptual framework for modeling the urban ecosystem. Although important progress has been made in various areas of urban modeling, operational urban models are still primitive in terms of their ability to represent ecological processes. On the other hand, environmental models designed to assess the ecological impact of an urban region are limited in their ability to represent human systems. I present here a strategy to integrate these two lines of research into an urban ecological model (UEM). This model addresses the human dimension of the Puget Sound regional integrated simulation model (PRISM)—a multidisciplinary initiative at the University of Washington aimed at developing a dynamic and integrated understanding of the environmental and human systems in the Puget Sound. UEM simulates the environmental pressures associated with human activities under alternative demographic, economic, policy, and environmental scenarios. The specific objectives of UEM are to: quantify the major sources of human-induced environmental stresses (such as land-cover changes and nutrient discharges); determine the spatial and temporal variability of human stressors in relation to changes in the biophysical structure; relate the biophysical impacts of these stressors to the variability and spatial heterogeneity in land uses, human activities, and management practices; and predict the changes in stressors in relation to changes in human factors.

1 Introduction

Planning agencies worldwide are increasingly challenged by the need to assess the environmental implications of alternative urban growth patterns—and policies to control them—in a comprehensive manner. Urban growth leads to rapid conversion of land and puts increasing pressure on local and global ecosystems. It causes changes in water and energy fluxes. Natural habitats are reduced and fragmented, exotic organisms are introduced, and nutrient cycles are severely modified. Although impacts of urban development often seem local, they cause environmental changes at larger scales. Assessments of urban growth that are timely and accurate, and developed in a transparent manner, are crucial to achieve sound decisions. However, operational urban models designed to analyze or predict the development of urban areas are still primitive in their ability to represent ecological processes and urban ecosystem dynamics. Though important progress has been made in various areas of urban modeling (Wegener, 1994; 1995), only a few scholars have attempted to integrate the environmental dimension. The majority of these models are designed to answer a set of fundamental but limited planning questions relevant to housing (Anas, 1995; Anas and Arnott, 1991; Kain and Apgar, 1985), land use (Landis, 1992; 1995; Prastacos, 1986; Waddell, 1998), transportation (Boyce, 1986; Kim, 1989) and in some cases the interactions among them (de la Barra, 1989; Echenique et al, 1990; Mackett, 1990; Putman, 1983; 1991; Wegener, 1983).

On the other hand, the environmental models designed to assess the ecological impact of an urban region are limited in their ability to represent human systems. These models represent people as static scenarios of land uses and economic activities and predict human-induced disturbances from aggregated measures of economic development and urban growth. Only with the increasing attention paid to the role of human activities in global environmental change has the need emerged to represent more explicitly human systems in environmental models. Whereas integrated assessment modeling can be traced back to the late 1960s (Forrester, 1969; Meadows et al, 1972), the first generation of operational integrated models has emerged only in the mid-1980s. During the last decade, integrated assessment modeling has been proposed as a new approach to link biophysical and socioeconomic systems in assessing climate change (Dowlatabadi, 1995). At present more than thirty integrated assessment models (IAMs) have been developed (Alcamo, 1994; Dowlatabadi, 1995; Rotmans et al, 1995). The focus of current IAMs is global; however, a new generation of spatially explicit regional integrated models is now emerging (Maxwell and Costanza, 1995). These models have started to treat human decisions explicitly but are still too limited in the representation of human behavior and the heterogeneity of urban land uses (Alberti, 1998).

Recent progress in the study of complex systems (Schneider and Kay, 1994) and the evolution of computer modeling capabilities (Brail, 1990) have made possible a more explicit treatment of the link between human and ecological systems. The development of GIS has provided the capability to integrate spatial processes. However, the greatest challenge for integrating urban and environmental modeling will be in interfacing the various disciplines involved. Urban subsystems have been studied for several decades but progress in urban-ecological modeling has been limited because of the difficulty in integrating the natural and social sciences. A recent National Science Foundation workshop on urban processes pointed out that ecologists, social scientists, and urban planners will need to work together to make their data, models, and findings compatible with one another and to identify systematically where fruitful clusters of multidisciplinary research problems can be developed (Brown, 1997). Such an approach can offer a new perspective on modeling urban systems.

In this paper I build on research in urban and ecological simulation modeling to develop an integrated urban-ecological modeling framework. This framework is part of a current effort to develop an urban–ecological model (UEM) at the University of Washington as part of the Puget Sound regional integrated simulation model (PRISM). UEM simulates the environmental impacts associated with human activities under alternative demographic, economic, policy, and environmental scenarios. Its objectives are to:

(1) Quantify the major sources of human-induced environmental stresses (such as land-cover changes and nutrient discharges);

(2) Determine the spatial and temporal variability of human stressors in relation to changes in the biophysical structure;

(3) Relate the biophysical impacts of these stressors to the variability and spatial heterogeneity in land uses, human activities, and management practices; and

(4) Predict the changes in stressors in relation to changes in human factors.

The development of an integrated urban-ecological framework has both scientific and policy relevance. It provides a basis for developing integrated knowledge of the processes and mechanisms that govern urban ecosystem dynamics. It also creates the basis for modeling urban systems and provides planners with a powerful tool to simulate the ecological impacts of urban development patterns.

2 The urban ecosystem

Early efforts to understand the interactions between urban development and environmental change led to the conceptual model of cities as urban ecosystems (Boyden et al, 1981; Douglas, 1983; Duvigneaud, 1974; Odum, 1963; 1997; Stearns and Montag, 1974). Ecologists have described the city as a heterotrophic ecosystem highly dependent on large inputs of energy and materials and a vast capacity to absorb emissions and waste (Boyden et al, 1981; Duvigneaud, 1974; Odum, 1963). Wolman (1965) applied an 'urban metabolism' approach to quantify the flows of energy and materials into and out of a hypothetical American city. Systems ecologists provided formal equations to describe the energy balance and the cycling of materials (Douglas, 1983; Odum, 1983). Although these efforts have never been translated into operational simulation models, they have laid out the basis for urban-ecological research. Urban scholars were rightly skeptical about the attempts to integrate biological and socioeconomic concepts into system dynamics models. None of these models represented explicitly the processes by which humans affect or are affected by the urban environment. At best, human behavior was reduced to a few differential equations. These models simplified the interactions of natural and social systems so much that they could provide little useful insight for planners and decisionmakers. Since then, however, urban and ecological research has made important progress with respect to understanding how urban ecosystems operate and how they differ from natural ecosystems.

Urban-ecological interactions are complex. Urban ecosystems consist of several interlinked subsystems—social, economic, institutional, and environmental—each representing a complex system of its own and affecting all the others at various structural and functional levels. Urban development is a major determinant of ecosystem structure and influences significantly the functioning of natural ecosystems through (a) the conversion of land and transformation of the landscape; (b) the use of natural resources; and (c) the release of emissions and waste. The earth's ecosystems also provide (d) important services to the human population in urban areas. Thus (e) environmental changes occurring at the local, regional, and global scale—such as the contamination of watersheds, loss of biodiversity, and changes in climate—affect human health and well-being. Humans respond to environmental change through (f) management strategies (figure 1).

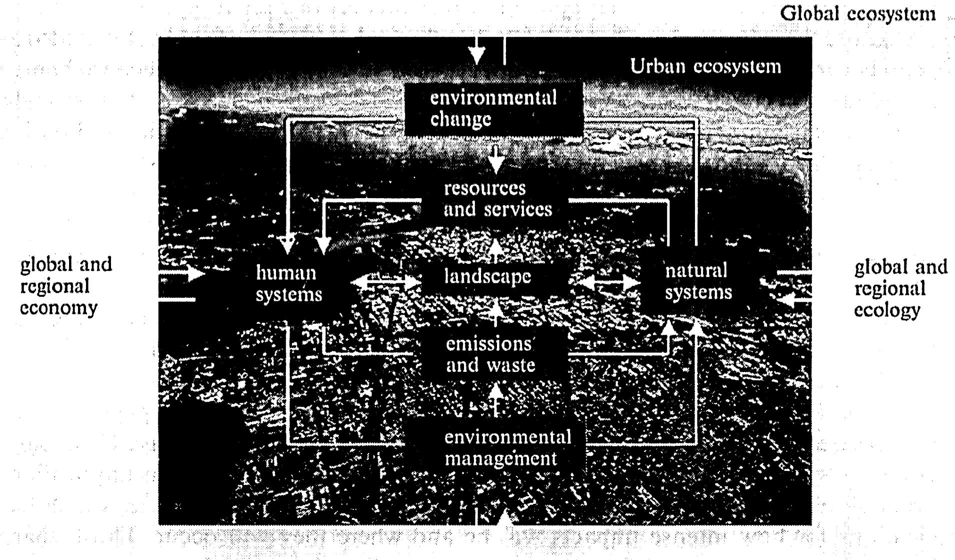

Figure 1. Human–natural systems interactions.

2.1 Human systems

Human drivers are dominant in urban ecosystem dynamics. Major human driving forces are demographics, socioeconomic organization, political structure, and technology. Human behaviors—the underlying rationales for the actions that give rise to these forces—directly influence the use of land and the demand for and supply of resources

(Turner, 1989). In urban areas these forces combine to affect the spatial distribution of activities and ultimately the spatial heterogeneity of natural processes and disturbances. It is increasingly clear to both social (Openshaw, 1995) and natural (Pickett et al, 1994) scientists that it is absurd to model the urban ecosystem without explicitly representing humans in them. Would ecologists exclude other species from models of natural ecosystems? However, as Pickett et al (1997) point out, simply adding humans to ecosystems without representing the way they function is not an adequate alternative. Today, social and natural scientists have the tools to explore the richness of interactions between the social and ecological functions of the human species.

Representing human actors and their institutions in models of urban ecosystems will be an important step towards representing more realistically the human dimension of environmental change. Many of the human impacts on the physical environment are mediated through social, economic, and political institutions that control and order human activities (Kates et al, 1990). Also, humans consciously act to mitigate these impacts and build the institutional settings to promote such actions. They adapt by learning both individually and collectively. How can these dimensions be represented? Lynch (1981, page 115) suggested that "a learning ecology might be more appropriate for human settlement since some of its actors, at least, are conscious, and capable of modifying themselves and thus changing the rules of the game", for example by restructuring materials and switching the path of energy flows. Humans, like other species, respond to environmental change but in a more complex way.

2.2 Natural systems

Environmental forces—such as climate, topography, hydrology, land cover, and human-induced changes in environmental quality—are important drivers of urban systems. Moreover, natural hazards—such as hurricanes, floods, and landslides—can cause significant perturbations in social systems. Most models of human systems, however, simply ignore these forces. In urban models, biophysical processes are at best included as exogenous variables and treated as constants. This is a severe limitation because human decisions are directly related to environmental conditions and changes. Surprisingly, urban modelers cannot remove the behavior of the job market or degradation of housing stocks from their models but can represent the dynamics of urban systems without considering the degradation of the environment and depletion of natural resources.

As we cannot simply add humans to ecological models, representing biophysical processes in urban models will require going beyond simply adding environmental variables to existing urban models. A number of models currently extend their modules to include changes in environmental variables such as air quality and noise (Wegener, 1995). However, these models may misrepresent complex ecological responses. Before we can model these responses, we need to recognize explicitly the properties of ecosystem organization and behavior that govern them. According to Holling (1978, pages 25–26) four properties of ecological systems determine how they respond to change. First, parts in ecological systems are connected to each other in a selective way that has implications for what should be measured. Second, events are not uniform over space, which has implications for how intense impacts will be and where they will occur. Third, sharp shifts in behavior are natural for many ecosystems. Fourth, variability, not constancy, is a feature of ecological systems that contributes to their self-correcting capacity.

2.3 Integrated modeling

In modeling the interactions between human and natural systems, we need to consider that many factors work simultaneously at various levels. Simply linking these models in an 'additive' fashion may not adequately represent system behavior because interactions occur at levels that are not represented (Pickett et al, 1994). On the basis of hierarchy theory, Pickett et al (1994) argue that the consideration of interactions only at the upper level may provide statistical relationship but cannot help explain or predict important feedback for future conditions. This is particularly true in urban ecosystems because urban development controls the ecosystem structure in complex ways. Land-use decisions affect species composition directly through the introduction of species and indirectly through the modification of natural disturbance agents. Production and consumption choices determine the level of resource extraction and generation of emissions and waste. Decisions about investing in infrastructures or adopting control policies may mitigate or exacerbate these effects. Because ecological productivity controls the regional economy, interactions between local decisions and ecological processes at the local scale can result in large-scale environmental change.

We also need to challenge the implicit assumption of most models that decisions are made by one single decisionmaker at one point in time. Urban development is the outcome of dynamic interactions among the choices of many actors, including households, businesses, developers, and governments (Waddell, 1998). These actors make decisions that determine and alter the patterns of human activities and ultimately affect environmental change. Their decisions are interdependent; for example, housing location is affected by employment activity and affects retail activity and infrastructure, which in turn affect housing development.

Human and natural systems, including their equilibrium conditions, change over time. One major problem in describing their relationships is that they operate at very different temporal and spatial scales. The lag times between human decisions and their environmental effects further complicate any attempt to understand these interactions. Moreover, the environmental effects of human actions may also be distanced over space (Holling, 1986). Simulating the behavior of urban-ecological systems requires not only an explicit consideration of the temporal and spatial dynamics of these systems, but also achieving consistency across the different temporal and spatial scales at which various processes operate.

Another source of difficulty in spelling out these interactions is their cumulative and synergistic impacts. In general, environmental impacts become important when their sources are grouped closely enough in space or time to exceed the ability of the natural system to remove or dissipate the disturbances (Clark, 1986). Human stresses in cities may cross thresholds beyond which they may irrevocably damage important ecological functions. In most ecological systems, processes operate in a stepwise rather than a smoothly progressive fashion over time (Holling, 1986). Sharp shifts in behavior are natural. This property of ecosystems requires the consideration of resilience: the amount of disturbance a system can absorb without changing its structure or behavior.

In modeling urban-ecological systems we also need to consider feedback mechanisms between the natural and human systems. These are control elements that can amplify or regulate a given output. At the global level, an example of negative feedback in the biosphere described by ecologists is the homeostatic integration of biotic and physical processes that keeps the amount of CO_2 in the air relatively constant. Feedback loops—both positive and negative—between human and environmental systems are not completely understood. We know that human decisions leading to the burning of fossil fuels and land-use change affect the carbon cycle, and that in turn the associated climate changes will affect human choices, but the nature of these interactions remains controversial. In particular, the feedback of environmental change on human decisions is difficult to represent because environmental change affects all people independently of who has caused the environmental impact in the first place, whereas the impact of each individual decisionmaker on the environment depends on the choices of others (Ostrom, 1991).

Modeling urban-ecological systems will require special attention to uncertainty. Uncertainty can arise from limited understanding of a given phenomenon, systematic and random error, and subjective judgment. Change in natural systems can occur in abrupt and discontinuous ways, and responses can be characterized by thresholds and multiple domains of stability. The knowledge of the environmental systems is always incomplete and surprise is inevitable (Holling, 1995). The explicit characterization and analysis of uncertainty should be a central focus of modeling integration.

3 The environmental dimension in urban models

Although extensive urban research has focused on the dynamics of urban systems, it has been described only partially through numerical models. Most operational urban models focus on a few subsystems such as housing, employment, land use, and transportation, with a limited set of elements influencing their dynamics. These models predict the spatial distribution of activities based on simple spatial interaction mechanisms and economic axioms. No operational urban models have attempted to describe the interactions between urban and environmental processes in a systematic way. Recently a few modelers have started to address a number of direct impacts of human activities, such as air pollution and noise, on the environment. However, as the idealized urban model proposed by Wegener (1994) depicts quite well, only unidirectional links between urban systems and the environment have been conceived in urban modeling. Today a vast literature synthesizes the theoretical and methodological foundation of urban simulation models (Batty and Hutchinson, 1983; Harris, 1996; Mackett, 1985; 1990; Putman, 1983; 1995; Wegener, 1994; 1995; Wilson et al, 1977; 1981). In this section I draw on this literature to explore how environmental variables are considered and how environmental processes are represented.

Operational urban models can be classified according to the approach they use to predict the generation and spatial allocation of activities or according to the solution proposed to a variety of model design questions (see table 1, over). It is difficult to classify the vast literature on urban modeling because of the great variability in emphasis that authors place on theory, techniques, and applications. Moreover, the various approaches are interrelated in complex ways. Six major classes of operational models discussed in the literature are relevant here: those relying on gravity, the economic market, optimization, input–output, microsimulation, and cellular automata.

3.1 Gravity, maximum entropy, and discrete-choice models

The dominant approach in urban modeling can be traced to Lowry's (1964) model, a simple iterative procedure in which nine equations are used to simulate the spatial distribution of population, employment, service, and land use. The model is based on the simple hypothesis that residences gravitate toward employment locations. Two schools of research have provided a statistical basis for the gravity model, guided by Wilson (1967, the entropy-maximizing principle) and McFadden (1973, utility maximization). The results obtained by the two methods were later shown to be equivalent (Anas, 1983). The models most often used by planning agencies in the USA—the disaggregated residential allocation model (DRAM) and the employment allocation model (EMPAL)—are derivatives of Lowry's model using maximum entropy formulation. Developed by Putman (1979), and incrementally improved since the early 1970s, DRAM and EMPAL are currently in use in fourteen US metropolitan areas (Putman, 1996). The integrated transportation land-use package (ITLUP), also developed by Putman (1983), provides a feedback mechanism to integrate DRAM, EMPAL, and various components of the urban transportation planning system (UTPS) models implemented in most metropolitan areas. Although these models substantially improve upon the initial Lowry model, they are based on the same simple assumption. No environmental variables are used in determining the spatial distribution of residence. The allocation of residential and employment activities must of course meet physical constraints and planning restrictions within the available zones. However, other than these constraints no other environmental considerations are included in the equation.

3.2 Economic market-based models

A second urban modeling approach is based on the work of Wingo (1961) and Alonso (1964), who introduce the notion of land-rent and land-market clearing. Wingo was the first to describe the urban spatial structure in the framework of equilibrium theory. Given the location of employment centers, a particular transportation technology, and a set of households, his model determines the spatial distribution, value, and extent of residential land requirements under the assumption that landowners and households both maximize their return. Wingo uses demand, whereas Alonso uses bid-rent functions to distribute the land to its users. The aim of both models is to describe the effects of the residential land market on location. Under this approach, households are assumed to maximize their utility and select an optimum residential location by trading off housing prices and transportation costs. The trade-offs are represented in a demand or bid-rent functional form which describes how much each household is willing to pay to live at each location. Anas (1983) introduced discrete-choice behavior into models with economically specified behavior and market clearing. Two models that use this approach are UrbanSim developed by Waddell (1998), and CUF2 developed by Landis and Zhang (1998a; 1998b). Both models are based on random utility theory and make use of logit models to implement key components. However, they differ in a substantial way. UrbanSim models the key decisionmakers—households, businesses, and developers—and simulates their choices that impact urban development. It also simulates the land market as the interaction of demand and supply with prices of land and buildings adjusting to clear the market. UrbanSim simulates urban development as a dynamic process as opposed to a cross-sectional or equilibrium approach. CUF2 models land-use transition probabilities based on a set of site and community characteristics such as population and employment growth, accessibility, and original use in the site and surrounding sites.

As indicated in table 1, most current operational models are based on an economic market-based approach and rely on random utility or discrete-choice theory. In these models, environmental variables are not part of the equation, except for environmental constraints. The value of the ecological services—such as clean air, clean water, and flood control—that ecosystems provide to households are not reflected in market prices. This is a severe limitation, because changes in environmental quality and other ecological services provided by ecosystems will affect the market behavior of the households (Mäler et al, 1994).

3.3 Mathematical programming-based models

A third approach to describing urban activity allocation is based on optimization theory. By using mathematical programming, these models design spatial interaction problems in order to optimize an objective function that includes transportation and activity establishment costs. Herbert and Stevens (1960) used linear programming to simulate the market mechanisms that affect location. Wheaton (1974) developed an optimization model by using nonlinear programming. More recently Boyce et al (1993) and Boyce and Southworth (1979) have explored the options for integrating spatial interactions of residential, employment, and travel choices within a single optimized modeling framework. The projective optimization land-use system (POLIS) developed by Prastacos (1986) is one of the few optimization land-use models used in

Table 1. Urban models.

Model	Subsystems	Theory or approach	Population or sectors
Clarke	Land use and/or cover	Complex systems Cellular automata Monte Carlo simulation	Aggregated
CUF2	Population Employment Housing Land use	Random utility Multinomial logit	Aggregated
IRPUD	Population Employment Housing Land use	Random utility Network equilibrium Land-use equilibrium Monte Carlo micro-simulation	Partially disaggregated
ITLUP	Population Employment Land use Travel	Random utility Maximization Network equilibrium	Partially disaggregated
Kim	Population Employment Transport Travel	Random utility General equilibrium Input–output	Aggregated
MASTER	Population Employment Housing Land use Travel	Random utility Maximization Monte Carlo micro-simulation	Disaggregated
MEPLAN	Population Employment Housing Land use Transport Travel	Random utility Maximization Market clearing Input–output	Aggregated
POLIS	Population Employment Housing Land use Travel	Random utility Optimization	Aggregated
TRANUS	Population Employment Housing Land use Transport Travel	Random utility Network equilibrium Land-use equilibrium Input–output	Aggregated
UrbanSim	Population Employment Housing Land use	Random utility Partial equilibrium Multinomial logit	Partially disaggregated

Model	Time	Space	Environmental factors	Source
Clarke	Dynamic	Dynamic Grid cell	Land cover Topography Hydrography	Clarke et al, 1997
CUF2	Static	Static 100 × 100 m grid cell	Percent slope	Landis and Zhang, 1998a; 1998b
IRPUD	Quasidynamic	Static Zone	Zone space constraints CO_2 emissions by transport	Wegener, 1995
ITLUP	Static	Static Zone	Zone space constraints Mobile source emissions	Putman, 1983; 1991
Kim	Static	Static Zone	Zone space constraints	Kim, 1989
MASTER	Quasidynamic	Static Zone	Zone space constraints	Mackett, 1990
MEPLAN	Static	Static Zone	Zone space constraints	Echenique et al, 1990
POLIS	Static	Static Zone	Zone space constraints	Prastacos, 1986
TRANUS	Static	Static Zone	Zone space constraints	de la Barra, 1989
UrbanSim	Quasidynamic	Static Parcels	Topography Stream buffers Wetlands 100 years floodplain area	Waddell, 1998

planning practice. This model, which has been implemented in the San Francisco Bay area, seeks to maximize both the location surplus and the spatial agglomeration benefits of basic employment sectors. As in previous models, only land availability is included as a determinant of employment allocation to zones.

3.4 Input – output models

Another important contribution from economic theory to urban modeling is the spatially disaggregated intersectoral input – output (I – O) approach, developed initially by Leontief (1967). The approach provides a framework for disaggregating economic activities by sector and integrating them into urban spatial interaction models. This transforms the basic structure of an I – O table, allowing the modeler to estimate the direct and indirect impacts of exogenous change in the economy on a spatially disaggregated scale. Operational urban models that use such an approach include MEPLAN, TRANUS, and the models developed by Kim (1989). MEPLAN includes three modules: LUS, the land-use model; FRED, which converts production and consumption into flows of goods and services; and TAS, a transportation model which allocates the transport of goods and passengers to travel modes and routes. The land-use component of MEPLAN is based on a spatial disaggregation of production and consumption factors that include goods, services, and labor. Total consumption is estimated by using a modified I – O framework subsequently converted into trips. MEPLAN, TRANUS, and Kim's models use I – O tables to generate interregional flows of goods. MEPLAN uses the results of the I – O framework to evaluate environmental impacts. I – O models have been extended to include environmental variables and incorporate pollution multipliers, but no urban model has attempted to implement this approach for describing economic-ecological interactions. The regional applications of such an approach have encountered various difficulties related to the specification of the ecological interprocess matrix and the assumption of fixed coefficients. A major limitation is that inputs and outputs are measured in values as opposed to physical flows.

3.5 Microsimulation

One major limitation in the way most urban models represent the behavior of households and businesses stems from the fact that they are aggregated and static. Individuals behave in ways that are influenced by their characteristics and the opportunities from which they choose. Without the explicit representation of these individuals it is impossible to predict the trade-offs they make between jobs, residential locations, or travel modes. A distinct approach to model the behavior of individuals is microanalytic simulation that explicitly represents individuals and their progress through a series of processes (Mackett, 1990). Microsimulation is a modeling technique that is particularly suitable for systems where decisions are made at the individual unit level and where the interactions within the system are complex. In such systems, the outcomes produced by altering the system can vary widely for different groups and are often difficult to predict. In microsimulation the relationships between the various outcomes of decision processes and the characteristics of the decisionmaker can be defined by a set of rules or by a Monte Carlo process. Furthermore, the actions of a population can be simulated through time and incorporate the dynamics of demographic change. An example is the microanalytical simulation of transport, employment, and residence (MASTER) model developed by Mackett (1990). The model simulates the choices of a given population through a set of processes. The outcome of each process is a function of the characteristics of the household or business, the set of available choices, and a set of constraints. This approach is applied less extensively in Wegener's (1982) Dortmund model. Although these models do not explicitly use microsimulation for modeling environmental impacts, it is clear that the greater disaggregation of the actors and behaviors has enormous advantages for modeling consumer behavior and environmental impacts.

3.6 Cellular automata

The use of cellular automata (CA) has been proposed to model spatially explicit dynamic processes not currently represented in urban models (Batty and Xie, 1994; Couclelis, 1985; White et al, 1997; Wu, 1998). Existing operational models are spatially aggregated and, even when they use or produce spatially disaggregated data, they rely on simple spatial geometric processing. A number of modelers have stressed the need to represent more realistically the spatial behavior of urban actors (White and Engelen, 1997). CA consist of cells arranged in a regular grid that change state according to specific transition rules. These rules define the new state of the cells as a function of their original state and local neighborhood. Clarke et al (1997) have developed a CA urban growth model as part of the Human-Induced Land Transformations Project initiated by the US Geological Survey. The model aims to examine the urban transition in the San Francisco Bay area from a historical perspective and to predict regional patterns of urbanization in the next 100 years (Clarke et al, 1997). These predictions are then used as a basis to assess the ecological and climatic impacts of urban change. There are four types of growth: spontaneous, diffusive, organic, and road-influenced. Five factors regulate the rate and nature of growth: a diffusion factor which determines the dispersiveness; a breed coefficient which specifies the likelihood of a settlement to begin its growth cycle; a spread coefficient which regulates growth of existing settlements; a slope resistance factor which influences the likelihood of growth on steeper slopes; and a road gravity factor which attracts new settlements close to roads.

4 The human dimension in environmental models

Environmental models have been developed for several decades to simulate atmospheric, land, and ecosystem dynamic processes, and to help assess the effects of various natural and human-induced disturbances. However, the use of these models in environmental management has become widespread only in the last three decades (Jørgensen et al, 1995). Since the early 1970s major environmental problems such as eutrophication and the fate of toxic substances have attracted the attention of environmental modelers, and very complex models were developed. More recently, the prospect of major changes in the global environment has presented the scientific community with the challenge of modeling the interactions between human and ecological systems in an integrated way. Over these decades a rich literature on environmental models has developed, but this is well outside the scope of this paper. In this review I focus on the treatment of the human dimension in these models (table 2, over).

4.1 Climate and atmospheric models

Atmospheric models can be classified according to the scale of the atmospheric processes they represent. At the global scale, sophisticated coupled atmospheric–ocean general circulation models (AOGCM) predict climate conditions by considering simultaneously the atmosphere and the ocean (Washington and Meehl, 1996). Using a set of climate parameters (that is, solar constant) and boundary conditions (that is, land cover, topography, and atmospheric composition), these models determine the rate of change in climatic variables such as the temperature, precipitation, surface pressure, and soil moisture associated with alternative scenarios of CO_2 concentrations. These models are currently being used by the Intergovernmental Panel on Climate Change (IPPC) to assess the impact of alternative greenhouse-gases emission scenarios up to the year 2100.

Regional models have been developed primarily to tackle the issue of acid rain. Aggregated emissions of sulfur and nitrogen compounds, estimated on the basis of

Table 2. Environmental models.

Model	Class	Media or subsystems	Scale
NCAR	Ocean – climate general circulation model	Climate – ocean	Global
CMAQ	Atmospheric model	Meteorological emission, Chemistry transport	Local or regional
UAM	Atmospheric model	Photochemical processes	Local or regional
OBM	Biogeochemical model	Terrestrial biosphere	Global
HRBM	Biogeochemical model	Terrestrial biosphere	Regional
DHSVM	Distributed hydrology soil vegetation model	Hydrology	Regional
JABOWA/ FORET	Population – community dynamic model	Trees	Local
CENTURY	Biogeochemical model	Nutrient cycles	Local
GEM	Process-oriented ecological model	Ecosystems	Local
PLM	Process-oriented landscape model	Terrestrial landscape	Regional
IMAGE 2	Process-oriented integrated simulation model	Energy – industry Terrestrial Environment Atmosphere – ocean	Global, 13 regions
ICAM-2	Optimization – simulation model	Climate Economy Policy	Global, 7 regions
RAINS	Optimization – simulation model	Emissions Atmospheric transport Soil acidification	Continental, Europe
TARGETS	Integrated simulation model	Population or health Energy or economics Biophysics, land, soils, or water	Global, 6 regions

Model	Time	Space	Human factors	Source
NCAR	Dynamic Minutes 100 years	Dynamic 4.5° × 7.5° (latitude × longitude) 9 layers	CO_2 concentration scenarios	Washington and Meehl, 1996
CMAQ	Dynamic 8-hour to 72-hour period	Dynamic Variable 3-D grid	Emissions of atmospheric pollutants	Novak et al, 1995
UAM	Dynamic 8-hour to 72-hour period	Dynamic Variable 3-D grid	Emissions of photochemical pollutants	Morris and Meyers, 1990
OBM	Dynamic 1 year	Dynamic 2.5° × 2.5°	Land use CO_2 concentration scenarios	Esser, 1991
HRBM	Dynamic 6 days	Dynamic 0.5° × 0.5°	Land use CO_2 concentration scenarios	Esser et al, 1994
DHSVM	Dynamic Hours	Dynamic 30 - 100 m	Land cover	Wigmosta et al, 1994
JABOWA/ FORET	Dynamic Up to 500 years 1 year	Dynamic 10 × 10 m grid	Land cover	Botkin, 1984
CENTURY	Dynamic 1 month Thousands of years	Dynamic 1 × 1 m grid cell	Land cover CO_2 concentration	Parton et al, 1987
GEM	Dynamic 12 hours	Dynamic 1 km cell	Land cover	Fitz et al, 1999
PLM	Dynamic 1 week	Dynamic 200 m grid 1 km grid	Land cover	Costanza et al, 1995
IMAGE2	Dynamic 1 day to 5 years	Dynamic Variable from 0.5° × 0.5° grid to region	CO_2 emissions Land use	Alcamo, 1994
ICAM-2	Dynamic 5 years	Static Latitude bands	Explicit treatment of uncertainties	Dowlatabadi and Ball, 1994
RAINS	Dynamic 1 year	Static 150 km × 150 km in deposition submodel and 0.5° × 1.0° impact submodel	Energy use Sulfur emissions	Alcamo et al, 1990
TARGETS	Dynamic 1 year	Static Regions	Energy use Water use Emissions Land cover	Rotmans et al, 1994

emissions factors of point, area, and mobile sources, serve as inputs for long-range transport models which predict the emissions and regional distribution of acid compounds. Two regional air-quality models developed by the Environmental Protection Agency (EPA) are the regional oxidant model (ROM) (Young et al, 1989) and the regional acid-deposition model (RADM) (Chang et al, 1990).

Emission factors for criteria pollutants are also used as inputs for urban atmospheric models. The EPA's urban airshed model (UAM) is a three-dimensional photochemical grid model designed to simulate the relevant physical and chemical processes affecting the production and transport of tropospheric ozone (Morris and Meyers, 1990). The basis for the UAM is a mass balance equation in which all of the relevant emissions, transport, diffusion, chemical reactions, and removal processes are expressed in mathematical terms (Morris and Meyers, 1990). A more recent model developed by EPA is the community multiscale air-quality (CMAQ) model. CMAQ is a third generation air-quality model that treats multiple pollutants simultaneously up to continental scales and incorporates feedbacks between chemical and meteorological components. The CMAQ modeling system contains three modeling components: a meteorological model, emission models for human-made and natural emissions, and a chemistry-transport model. The target-grid resolutions and domain sizes for CMAQ range spatially and temporally over several orders of magnitude. In these models human decisions are represented by emission factors developed by the EPA (Novak et al, 1995).

4.2 Biogeochemical models

A number of global models aim to simulate the impacts of human activities on biogeochemical cycles—the continuous cycling of carbon, nitrogen, and sulfur through the biosphere which sustains life. Two examples are the Osnabrück biosphere model (OBM) and the high-resolution biosphere model (HRBM) developed in Germany (Esser, 1991; Esser et al, 1994). These spatially explicit models simulate the dynamics of the carbon cycle through the terrestrial biosphere in response to climate and CO_2 forcing. OBM uses a grid cell of $2.5° \times 2.5°$ (latitude $\times$ longitude) and an annual time step. HRBM has a greater spatial resolution ($0.5° \times 0.5°$) and a finer (6 days) time step. They compute the storage and transfer of carbon from each cell by using a series of rate constants and coefficients. In these models human impacts are generated through scenarios of land-use change and CO_2 concentrations. However, these models do not represent more complex interactions between human behavior and biogeochemical cycles. For example, land-use decisions affect the carbon cycle not only directly but also through its impact on transportation patterns and related CO_2 emissions in the atmosphere.

4.3 Hydrological models

Human-induced changes in water and sediment fluxes have been modeled through run-off models. Human activities can cause four major impacts on the hydrological cycle: floods, droughts, changes in surface and groundwater regimes, and water pollution (Rogers, 1994). Primarily, changes in land uses and channelization cause these impacts. The water balance model developed by Vorosmarty and Moore (1991) is an example of a regional model used to predict changes in the water cycle. It uses spatially explicit biophysical data including precipitation, temperature, vegetation, soils, and elevation to predict run-off, evapotranspiration, river discharge, and floodplain inundation at a grid resolution of $0.5° \times 0.5°$. Another example is the distributed hydrology soil vegetation model (DHSVM), a spatially distributed hydrologic model developed by Wigmosta et al (1994) for use in complex terrain. The DHVSM represents dynamically the spatial distribution of land-surface processes (that is, soil moisture, snow cover, evapotranspiration, and run-off) at high resolution (typically 30 – 100 m). While their aim is to assess the hydrologic effects of land-use decisions, the human dimension in these models is represented by static scenarios of climate and land-use changes.

4.4 Ecosystem models

Ecosystem dynamics can be simulated through three classes of models: plant physiology, population community, and ecosystem (Melillo, 1994). Plant physiology models are used to predict plant growth and water balance and are particularly useful in the analysis of plant responses to climate change and CO_2. Population community models simulate the dynamics of tree growth on small forest patches as influenced by limiting factors, space, and stand structure. Ecosystem models are process-based models that take into account carbon and nutrient fluxes. These models, such as CENTURY and GEM, simulate changes in ecosystem structure and function over a period from decades to centuries. CENTURY computes the flow of carbon, nitrogen, phosphorus, and sulfur through four compartments: soil organic matter, water, grassland, and forest (Parton, 1996). GEM simulates ecosystem dynamics for a variety of habitats by incorporating ecological processes that determine water levels, plant production, and nutrient cycling associated with natural and human-induced disturbances. Inputs in these models are static scenarios of nutrient loads and climate change.

4.5 Earth systems models

Important progress in linking biophysical models has been made through the development of earth systems models (Meyer and Turner II, 1994). In 1990 the US Global Change Research Program (USGCRP) set itself the goal of linking general circulation models, land-surface parametrization models, and ecosystem dynamics models to predict energy and water fluxes between land and the atmosphere (US Global Change Research Program Act, 1990). However, coupling atmospheric, terrestrial, and ecosystem dynamics is not a straightforward task owing to the different spatial and temporal resolutions between land-surface and ecosystem processes. Models can be integrated through a nested approach that allows users to calculate parameter values across models of various resolutions. With the help of advances in computer processing these models are rapidly increasing in sophistication. However, earth systems models are still too limited in representing the complex interactions between the earth's subsystems and human systems. Human actions in these models are represented by static scenarios of highly aggregated land uses and pollution loads into the atmosphere, water, and land.

4.6 Integrated assessment models

In response to the need to incorporate a more realistic representation of human and ecological processes in existing models, natural and social scientists have built integrated assessment models (IAMs). IAMs incorporate two tasks. They allow users (1) to integrate various knowledge domains to predict environmental changes associated with the behavior of complex socioeconomic and environmental systems, and (2) to assess the likelihood, importance, and implications of predicted environmental changes to inform policymaking. IAMs have gained interest primarily as a new approach to link biophysical and socioeconomic systems in assessing global environmental change (Dowlatabadi, 1995; Parson and Fisher-Vanden, 1995; Rotmans et al, 1995; Weyant et al, 1996). Since 1994 the USGCRP has made IA modeling its central priority.

The integrated model to assess the greenhouse effect (IMAGE 2) developed by the Dutch National Institute of Public Health and Environmental Protection (RIVM) is designed to simulate the dynamics of the global society–biosphere–climate system (Alcamo, 1994). IMAGE 2 is the first IAM to represent environmental phenomena at a fine spatial scale. It performs many calculations on a global grid ($0.5° \times 0.5°$). The time horizon extends to the year 2100 and the time steps of different submodels vary between one day and five years. The model consists of three fully linked subsets of models: the energy–industry system; the terrestrial environment system; and the atmosphere–ocean system.

The energy–industry models compute the emissions of greenhouse gases in thirteen world regions as a function of energy consumption and industrial production. End-use energy consumption is computed from various economic driving forces. It includes four submodels: energy economy, energy emissions, industrial production, and industrial emissions. The terrestrial environment models simulate the changes in global land cover on a grid scale based on climatic and economic factors. The roles of land cover and other human factors are then taken into account to compute the flux of CO_2 and other greenhouse gases from the biosphere to the atmosphere. This subsystem includes five submodels: agricultural demand, terrestrial vegetation, land cover, terrestrial carbon, and land-use emissions. The atmosphere–ocean models compute the buildup of greenhouse gases in the atmosphere and the resulting zonal-average temperature and precipitation patterns. Four submodels are included: atmospheric composition, zonal atmospheric climate, oceanic climate, and oceanic biosphere and chemistry.

IMAGE 2 makes a major scientific contribution by representing many important feedback mechanisms and linkages between models in the subsystems, and between subsystems. IMAGE 2 links explicitly and geographically the changes in land cover with the flux of CO_2 and other greenhouse gases between the biosphere and atmosphere, and, conversely, takes into account the effects of climate in the changing productivity of the terrestrial and oceanic biosphere. It also dynamically couples natural and human-induced emissions with chemical and physical processes in the atmosphere and ocean and then feeds climate change back to the biosphere.

Another example of IAM is ICAM-2, an optimization model developed at Carnegie Mellon University to assess the effectiveness of climate change policies (Dowlatabadi and Ball, 1994). Although most IAMs focus on climate changes, more recent efforts in integrated modeling have attempted to address a broader set of policy questions. TARGETS (tool to assess regional and global environmental and health targets for sustainability) is an example of a model designed to inform the policy debate on a broader set of global change issues related to economic development and sustainability. TARGETS is currently being developed by RIVM as part of its research program on global dynamics and sustainable development (Rotmans et al, 1994). This model aims to assess simultaneously several human stresses on various global and regional issues such as climate change, tropospheric ozone, deforestation, and the dispersion of chemicals. None of the current integrated modeling efforts, however, has addressed urban ecosystems.

5 A conceptual framework for modeling the urban ecosystem

In this section I present a framework to integrate urban and ecological modeling. This framework is part of a strategy that Alan Borning, Paul Waddell, and I have developed at the University of Washington to build an urban ecological model as part of PRISM, which is a multidisciplinary initiative aimed at developing a dynamic and integrated understanding of the environmental and human systems in the Puget Sound. Our aim is to integrate the various components of the Puget Sound into a metamodel. The urban-ecological model addresses the societal dynamics of environmental change.

5.1 Model objectives

One major aim of the PRISM human dimension is to describe how human actions generate environmental stresses and to predict the impacts of changes in human actions on the biophysical system. Human decisions in PRISM will be treated explicitly through the development of UEM which will represent the principal actors and behaviors affecting environmental change. This model will predict the environmental stresses associated with urban development and related changes in land-use and human activities under alternative demographic, economic, environmental, and policy scenarios. We start with the assumption that urban development is the outcome of the interactions between the choices of households, businesses, developers, and governments. These actors make decisions that alter the patterns of land-use and human activities. UEM will be designed to model these processes in a dynamic and spatially explicit framework that links these decisions to changes in the biophysical structure of the Puget Sound. This is a first step, we believe, toward coupling human and biophysical processes in the urban ecosystem.

5.2 Conceptual framework

The urban ecosystem will be represented by a number of human and biophysical variables. Figures 2(a) and 2(b) are schematic diagrams of the major subsystems

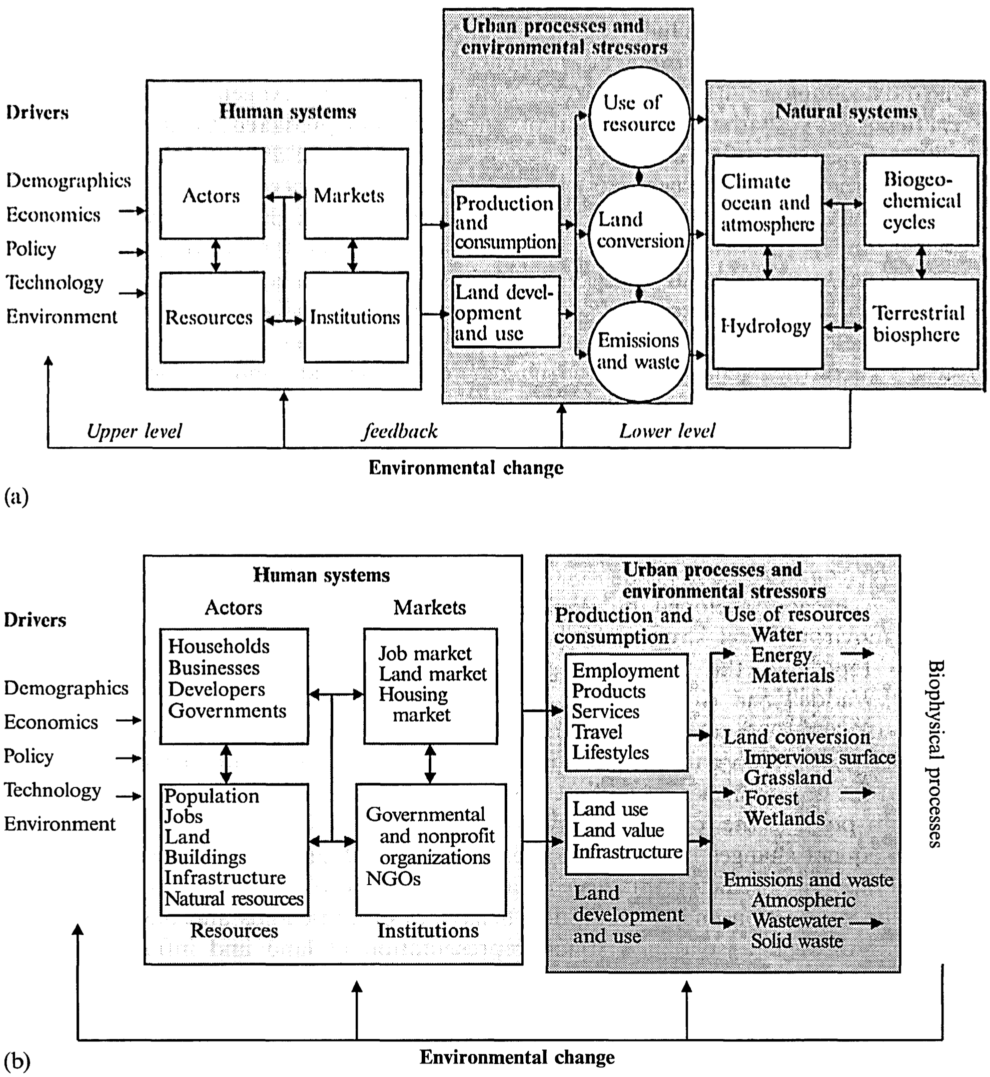

Figure 2. Urban ecological frameworks.

considered in the model and their interactions. Human systems are represented by four components: actors, resources, markets, and institutions. Major resource-stock variables are population, economic activities (jobs), land, buildings (residential and nonresidential), infrastructure (transportation, energy, water supply, wastewater), and natural resources (water, forests, and ecosystems). The *actors*—households, businesses, developers, and governments—make decisions about *production and consumption* activities and their location, leading to changes in *land use.* These decisions affect, directly and indirectly, the biophysical system through *land conversion*, the *use of resources*, and the generation of *emissions and waste.* Businesses make choices about production, location, and management practices. Households make choices about employment, location, housing type, travel mode, and other lifestyle factors leading to consumption. Developers make decisions about investing in development and redevelopment. Governments make decisions about investing in infrastructures and services and adopting policies and regulations. Decisions are made at the individual and community levels through the economic and social institutions. The actors interact in three submarkets: the job market, the land market, and the housing market. These actors also interact in nonmarket institutions including governmental and other nonprofit and nongovernmental organizations. Decisions are influenced by demographic, socioeconomic, political, and technological factors represented in the model by exogenous scenarios, and are affected by environmental conditions and changes predicted by the biophysical modules. The types of activity and the context in which the activity takes place both determine the level of pressure and the patterns of disturbances.

The output of the urban ecosystem model will serve as the input to several biophysical models such as the climate and atmospheric model, the hydrology model, and the aquatic and terrestrial ecosystem models. The urban-ecological framework is designed to take into account the interactions between the ecological impacts and urban processes at various levels of the hierarchy of processes. These include feedback from the ecological changes on the choices of households and business locations, market prices, availability of land and resources, and regulation. Feedback is also included at the levels of the processes of production and consumption, and land development.

5.3 Model structure

Using the framework described above we plan to develop an object-oriented model that links urban and ecological processes. We build on UrbanSim, an existing urban simulation model developed by Waddell (1998), to predict three types of human-induced environmental stressors: land conversion, use of resources, and emissions. Figure 3 represents the urban-ecological dynamics that the integrated model will address (Waddell and Alberti, 1998). Our initial focus will be on modeling changes in land use and land cover. Instead of linking the urban and ecological components sequentially, we propose to integrate them at a functional level. Our current strategy is to extend the object properties and methods now implemented in the UrbanSim model. UrbanSim predicts the location behaviors of households, businesses, and developers, and consequent changes in land uses and physical development. These are among the required inputs to predict the changes in land cover and ecological impacts. We propose to add the production and consumption behaviors of households and businesses, and link them through a spatially explicit representation of land and infrastructure to ecological processes.

The UrbanSim data structure is currently being revised from the current aggregate approach to one based on microsimulation and from a zone description of space to a high-resolution grid structure (Waddell and Alberti, 1998). We use a combination of

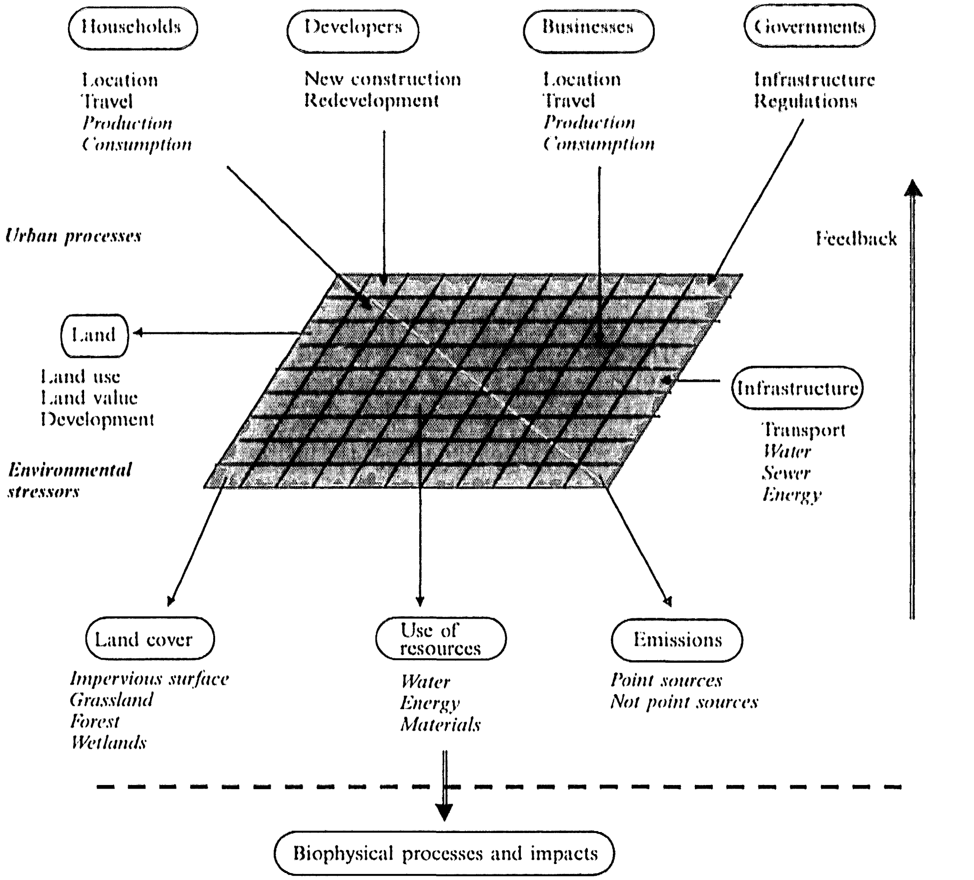

Figure 3. UEM structure. Note that processes in italics are new components not presently modeled in UrbanSim (source: Waddell and Alberti, 1998).

the aggregated economic I – O methodology and a microsimulation approach to model the production and consumption behavior of individual businesses and their location. A microsimulation approach is also being implemented to model households' choices of jobs, location, and lifestyles. A highly disaggregated representation of households (that is, individuals) and businesses (that is, the standard industrial classification) will allow us to represent explicitly detailed production, consumption, and location behaviors of various actors and to link these behaviors to ecological impacts.

The urban ecosystem model simulates three types of human-induced environmental stressors: land conversion, use of resources, and emissions. Changes in land use – cover will be modeled based on a set of land use – cover determinants, including original use, accessibility, environmental conditions, cost of conversion, and policy constraints. Land conversion will be predicted based on the changes in housing and commercial buildings, household and business characteristics occupying these buildings, and the biophysical characteristics of the land parcels. The resource models will be represented by various modules, each predicting the use of water, energy, and materials, which will be linked to the UEM on the basis of consumption and infrastructure capacity. The emission modules are mass-balance models that will simulate pollution loads into the atmosphere, water, and soil, and relative contributions from the various media.

5.4 Spatial and temporal dynamics

Efforts to represent more realistically the spatial and temporal dynamic behavior of urban ecosystems are particularly relevant if urban and ecological processes need to be integrated. An explicit treatment of space will be realized in two steps. First, we will develop and implement a grid of variable resolution to georeference all spatially located objects in the model. This gives us the flexibility to vary spatial resolutions for different processes and to test spatial scale effects on model predictions. The second step will involve the explicit treatment of spatial processes across the area. The grid provides a foundation for linking urban spatial processes to processes that occur in the natural environment.

We will also improve the treatment of time. Most urban models assume a static cross-sectional approach. The current UrbanSim model uses annual time steps to simulate household choices, real-estate development and redevelopment, and market-clearing and price-adjustment processes within the market (Waddell, 1998). Travel accessibility is updated by a travel model simulation run every ten years, or when significant changes in the transportation system have occurred. Improvements can be achieved by implementing different time steps for different behaviors represented in the model, such as location choices and real-estate development.

5.5 Feedback mechanisms

The model framework accounts for the interactions between the ecological impacts and urban processes. Ecological changes will feed back on the location choices both of households and businesses, and on the availability of land and resources. For example, the amount and distribution of vegetation-cover canopy in urban areas and its health have both social and ecological functions. Among the most obvious social functions are the attractiveness of the area and its consequent economic value. Important ecological functions include removal of air pollutants, mitigation of microclimate, and consequent savings in building energy, and reduction of storm water run-off. All these factors improve urban environmental quality and provide ecological services to urban residents. These benefits are not currently reflected in land values but eventually will affect long-term urban development. We will define a set of environmental quality indices (for example air quality, water quality, etc) and risk indices (for example floods, landslides, etc) that influence location choices and profitability of development.

6 Implications for future research

In this paper I have argued that integration between urban and environmental models needs to be achieved at a functional level to answer critical planning questions. The question is how to represent human processes explicitly in ecological models, and ecological processes explicitly in human models. Although there is no universally valid protocol for designing an integrated UEM, a few considerations emerge from recent experience in the two lines of modeling research. Based on the discussion offered in this paper I indicate a set of attributes that need to be considered to integrate urban-ecological modeling. Above all it is critical that the modeling effort is transparent to users (Smith, 1998). It is important to emphasize that a model is not an end in itself, but rather a tool that will provide its developers and users with a new perspective on the problem being analyzed.

Problem definition. One major concern of Lee's (1973) famous "Requiem for large-scale models" was that modeling efforts had failed to reproduce realistically the problems that planning agencies face and thus to provide useful tools for decisionmaking. The first critical step in defining rules for modeling is to be clear about the questions that need to be answered (Wilson, 1974). The current impasse in coupling ecological and human systems models would suggest that even more important is the way we formulate such questions. The integration of urban and ecological models, I have said, cannot be achieved simply by inserting humans into ecosystems or biophysical elements into human systems because the interactions occur at various levels. This implies that the traditional questions, such as how humans affect natural systems and how natural systems affect humans, need to be reformulated to reflect an integrated approach. For example, we will ask how natural and human-generated landscape patterns and energy flows affect natural disturbance regimes and how land-use choices and practices are controlled by human-induced environmental change.

Multiple actors. Urban decisionmakers are a broad and very diversified group of people who make a series of relevant decisions over time. In order to model urban-ecological interactions we must represent explicitly the location, production, and consumption behavior of these multiple actors. This requires a highly disaggregated representation of households and businesses. Disaggregation of economic sectors could be achieved by using a revised version of the I – O model methodology. Microsimulation could help address the difficult trade-offs that households and businesses make between location, production, and consumption preferences (Wegener and Spiekermann, 1996). Morgan and Dowlatabadi (1996) suggest that new methods must be developed to incorporate separate multiattribute utility functions by different social actors in integrated models.

Time. Time needs to be treated explicitly if relevant temporal dynamics of urban and environmental change are to be represented. Time can be represented as a discrete or continuous variable. Though treating time continuously is certainly a daunting task, introducing time steps or using multiple time steps for different processes modeled can provide an important improvement over current models. Today, most operational urban models are based on a cross-sectional, aggregate, equilibrium approach. Improvement over these models could be achieved by representing time explicitly as a discrete variable. A more ambitious continuous approach to the treatment of time will need to be explored.

Space. We need to represent more realistically the spatial behavior of urban processes, both human and ecological. Existing operational urban models are spatially aggregated and, even when they use or produce spatially disaggregated data, they rely on simple spatial geometric processing. Several scholars have developed various functionalities in modeling spatial processes that can be implemented in UEMs. Additional research is required to explore the potential for using CA to model spatially explicit urban dynamic processes efficiently. A more flexible conception of space could help reconcile the spatial resolution needed to model different urban processes. This will require implementing a data structure that will accommodate process resolution ranging from cells to various land units as well as various levels of aggregation across several hierarchical scales.

Scale. The appropriate scales for modeling depend not only on the problem being tackled, but also on considerations of consistency across spatial and temporal aggregations (Lonergan and Prudham, 1994). Modeling urban ecosystem dynamics requires crossing spatial and hierarchical scales. According to hierarchy theory, landscape processes and constraints change across scales (O'Neill et al, 1986). Because landscapes are spatially heterogeneous areas, the outcome of changes in driving forces can be relevant only at certain scales. Yet our current understanding of spatial scale links is still limited. Two scale issues must be addressed in modeling land-use and land-cover change (Turner II et al, 1995). First, each scale has its specific units and variables. Second, the relationships between variables and units change with scale. To tackle these issues, a hierarchical approach needs to be developed.

Feedback. Representing feedback mechanisms in UEMs could improve substantially the ability to predict human behaviors and their ecological impacts. This could be achieved by developing a set of environmental quality indices derived from the biophysical models. We could evaluate not only the relative magnitude of human and natural systems controls in urbanized regions, but also how this will vary in relation to alternative urban structure and management strategies. The explicit representation of feedback loops is also crucial in analyzing the interaction between multiple resource uses and in assessing their overall ecological impact.

Uncertainty. The behavior of ecological and human systems is highly unpredictable owing to their inherent complexity. Modeling these systems is subject to uncertainty. The treatment of uncertainty goes beyond the scope of this paper. It is clear that the use of advanced techniques, such as the Latin hypercube sampling techniques to map the relevance of uncertainty in input data and model parameters needs to be explored.

The integrated knowledge of the processes and mechanisms that govern urban ecosystem dynamics is crucial to advance both ecological and social research and to inform planners and policymakers. It is also crucial to planning education to provide a new framework and more sophisticated tools for the next generation of urban planners and practitioners.

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