Integrated Assessment 1 (2000) 215–227

An integrated urban development and ecological simulation model

Marina Alberti [a] and Paul Waddell [b]

[a] *Department of Urban Design and Planning, University of Washington, Box 355740, Seattle, WA 98195, USA*
E-mail: malberti@u.washington.edu

[b] *School of Public Affairs and Department of Urban Design and Planning, University of Washington, Box 353055, Seattle, WA 98195, USA*
E-mail: pwaddell@u.washington.edu

Received 28 June 1999; revised 8 March 2000

This paper develops an integrated strategy to model the urban development and ecological dynamics in the Central Puget Sound Region. This effort is part of the Puget Sound Regional Integrated Synthesis model (PRISM) – an interdisciplinary initiative at the University of Washington aiming to develop a dynamic and integrated understanding of the environmental and human systems in the Puget Sound. We describe a model that predicts 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 build on UrbanSim, an existing urban simulation model developed by Waddell [42]. The principal urban actors, represented in the model as objects corresponding to businesses, households, developers, and governments, make choices about location of activities and land development. We extend the object properties and methods now implemented in the UrbanSim model to predict three types of human-induced environmental stressors: land conversion, resource use, and emissions. The core location model in UrbanSim will be revised from its current aggregate structure to one based on microsimulation, and from a zone description of space to one based on a high-resolution grid structure. We will use a spatially explicit process-based landscape modeling approach to replicate ecosystem processes and represent land use–cover interactions at the regional scale. The output of the urban ecological model will serve as the input to several biophysical models for hydrology, hillslope stability, water quality, atmosphere, and ecosystems. Ecological changes will feed back on the choices of both households and business locations, and availability of land and resources.

1. Introduction

One of the greatest challenges for natural and social scientists in the next decades is to understand how metropolitan areas evolve through the interactions between human behaviors and biophysical processes. The complexity of these interactions is extraordinary. However, our failure to understand and to account adequately for them in policy decisions has historically yielded infrastructure investment and land use decisions with unintended long-term effects. Assessments of future urban growth scenarios that are timely and accurate are crucial to achieve sound decisions. The development of integrated models is critical to provide useful inputs to urban growth management strategies that will result in more efficient urban land use arrangements, by preventing development pressure on the urban fringe, reducing resource use and emissions of pollutants, and minimizing impacts on aquatic and terrestrial ecosystems.

A broad set of processes contribute to urban development and ecology and many theoretical perspectives have been developed to explain or predict them. Urban development evolves over time and space as the outcome of the microscopic interactions of individual choices and actions taken by multiple agents – households, businesses, developers, and governments. Households and businesses make decisions about production and consumption activities and their location. Developers make decisions about investing in development and redevelopment. Governments make decisions about investing in infrastructures and services and adopting policies and regulations. These decisions affect ecosystem structures and functions through the conversion of land, the use of resources, and the generation of emissions and waste. Environmental changes at the local and regional scale, in turn, affect individuals' wellbeing and preferences, and the decisions they make.

Although extensive urban research has focused on the dynamics of urban systems and their ecology, these diverse urban processes have yet to be synthesized into one coherent modeling framework [1]. Modeling efforts have proceeded separately and disciplinary approaches have not adequately addressed the processes and variables that couple human and natural systems. Scholars of both urban economics and ecology have begun to recognize the importance of explicitly representing human and ecological processes in modeling urban systems [33]. Simply linking existing models in an "additive" fashion may not adequately address system behavior because interactions between human and environmental processes occur at levels that are not represented [35].

The objective of this paper is to develop an integrated framework for modeling urban development and ecological dynamics in the Puget Sound Region. Instead of separately simulating urban growth and its impacts on ecosystems we propose a framework to simulate metropolitan areas as they evolve through the dynamic interactions between socio-economic and ecological processes. We build on several modeling traditions – urban economics, landscape ecology, and complex system science – each offering a different perspective on modeling urban dynamics. We choose to model human and ecological processes explicitly and link them through a spatially explicit representation of the land. The emphasis is on providing a tool for policy makers to explore the links between human behaviors and environmental change.

This modeling effort is part of the Human Dimension of PRISM, the Puget Sound Regional Integrated Synthesis Model. PRISM is an interdisciplinary initiative at the University of Washington that aims to develop a dynamic and integrated understanding of the environmental and human systems in the Puget Sound. The project also represents a component of a National Science Foundation research effort to develop reusable modeling components for land use, transportation and land cover. We begin with a discussion of urban ecological dynamics and a review of alternative urban modeling approaches. We then present a strategy to develop an integrated framework for linking urban and ecological models. Finally, we focus on the integration of the land use and land cover components and elaborate on the possible specifications for coupling socio-economic and biophysical processes.

2. Modeling urban development and ecology

2.1. Urban economic models

Most operational urban models are rooted in urban economic theory. Classic economic land use models rest on the assumption that landowners and households both seek to maximize their economic return [2,53]. These models originate with the theory of land rent and land market clearing. Given the location and physical qualities of any parcel of land, it will be used in the way that earns the highest rent. Wingo [53] was the first to describe the urban spatial structure in the framework of equilibrium theory. While Wingo used demand, Alonso [2] used bid-rent functions to model the distribution of land to its users. Both models aimed to describe the effects of the residential land market on location. In this approach, households are assumed to maximize their utility and select their 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. These urban economic models are cross-sectional and general equilibrium in nature, and the tractable models assume a monocentric pattern of employment location. These constraints limit the utility of the approach for integration with dynamic ecological models.

Another urban economic contribution to urban modeling is the spatial disaggregated intersectoral input-output (I/O) approach, based on the initial input-output model developed by Leontief [26]. The approach models the spatial allocation of economic flows between sectors of the economy with costs of transport influencing location. Operational urban models that use such an approach include MEPLAN, TRANUS and the models developed by Kim [22]. These models use input-output tables to generate interregional flows of goods, not directly to model economic–ecological interactions, although MEPLAN uses the results of the I/O framework to evaluate environmental impacts [13]. The high level of spatial aggregation used in these models, which also rely on cross-sectional equilibrium, is not suitable for integration with ecological models at a spatially detailed level.

A more flexible modeling approach now becoming widely used is the class of discrete-choice models. This approach was first proposed by McFadden [31], and uses random-utility theory to model consumer choices among discrete location alternatives based on the utility each alternative provides. Ellickson [14] is the first to develop a logit model based on a bid-rent function rather than the utility function. His approach focuses on the landowner's problem of selling to the highest bidder instead of the consumer's problem of choosing among properties based on maximizing their utility function. Anas [3] developed a general equilibrium model based on discrete choice modeling, extending the traditional urban economic model.

Martinez [29] fully integrates bid-rent theory and discrete-choice random utility theory by showing the consistency of these approaches. He develops a "bid-choice" land use model that simultaneously deals with both land supplier and consumer perspectives through a logit formulation. The approach taken by Martinez is also based on equilibrium assumptions.

$$P_{h|i} = \frac{\exp(\Theta_{hi} - b_i)}{\sum_j \exp(\Theta_{hj} - b_j)},$$

where $P_{h|i}$ is the probability that a consumer h will choose lot i, Θ_{hi} is the willingness of individual h to pay for lot i, and b_i is the market price for lot i.

Two models that use a logit framework and use a more dynamic approach are UrbanSim developed by Waddell [42] and CUF II developed by Landis and Zhang [23–25]. Both models use a highly spatially disaggregate representation of the urban landscape, and use GIS techniques to integrate multiple attributes of the land into a spatial database for use in the models. The theoretical and behavioral implementations of the models differ significantly, however. UrbanSim models the key decision makers – 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 adjusting to clear the market. In the CUF II model, on the other hand, land use change is estimated as a transition probability based on the surrounding land characteristics, and without an explicit representation of actors and choices representing demand and supply of urban development. Based on the need to integrate an urban development model with models of urban ecology, the UrbanSim model has been selected as the basis of the urban development component of the larger integrated model we propose here.

A final method we consider in modeling urban development is microsimulation. One major limitation of most current urban models in representing the spatial choice behavior of households and businesses is that they are aggregate and static. Wegener [46,48,49] and Mackett [27,28] propose a microsimulation approach to explicitly represent individuals and directly model the choices of job locations that individual workers make based on their occupation and residential location, and other constraints. Micro-analytic simulation is a modeling technique based on Monte Carlo simulation that is particularly suitable for systems where decisions are made at the individual unit level and where the interactions within the system are complex. It is also particularly appropriate where there is a need for spatial disaggregation, such as to the land parcel or small grid cells. An extension of the UrbanSim model using microsimulation to represent household formation, housing choice and travel behavior has been described by Wegener et al. [50] and will be incorporated into the integrated model we propose here.

2.2. Landscape ecology models

Ecologists have primarily modeled the dynamics of species populations, communities, and ecosystems in non-urban environments. Only in the last decade has their attention turned to the study of urban ecosystems. Their primary concern has also been on describing the processes that created the patterns observed in the environment. Interest in studying the effects of patterns on processes is recent. Ecologists have started to develop studies to answer the following questions: What are the fluxes of energy and matter in urban ecosystems? And how does the spatial structure of ecological, physical, and socio-economic factors in the metropolis affect ecosystem function? Landscape ecology is perhaps the first consistent effort to study the reciprocal effects of spatial patterns (e.g., patch composition) on ecological processes (e.g., fluxes of organisms and materials).

During the last few decades, landscape models have evolved from indices of climatic variables, towards more sophisticated models of species demography and growth. Landscape ecologists originally extrapolated vegetation cover from climatic models (e.g., the Holdridge life zone classification system). Such approaches have been recently replaced by more sophisticated simulations of the biological dynamics of vegetation and its interactions with abiotic factors such as soil and topography. Species demographic and growth models have the advantage of introducing more realistic representations of multiple species and their interactions. However, they are data-intensive and difficult to implement on a large area. More recently traditional demographic models termed "gap models" are being replaced by transition probability models.

Three general classes of ecological models are used to predict changes in landscape structure:

– Individual-based models combine the properties of individual organisms and the mechanisms by which they interact within the environment.
– Process-based landscape models (mass balance) predict flows of water and nutrients across the landscape and biotic responses in order to predict changes in spatial landscape patterns.
– Stochastic landscape models predict changes in spatial patterns based on the characteristics of a given cell, the structural configuration of a given patch to which the cell belongs, and its conditional transition probability.

Spatially explicit stochastic and process-based simulation models have been applied to various landscapes and biophysical processes [40,41]. The land-use change analysis system (LUCAS) is an example of a spatially explicit stochastic model [6]. LUCAS is structured around three modules linked by a common database. The socioeconomic models are used to derive transition probabilities associated with change in land cover. The landscape-change model receives as its input the transition matrix produced in the socioeconomic models. Through the LUCAS simulation, the landscape condition labels in the input cover are matched with equivalent landscape condition values in the transition probability matrix (TPM). The impact models utilize the landscape-change output to estimate impacts to selected environmental and resource-supply variables. The probability of transition is generated through a multinomial logit:

$$P[i \to j] = \frac{\exp(\alpha_{i,j} + \vec{z}^t \vec{\beta}_{i,j})}{\sum_{k=1}^{n} \exp(\alpha_{i,j} + \vec{z}^t \vec{\beta}_{i,j})},$$

where z is a column vector composed of elements described in the landscape condition label, $a_{i,j}$ is an estimated constant (intercept), n is the number of cover types, and $P[i \to j]$ is the probability of land cover at a given grid cell at time t having the same cover class at time $t+1$ or changing to another cover class.

Landscape transition probability models, however, do not represent the biophysical processes that drive landscape change. Spatially explicit process-based models are considered more realistic since they represent biological and physical processes and can relate cause and effects in simulating real landscape [38]. Within process-based models, the landscape is modeled by compartments representing different sectors and by flows between compartments representing transfers of materials and energy dissipation. One example of a process-based spatial simulation model is the Patuexent landscape model (PLM), which can simulate the succession of complex ecological systems across the landscape. The PLM builds on the coastal ecological landscape spatial simulation (CELSS) model developed by Costanza et al. [9]. At the core of the PLM is a general ecosystem model (GEM) which simulates the dynamics of various ecosystem types. The PLM divides the study area into 6,000 spatial cells in which a GEM with 21 state variables is replicated to simulate landscape change at the regional scale.

Recent theoretical developments in landscape ecology have emphasized the importance of spatial heterogeneity in understanding the relationship between pattern and process [40]. Various approaches to predict changes in the landscape structure are based on the premise that certain characteristics of the landscape are linked to structural and functional characteristics of ecosystems. Increasing attention is given to ecosystems as hierarchical mosaics of patches [58]. Hierarchical patch dynamic models are being developed to incorporate the effects of spatial heterogeneity on ecosystem dynamics. Wu and Levin [57] describe a model that combines a spatially explicit, age/size-structured patch demographic model and a multi-specific population model. While most landscape spatially explicit models are grid-based, spatially explicit patch dynamics models emphasize the importance of representing patch dynamic at the patch level. These more sophisticated models provide a more realistic representation of ecosystem dynamics.

2.3. Complexity and self-organization

Perhaps the last understood aspects of urban development and ecosystem dynamics are the way in which local interactions affect the global composition and dynamics of whole metropolitan regions. Urban ecosystems exhibit some fundamental features of complex and self-organizing systems [4,5,10,11,51,52]. The urban spatial structure can be described as a cumulative and aggregate order that results from numerous locally made decisions involving a large number of intelligent and adaptive agents. The behaviors of these agents are subject to changing their rules of action based upon new information. Local behavior of multiple decision-makers eventually can lead to qualitatively different global patterns. Furthermore, in these disequilibrium systems, uncertainty is important since any change that departs from past trends can affect the path of system evolution [54].

The use of cellular automata (CA) has been proposed to model complex spatially explicit urban dynamics. CA are 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. CA models have been used successfully to simulate a wide range of environmental systems, including fire spread [20], starfish outbreaks [21], spread of diseases [18], and forest dynamics [17]. Green [19] applied a cellular automata approach to model species distribution patterns and the dynamics of ecosystems. Recently the interest in CA has spread to modelers of urban and regional development [5,10,11,51,52,54,56]. Among the advantages of applying CA to urban phenomena are their intrinsically geographic nature [10,39], their relative simplicity [34], and their capacity to mirror how urban systems work [4,5].

Using a CA approach land use–cover changes can be simulated through iteration of rules. Land use state at time $t+1$ is determined by the state of the land and development in its neighborhood at time t in accordance with a set of transition rules [55]:

$$S_{ij}^{t+1} = F\big(S_{ij}^{t}, \Omega_{ij}^{t}\big),$$

where S_{ij} is the state of land use at location ij, Ω_{ij} is the development situation in the neighborhood space of the location ij, and F is the state transition function consisting of a set of rules.

Alternative transition rules have also been adopted ranging from simple deterministic rules [51], to stochastic rules [52], to self-modification [7], to utility maximization [54]. Wu [54] has developed a CA probabilistic simulation according to the discrete utility theory. The condition probability that a transition x from one state to another occurs at the location ij can be formulated in a multinomial logit form:

$$P_{(x|ij)} = \frac{\exp(U_{x,ij})}{\sum_x \exp(U_{x,ij})}.$$

Urban modelers have achieved CA generalization by relaxing some standard CA characteristics that do not fit the representation of urban systems. Common generalizations of CA include the following: space is irregular; states are not uniform; neighborhoods do not remain stationary, transition rules are not universal; time is not regular; and systems are open [10,11]. White and Engelen [51], for example, applied CA to simulate urban land uses; they define heterogeneous cell-states across the cell-space. Their cellular automaton is open to outside demographic, macroeconomic, and environmental forcing. Important progress needs to be made, however, with respect to realism before CA can be applied to real urban problems.

3. An integrated framework for urban simulation

In this section we develop a strategy to integrate urban development and ecological modeling. We build on UrbanSim, an existing urban simulation model developed by Waddell [42]. We extend the object properties and methods now implemented in the UrbanSim model to predict three types of human-induced environmental stressors: land conversion, resource use, and emissions in a dynamic and spatially explicit framework that links human decisions to changes in the Puget Sound's biophysical structure.

We build on key characteristics of alternative modeling frameworks to develop a model that can effectively: (a) predict the impact of alternative policy scenarios by linking human behaviors to changes in biophysical processes; (b) determine the spatial and temporal variability of human induced stresses in relation to changes in the biophysical structure; and (c) represent feedback from the biophysical model into the behavioral model by incorporating the environmental qualities of land parcels and neighborhoods.

We first present the overall model design. We then focus on the land use–cover integration and elaborate on the possible options and specification.

3.1. UrbanSim

The UrbanSim model, described in detail elsewhere [42–44], integrates and extends elements of the consumer surplus approach taken by Martinez [29], a real estate stock adjustment model [12], and a dynamic mobility and location choice modeling approach. The theoretical basis of the model draws on random utility theory and the urban economics of location behavior of businesses and households. This is embedded within a larger simulation modeling framework that deals with land market clearing, land development, and aggregate metropolitan changes in the distribution of households and businesses by type [42].

The model predicts the location of businesses and households, developer choices to develop real estate on vacant land or to redevelop existing buildings, and the price of land and buildings. Households, businesses, developers, and government, respectively, make decisions about location, production, consumption, and investments. They dynamically interact in the land and real estate markets and generate physical development and relocation. Since accessibility is a key influence on location choices, the model is interfaced with travel demand models to account for the feedback relationships between land use and transportation.

UrbanSim is based on an object-oriented framework that models the key market behaviors of urban actors which provide a transparent theoretical structure. The demand component currently represents space using zones that correspond to metropolitan travel analysis zones demand, with which it is designed to integrate. The supply of land is represented at the land parcel level. The model uses annual time steps to simulate the mobility and location choices of households, the development and redevelopment of real estate, and the market clearing and price adjustment processes within the market. Travel access is updated on periodic years, triggered by a travel model simulation run in years that have significant transportation system changes.

3.2. Model structure

Figure 1 represents the urban development and ecological dynamics that the integrated model will address [1,42, 45]. UrbanSim predicts the location behaviors of households, businesses, and developers, and consequent changes in land uses and physical development. These are among the inputs required to predict the changes in land cover and ecological impacts. Our current strategy is to extend the object properties and methods now implemented in the UrbanSim model. Instead of linking the urban and ecological components sequentially, we propose to integrate them at a functional level. We propose to add the production and consumption behaviors of households and businesses, and link these through a grid representation of land to infrastructure and natural systems. The structure of the integrated model

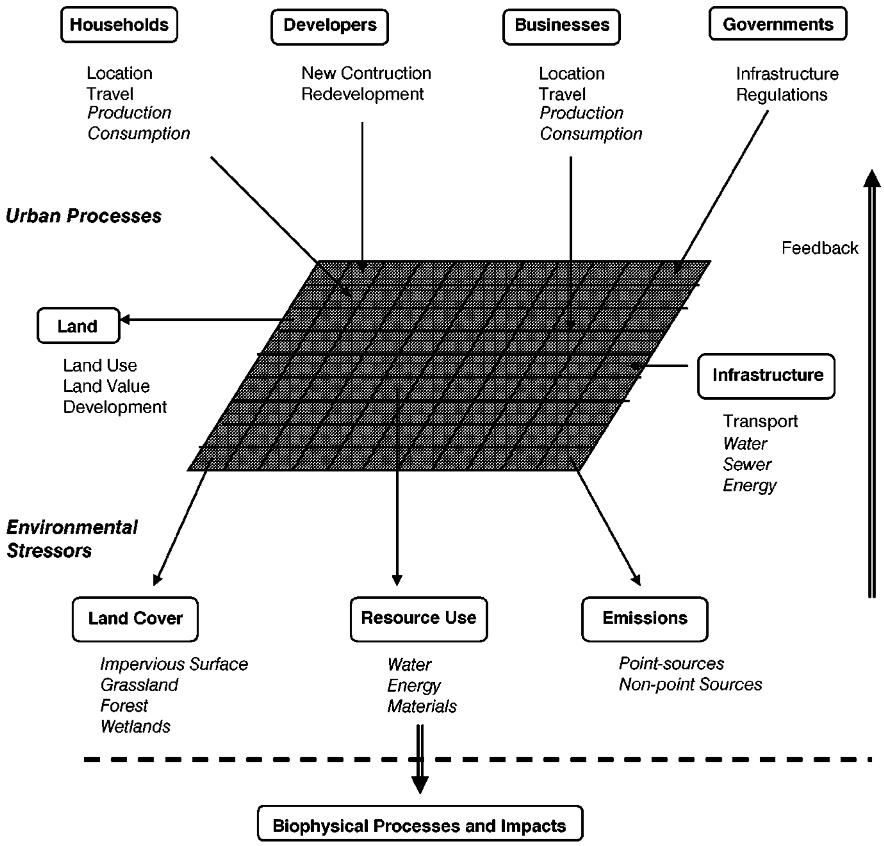

Figure 1. Urban ecological dynamics modeled in UrbanSim. Note: processes in italics are new model components not presently modeled in UrbanSim. Source: Waddell and Alberti (1998).

identifies the principal objects as households, businesses, buildings, land, infrastructure, natural resources, and various biophysical components.

The principal urban actors, represented in the model as objects corresponding to businesses, households, developers, and governments, each make choices that alter the spatial patterns of urban development and household and economic activity. Households, businesses, buildings and land parcels are linked explicitly to individual cells of appropriate resolution. The choices that households make about jobs, location, and consumption will be handled through a microsimulation approach to forecast the demand for specified building types and location, environmental quality, and services. UrbanSim will interface with travel, environmental, and infrastructure models, to account for change in transportation, infrastructure, and environmental conditions and reflect them in the model. These factors are operationalized through indices of accessibility, infrastructure capacity, and environmental quality for a given location computed at the appropriate spatial and temporal resolution.

3.3. Model components

The architecture of the UrbanSim model is currently being redesigned to support microsimulation of the behavior of households, businesses, and developers and the spatially explicit interactions. Existing components are being revised and new components are being added. Figure 1 depicts the model components in the proposed model system, and highlights the new components representing land cover, water consumption and nutrient emissions.

3.3.1. Location models

Urbansim predicts the probability that a household and a business that is either new or has decided to move within the region, will choose a particular combination of location and building type. A multinomial logit specification predicts the joint probability of building type and location. These components represent the demand for residential and commercial real estate, the supply of which is predicted in the land development component. Currently the location model components treat real estate in a moderately aggregate form, aggregating land parcels and their housing and commercial square footage into zones by type of space. We propose to modify the location components using microsimulation, and disaggregating the location choice to the level of individual housing units or nonresidential buildings, which are in turn located within specific parcels and on specific grid cells. This extension will allow the addition of localized context and environmental considerations into the demand for buildings. Issues such as open space, pedestrian accessibility, and other local considerations could be incorporated in this way.

3.3.2. Production and consumption

Production and consumption activities of households and businesses drive the interaction between human decision and environmental processes. Production and consumption by businesses will be modeled using a combination of the aggregate economic input-output methodology and a microsimulation at the level of individual business establishments geocoded to a particular location. The input-output model reflects the structure of consumption and production within the economy, aggregated into sectors. Using microsimulation, these aggregate flows will be allocated to individual business establishments geocoded to a cell, according to the industry and size of the individual business. Consumption by households will be handled through a microsimulation approach to forecast the demand of specified products and services. This technique is flexible enough to represent sensitivity to a variety of technological and policy factors that affect consumer behavior. By incorporating for example the lifecycle of products and services it would enable us to account for technological substitution.

3.3.3. Land use

Changes in land use in UrbanSim are modeled through a land development model. The demand for new real estate development, or redevelopment of existing real estate, is triggered by monitoring the vacancy rate within real estate submarkets. When vacancy rates fall below a structural threshold, then prices begin to rise, and new development is stimulated. The actual simulation of land development in the UrbanSim model currently uses individual land parcels as the unit of development. The model predicts the feasibility of development under the constraints of the land use plan and other environmental or regulatory restrictions, and then estimates the profitability of development into any of the allowed urban uses. Development projects that are most profitable are simulated, adding to the existing stock of buildings in the real estate market, and linking them to specific land parcels. Revisions to the existing land development component will be based on an extended spatial database that cross-references parcels and buildings to a location grid, allowing the use of spatial metrics to further inform the expected profitability of development, based on the characteristics and development trends in the proximate area. In addition, the model will be fully converted to a logit formulation, consistent with the demand components in the current model. We plan to add new components for modeling competing non-urban land uses such as timber and agriculture production and related land management practices which may affect the land market at the urban fringe. The developer component of the model is the one most directly influenced by local policies such as the comprehensive plan, density constraints, the Urban Growth Boundary, environmental constraints, and development impact fees or other development costs set by local governments.

3.3.4. Land cover

The land cover component that we discuss more extensively in the next section is central to integrating socio-economic and ecological processes. Land cover change is affected by production and consumption patterns of households and businesses, their location preferences, and land development and redevelopment. Change in land cover in turn affects these patterns, preferences, and ultimately development. We will model land cover change as influenced by both economic and biophysical processes. We propose to link UrbanSim to a process-based landscape and a patch-dynamic approach. Land conversion is modeled based on the changes in housing and commercial buildings predicted in the land development component, household and business characteristics occupying any buildings on a specific land parcel, and other landscape characteristics of the parcel. We will allocate specific buildings and associated infrastructure to individual cells of high resolution to predict change in land cover patch structure and function. The predicted land use will constitute the input of a process-based landscape model. The advantage of this approach is the explicit representation of the landscape processes that affect ecological conditions which will successively feed back into the land cover and land use model. A set of spatial metrics of urban development and ecological patterns of parcels and neighborhoods will be used to better represent the land conversion dynamics.

3.3.5. Water use

The resource demand models in UrbanSim will include various modules each predicting the use of water and energy on the basis of consumption, infrastructure capacity, and efficiencies of technologies. Our current focus is on developing a water-use component. The water resource component will be represented by a water demand model that will be linked to the grid structure on the basis of water consumption patterns of households and businesses and water supply capacity. A component water use forecasting method will be implemented to estimate future household water use as a function of household characteristics (size, income, etc.), parcel characteristics (building typology, lot size, density, etc.), climatic conditions (monthly precipitation and temperature), and marginal price of water. In addition non-price demand side management (DSM) policies are expected to influence water demand. The predicted water demand is linked to the infrastructure and natural systems through a spatial grid and can be used to evaluate alternative growth scenarios and water supply system capacity.

3.3.6. Nutrient loads

The emission modules in UrbanSim simulate the emission of various pollutants into the atmosphere, water, and soil. These emission model outputs ultimately will serve to construct whole urban ecosystem mass balances of materials and relative contributions from the various media. Our current focus is on modeling nutrient (phosphorous and nitrogen) export from urban land uses. We will build a spatially-explicit nutrient export model for the Puget Sound. Nutrient loads are modeled based on runoff coefficients and expected pollution concentrations related to land use, density, type of building, type of business, and treatment plant. The export coefficient model is particularly suitable as a basis for estimating nutrient loading because it uses the areal extent of different land use types and estimated runoff coefficients.

3.4. Feedback

The proposed model framework is designed to take into account the interactions between the ecological impacts and urban processes. The output of the integrated urban model will serve as the input to several biophysical models addressing hydrology, hillslope stability, water quality, atmosphere, and aquatic and terrestrial ecosystems. Ecological changes will feed back on the choices of both households and business locations, and availability of land and resources. We propose to use a set of parcel- and cell-based environmental quality indices (e.g., air quality, water quality, noise, etc.) and potential risk or hazard indices (e.g., floods, landslides, etc.) that influence location choices and profitability of development. In addition a set of spatial metrics will be implemented to inform land use demand and development by taking into account spatial proximity to amenities and disamenities and neighborhood effects.

4. Land use–cover change: a strategy for model integration

Land use and land cover dynamics are at the core of the integrated urban ecological modeling framework. They are distinct but closely linked processes. Land cover change is driven by both biophysical and socio-economic forcing. Changes of land cover driven by socio-economic forcing are currently the most important and most rapid of all changes. Biophysical processes, such as vegetation dynamics, involve alterations in cover due to natural changes in climate and soils. We distinguish two types of changes in land cover: conversion and modification [37]. Land conversion is a change from one cover type to another. Land modification is a change in conditions within the same cover type. Here we consider only the effects of land use change on land conversion. We develop a strategy for modeling land use and land cover dynamics by building on various modeling approaches rooted in economics, landscape ecology, and complex system science. Our hybrid model structure combines: (a) a microsimulation of actor choices (location, housing, travel, production consumption, and land development); (b) a process-based model of physical and ecological dynamics (hydrology, nutrient cycling, primary production, and consumer dynamics); and (c) a spatially-explicit, grid-based model structure which represents the dynamics inherent in land use and land cover change and detailed spatial queries and simulation.

4.1. Socio-economic processes

The demand for built space for various activities is generated through microsimulation of demographic and economic processes, and location choices of households and businesses. These are integrated with a market-clearing component. Land use change is modeled through a spatially explicit microsimulation of land development and redevelopment. We develop a hybrid spatially-explicit microsimulation structure by combining the current UrbanSim behavioral approach, which explicitly represents the land development process, with a spatially explicit approach which explicitly represents local spatial dynamics and neighborhood effects of both land use and land cover.

4.1.1. Demographic and economic processes

The modeling of economic and demographic processes within metropolitan economies are most commonly done through macro-economic models, using either an input/output, structural equations, or hybrid approach. Demographic processes are often modeled as a function of cohort survival that involves ageing of an age-sex population pyramid, with fertility and death probabilities applied to the population counts in each age-sex cohort, with age-sex specific net migration rates predicted as a function of employment opportunities. Hybrid approaches such as the Washington Simulation and Projection model developed by Conway [8] provide a reasonably robust means of linking the simulation of the evolution of the economic structure of a region or state to broader national and global economic trends and influences.

The alternative to a macroeconomic approach to modeling these economic processes is the development of a purely microsimulation approach to economic and demographic processes. There is established work on the microsimulation of household evolution that addresses the demographic processes of ageing, birth, death, and household formation and dissolution. Wegener [49] suggests that many of these processes are typically modeled as transition probabilities using Monte Carlo simulation rather than choices to be modeled using a behavioral specification. Very little work has been published, to date, on the microsimulation of economic processes at the level of the firm.

One of the major challenges faced in the future development of a full microsimulation model of the type we propose here is the reconciliation of microsimulation of land demand and supply processes as describe below, with macroeconomic processes. We propose at this time to adopt the approach taken in the Washington Economic Simulation model, which contains a hybrid input/output and structural equations model of the macroeconomy of the State of Washington, and to link this to the microsimulation of the processes described below. The basis for this choice is that there is a substantial degree of remaining research to be done before a microsimulation of the macro-behavior of a regional economy can be effectively implemented, in a way that captures interactions not only within the region, but also interaction with economic processes in the nation and the world.

4.1.2. Households and business demand

The modeling of household and business demand for real estate at different locations will be modeled using an extension of the existing framework already implemented in UrbanSim. The primary difference will be the implementation of a full sample enumeration of households, and buildings, in the demand components of the model. With the linkage of buildings to a location grid, and an infrastructure for spatial query and analysis that is in development, we plan to enrich the demand components of the model to incorporate more spatially-explicit attributes of location demand.

With reference to residential location demand, the micro-location attributes may include attributes of the pedestrian environment, such as the street pattern, the availability of open space, and the walk access to shopping and entertainment opportunities. In addition, the spatial metrics to be described later may be adapted to describe aspects of the spatial pattern of land use, and environmental characteristics, that could inform the demand functions of different types of households. This last step will open the possibility to establish feedback from the biophysical processes and land cover change to demand for residential locations. We propose to implement a microsimulation of the demand components of the model following the approach developed by Wegener et al. [50].

With reference to business location, the opportunity to develop more spatially detailed and explicit representation of the context surrounding available sites should significantly increase the feasibility of enriching the demand behavior of the model. Site characteristics such as frontage or proximity to transportation facilities, the pedestrian environment, and other environmental quality characteristics would be potential influences on business demand for locations that could be explored.

4.1.3. Market clearing and price adjustment

The market clearing and adjustment of prices of land and buildings is currently addressed in UrbanSim through a process that matches moving households and businesses to vacancies in the housing or nonresidential building stock based on the consumer surplus of the match. Consumer surplus measures the degree to which the willingness to pay for an alternative exceeds its market cost [14,29,42]. Once the matching of active consumers and available vacancies is completed, prices in the real estate submarkets are adjusted according to their relationship between the current vacancy rate in a submarket and the structural vacancy rate, following an approach described by DiPasquale and Wheaton [12]. When current vacancy rates dip below the structural vacancy rates, prices adjust upwards, and conversely, exceptionally high vacancy rates pull prices downward.

The microsimulation implementation of the market clearing process may involve moving to a more explicit housing search process, with the search generating a set of alternatives that are subsequently evaluated using a logit modeling approach. There remains a potential, as a long-term research topic, for more fully representing the macro-economic processes as emergent behavior from the microsimulation of the matching of consumers and suppliers within this market clearing and price adjustment process. The feasibility of this approach has not yet been explored.

4.1.4. Land development and redevelopment

Existing urban models formulate change in land use in two ways: (1) as the developer's decision to build a given project on a given parcel; or (2) as the transition of a given land parcel from its original use to a new use. The first formulation implies a microsimulation of the behavior of developers who make profitability calculations on converting each land parcel to alternative development projects. Land use and environmental policies and development fees can directly influence the behavior of the developer. The second approach emphasizes the probability of transition based on local dynamic and spatial self-organization of urban land uses. Thus it provides a framework in which to address the evolutionary and non-linear nature of land use change.

Our hybrid model structure combines the two approaches. Land development will be treated as a stochastic formulation of the profitability of a given development project to be realized in a given parcel or group of parcels. The probability that housing type b is developed at location ij can be formulated in a multinomial logit form to simulate the profit-maximization behavior of developers. We predict land use change based on expected revenues and on costs of development of alternative parcels into allowable developed uses. Available parcels are developed until the aggregated demand for built space is satisfied. Based on the predicted land use we will allocate specific buildings and associated infrastructure to individual cells of high resolution. We will add building stories as attributes of development projects to predict additional built space. This will then be allocated to individual cells based of the estimated probability of conversion of various land cover types within each parcel.

We represent spatial dynamics into the behavioral models by incorporating land use and cover pattern characteristics of developable and re-developable parcels. Profitability calculations take into account the patterns and dynamics of both land use and land cover at each location. Parcels are represented by a spatially explicit grid structure whose cells have been assigned functional (land use) and structural (land cover) characteristics. Cells belong to land parcels and cover patches. To incorporate the effect of both land use and cover patterns in the land use (demand and development) models, we will use a set of spatial metrics described later in this paper.

4.2. Biophysical processes

To fully integrate land use and land cover dynamics we propose to link UrbanSim to a process-based landscape modeling approach (figure 2). We propose to build on the general ecosystem model (GEM) developed by Fitz et al. [15] and revise it to match the complexity of urban ecosystems. 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. The spatial processes will be modeled using a grid-based structure like that developed by Costanza et al. [9] in the Patuexent landscape model (PLM) to replicate ecosystem processes in the watershed. We will model three aspects of land cover: (1) patch structure, (2) patch function, and (3) patch dynamic. Patch structure refers to the composition and spatial configuration of the distinctive cover elements, which describe the distribution of energy, materials, and species. Patch function refers to the flows of energy, materials, and species among the component ecosystems, which describe the interactions among the spatial elements. Patch dynamics refers the natural and human-induced disturbances that alter the structure and function of the ecological mosaic over time [41].

The choice of a process-based approach is dictated by the choice to explicitly represent the links between human-induced causes and ecological effects. Stochastic transition models cannot relate causes and effects, nor they can incorporate feedback mechanisms and acquire a dynamic property. Since our focus is the impact of urban development on land cover, several important processes need to be considered. They include: hydrology (infiltration, percola-

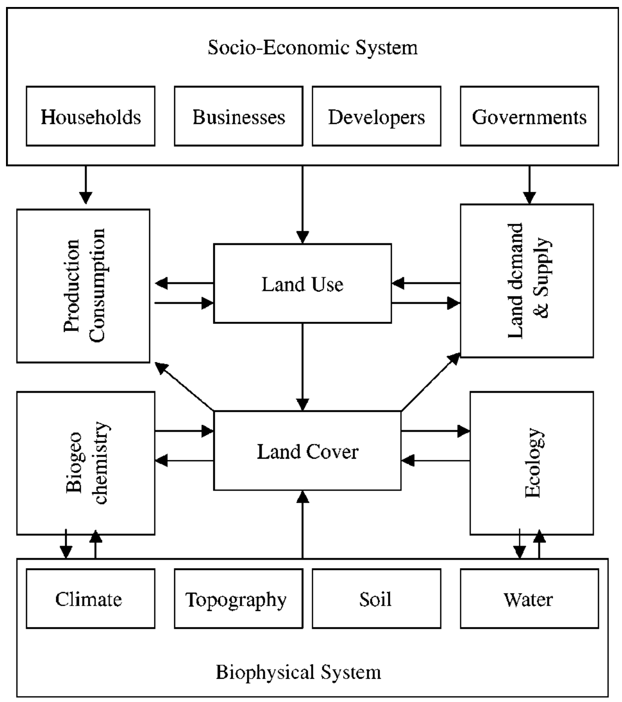

Figure 2. Land use–cover integration.

tion, etc.); nutrient movements (through water flows) and cycling (plant uptake, nutrient fixing, etc.); primary productivity (plant growth and responses to limiting factors); and consumer dynamics (total material flows in a habitat). These are modeled through a process-based approach which explicitly represents physical and biological processes and the mechanisms of change in landscapes.

4.2.1. Ecosystem processes

Ecosystem processes will be modeled using the GEM model structure. The GEM model includes sectors for hydrology, nutrient movement and cycling, terrestrial and estuarine primary productivity, and aggregated consumer dynamics [15]. The hydrology model simulates vertical water flows within each cell and constitutes the core of other fundamental processes. Nutrients (phosphorus and nitrogen) are cycled through plant uptake and organic matter decomposition. The sector for macrophytes includes growth response to various environmental constraints (i.e., water and nutrient availability), changes in canopy structure, mortality, and other plant dynamics. In addition, feedback mechanisms among the biological, chemical, and physical model components are important structural attributes of the model.

GEM simulates ecological processes within a unit cell and horizontal processes link the cells together across the landscape. While GEM models only the physical processes and lower trophic levels, it provides a basis for linking in the future additional models of higher trophic level including fish and wildlife population.

4.2.2. Landscape dynamics

Landscape processes will be treated through a spatially-explicit model that integrates the biophysical processes to predict the changes in the form and functions of the entire landscape. We will integrate the process-based approach described above with a spatially explicit hierarchical patch dynamic approach to incorporate the effects of spatial heterogeneity on ecological dynamics. Patch dynamic models describe ecological systems as hierarchical, dynamic patch mosaics generated and maintained by processes of patch formation, patch development, and disappearance [57]. Anthropogenic disturbances, particularly land use changes are important drivers of these processes (e.g., fragmentation). These disturbances together with environmental heterogeneity create patchiness in ecological systems in time and space. To incorporate patch dynamics into the land use–cover model we will predict land use disturbances in terms of both patch composition (type, diversity, dominance, etc.) and structure (size, shape, interconnectivity, etc.). The model will allow patch succession to occur based on changes in the biophysical environment.

4.3. Spatial metrics

Spatially-explicit model structures specify the location of each object of interest. Thus the spatial relationship between land use processes and land cover structure can be explicitly defined. We can improve the realism of the land use–cover change component by specifying land cover attributes of parcels and their neighborhoods for potential development or redevelopment in both the location choice model and the development model. Adding spatial configuration and neighborhood effects of both parcels and patches also provides additional realism to the urban and land cover models.

We will use a set of landscape metrics derived from information theory to model the effect of the complex spatial pattern of land use and cover on human and ecological processes (table 1). These metrics characterize the composition (e.g., diversity, dominance, etc.), spatial configuration (e.g., density, size, shape, edge, connectivity, fractal dimension) and spatial neighborhood (e.g., heterogeneity and contagion) of the landscape. Landscape composition refers to features associated with the presence and amount of each land use and cover patch type within the landscape, but without being spatially explicit. Landscape configuration refers to the spatial distribution of land use and cover patches within the landscape.

The implementation of a high-resolution spatial grid allows us to estimate changes in landscape metrics. In landscape ecology these metrics are good predictors of the ecosystem ability to support important ecosystem functions [36].

These spatial metrics will be also used to model the effects of land use and cover patterns and ecosystem change on human decisions. Increasing evidence show that these patterns influence human preference and wellbeing [16]. Using selected spatial metrics we will incorporate these effects into the demand and development models. These metrics include the composition, spatial configuration and spatial neighborhood of both land use and land cover. Two types of neighborhood effects will be also captured: (1) the development conditions of the parcels, and (2) the land cover state of the patches in the neighborhood. Each cell in the neighborhood of a given parcel makes a contribution to the attractiveness or profitability of development depending on its use and location. Likewise the land cover patch structure in the neighborhood affects the dynamic of a specified patch. The effect can vary, in terms of both its importance and its sign, depending on its distance. In incorporating spatial metrics of land use and cover patterns, variations across scales need to be considered.

4.4. Resolution and scale

4.4.1. Spatial resolution

We will treat land use and land cover using different spatial units. Land development will be treated at the parcel or multiple-parcel level and land cover at the patch level. The parcel level has a single use, is the basis of all land transactions, and is the level at which government can intervene through land use policies and zoning. The supply of built space can be aggregated into sub-markets of housing and neighborhood types where it interacts with the demand

Table 1
Spatial metrics.[a]

Spatial metrics that apply to both land development and cover dynamics	
Diversity (H)	$H = -\sum_{k=1}^{s}(P_k)\ln(P_k)$ P_k – proportion of the land in cover k S – number of land categories observed
Dominance (D_0)	$D_0 = H_{\max} + \sum^{s}(P_k)\ln(P_k)$ P_k – proportion of the land in cover k S – number of land categories observed $H_{\max}$ – ln(s) the maximum diversity when land cover types occur in equal proportion
Edges (E)	$E_{i,j} = \sum e_{i,j} l$ $e_{i,j}$ – number of horizontal and vertical interface between cells of types i and j l – the length of the edge of the patch
Shape (S)	$S = \frac{p_{ij}}{2\sqrt{\pi - a_{ij}}}$ p – perimeter of the patch a – area of the patch
Nearest-neighbor distance (NN-D)	NN-D $= h_{ij}$ h_{ij} – distance to the nearest neighboring patch of the same type, based on shortest edge-to-edge distance
Fractal dimension (d)	$d = \frac{2\ln p_{ij}}{\ln a_{ij}}$ a – area of two dimensional patch p – perimeter of the patch at a particular length scale d – fractal dimension
Contagion (C)	$C = 2s\log s + \sum^{m}\sum^{n} q_{i,j}\log q_{i,j}$ $q_{i,j}$ – probability of land cover i being adjacent to land cover j s – number of land cover observed

[a] Sources: Turner and Gardner (1990); O'Neil et al. (1988); Hunsaker and Levine (1995).

through market clearing and price adjustments. The patch level has a single cover, and is the basis of spatial ecosystem processes at the watershed level through patch dynamics, which influences and is influenced by flows of materials and energy. The cell structure of variable resolution could constitute the unit of integration of land use and land cover by providing a locational cross-reference for all spatial objects in the model. A nested grid-cell also has the advantage of capturing the spatial dynamics of both land use and land cover in a common spatial data structure and can provide spatial analysis capacity that are extremely complex with the vector data structure. The grid cell should also allow for data aggregation and use as input in various biophysical models.

4.4.2. Temporal resolution

We will make the treatment of time more flexible to allow to vary the time step of various behaviors and processes represented in the model. We will extend the current user-defined timetable for different scale development projects to other model components and processes. For example, we could assume different time steps for land use and land cover changes. This could also facilitate the integration with the time steps of biophysical models. A more realistic event-driven approach would be more consistent with the behavioral and object-oriented structure of the model structure. This could be implemented through a grid-based structure with asynchronous state changes.

4.4.3. Spatial and temporal scale

Since landscapes are spatially heterogeneous areas, the structure, function, and change of landscapes are scale dependent. Spatial heterogeneity constrains our ability to directly translate information from one scale to another. We need to consider that each scale has its specific units and variables and that the relationships between variables and units change with scale. We will do this by constructing artificial scales based on grid aggregations. By adopting this approach we will be able to vary spatial resolutions for different processes, and test the effect of resolution on the realism of the model outputs.

5. Conclusions

We have developed an integrated framework for urban ecological modeling that combines approaches rooted in economics, landscape ecology, and complex system science. This approach enables us to represent human decisions and their dynamics interactions with ecosystem dynamics explicitly. It also provides a means to represent spatially-explicit interactions at various levels of the ecological hierarchy and to allow local urban dynamics to affect global trends. This approach involves the integration of three elements: (a) a microsimulation of actor choices (location, housing, travel, production consumption, etc.); (b) a process-based model of physical and ecological dynamics (hydrology, nutrient cycling, primary production, and consumer dynamics); and (c) a spatially-explicit, grid-based model structure which represents the dynamics inherent in land use and land cover change.

The proposed framework aims to improve existing urban models and their ability to represent biophysical processes. Current urban simulation models are very aggregated representing actor behaviors. Their cross-sectional equilibrium framework also assumes no relevant temporal dynamics. The assumption of these models is that urban development can be modeled without representing the dynamics of urban development over time. This extreme simplification of urban processes makes them unrealistic and inadequate for integration with models of dynamic environmental processes.

We believe that the integrated framework proposed here will improve both planning practice and research. A highly disaggregated dynamic urban ecological model will not only improve our ability to predict the impact of urban development and better understand human response to environmental change. It will also allow us to address new research questions. Used in combination with empirical research this framework will allow us to test formal hypotheses about what changes in ecological conditions are associated with what changes in urban patterns, and at what scales these interactions are controlled. This knowledge is critical if we want to effectively address current complex urban ecological problems.

References

[1] M. Alberti, Modeling the urban ecosystem: a conceptual framework, Environmental and Planning B: Planning and Design 26 (1999), forthcoming.

[2] W. Alonso, *Location and Land Use* (Harvard University Press, Cambridge, MA, 1964).

[3] Anas, Discrete choice theory, information theory and the multinomial logit and gravity models, Transportation Research 17B (1983) 13–23.

[4] M. Batty, Cellular automata and urban form: a primer, Journal of the American Planning Association 63 (1997) 266–269.

[5] M. Batty and Y. Xie, From cells to cities, Environmental and Planning B: Planning and Design 21 (1994) 531–548.

[6] M.W. Berry and K.S. Minser, Distributed Land-Cover Change Simulation Using PVM and MPI, *Land Use Modeling Workshop*, USGS EROS Data Center, Sioux Falls, SD, 5–6 June 1997.

[7] K.C. Clarke, L. Gaydos and S. Hoppen, A self-modifying cellular automaton model of historical urbanization in the San Francisco Bay area, Environment and Planning B 24 (1997).

[8] R. Conway, The Washington projection and simulation model: a regional interindustry econometric model, International Regional Science Review 13 (1990) 141–165.

[9] R. Costanza, L. Wainger and N. Bockstael, in: *Integrating Economics and Ecological Indicators*, eds. J.W. Milon and J.F. Shogren (Praeger, Westport, CT1995).

[10] H. Couclelis, Cellular worlds: a framework for modeling micro–macro dynamics, Environmental and Planning A 17 (1985) 585–596.

[11] H. Couclelis, From cellular automata to urban models: new principles for model development and implementation, Environmental and Planning B 24 (1997) 165–174.

[12] D. DiPasquale and W. Wheaton, *Urban Economics and Real Estate Markets* (Princeton Hall, Englewood Cliffs, NJ, 1996).

[13] M.H. Echenique, A.D. Flowerdew, J.D. Hunt, T.R. Mayo, I.J. Skidmore and D.C. Simmonds, The MENPLAN models of Bilbao, Leeds and Dortmund, Transport Reviews 10 (1990) 309–322.

[14] B. Ellickson, An alternative test of the hedonic theory of housing markets, Journal of Urban Economics 9 (1981) 56–79.

[15] H.C. Fitz, E.B. DeBellevue, R. Costanza, R. Boumann, T. Maxwell and L. Wainger, Development of a general ecosystem model for a range of scales and ecosystems, Ecological Modeling 88 (1996) 263–295.

[16] J. Geoghegan, L.A. Wainger and N.E. Bockstael, Spatial landscape indices in a hedonic framework: an ecological economics analysis using GIS, Ecological Economics 23 (1997) 251–264.

[17] D.G. Green, Simulated effects of fire, dispersal and spatial pattern on competition within vegetation mosaics, Vegetation 82 (1989) 139–153.

[18] D.G. Green, in: *Complex Systems – From Biology to Computation*, eds. D.G. Green and T.J. Bossomaier (IOS Press, Amsterdam, 1993).

[19] D.G. Green, Connectivity and complexity in ecological systems, Pacific Conservation Biology 1 (1994) 194–200.

[20] D.G. Green, A. Tridgell and A.M. Gill, Interactive simulation of bushfire spread in heterogeneous fuel, Math. Comput. Modelling 13 (1990) 57–66.

[21] P. Hogeweg and B. Hesper, in: *Acanthaster and the Coral Reef: a Theoretical Perspective*, ed. R.H. Bradbury (Springer, Berlin, 1990).

[22] T.J. Kim, *Integrated Urban System Modeling: Theory and Practice* (Martinus Nijhoff, Norwell, MA, 1989).

[23] J.D. Landis, *BASS II: A New Generation of Metropolitan Simulation Models* (Institute of Urban and Regional Development, University of California at Berkeley, 1992).

[24] J.D. Landis, Imagining land use futures: applying the California urban futures model, Journal of the American Planning Association 61 (1995) 438–457.

[25] J.D. Landis and M. Zhang, *The Second Generation of the California Urban Futures Model*, Model Logic and Theory, Part I (1998).

[26] W. Leontief, *Input-Output Economics* (Oxford University Press, New York, 1967).

[27] R.L. Mackett, MASTER Model, Micro-Analytical Simulation of Transport, Employment and Residence, Report SR 237 (Transport and Road Research Laboratory, Crowthorne, 1990).

[28] R.L. Mackett, Micro Simulation Modeling of Travel Demand and Location Processes: Testing and Further Development, Report to the Transport and Road Research Laboratory (University College London, London, 1992).

[29] F. Martinez, The bid-choice land use model: an integrated framework, Environment and Planning A 24 (1992) 871–885.

[30] M.J. McDonnel and S.T.A. Pickett, Ecosystem structure and function along urban-rural gradients: an unexploited opportunity for ecology, Ecology 71 (1990) 1231–1237.

[31] D. McFadden, in: *Spatial Interaction Theory and Planning Models*, eds. A. Karlqvist, L. Lundqvist, F. Snickars and J.W. Wiebull (North Holland, Amsterdam, 1978).

[32] R. O'Neill, D.L. DeAngelis, J.B. Wide and T.H.F. Allen, *A Hierarchical Concept of Ecosystems* (Princeton University Press, Princeton, 1986).

[33] S. Openshaw, Human systems modelling as a new grand challenge area in science: what has happened to the science in the social science?, Environment and Planning A 27 (1995) 159–164.

[34] M. Phipps and A. Langlois, Spatial dynamics, cellular automata, and parallel processing computers, Environmental and Planning B 24 (1997) 193–204.

[35] S.T.A. Pickett, I.C. Burke, V.H. Dale, J.R. Gosz, R.G. Lee, S.W. Pacala and M. Shachak, in: *Integrated Regional Models*, eds. P.M. Grogffman and G.E. Likens (Chapman & Hall, New York, 1994).

[36] S.T.A. Pickett, I.C. Burke, S.E. Dalton, T.W. Foresman, J.M. Grove and R. Rowntree, A conceptual framework for the study of human ecosystems in urban areas, Urban Ecosystems 1 (1997) 185–199.

[37] E.W. Riebsame, W.B. Meyer and B.L. Turner II, Modeling land use and cover as part of global environmental change, Special Issue, Climatic Change 28 (1994) 45–65.

[38] F.H. Sklar and R. Costanza, in: *Quantitative Methods in Landscape Ecology*, Springer-Verlag Ecological Studies, Vol. 82, eds. M.G. Turner and R. Gardner (Springer, New York, NY, 1991).

[39] W.R. Tobler, Smooth pycnophylactic interpolation for geographic regions, Journal of the American Statistical Association 74 (1979) 519–530.

[40] M. Turner, Landscape ecology: the effect of pattern on process, Annual Review Ecological Systems 20 (1989) 171–197.

[41] M. Turner and R. Gardner, *Quantitative Methods in Landscape Ecology* (Springer, New York, 1991).

[42] P.A. Waddell, A behavioral simulation model for metropolitan policy analysis and planning: residential location and housing market components of UrbanSim, Environment and Planning B: Planning and Design 27 (2000) 247–263.

[43] P.A. Waddell, Simulating the Effects of Metropolitan Growth Management Strategies, Prepared for Presentation at the 1998 Conference of the Association of Collegiate Schools of Planning, November 1998, Pasadena, California (1998).

[44] P.A. Waddell, Monitoring and Simulating Land Capacity at the Parcel Level, Lincoln Institute of Land Policy Conference on Land Capacity Monitoring, Seattle, Washington (1998).

[45] P.A. Waddell and M. Alberti, Integration of an urban simulation model and an urban ecosystems model, in: *Proceedings of the International Conference on Modeling Geographical and Environmental Systems with Geographical Information Systems*, Hong Kong, 1998.

[46] M. Wegener, Description of the Dortmund Region Model, Working Paper 8, Dortmund, Institute für Raumplanung (1983).

[47] M. Wegener, Operational urban models: state of the art, Journal-of the-American-Planning-Association 60 (1994) 17–30.

[48] M. Wegener, in: *LandUse Modeling Conference Proceedings*, 19–21 February, 1995, ed. G.A. Shunk, Report DOT-T-96-09 (US Department of Transportation, Washington, DC, 1995).

[49] M. Wegener and K. Spiekermann, The potential of microsimulation for urban modelling, in: *Proceedings of the International Workshop on Application of Computers in Urban Planning*, Kobe University, Kobe, 1997, pp. 129–143.

[50] M. Wegener, P. Waddell and I. Salomon, Sustainable lifestyles? Microsimulation of household formation, housing choice and travel behaviour, in: *Proceedings of the National Science Foundation–European Science Foundation Conference on Social Change and Sustainable Transportation*, Berkeley, California, 1999.

[51] R. White and G. Engelen, Cellular automata as the basis of integrated dynamic modeling, Environment and Planning B 24 (1997) 235–246.

[52] R. White, G. Engelen and I. Uljee, The use of constrained cellular automata for high-resolution modeling of urban land use dynamics, Environment and Planning B 24 (1997) 323–343.

[53] L. Wingo, *Transportation and Urban Land* (The Johns Hopkins University Press, Baltimore, MD, 1961).

[54] F. Wu, An experiment on the generic polycentricity of urban growth in a cellular automata city, Environment and Planning B 25 (1998) 731–752.

[55] F. Wu, Simulating urban encroachment on rural land with fuzzy-logic controlled cellular automata in a geographical information system, Journal of Environmental Management 53 (1998) 293–308.

[56] F. Wu and C.J. Webster, Simulation of land development through the integration of cellular automata and multicriteria evaluation, Environmental and Planning B 25 (1998) 103–126.

[57] J.G. Wu and S.A. Levin, A patch-based spatial modeling approach: conceptual framework and simulation scheme, Ecological Modelling 101 (1997) 325–346.

[58] J.G. Wu and O.L. Loucks, From balance of nature to hierarchical patch dynamics: a paradigm shift in ecology, Quarterly Review of Biology 70 (1995) 439–466.