

New Directions for Urban Economic Models of Land Use Change: Incorporating Spatial Heterogeneity and Transitional Dynamics

Elena G. Irwin¹

Associate Professor

Department of Agricultural, Environmental and Development Economics
Ohio State University

Invited paper prepared for the Journal of Regional Science 50th Anniversary Symposium,
Federal Reserve Bank of New York, April 23-24, 2009

Under revision for publication in Journal of Regional Science

(this version: September 2008)

¹ Full mailing address: 2120 Fyffe Rd., Columbus, OH 43210. Phone: 614-292-6440. Fax: 614-292-0078. Email: irwin.78@osu.edu.

New Directions for Urban Economic Models of Land Use Change: Incorporating Spatial Heterogeneity and Transitional Dynamics

Abstract: We review the usefulness of spatial economic models of land use change for the study and policy analysis of spatial land use-environment interactions. We find that meaningful progress has been made in econometric and monocentric models extended to account for multiple sources of spatial heterogeneity and in the development of general equilibrium models with spatial dynamics. Despite these advances, more work is needed in developing models with greater realism. Most agent-based computational models of urban land use change currently lack economic fundamentals, but provide a flexible means of linking micro-level behavior and interactions with macro-level land use dynamics. In combination with empirical methods to identify parameters, this framework provides a promising approach to modeling spatial land use dynamics and policy effects.

Introduction

Key policy questions concerning global environmental change center on the multiple feedbacks between humans and natural systems (Grimm et al. 2008a; Levin 2006; Lui et al. 2007; Pickett et al. 2001; Turner et al. 2007), including the cumulative environmental impacts of individual and community resource decisions and the behavioral responses of individuals to policies that seek to manage these impacts (Daily et al. 2009). Among human-induced impacts, land use is second only to climate in its effects on the functioning of the Earth's terrestrial and aquatic ecosystems (Grimm et al. 2008a). Urban and urbanizing land, while only a small fraction of the total land area worldwide, generates a disproportionate share of environmental impacts (Alberti 2005; Collins et al. 2000). A growing interest in the underlying processes of land use and land cover patterns among biophysical scientists has led to increased emphasis on an understanding of human behavior (e.g., Wu and Hobbs 2002) and for integration of socioeconomic and demographic models of human settlement, consumption and land management dynamics with biophysical models (Grimm et al. 2008b, Pickett et al. 2001). In a recent list of the "ten top research questions" in landscape ecology, for example, research on the causes and processes of land use and land cover change was described as one of the most important and challenging research areas (Wu and Hobbs 2002). Research funding agencies, most notably the National Science Foundation, now allocate considerable funds annually to interdisciplinary research on human-environment interactions.²

In many ways, economists are well-positioned to respond to these calls for greater integration of behavioral land use and biophysical models and indeed, some have done so. However, differences in research questions, methods and data that traditionally led ecologists and economists to emphasize different aspects of land use and land cover change still persist today. For example, economists have focused on development decisions by landowners or location decisions of households and firms at an individual level within an aspatial or highly stylized spatial setting. This approach has permitted consideration of key dimensions of constrained decision making, e.g. durability of capital (Harrison and Kain 1974; Anas 1978), intertemporal decisions (Arnott 1980; Capozza and Helsley 1989; Fujita 1982; Ohls and Pines 1975) and uncertainty (Mills 1981; Capozza and Helsley 1990), and how these features influence the resulting price gradient and land use pattern. These models posit that transportation costs generate smooth spatial variation across an otherwise featureless plane. Other forms of spatial heterogeneity, particularly those that are discrete and locally varying, have been considered in empirical modeling, but largely abstracted from in theoretical models of land use. On the other hand, ecologists consider spatial heterogeneity at all spatial scales to be a central causal factor in ecological systems (Alberti 2005; Grimm et al. 2008b; Pickett and Cadenasso 1995; Pickett et al. 2001) and the spatial and temporal dynamics of land use are viewed as fundamental questions.

² According to recent tabulations, NSF currently allocates approximately \$22.5 million in competitive research funds to human-environment research, a substantial portion of which involves land use models. This is approximately the same annual budget for the NSF economic program, which on average allocates a very small proportion of its budget to urban-related research.

The goals of this paper are two-fold: (i) to assess the usefulness of urban economic models for the study of land use-environment interactions and for policy analysis in this area and (ii) given the current limitations of these models in this regard, to discuss the advantages of integrating economic fundamentals with computational models that can incorporate spatial dynamics and multiple sources of spatial and agent heterogeneity. In assessing the utility of current economic models of urban land use, we find that meaningful progress has been made in econometric-based models that account for multiple sources of spatial heterogeneity and that then use spatial simulation to generate land use pattern predictions. Progress has also been made in using spatial simulation to extend the basic monocentric model to account for additional sources of spatial heterogeneity and in developing spatial dynamic economic models of urban growth that incorporate some form of spatial dynamics. However, these latter models remain highly stylized and, for policy purposes, more work is needed in developing spatial dynamic models with greater realism.

Because land use is a multi-disciplinary topic, many of the recent efforts to develop spatially dynamic land use models have occurred outside of economics. Agent-based computational models are at the forefront of the most recent wave of simulation-based modeling and increasingly have been adapted by every discipline save economics as the land use modeling method of choice. Economists have been slow to embrace this approach, perhaps because these models typically have omitted explicit representation of land markets and thus have largely attracted economists' disdain rather than interest. On the other hand, the methodology permits modeling of individual behavior, multiple sources of spatial and agent heterogeneity and, because the simulation approach allows one to "step the system through time," a ready means to modeling transitional dynamics. The gains to applying agent-based models of urban land use to policy analysis are substantial due to greater model flexibility and realism that allow one to investigate, for example, heterogeneous individual responses to a spatially delineated policy and their cumulative effect on a particular ecosystem service. While the fixed costs of learning a new method and the work of integrating economic fundamentals into these "bottom-up" models is not trivial, I conclude that the consequences for economists remaining on the sidelines are far more costly.

Before proceeding, it is useful to clarify terminology. First, the word **structural** is used in the economic sense of a model with structural parameters³ that correspond to a microeconomic process that determines macro-scale outcomes, e.g., the parameters of a land developer's cost function or of a household's demand function that influence the resulting market prices. Structural models are akin to what ecologists call **process-based** models and are distinguished from **pattern-based** models. Much like reduced form models in economics, pattern-based models describe meso- or macro-scale correlations between observed patterns and other observable variables. Patterns, either static or evolving over time, are the outcomes of processes. Patterns are revealed by spatial land use/land cover data, but processes are not. A process-based model focuses on the structural micro foundations of the observed outcomes that in aggregate generate the observed land use pattern.

³ See Holmes, this issue, for a very informative discussion of different types of applied work in economics.

Second, a **dynamic** process is one that transitions over time. Economists also use the word dynamic to mean forward-looking expectations, i.e., individual decisions are dynamic if they consider future expected benefits and costs. It is common to have an economic model of dynamic decision making at an individual level (e.g., intertemporal choice of land development) that describes a static spatial equilibrium at an aggregate level. To avoid confusion, we refer to dynamic decision making at an individual scale as **forward-looking behavior** and use the term **dynamic** or **transitional dynamics** to refer to a process that is evolving over time.

Third, we emphasize two sources of heterogeneity that are important in land use models: **spatial heterogeneity** refers to spatial variations at local scales, e.g., land parcel or a local neighborhood around a given location, and **agent heterogeneity** refers to key differences among individual households, firms or other agents, e.g., differences in preferences, wealth, technology or expectations.

Fourth, the term **spatial dynamics** is used to mean a spatially dependent dynamic process in which a change over time at one location is dependent on the state or changes in the state at other locations. This type of endogenous spatial dependence may arise, for example, from local interactions among spatially distributed agents or cumulative spatial feedbacks generated by the decisions of many individual agents over time and space. It is useful to note that a process may be dynamic and spatially heterogeneous, but not a spatial dynamic process (Pickett et al. 2001; Smith et al. 2009). For example, land development as a function of spatially heterogeneous and exogenous soils is a process that generates a spatial pattern, but lacks spatial dynamics. This process may be dynamic, e.g., due to population or income growth, but land use at one location is independent of land uses at other locations. In contrast, land development in response to local land use spillovers is a spatial dynamic process that arises from the endogenous interactions of neighboring agents. These interactions lead to spatially interdependent land development decisions that in turn determine the changes in land use over time and space.

Lastly, we clarify the sometimes maligned notion of **equilibrium** in economics. A common understanding of a system in equilibrium is a system that is in an unchanging state and indeed, economists often use the term equilibrium to mean a static and unchanging “steady state” in which prices, goods, population, technology and all other economic fundamentals are constant over time. However, the notion of equilibrium also has a much less restrictive meaning in economics. Equilibrium may instead refer to other aspects of the system that are unchanging, most notably that market clearing conditions are continually met over time. The market clearing condition rests on the assumption that prices instantaneously adjust, so that excess demands are always zero in all factor and goods markets. In this case, the market is said to be in equilibrium and prices are referred to as equilibrium prices, but this does *not* imply that prices, quantities and other aspects of the economy are unchanging over time. On the contrary and depending on the underlying micro foundations, market processes have been shown to exhibit any number of transitional dynamics that can range from a smooth transitional dynamic path that approaches a global steady state equilibrium to transitions between two or more steady states that may exhibit persistent fluctuations, regime switching, or chaotic dynamics (e.g., Benhabib and Farmer 1994, Brock and Hommes 1997, De Grauwe and Grimaldi 2006, Dufourt et al. 2008, Kiyotaki and Moore

1997). Because these models represent dynamic processes based on an assumption of market clearing, they are referred to as **dynamic equilibrium** models. This is the standard approach to modeling dynamics in economics, e.g., Desmet and Rossi-Hansberg (this issue) use this approach to model regional spatial dynamics.

An alternative approach to modeling dynamics is agent-based computational modeling that seeks to understand macro-level dynamics by explicitly modeling individual trades between agents without imposing aggregate market equilibrium conditions. These models have been adapted and developed by some economists, particularly in the area of finance (LeBaron and Tesfatsion 2008, LeBaron 2006). By modeling individual traders and the entire trading process from the bottom up, these computational models offer the potential for exploring a wider range of price formation mechanisms and market dynamics, for example the so-called “order book” mechanism in which agents post offers to buy and sell and orders are matched using defined trading rules (Chiarella and Iori 2002) and price adjustments that respond to non-zero excess demands (Chen and Yeh 2001). Because these models use simulation to relate micro-level behaviors and interactions to macro-level outcomes, they do not rely on market clearing (equilibrium) assumptions to describe market dynamics and thus are considered **out-of-equilibrium** or **disequilibrium models**. We return to a discussion of these and other computational models and their advantages and disadvantages in modeling land use dynamics later in the paper.

Some Ecological Considerations of Urban Land Use Pattern

To motivate the need for spatial dynamic models of land use change, it is useful to consider some basic ecological principles from landscape and urban ecology that highlight the importance of space and spatial dynamics. Ecologists’ study of landscape processes and patterns emphasizes the critical role of space at all spatial scales. Multiple local sources of spatial heterogeneity create discrete differences in ecosystem function across the landscape. This has led landscape ecologists to focus on the spatial heterogeneity of landscapes as a primary aspect of linking ecosystem processes and pattern. The spatial landscape “patch” is a basic building block for ecological landscape research. A landscape patch is defined as a relatively homogeneous area that differs from its surroundings in terms of key ecological features, including land use and land cover (Forman 1995). Depending on the landscape and level of urbanization, patches with natural vegetation (e.g., forests, grasslands, wetlands) may vary from large contiguous blocks in more rural areas to smaller, more isolated patches in urban areas to larger, but highly fragmented patches in suburban and exurban areas. For example, in a novel study of land cover patches distinguished by differences in vegetation structure and other relevant factors, Cadenasso et al. (2009) report that the average patch size in an urbanized watershed in Baltimore, Maryland was approximately 18 acres, ranging from less than a quarter of an acre to just under 1800 acres in size. If the goal is to integrate a human behavioral model with a biophysical model to better understand land use-environment interactions, then the behavioral model should be capable of generating predictions of land use patterns at a similar minimum resolution (e.g., a quarter acre plot). In doing so, the goal is not to predict the exact plots of land that will be developed, since such modeling accuracy isn’t possible. Instead, the goal is to understand how various causal factors influence the qualitative aspects of the observed land use pattern (e.g., the degree of contiguity, fragmentation, concentration, density of

various land uses) and changes over time in these pattern measures at a detailed spatial scale of analysis.

From an ecological perspective, urban development affects the patch structure of natural areas by altering its spatial pattern. Patch structure, including the shape, size edge and connectivity of natural patches, is important to species habitat, resource availability, competition and hence species survival (Alberti 2005). Connectivity of natural patches is critical for facilitating the movement of resources and organisms (Turner and Gardner 1991). Spatial patch dynamics (i.e., changes in the configuration of patches over time) is equally critical for ecosystem function (Pickett and Rogers 1997). For example, the water quality of urban streams is largely determined by the dynamics of soil erosion, sediment transport and alterations in the timing and delivery of nutrient transport (Pickett et al. 2001). The timing and quantity of nutrients delivered and the ability of streams to effectively process nutrients are strongly influenced by the spatial pattern of land uses in the watershed, e.g., the presence of riparian buffers, and their changes over time (Groffman et al. 2003).

Cadenasso et al. (2006) outline three critical dimensions of spatial complexity of ecosystem structure: heterogeneity (patch patterns across a landscape), connectivity (how patch patterns affect ecological functions) and contingency (patch history). Complexity in ecosystems is characterized by increasing spatial and temporal complexity in any of these three dimensions. Complexity in heterogeneity is described by the shifts in the mosaic of spatial patches across time and space; complexity in connectivity is embodied by dynamic interactions among patches that influence the functional dynamics of patches at individual and aggregate scales; and complexity in historical contingency is characterized by historical “legacy effects,” in which past states influence current functioning, and slowing emerging effects that influence current functioning and result from the evolution of one or more variables over a long period of time. They argue that all three dimensions are critical to the empirical study of urban ecosystems that are characterized by many interacting ecological and social processes at multiple spatial and temporal scales.

In summary, an understanding of the ecological processes that generate changes in ecosystem services requires an approach that accounts for spatial heterogeneity and spatial dynamics across multiple spatial and temporal scales. Likewise, an understanding of how individual decisions and actions impact ecological processes requires a model that can account for the location of human activity and changes in these activities at multiple spatial and temporal scales. The appropriate level(s) of spatial disaggregation will depend on the problem at hand. If the research question concerns regional adjustments in land allocation in response to a macro-level policy or process (e.g., global warming or national energy policy), then modeling land use dynamics at a land parcel scale is unnecessary. However, if the research question concerns the impact of land use on spatially distributed ecological processes (e.g., species survival, predator-prey dynamics, nutrient run-off and water quality), then spatially disaggregate models of land use dynamics at the scale of land parcels are needed. Here we focus our discussion on urban economic models that can be adapted to consider land use dynamics at these more spatially disaggregate scales.

Spatial Economic Models of Urban Land Use Change

A review of the recent literature on urban land use modeling published since 2003 reveals two striking facts (see Table 1 and Figure 1):

- Many researchers other than economists are actively modeling urban land use patterns. In fact, out of the 100 papers that most closely met the criteria of developing an empirical, analytical or simulation model of urban land use change, only 26 were published in an economics journal.
- Modeling methods vary dramatically across disciplines. Differences across disciplines are most evident between economics and quantitative geography (or GI Science). Over 60 percent of the papers published in economics journals were statistical, either in their entirety or with a spatial simulation extension; another 30 percent were analytical, either entirely or with a simulation extension. In contrast, 94 percent of the papers published in geography were simulation models, specifically either cellular automata or agent-based models.

To be fair, cellular automata and agent-based models often use statistical analysis to parameterize the model and agent-based models can be grounded in one or more theories of behavior. However, the distinctions shown in Figure 1 are nonetheless meaningful, as I explain in further detail below, and signal substantial differences in perceptions of the fundamental features of urban land use processes.

In reviewing models of urban land use change, I focus on economic models that generate predictions of land use pattern derived from structural economic models of land development decisions or residential location choice. In addition, the focus is on models that have explicitly incorporated spatial heterogeneity of landscape characteristics at a local (e.g., land patch or parcel) scale. This precludes much of literature in urban and regional economics on location and land use, including the canonical urban economic model, the monocentric model. Because this model only allows for a single source of spatial heterogeneity—transportation costs to a central location—it is of limited value in addressing ecological questions and I do not focus on it here. However, I do review several models that have extended this basic model to include other sources of spatial heterogeneity and thus, this model remains an important foundation for more realistic spatial models.

Econometric Land Use Models with Spatial Simulation

Econometric models of land use change derive from economic models of individual land use decisions in which landowners choose a land use in a given time period such that net expected returns over time are maximized. The theoretical framework for these models is well-established in urban economics (e.g., Arnott 1980; Arnott and Lewis 1979; Capozza and Helsley 1989, 1990; Capozza and Li 1994). While the models vary in their assumptions about space, expectations, durability of capital and uncertainty, they are forward-looking given that landowners make intertemporal land use decisions conditional on expectations over changes in land rents, e.g., due to population or income growth.

Econometric-based models of spatially heterogeneous land use patterns proceed in two steps. First, the econometric model is specified with a categorical variable representing land use as the dependent variable, which hypothesized to depend on land rents in a particular (e.g., agriculture or urban) land use. Factors hypothesized to influence expected land rents are included as independent variables. These typically include multiple spatially heterogeneous landscape (e.g., soil and slope variables) and location features (e.g., distance to CBD, presence of local amenities, neighborhood land uses) and policy constraints (e.g., zoning). This model is then estimated using spatial micro panel data on land use over time at the scale of land ownership, e.g., land parcels, and additional spatially detailed data on the independent variables. A variety of estimation models are possible, including binary or multinomial discrete choice models (Bockstael 1996; Nelson and Hellerstein 1997), duration models that account for time-varying variables (Irwin and Bockstael 2002; Towe et al. 2008) and option value models that account for the influence of uncertainty over future prices (Cunningham 2007; Towe et al. 2008). Second, parameter estimates are used to simulate hypothetical changes in land use pattern, e.g., under baseline and alternative scenarios, using a spatially explicit, GIS-based model of the actual landscape. This permits the role of individual-level factors in generating regional land use patterns, including land use policies and other spatially heterogeneous features of the landscape, to be investigated. The results can then be compared using spatial statistics or landscape metrics to draw conclusions regarding the predicted influence of these factors on the concentration, fragmentation or other spatial dimensions of land use. This two-step approach has been used to model urbanization and sprawl (e.g., Carrion-Flores and Irwin 2004; Irwin and Bockstael 2002); the effects of land policies on urbanization patterns (e.g., Irwin et al. 2003; Irwin and Bockstael 2004; Langpap et al. 2008; Lewis et al. forthcoming; Newburn and Berck 2007); and the conversion of forest and agricultural land (e.g., Lewis and Plantinga 2007). Because of their ability to account for multiple sources of spatial heterogeneity, ecological features can be readily incorporated. In addition, the land use simulations can be linked with environmental impact models in which land use is the driver of environmental change to permit a fuller examination of the predicted effects of policy and other variables on ecosystem services. This approach has been used, for example, to study the impacts of conservation payments on landowner decisions and biodiversity loss (Lewis et al. 2008), the effectiveness of targeting strategies on land conservation (Newburn et al. 2006) and the effect of land use policies on watersheds (Langpap et al. 2008).

A number of econometric challenges arise in estimating these models. Primary among these are spatial error dependence and endogenous spatial regressors. Spatial error autocorrelation is common in models that use spatial data in which the spatial delineation of the data collection process does not correspond to the spatial scale of the data generating process (e.g., average housing values are measured by census tract, but the processes that influence housing values have no correspondence to the spatial unit of census tracts) (Anselin 1988). Endogenous spatial regressors complicate the analysis since, in addition to the standard identification problem that arises from the endogeneity, they are likely to be spatially correlated with the errors. This can also lead to biased estimates (Irwin and Bockstael 2001). Other econometric challenges that arise include endogenous policy variables, in which the endogeneity arises because growth controls and other land use policies are often adopted in response to increased growth pressures that arise from households' and firms' demand for new development in a

region, and spatial instability of parameters. If ignored, these problems will lead to biased or inconsistent estimates and are thus inappropriate for hypothesis testing and spatial prediction. Methodological issues also arise in the simulation used to generate land use pattern predictions. For example, Lewis (2008) points out the importance of accounting for uncertainty in the simulation predictions rather than treating the predicted probabilities as deterministic.

While the modeling approach is rigorous and the results have generated useful insights, this approach provides only a limited means to modeling land use dynamics (Parker et al. 2003). Because they typically do not account for individual heterogeneity that may influence decisions, e.g., age, experience and expectations, the approach is unlikely to fully identify parameters of the underlying structural model. In addition, empirical models cannot capture recursive interactions or feedbacks across multiple spatial or temporal scales particularly well and thus they are not well-suited for modeling the full evolution of spatial systems over time. Thus empirical-based simulations are valid for shorter time periods (e.g., 5-10 years) over which the underlying processes may reasonably be assumed to be stationary.

It is worth pointing out that this two-step statistical-based approach bears many similarities to empirical spatial cellular automata models in which the landscape is represented by an array of equal-sized cells, each of which corresponds to a land use. These models have enjoyed tremendous popularity in geography, environmental science and other related disciplines (Table 1 and Figure 1). Raster data⁴ on land use change over time are used to empirically estimate the cell-based land use transitions. The model is then simulated forward in time using the empirically derived transition probabilities to generate predictions of land use patterns and change. This second stage is very similar to the simulation approach described above although the spatial unit of analysis is different since parcel-based models use actual land ownership boundaries rather than cells. However the first stage estimation approach differs in more substantive ways. Raster data are delineated by equal-area cells rather than the boundaries of the decision making unit (in this case, parcels) and thus massive problems of spatial dependence arise in using these data to estimate a land use change model. For example, if the raster data are defined with a relatively small cell size (e.g., 30m x 30m is common), then multiple cells will often correspond to the same land parcel. Because ownership boundaries are unobserved, any transition in land use that is modeled using cells as the unit of observation will falsely treat cells that correspond to the same parcel as independent observations. For the same reason, these models will generate biased estimates of local interactions –e.g., they will estimate a positive land use interaction among neighboring cells when in fact none may exist. In such cases, parameter estimates reveal correlations, but not causal relationships. This substantially limits the usefulness of the simulation if the

⁴ Raster data are defined by a matrix of cells in which each cell is assigned a categorical (e.g., land use) or continuously varying (e.g., slope) value. This is in contrast to vector data, in which X and Y coordinates are used to define the locations of points, lines, and areas (polygons) that correspond to discrete map features (e.g., roads, parcels, jurisdictions).

purpose is to uncover the causal effects of hypothesized socioeconomic or biophysical factors on land use pattern.

Spatial Equilibrium Models of Urban Land Use Pattern

As Ed Glaeser writes in his 2008 book “Cities, Agglomeration and Spatial Equilibrium,” the spatial equilibrium assumption is the bedrock of urban economics upon which everything else stands. This assumption is the spatial version of the market clearing equilibrium condition discussed earlier: prices are assumed to instantaneously adjust so that excess demands are zero, land and housing markets are always in equilibrium and no opportunity for spatial arbitrage exists (Roback 1982). The concept is motivated by the mobility of people and firms from one location to another. In its simplest setting, competition for spatially heterogeneous locations among homogeneous households results in equilibrium prices that perfectly offset locational differences so that people are spatially indifferent and utilities are equalized across space. Models of locational equilibrium with heterogeneous households, while abstracting from any explicit representation of space, provide another example of locational indifference: a sorting equilibrium is defined in these models as a set of individual location decisions that are optimal given the location decisions of all other individuals in the population (e.g., Bayer and Timmins 2005, Epple and Platt 1998, Epple and Sieg 1999).

Spatially heterogeneous models of urban land use patterns rely on the assumption of a spatial equilibrium to account for the influence of additional sources of spatial variation on equilibrium prices. A common starting point is the basic monocentric model, in which transportation costs to a central business district generate spatially differentiated land rents. The spatial equilibrium implies that land rents will adjust such that the marginal increase in transport costs from locating farther away are exactly offset by the decrease in land rents. There is a long history in urban economics of then incorporating other features of space into the monocentric model, e.g., traffic congestion, local public goods and neighborhood crowding (Fujita 1989). Analytical tractability requires that these features also vary with distance to the central business district and thus the model is unable to account for variations in pattern at a local scale.

While non-monocentric models (e.g., Fujita and Ogawa 1982) and game theoretic models (Turner 2005) have been developed that allow for local interactions that are also analytically tractable, these models are by necessity highly stylized and cannot account for multiple sources of spatial heterogeneity at local scales. In such cases, spatial simulation has been used as an alternative approach to extending the basic monocentric model to account for additional sources of local spatial heterogeneity. Wu and Plantinga (2003) and Caruso et al. (2007) provide good examples of this approach. While the models differ in their details, they both start with the assumptions of a static, open-city monocentric model and then incorporate additional sources of spatial heterogeneity by assuming households’ have preferences over these additional landscape features. Equilibrium land rents are a function of both distance to the central business district and these other spatial features. Wu and Plantinga (2003) consider access to exogenously determined open space (e.g., public parks) whereas Caruso et al. (2007) consider the local endogenous spillover effects of surrounding open space and

development. Given an analytical expression for land rents as a function of heterogeneous space, spatial simulation is used to derive the implications for locally varying land use patterns. Wu and Plantinga (2003) use this approach to describe the long run spatial equilibrium patterns that result within the context of an open city model. On the other hand, Caruso et al. (2007) model the evolution of land use patterns over time by distinguishing a short run equilibrium, in which household utility is equalized within the region but is greater than the rest of the world. The distinction is assumed to arise from temporary monopsony power attributed to a single and unique migrant that enters the region each period. This is an awkward assumption of the model, but, by preventing land rents from adjusting instantaneously in each period, it achieves an ordering over time of each new household's preferred location.

Dynamic spatial equilibrium models of urban land use build from their static counterpart by introducing some exogenous growth mechanism (e.g., population or income growth, technological innovation) and assumptions about expectations (myopic, perfect foresight or rational expectations). The models often assume a monocentric urban area with centralized employment (e.g., Anas 1978, Arnott 1980, Braid 2001, Capozza and Helsley 1989, Hockman and Pines 1981, Turnbull 1988), but in other cases space is defined more generally along a line (e.g., Berliant and Wang 2008, Lucas and Rossi-Hansberg 2002). These models have been used to study various aspects of urban spatial growth and decline, including leapfrogging and other forms of discontinuous urban development patterns (Ohls and Pines 1976, Fujita 1976, Mills 1981, Wheaton 1982). A critical distinction between the dynamic monocentric models and the "nonmonocentric" models in which space is more generally defined is that the latter are much better suited for modeling local *spatial* dynamics, i.e., spatially interdependent processes in which the outcome or change at one location is dependent on the states of neighboring locations. However, because of the need for tractability, these models remain highly stylized in terms of space. A second shortcoming is that the partial equilibrium framework that is used to develop most of these models prevents a full analysis of transitional dynamics. Most urban spatial economic models ignore labor and multiple output markets and thus are limited to considering a comparison of steady states in which only one or two margins of adjustment (e.g., land rents, development density gradient) are modeled. While such an approach is reasonable for understanding a particular aspect of the urban-regional system, it arbitrarily ignores other margins of adjustment (e.g., work force participation, migration, firm mobility, etc.). For the purposes of policy analysis, these multiple channels of adjustments are the critical issue (Combes et al. 2005).

Although it is not the focus of our discussion here, it is worth noting that agent heterogeneity is also an important source of urban spatial dynamics as it is clearly interacts with spatially heterogeneous variables in fundamental ways that influence changes in urban land use pattern over time. For example, the traditional suburbanization process can only be understood within the larger context of heterogeneous households that sort themselves by migrating from the city to more homogeneous and typically wealthier suburban communities. Heterogeneous agent models in urban economics (e.g., Bayer and Timmins 2005, Epple and Sieg 1999, Sieg et al. 2002) have focused on the sorting process of households across local jurisdictions in which the location choice of households and the attributes of the

jurisdiction are simultaneously determined. These models have provided empirical evidence of the importance of agent heterogeneity and sorting in explaining observed patterns of household location in urban areas and have sparked exciting new research on household location, local amenities and urban housing markets (e.g., Bayer et al. 2009, Kuminoff 2009, Smith et al. 2004, Walsh 2007). While the models that have been developed to-date are static and do not incorporate any form of spatial heterogeneity, promising work on both fronts is currently underway (e.g., see Epple et al., this issue, for a discussion and example of incorporating local spatial heterogeneity).

Agent-Based Computational Models

An emerging view among some economists describes the economy as a dynamic adaptive system (Anufriev and Branch 2009, Colander et al. 2008, Tesfatsion 2006), in which interactions among agents, who are likely distinguished by different expectations or other key sources of heterogeneity, are viewed as a fundamental determinant of macro-level outcomes. Rather than studying the long run steady state equilibrium or equilibria of the system, the focus is on the transitional dynamics that arise from individual-level decisions and interactions and the conditions under which complex dynamics (e.g., bifurcations, regime shifts or other non-linear dynamics) emerge. This viewpoint has been at the edges of urban and regional economic theory and modeling for a long time. In fact, regional scientists during the 1970's and 1980's sustained an active area of research that adapted physical models to the complex dynamics of regional economies (e.g., De Palma and Lefevre 1985). Renewed interest in urban and regional systems as complex, adaptive systems has come from the growing interdisciplinary field of complexity theory, a field that has been championed by research organizations such as the Santa Fe Institute and research programs such as the National Science Foundation's Coupled Natural-Human Systems program.

Agent-based computational economics (ACE) constitutes a relatively new modeling approach that seeks to link the behavior and interactions of heterogeneous agents with complex dynamics at higher scales of aggregation. Although ACE models are still in their relative infancy in economics, they have gained a foothold because of their flexible modeling framework and, in some cases, their ability to explain empirical regularities that conventional models cannot.⁵ The essential features of these models are multiple heterogeneous agents, defined in terms of a set of behavioral rules within a computationally constructed world, and their interactions that evolve the system over time. Given a set of detailed initial conditions (e.g., that fully specify the institutional arrangements, initial number and types of consumers and firms, endowments, behavioral rules, geography, trading protocols), agents carry out production, pricing and trade activities, which generate feedbacks (e.g., profits, utility, learning, institutional change) that determine future behaviors and interactions. A key departure of agent-based economic models is the lack of any kind of equilibrium constraint: given the initial

⁵ For comprehensive reviews and discussions see the [Handbook of Computational Economics](#), 2006, edited by Leigh Tesfatsion and Kenneth Judd. The description of ACE models here is based on the discussion by Tesfatsion (2006).

specifications of the economic system, the transitional dynamics are driven solely by agent trading that is not subject to an aggregate-level market clearing constraint or other equilibrium conditions.

The ACE methodology has been used in some areas of economics, particularly finance, as a complementary method to analytical models, human subject experiments and reduced form empirical models. The bottom-up approach permits study of out-of-equilibrium dynamics, the conditions under which the system comes close to a market equilibrium (or doesn't) and over what time scale it is reached (or isn't). However, this advantage of model flexibility is also a disadvantage in terms of model complexity, since isolating the causal linkages between micro-level structure and macro-level outcomes becomes much more difficult. Concerns over the large number of parameters and many degrees of freedom have generated skepticism among some regarding the "wilderness" of agent-based computational methods (not unlike the "Anything Goes" critique of general equilibrium theory). To allay these concerns, researchers stress the importance of estimating or calibrating parameters using data to limit the plausible number of model outcomes, but the data required to do so are often very extensive. In response to this debate, some advocate for a middle way: using simple and parsimonious models that admit the most salient features of agent heterogeneity while still retaining the assumption of continual market clearing as a means of guiding the development of agent-based models (Hommes 2006).

Spatial agent-based models of urban land use change

Parker et al. (2003) review the applicability of agent-based models to modeling land use and land cover change. The reasons are compelling if one is interested in the dynamics of spatially heterogeneous patterns over time and linking these patterns with the behaviors of households, land developers, firms and other agents that influence land use. In particular, because they are carried out in a simulation environment, these models can readily incorporate sources of spatial and agent heterogeneity that are intractable in analytical models. In addition, the simulation-based approach permits one to step agents through time and derive aggregate land use patterns from the bottom-up. However, a rigorous treatment of land markets in this framework has not been developed. As in other areas of economics, there is little guidance from standard economic models on how to model agent trading in the absence of market equilibrium conditions (Tefatsion 2006). The spatial fixity of land and location raises particular concerns over the ability of agent-based models to model the capitalization process (i.e., land rents) in the absence of an assumption of spatial equilibrium. Models of agent trading that do not reflect the influence of excess demands for locational attributes clearly are insufficient and basic questions remain regarding the best way forward in modeling urban land markets in an agent-based world.

Because of the conspicuous absence of economists from this arena of model development, land and housing markets have been ignored by most agent-based urban land use models. Instead, these models tend to focus largely on spatial and agent heterogeneity and specification of the decision making rules of households and other agents in the model. For example, Otter et al. (2001) model firm and household location interactions to study the emergence of urban clusters. Several different types of households and firms are defined, distinguished by their characteristics and preferences. Competition is

omitted from the model, however (once an agent locates in a cell the cell is occupied and cannot be contested by others) and thus the model lacks any representation of land markets. Likewise, Brown and Robinson (2006) model agent decision making within a utility maximizing framework, but choices are unconstrained by land prices since they are omitted from the model. While several of the more economic-oriented models include some representation of land or housing prices, this is done in an adhoc way. For example, Benenson (1998) develops a model of urban population dynamics in which housing price is modeled as a function of the households' income and the average value of neighboring houses. Warren et al. (2009) develop a model of segregation across a central city and suburbs in which prices are modeled as a function of lot size and two variables intended to capture the relative demand for housing in a given neighborhood, the occupancy rate of housing and the net rate of population growth in the neighborhood.

A few of the integrated transportation-land use microsimulation models that consider transitional dynamics have included urban land market models. Waddell (2000) and Waddell et al. (2003) describe the design and implementation of the well-known UrbanSim model, a microsimulation model of urban development that seeks to model urban land use patterns as the result of household and business location choices and land developer decisions. The evolution of land prices over time is modeled using a two-step approach. First, the relative implicit prices associated with the heterogeneous characteristics of each location are assumed to be stable through time and calculated with a single estimation of a hedonic price function using transactions data. Second, overall price changes over time are assumed to be captured by a shifting intercept term, which is modeled as a function of relative vacancy rates in each time period in the residential and commercial real estate markets. As a means of modeling capitalization, this approach recognizes the importance of tracking excess demands, but otherwise is not consistent with economic fundamentals. Changes in the relative implicit prices will cause households to adjust their optimal bundle of housing attributes and firms to adjust their production of these attributes and the hedonic equilibrium will be renegotiated. Assuming that the shape of the hedonic function remains constant and that relative price changes only reflect shifts in the intercept term ignores substitution and income effects. Other microsimulation models that incorporate some representation of urban land markets include Miller et al. (2004). These authors present a detailed agent-based model of urban land use and transportation, which they present as an alternative to the more aggregate zonal-based transportation-land use models. Individually negotiated prices are used to derive a zonal average price, which is then adjusted based on excess demand for housing within each zone. This approach appears more promising, but it is unclear exactly how this adjustment is carried out or how it should be carried out.

Work by Filatova et al. (2009) and related papers by these authors (Filatova et al. 2008; Parker and Filatova 2009) represents the most serious effort to-date to explicitly model land markets within an agent-based framework.⁶ Like other spatial simulation models of urban land use, households have

⁶ As pointed out by Parker and Filatova (2009), agricultural economists have had success in applying ABMs to agricultural land markets (e.g., Berger 2001; Happe, Kellermann and Balmann 2006). Here we focus on the application of ABMs to urban land markets.

preferences over locally varying open space amenities and are constrained by transportation costs to the CBD. However, rather than equilibrium prices, transactions between individual buyers and sellers are modeled explicitly in terms of the process of locating trading partners, bid and ask prices and price negotiations. While household bid prices reflect the added value of open space amenities, these individual price negotiations cannot fully capture the market-wide capitalization process. Parker and Filatova (2009) provide some discussion of modeling strategies for “initializing and updating” rents, but these are admittedly ad hoc. In reviewing the “open questions” that confront researchers in developing agent-based models of urban land markets, Parker and Filatova (2009) focus on how the detailed aspects of the individual trades (e.g., the process by which ask and bid prices are set, subsequent price negotiations, how gains from trade are divided) should be modeled, which arise because a spatial equilibrium is no longer imposed.

Future Directions in Spatial Dynamic Models of Urban Land Use

Based on our review of the literature on urban land use modeling, several conclusions regarding future directions for modeling the spatial dynamics of urban land use emerge. First, it is clear that highly stylized models of space that omit spatial dynamics and multiple sources of spatial heterogeneity are not useful for the policy analysis of land use and environment interactions. Increasingly the questions that policy makers are asking, from local planners to global leaders, require spatially dynamic and heterogeneous models. Second, models that omit an explicit description of transitional dynamics of urban land use over time are also of limited use in analyzing land use-environment interactions. Because ecological systems evolve over multiple time scales (e.g., hours, days, years, decades) that do not necessarily correspond to the time scales over which people adjust and make decisions, transitional dynamic models that can account for divergent time scales are needed for policy analysis (Chen et al. 2009). Third, models that only consider the direct effect of an exogenous change or stochastic shock on land use and ignore the indirect effects of other market adjustments (e.g., labor markets and goods markets) will fail to correctly characterize the transitional dynamics and thus are not useful for policy analysis. Fourth, recent empirical models provides strong evidence of the importance of agent heterogeneity in determining intra-metropolitan patterns of household location, which suggests that heterogeneity among households and firms is also an important determinant of urban spatial dynamics.

Incorporating all of these complicating features into models of urban land use built from micro foundations is minimally very daunting, likely intractable and perhaps not even desirable given the problems that accompany such model complexity. Rather than introducing all these complexities at once, a necessary approach is to proceed slowly and methodically in making models more dynamic and detailed in terms of their levels of spatial, sectoral and agent disaggregation. Indeed, recent work in extending urban spatial models to more dynamic settings that uses simulation as a means of fully characterizing the dynamic general equilibrium has done just this (e.g., Desmet and Rossi-Hansberg, this issue). This line of research provides a clear path forward in the further development of urban spatial dynamic models. However, despite their advantages over traditional urban economic models, these models are still bound by the need for some analytical tractability and incorporating additional complexities into this framework is technically very difficult (Colander et al. 2008). It is unclear what the

eventual pay-off of this approach will be if the goal is to develop more realistic models for policy analysis.

Agent-based models offer an alternative way forward in terms of developing more realistic spatial dynamic models by freeing the researcher from the bonds of analytical constraints. However, being free of these bonds comes with its own set of challenges that requires economists to reformulate their models of exchange in a much greater level of detail, for example in terms of specifying the institutional setting and heterogeneous agent behaviors and constraints. Because of the large degrees of freedom afforded by these models and the potential to model too much detail, a methodical approach to developing these models is also critical. Towards this end, we agree with a middle road approach that Hommes (2006) and others (Brock, personal communication) have advocated that relies on using more realistic (and thus more technically difficult) dynamic equilibrium models to guide the development of agent-based models. In addition, agent-based models should follow standard best-practices for model building. Namely, agent-based models should not attempt to model all or even many aspects of the real world, but instead should be tailored to the research question and incorporate only the complications that are necessary for the question at hand.

The potential for agent-based models to be “too loose” and the importance of simplicity in model specification point to the necessity of empirical analysis. Empirical analysis is needed to guide model specification by uncovering the most important sources of model complexity (e.g., critical sources of agent heterogeneity) and providing guidance in constraining parameter values. That economists are well-trained in empirical identification methods is very encouraging in this respect. As discussed in more detail by Holmes (this issue), economists have developed a suite of empirical methods aimed at parameter identification. Structural empirical models rely on explicit assumptions about the structural errors in order to recover the behavioral parameters of interest whereas reduced form models focus on recovering targeted parameters using as few structural assumptions as possible in order to isolate causality. Reduced form empirical methods include a variety of approaches in which the emphasis is on eliminating endogenous variables and relying on exogenous within-sample variation to isolate causal effects. Various research designs are used and include, for example, quasi-experimental and regression discontinuity methods that rely on exogenous variation to identify so-called treatment effects. Other approaches include lab and field experiments that seek to identify effects through full randomization. Both structural and reduced form methods can be useful for identifying the behavioral parameters of interest.⁷ Such empirical methods are critical in developing agent-based economic models for policy analysis that can be used to link individual responses to policy to macro-level urban land use dynamics.

Concluding Thoughts

We find that both dynamic equilibrium and agent-based models provide potential paths forward in developing more realistic and comprehensive models of urban spatial dynamics. In either case,

⁷ Also see Timmins and Schlenker (2009) for additional discussion and comparison of structural and reduced form empirical methods and applications in environmental and natural resource economics.

empirical methods will play a necessary and highly complementary role in “taming” these models and enabling the specification of models that are appropriate for policy analysis. Figure 2 provides a synthesis of modeling approaches. First, the structural dynamic economic model that links micro-scale behavior and interactions with macro-scale land use dynamics is developed using either an agent-based or dynamic equilibrium framework. In either case, the model complexities are likely to result in a system that is characterized by multiple steady state equilibria (or a continuum of equilibria or no equilibria) and potentially complex transitional dynamics. Empirical assessment of functional forms and parameter values is necessary to make the model useful for policy analysis. Given parameterization of the micro-level behavioral functions of the model and other specifications required by the modeling framework (e.g., agent-based models require specification of other aspects of the trading process), the transitional and steady state dynamics of the system can be described using spatial simulation on either an actual or hypothetical landscape. Other dynamic analysis methods, such as phase portrait graphs that delineate the possible equilibria and their corresponding basins of attraction,⁸ may also be possible. An investigation of the potentially non-marginal and multiple channels of adjustment through which a policy change may influence land use dynamics is then possible, although by no means likely to be easy, within this dynamic framework.

In summary, if spatial dynamic economic models of land use can be developed that permit the full analysis of system dynamics while also retaining a correspondence between individual location or land use behavior and aggregate economic outcomes, the results would be transformative. Rather than focusing on long run equilibrium conditions, such models would spawn a variety of new research questions made possible by consideration of the full dynamics and cross-scale interactions of urban systems. These models would take economic policy analysis to a new level of realism and relevance by incorporating multiple sources of spatial heterogeneity and examining the effect of policies on the heterogeneous behavior of individuals and the resulting evolution of prices, land use and urban spatial structure over time. Agent-based models provide a promising modeling approach that deserves the serious attention of urban and regional economists interested in spatial dynamics. The gap between a rigorous and fully specified economic agent-based model of urban land use and the existing set of agent-based land use models is substantial. We have enumerated a few of the key challenges and pitfalls of this method. Meaningful progress relies on the considerable and sustained efforts of economists and others who already have expertise in this methodology. Despite the challenges, the advantages of the model flexibility afforded by agent-based models combined with the empirical methods for parameter identification that are already well-established in economics points a clear way forward for economists interested in land use dynamics, integrated human-environment models and policy analysis with greater realism.

⁸ Chen et al. (2009) provide an example of a two-variable dynamical regional ecological-economic system in which numerical methods are used to solve the system and generate such phase portraits.

Acknowledgements

I am very thankful to Gilles Duranton for excellent feedback on the initial draft of this paper, as well very helpful feedback from Carmen Carrion-Flores and other participants at the Journal of Regional Science 50th Anniversary Symposium. I gratefully acknowledge feedback from Buz Brock and ongoing discussions with Ciriya Jayaprakash on a variety of topics relevant to this paper, including agent-based models, complex systems, equilibrium and the multiple meanings of the word “dynamics.” Likewise, I am grateful to Kathleen Bell, Nancy Bockstael, Dan Brown, Jackie Geoghegan, Darla Munroe, Dave Newburn and Dawn Parker for their helpful discussion of land use modeling. I thank Tom Baerwald for his input on recent NSF program spending levels and Doug Wrenn for his assistance in gathering and analyzing the data reported in Tables 1 and Figure 1. This research is supported by research funding from the James S. McDonnell Foundation, the National Science Foundation under DEB-0410336 and Grant No. 0423476, and the U.S. Department of Agriculture Forest Service Northern Research Station.

References

- Alberti, M. 2005. ‘The effects of urban patterns on ecosystem function,’ *International Regional Science Review*, 28(2), 168-192.
- Anas, A. 1978. ‘Dynamics of urban residential growth,’ *Journal of Urban Economics*, 5, 66-87.
- Anufriev, M. and W.A. Branch. 2009. Introduction to the special issue on complexity in economics and finance,’ *Journal of Economic Dynamics and Control*, 33, 1019-1022.
- Anselin, L. 1988. *Spatial Econometrics: Methods and Models*. Netherlands: Kluwer Academic Publishers.
- Arnott, R.J. 1980. ‘A simple urban-growth model with durable housing,’ *Regional Science and Urban Economics*, 10(1), 53-76.
- Arnott, R.J. and F. Lewis. 1979. ‘The Transition of Land to Urban Use,’ *Journal of Political Economy*, 87(11), 161-69.
- Bayer, P., N. Keohane and C. Timmins. 2009. ‘Migration and hedonic valuation: The case of air quality,’ *Journal of Environmental Economics and Management*, 58, 1-14.
- Bayer, P. and C. Timmins. 2007. ‘Estimating equilibrium models of sorting across locations,’ *Economic Journal*, 117(518), 353-374.
- Bayer, P. and C. Timmins. 2005. ‘On the equilibrium properties of locational sorting models,’ *Journal of Urban Economics*, 57, 462-477.
- Benenson, I. 1998. ‘Multi-agent simulations of residential dynamics in the city,’ *Computers Environment and Urban Systems*, 22(1), 25-42.

- Benhabib, J. and R. Farmer. 1994. 'Indeterminacy and increasing returns,' *Journal of Economic Theory*, 63, 19-41.
- Berliant, M. and P. Wang. 2008. 'Urban growth and subcenter formation: A trolley ride from the Staples Center to Disneyland and the Rose Bowl,' *Journal of Urban Economics*, 63, 679-693.
- Bockstael, N.E. 1996. 'Modeling economics and ecology: The importance of a spatial perspective,' *American Journal of Agricultural Economics*, 78(5), 1168-1180.
- Braid, R. 2001. 'Spatial growth and redevelopment with perfect foresight and durable housing,' *Journal of Urban Economics*, 49, 425-452.
- Brock, W.A. and C.H. Hommes. 1997. 'A rational route to randomness,' *Econometrica*, 65, 1059-1160.
- Brown, D.G. and D.T. Robinson. 2006. 'Effects of heterogeneity in residential preferences on an agent-based model of urban sprawl,' *Ecology and Society*, 11(1), Article Number 46.
- Cadenasso, M.L., S.T.A. Pickett and J.M. Grove. 2006. 'Dimensions of ecosystem complexity: Heterogeneity, connectivity and history,' *Ecological Complexity*, 3, 1-12.
- Capozza, D and R. Helsley. 1989. 'The Fundamentals of Land Prices and Urban Growth,' *Journal of Urban Economics*, 26(3), 295-306.
- Capozza, D and R. Helsley. 1990. 'The Stochastic City,' *Journal of Urban Economics*, 28(2), 187-203.
- Capozza, D and Y.M. Li. 1994. 'The intensity and timing of investment - the case of land,' *American Economic Review*, 84(4), 889-904.
- Carrion-Flores, C. and E.G. Irwin. 2004. 'Determinants of residential land use conversion and sprawl at the rural-urban fringe.' *American Journal of Agricultural Economics*, 86(4), 889-904.
- Caruso, G., D. Peeters, J. Cavailhes and M. Rounsevell. 2007. 'Spatial configurations in a periurban city. A cellular automata-based microeconomic model,' *Regional Science and Urban Economics*, 37(5), 542-567.
- Chen, S.H. and C.H. Yeh. 2001. 'Evolving traders and the business school with genetic programming: A new architecture of the agent-based artificial stock market,' *Journal of Economic Dynamics and Control*, 25, 363-394.
- Chen, Y., E.G. Irwin and C. Jayaprakash. 2009. 'Dynamic modeling of environmental amenity-driven migration with ecological feedbacks.' *Ecological Economics*, 68, 2498-2510.
- Chiarella, C. and G. Iori. 2002. 'A simulation analysis of the microstructure of double auction markets,' *Quantitative Finance*, 2, 346-353.
- Colander, D., P. Howitt, A. Kirman, A. Leijonhufvud and P. Mehrling. 2008. 'Beyond DSGE model: Toward an empirically based macroeconomics,' *American Economic Review: Papers and Proceedings*, 98:2, 236-240.

- Collins, J.P., A. Kinzig, N.B. Grimm, W.F. Fagan, D. Hope, J.G. Wu and E.T. Borer. 'A new urban ecology,' *American Scientist*, 88(5), 416-425.
- Combes, P.P., G. Duranton and H.G. Overman. 2005. 'Agglomeration and the adjustment of the spatial economy,' *Papers in Regional Science*, 84(3), 311-349.
- Cunningham, C. 2007. 'Growth controls, real options, and land development.' *Review of Economics and Statistics*, 89(2), 343-358.
- Daily, G.C., S. Polasky, J. Goldstein, et al. 'Ecosystem services in decision making: time to deliver,' *Frontiers in Ecology and the Environment*, 7(1), 21-28.
- De Grauwe, P. and M. Grimaldi. 2006. 'Exchange rate puzzles: A tale of switching attractors,' *European Economic Review*, 50, 1-33.
- De Palma, A. and C. Lefevre. 1985. 'Residential Change and Individual Choice Behavior,' *Regional Science and Urban Economics*, 15, 421-34.
- Desmet, K. and E. Rossi-Hansberg (this issue). 'On spatial dynamics,' *Journal of Regional Science*.
- Dufourt, F., T. Lloyd-Braga and L. Modesto. 2008. 'Indeterminacy, bifurcations and unemployment fluctuations,' *Macroeconomic Dynamics*, 12 (Supplement 1), 75-89.
- Epple, D., B. Gordon and H. Sieg (this issue). 'Drs. Muth and Mills meet Dr. Tiebout: Integrating location-specific amenities into multi-community equilibrium models,' *Journal of Regional Science*.
- Epple, D. and H. Sieg. 1999. 'Estimating equilibrium models of local jurisdictions,' *Journal of Political Economy*, 107(4), 645-681.
- Filatova, T., D. Parker and A. van der Veen. In Press. Agent-Based Urban Land Markets: Agent's Pricing Behavior, Land Prices and Urban Land Use Change. *Journal of Artificial Societies and Social Simulation*.
- Filatova T., D.C. Parker and A. van der Veen. 2008. Agent-based land markets: Heterogeneous agents, land prices and urban land use change. Manuscript.
- Forman, R.T.T. 1995. *Land Mosaics: The Ecology of Landscapes and Regions*. Cambridge: Cambridge University Press.
- Fujita, M. 1982. 'Spatial patterns of urban development.' *Journal of Urban Economics*, 12, 22-52.
- Fujita, M. 1989. *Urban Economics: Land Use and City Size*. Cambridge: Cambridge University Press.
- Fujita, M. and H. Ogawa. 1982. 'Multiple Equilibria and Structural Transition of Non-monocentric Urban Configurations,' *Regional Science and Urban Economics*, 12, 161-196.

- Glaeser, E. 2008. *Cities, Agglomeration and Spatial Equilibrium*. Oxford: Oxford University Press.
- Grimm, N.B., S.H. Faeth, N.E. Golubiewski, C.H. Redman, J. Wu, X. Bai and J.M. Briggs. 2008a. 'Global change and the ecology of cities,' *Science*, 319(5864), 756 – 760.
- Grimm, N.B., D. Foster, P. Groffman, J.M. Grove, C.S. Hopkinson, K.J. Nadelhoff, D.E. Pataki and D.P.C. Peters. 2008b. 'The changing landscape: ecosystem responses to urbanization and pollution across climatic and societal gradients.' *Frontiers in Ecology*, 6(5), 264-272.
- Groffman, P., D.J. Bain, L.E. Band, et al. 2003. 'Down by the riverside: urban riparian ecology,' *Frontiers in Ecology and the Environment*, 1(6), 315-321.
- Harrison, D. and J.F. Kain. 1974. 'Cumulative urban growth and urban density functions.' *Journal of Urban Economics*, 1, 61-98.
- Hochman, O. and D. Pines. 1982. 'Costs of adjustment and the spatial pattern of a growing open city,' *Econometrica*, 50, 1371-1391.
- Holmes, T. (this issue). 'Structural, experimentalist and descriptive work in regional economics' *Journal of Regional Science*.
- Hommel, C.H. 2006. 'Heterogeneous agent models in economics and finance.' In *Handbook of Computational Economics*, Volume 2, eds. L. Tesfatsion and K.L. Judd. Amsterdam: North-Holland, pp. 1109-1179.
- Irwin, E.G., K. P. Bell, and J. Geoghegan. 2003. 'Modeling and managing urban growth at the rural-urban fringe: A parcel-level model of residential land use change,' *Agricultural and Resource Economics Review*, 32(1), 83-102.
- Irwin, E.G. and N.E. Bockstael. 2004. 'Land use externalities, growth management policies, and urban sprawl.' *Regional Science and Urban Economics*, 34(6), 705-25.
- Irwin, E.G. and N.E. Bockstael. 2002. 'Interacting agents, spatial externalities, and the endogenous evolution of residential land use pattern,' *Journal of Economic Geography*, 2(1), 31-54.
- Irwin, E.G. and N.E. Bockstael. 2001. 'The problem of identifying land use spillovers: Measuring the effects of open space on residential property values,' *American Journal of Agricultural Economics*, 83(3), 698-704.
- Kiyotaki, N. and J. Moore. 1997. 'Credit Cycles,' *Journal of Political Economy*, 105(2), 211-248.
- Kuminoff, N. 2009. 'Decomposing the structural identification of non-market values,' *Journal of Environmental Economics and Management*, 57(2), 123-139.
- Langpap, C., I. Hascic and J. Wu. 2008. 'Protecting watershed ecosystems through targeted local land use policies,' *American Journal of Agricultural Economics*, 90(3), 684-700.

- LeBaron, B. 2006. 'Agent-based computational finance.' In *Handbook of Computational Economics*, Volume 2, eds. L. Tesfatsion and K.L. Judd. Amsterdam: North Holland, pp. 1189-1233.
- LeBaron, B. and L. Tesfatsion. 2008. 'Modeling macroeconomies as open-ended dynamic systems of interacting agents,' *American Economic Review: Papers and Proceedings*, 98(2), 246-250.
- Lewis, D.J. 2008. 'An economic framework for forecasting land use and ecosystem changes,' unpublished manuscript.
- Lewis D.J. and A.J. Plantinga. 2007. 'Policies for habitat fragmentation: Combining econometrics with GIS-based landscape simulations,' *Land Economics*, 83(2), 109-127.
- Lewis, D.J., A.J. Plantinga, E. Nelson and S. Polasky. 2008. 'The efficiency of voluntary incentive policies for preventing biodiversity loss,' unpublished manuscript.
- Lewis, D.J., B. Provencher and V. Butsic (forthcoming). 'The dynamic effects of open space conservation policies on residential development density,' *Journal of Environmental Economics and Management*.
- Levin, S.A. 2006. 'Learning to live in a global commons: socioeconomic challenges for a sustainable environment,' *Ecological Research*, 21,328-33.
- Liu, J., T. Dietz, S.R. Carpenter, M. Alberti, C. Folke, et al. 2007. 'Complexity of coupled human and natural systems,' *Science* ,317(5844), 1513-1516.
- Lubowski, R.N., A.J. Plantinga and R.N. Stavins. 2006. 'Land-use change and carbon sinks: Econometric estimation of the carbon sequestration supply function.' *Journal of Environmental Economics and Management*, 51(2),135-52.
- Lucas, R.E. Jr. and E. Rossi-Hansberg. 2002. 'On the internal structure of cities,' *Econometrica* 70, 1445–1476.
- Miller, E., J.D. Hunt, J.E. Abraham and P.A. Salvini. 2004. 'Microsimulating urban systems,' *Computers, Environment, and Urban Systems*, 28, 9-44.
- Mills, D. 1981. 'Growth, speculation, and sprawl in a monocentric city,' *Journal of Urban Economics*, 10, 201-26.
- Nelson, G.C. and D. Hellerstein. 1997. 'Do roads cause deforestation? Using satellite images in econometric analysis of land use,' *American Journal of Agricultural Economics*, 79(1), 80-88.
- Newburn, D.A. and P. Berck. 2006. 'Modeling suburban and rural-residential development beyond the urban fringe.' *Land Economic*, 82(4), 481-499.
- Newburn, D.A., P. Berck and A.M. Merenlender. 'Habitat and open space at risk of land –use conversion: Targeting strategies for land conservation,' *American Journal of Agricultural Economics*, 88(1), 28-42.

- Ohls, J.C. and D. Pines. 1975. 'Discontinuous urban development and economic efficiency,' *Land Economics*, 51(3), 224-234.
- Otter, H. S., A. van der Veen, H.J. de Vriend. 2001. 'ABLOoM: Location behaviour, spatial patterns, and agent-based modeling,' *Journal of Artificial Societies and Social Simulation*, 4(4),2, <http://www.soc.surrey.ac.uk/jasss/4/4/2.html>.
- Parker, D.C. and T. Filatova (forthcoming). 'A conceptual design for a bilateral agent-based land market with heterogeneous economic agents,' *Computers, Environment, and Urban Systems*.
- Parker, D.C., S.M. Manson, M.A. Janssen, M. Hoffmann and P. Deadman. 2003. 'Multi-agent systems for the simulation of land use and land cover change: A review,' *Annals of the Association of American Geographers*, 93(2), 314-317.
- Pickett, S.T.A., M.L. Cadenasso, J.M. Grove, C.H. Nilson, R.V. Pouyat, W.C. Zipperer and R. Costanza. 2001. 'Urban ecological systems: Linking terrestrial ecological, physical, and socioeconomic components of metropolitan areas,' *Annual Review of Ecology and Systematics*, 32, 127-157.
- Pickett, S.T.A. and M.L. Cadenasso. 1995. 'Landscape ecology: Spatial heterogeneity in ecological systems,' *Science*, 269, 331-334.
- Pickett, S.T.A. and K.H. Rogers. 1997. 'Patch dynamics: The transformation of landscape structure and function.' In Bissonette JA (ed), *Wildlife and Landscape Ecology: Effects on Pattern and Scale*. New York: Springer-Verlag, pp. 101-127.
- Roback, J. 1982. 'Wages, rents, and the quality of life,' *Journal of Political Economy*, 90(6), 1257-1278.
- Sieg, H., V.K. Smith, H.S. Banzhaf, and R. Walsh. 2002. 'Interjurisdictional housing prices in location equilibrium,' *Journal of Urban Economics*, 52, 131-153.
- Smith, M., J. Sanchirico, J. Wilen. 2009. 'The economics of spatial-dynamic processes: Applications to renewable resources,' *Journal of Environmental Economics and Management*, 57, 104-121.
- Smith, V.K., H. Sieg, H.S. Banzhaf, and R. Walsh. 2004. 'General Equilibrium Benefits for Environmental Improvements: Projected Ozone Reductions under EPA's Prospective Analysis for the Los Angeles Air Basin,' *Journal of Environmental Economics and Management*, 47, 559-584.
- Tesfatsion, L. 2006. 'Agent-based computational economics: A constructive approach to economic theory.' In *Handbook of Computational Economics*, Volume 2, L. Tesfatsion and K. Judd, eds. Amsterdam: North-Holland, pp. 831-877.
- Timmins, C. and W. Schlenker. 2009. 'Reduced-form versus structural modeling in environmental and resource economics,' *Annual Review of Resource Economics*, 1, 351-380.

- Towe, C., C. Nickerson, and N.E. Bockstael. 2008. 'An empirical examination of the timing of land conversions in the presence of farmland preservation programs,' *American Journal of Agricultural Economics*, 90(3), 613–626.
- Turnbull, G.K. 1988. 'Residential development in an open city,' *Regional Science and Urban Economics*, 18, 307-320.
- Turner, M.A. 2005. 'Landscape preferences and patterns of residential development,' *Journal of Urban Economics*, 57(1), 19-54.
- Turner, M. and R. Gardner, eds. 1991. *Quantitative methods in landscape ecology*. Springer: New York.
- Waddell, P. 2000. 'A behavioral simulation model for metropolitan policy analysis and planning: Residential location and housing market components of UrbanSim,' *Environment and Planning B*, 27(2), 247-263.
- Waddell, P., A. Borning, M. North, N. Freier, M. Becke and G. Ulfarsson. 2003. 'Microsimulation of urban development and location choices: Design and implementation of UrbanSim,' *Networks and Spatial Economic*, 3, 43-67.
- Walsh, R.L. 2007. 'Endogenous Open Space Amenities in a Locational Equilibrium,' *Journal of Urban Economics*, 61, 319-344.
- Warren, K., C. Jayaprakash, E.G. Irwin (forthcoming). 'The Interaction of Segregation and Suburbanization in an Agent-Based Model of Residential Location,' *Environment and Planning B*.
- Wheaton, W.C. 1982. 'Urban spatial development with durable but replaceable capital,' *Journal of Urban Economics*, 12, 53-67.
- Wu, J. and R. Hobbs. 2002. 'Key issues and research priorities in landscape ecology,' *Landscape Ecology*, 17, 355–365.
- Wu, J. and A.J. Plantinga. 2003. 'The influence of public open space on urban spatial structure,' *Journal of Environmental Economics and Management*, 46(2), 288-309.

<i>Model Type</i>	<i>Journal Type</i>							Grand Total
	Economics		Geography		Urban Planning		Environ. Studies	
	Environ./ Resource Economics	Regional Science/ Urban Economics	Geography/ GI Science	Computers/ Urban Systems	Urban Planning/ Policy Studies	Urban Planning/ Ecology	Environ. Studies/ Ecology	
Agent Based Simulation	0	0	5	2	1	0	6	14
Cellular Automata Simulation	0	1	7	3	2	6	11	30
Statistical with Simulation	4	3	1	0	2	3	9	22
Analytical with Simulation	2	3	0	0	1	0	0	6
Statistical Only	5	5	0	0	4	2	4	20
Analytical Only	1	2	0	0	1	0	2	6
Systems Dynamics	0	0	0	0	1	0	1	2
Grand Total	12	14	13	5	11	11	32	100

Note: This summary is based on the 100 “most relevant” articles published since 2003 on urban land use pattern modeling. Articles were judged by whether the paper presented a theoretical, empirical or simulation-based model of urban land use change that also provided some description or quantification of changes in land use pattern.

Table 1: Count by model and journal type of recent research articles on urban land use pattern modeling

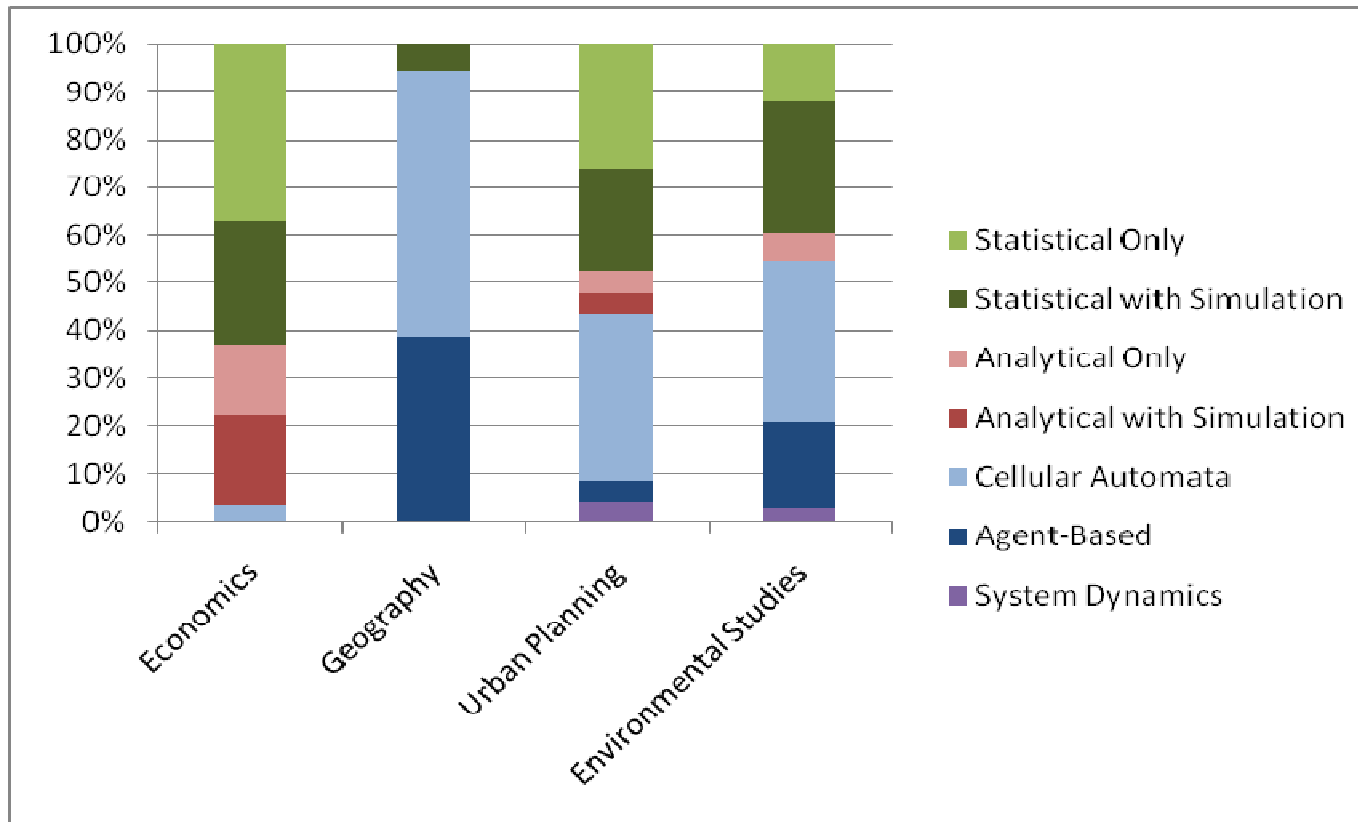


Figure 1: Relative proportion of modeling methods used within each discipline (based on raw values reported in Table 1)

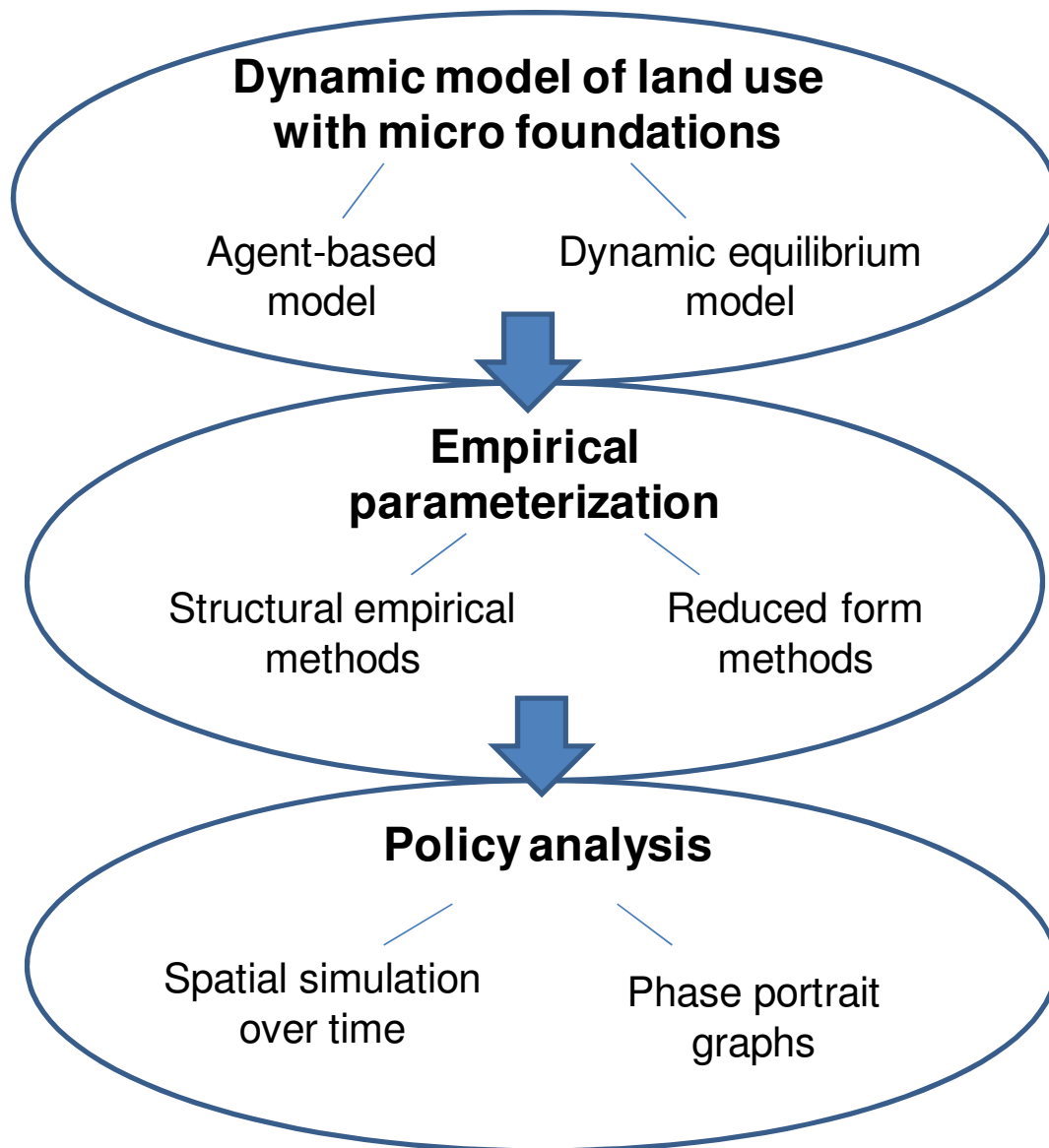


Figure 2: Complementarities of theoretical and empirical methods needed to develop spatial dynamic models of land use suitable for analysis of policies and land use-environment interactions