NEW DIRECTIONS FOR URBAN ECONOMIC MODELS OF LAND USE CHANGE: INCORPORATING SPATIAL DYNAMICS AND HETEROGENEITY

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ABSTRACT. We review the usefulness of urban 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 microlevel behavior and interactions with macrolevel 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.

1. INTRODUCTION

Key policy questions concerning global environmental change center on the multiple feedbacks between humans and natural systems (Pickett et al., 2001; Levin, 2006; Liu et al., 2007; Turner, Lambin, and Reenberg, 2007; Grimm et al., 2008a), 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
### TABLE 1: Count by Model and Journal Type of Recent Research Articles on Urban Land Use Pattern Modeling

<table>
<thead>
<tr>
<th>Model Type</th>
<th>Economics</th>
<th>Geography</th>
<th>Urban Planning</th>
<th>Environ. Studies</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Environ./</td>
<td>Geography</td>
<td>Urban Planning</td>
<td>Environ. Studies</td>
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<tr>
<td></td>
<td>Resource</td>
<td>GI Science</td>
<td>Policy Studies</td>
<td>Ecology</td>
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<td></td>
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<td></td>
<td>Economics</td>
<td>Systems</td>
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<td></td>
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<tr>
<td>Agent based simulation</td>
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<td>0</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>Cellular automata simulation</td>
<td>0</td>
<td>1</td>
<td>7</td>
<td>3</td>
</tr>
<tr>
<td>Statistical with simulation</td>
<td>4</td>
<td>3</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Analytical with simulation</td>
<td>2</td>
<td>3</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Statistical only</td>
<td>5</td>
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<tr>
<td>Analytical only</td>
<td>1</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Systems dynamics</td>
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<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Grand total</td>
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<td>14</td>
<td>13</td>
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**Notes:** 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.
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 (Collins et al., 2000; Alberti, 2005). 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 integration of socioeconomic and demographic models of human settlement, consumption and land management dynamics with biophysical models (Pickett et al., 2001; Grimm et al., 2008b). 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.1

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

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1According 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.
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 (Ohls and Pines, 1975; Arnott, 1980; Fujita, 1982; Capozza and Helsley, 1989), 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 urban land use. On the other hand, ecologists consider spatial heterogeneity at multiple spatial scales to be a central causal factor in ecological systems (Pickett and Cadenasso, 1995; Pickett et al., 2001; Alberti, 2005; Grimm et al., 2008b) and the spatial and temporal dynamics of land use are viewed as fundamental questions.

The goals of this paper are twofold: (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 consider the advantages of integrating economic fundamentals with agent-based 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 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 multidisciplinary 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 and spatial dynamics. The potential 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, we conclude that the consequences of economists remaining on the sidelines are 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 parameters that correspond to a microeconomic process that determines macroscale 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 macroscale 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 microfoundations of the observed outcomes that in aggregate generate the observed land use pattern.

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, various dimensions of heterogeneity are important in land use modeling: “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. In this review, we focus mainly on models that incorporate multiple sources of spatial heterogeneity, but acknowledge that agent heterogeneity is likely just as important for modeling spatial land use dynamics.

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

\(^2\)See Holmes (this issue) for an informative discussion of different types of applied work in regional and urban economics.
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, Sanchirico, and Wilen, 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 eco-
nomics. A common understanding of a system in equilibrium is a system that 
is in an unchanging state and indeed, economists often use the term equilib-
rium 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 can also have much less restrictive 
applications in economics. Equilibrium may instead refer to other aspects of 
the system that are unchanging, for example 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 mi-
icrofoundations, 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; Kiyotaki and Moore, 1997; De Grauwe and Grimaldi, 2006; Dufourt, 
Lloyd-Braga, and Modesto, 2008). Because these models represent dynamic 
processes based on market equilibrium assumptions, they are referred to as 
“dynamic equilibrium” models (e.g., Desmet and Rossi-Hansberg, this issue). 
While market clearing conditions are the most common definition of equilib-
rium in urban and regional economic models, some models of housing market 
dynamics explicitly incorporate “market frictions” (e.g., informational asym-
metry, credit constraints, construction lags, search costs) that prevent market 
clearing in the short run (e.g., Wheaton, 1990; Chinloy, 1996; Ortalo-Magné 
and Rady, 2006). A “short run dynamic equilibrium,” in which price adjust-
ments are constrained by these market frictions, is derived based on aggregate 
market conditions.

An alternative approach to modeling dynamics is agent-based computa-
tional modeling that seeks to understand macrolevel dynamics by explicitly 
modeling individual trades between agents. These models have been adapted
and developed by some economists, particularly in the area of finance (LeBaron, 2006; LeBaron and Tesfatsion, 2008). 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 individual price adjustments that respond to nonzero excess demands (Chen and Yeh, 2001). Because these models use simulation to relate microlevel behaviors and interactions to macrolevel outcomes, they typically do not rely on aggregate market conditions (e.g., market clearing or aggregate market adjustments) to derive market outcomes and thus are sometimes referred to as “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.

2. 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 (personal communication, 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 1,800 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 modeling land use patterns at a corresponding spatial resolution. It is important to note that, in doing so, the goal is not to predict the exact plots of land that will be developed, since such modeling accuracy simply 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 spatially disaggregate 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 (defined as 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. In turn, 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, Bain, and Band, 2003).

Cadenasso, Pickett, and Grove (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 macrolevel policy or process (e.g., global warming or national energy policy), then modeling land use dynamics at a land parcel scale may be 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, 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.

3. 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 we explain in further detail below, and signal substantial differences in perceptions of the important features of urban land use processes.

In reviewing models of urban land use change, we 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 use 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. However, we 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.

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Econometric Land Use Models With Spatial Simulation

Econometric models of land development derive from economic models of individual land use decisions in which landowners choose to develop 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 and Lewis, 1979; Arnott, 1980; 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 is hypothesized to depend on land rents from current and alternative land uses. 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 micropanel data on land use over time at the scale of land ownership (i.e., 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, Nickerson, and Bockstael, 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., Irwin and Bockstael, 2002; Carrion-Flores and Irwin, 2004); the effects of land policies on urbanization patterns (e.g., Irwin, Bell, and Geoghegan, 2003; Irwin and Bockstael, 2004; Newburn and Berck, 2006; Langpap, Hascic, and Wu, 2008; Lewis, Provencher, and Butsic, 2009); 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., 2009), the effectiveness of targeting strategies on land conservation (Newburn, Berck, and Merenlender, 2006) and the effect of land use policies on watersheds (Langpap, Hascic, and Wu, 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 (2009) demonstrates 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, these models provide only a limited means to modeling land use dynamics. Careful econometric specification can identify one or several key parameters of the model, which is often the focus of the analysis, but this approach is unlikely to recover all the structural parameters of the behavioral process. In contrast to empirical structural models (such as those discussed by Epple, Gordon, and Sieg, this issue), the focus is not on backing out the structural errors as a means of identifying the parameters of the behavioral model and thus important behavioral functions may be omitted from the analysis. For example, these models typically do not account for sources of landowner heterogeneity that may influence decisions, such as age, experience and expectations. Without a complete specification of the underlying structure and because of their partial equilibrium nature, the models cannot fully capture spatial or transitional dynamics and may miss important feedbacks that cause attributes to be endogenous over longer periods of time (e.g., neighborhood features such

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3See McMillen (this issue) for an in depth discussion of endogenous spatial regressors.
as school quality). This also limits their usefulness in studying nonmarginal policy changes. Thus these empirical-based simulations are more appropriate for the analysis of marginal effects over shorter time periods (e.g., 5–10 years).

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 data\(^4\) 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 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., \(30 \text{ m} \times 30 \text{ m}\) 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 goal is to uncover the causal linkages between hypothesized socioeconomic or biophysical factors and changes in land use pattern.

**Spatial Equilibrium Models of Urban Land Use Pattern**

As Glaeser (2008) writes in his 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

\(^4\)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, and jurisdictions).

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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., Epple and Platt, 1998; Epple and Sieg, 1999; Bayer and Timmins, 2005).

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 discrete variations in pattern at a local scale.

While nonmonocentric 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 over a two-dimensional area has been used as an alternative approach to extend the basic monocentric model to account for additional sources of local spatial heterogeneity. While the models differ in their details, they typically start with the assumptions of a static, and in most cases open-city, monocentric model and then incorporate additional sources of spatial heterogeneity over which households have defined preferences. Equilibrium land rents are a function of both distance to the central business district and these other spatial features, which may be exogenously or endogenously determined in the model. Given an analytical expression for land rents as a function of heterogeneous space, spatial simulation over a two-dimensional area 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 given the location of exogenously determined open space (e.g., public parks) within the context of an open city model. Tajibaeva, Haight, and Polasky (2008) build from the discrete space model of Yang and Fujita (1983) to consider the implications of open space amenities for residential location and land markets within a multicentric urban area. The paper is particularly innovative in its consideration of the local government’s decision to provide open space amenities to local
neighborhoods and the consideration of how open space spillovers across neighborhoods influence the optimal long run equilibrium pattern of open space. 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 instantaneously adjusting, 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 (typically perfect foresight or rational expectations). The models often assume a monocentric urban area with centralized employment (e.g., Anas, 1978; Arnott, 1980; Hochman and Pines, 1982; Turnbull, 1988; Capozza and Helsley, 1989; Braid, 2001), but in other cases space is defined more generally along a line (e.g., Lucas and Rossi-Hansberg, 2002; Berliant and Wang, 2008). 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 (Fujita, 1976; Ohls and Pines, 1975; 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, Duranton, and Overman, 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 clearly interacts with spatially heterogeneous variables in fundamental ways that influence 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., Epple and Sieg, 1999; Sieg et al.,

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2002; Bayer and Timmins, 2005, 2007) 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., Smith et al., 2004; Walsh, 2007; Bayer, Keohane, and Timmins, 2009; Kuminoff, 2009). 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).

4. AGENT-BASED COMPUTATIONAL MODELS

An emerging view among some economists describes the economy as a dynamic adaptive system (Tesfatsion, 2006; Colander et al., 2008; Anufriev and Branch, 2009), 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 macrolevel 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 nonlinear 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 1970s and 1980s 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 NSF’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. 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

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5For 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).
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 specifications of the economic system, the transitional dynamics are driven solely by agent trading that is not typically 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 does not) and over what time scale it is reached (or is not). However, this advantage of model flexibility is also a disadvantage in terms of model complexity, since isolating the causal linkages between microlevel structure and macrolevel 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. 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 have advocated a middle way: first, use simple and parsimonious models that admit the most salient features of agent heterogeneity, but that retain the assumption of continual market clearing and then use these models to guide the further development of more detailed agent-based models (Hommes, 2006; Brock, personal communication, 2009).

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

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6This is not unlike the “Anything Goes” critique of general equilibrium theory, which points out the limitations of this theory in deriving precise predictions of aggregate demand from microeconomic behavioral assumptions. Because a unique equilibrium is not guaranteed, some have argued that the theory is too loose and therefore not useful for policy analysis. Others argue that multiple equilibria are characteristic of real life economies and that the result underscores the need for empirical parameterization (e.g., Mas-Colell, 1989).
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 (Tesfatsion, 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 a spatial equilibrium. Models of agent trading that do not reflect the influence of excess demands for locational attributes on land rents 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 dearth of economists in 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, Van Der Veen, and de Vriend (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 so 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. Jayaprakash 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.

Some 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, an extensive 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 housing 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 inconsistent with economic fundamentals. Changes in the relative implicit prices will cause households to adjust their optimal bundle of housing attributes (e.g., due to income and substitution effects) and firms to adjust their production of these attributes. The hedonic equilibrium will be renegotiated, implying that the entire hedonic function will change over time and not just the intercept term. 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.

A few agent-based models that are explicitly focused on urban land markets have recently been developed.7 For example, work by Filatova, Parker, and Van Der Veen (2009a, 2009b) posits buyer and seller households who have preferences over locally varying open space amenities and who are constrained by transportation costs to the CBD. Rather than prices determined by aggregate market conditions, 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. Likewise, Devisch et al. (2006, 2009) develop a highly detailed model of household search and negotiation in the housing market in which household beliefs determine bids and are continually updated based on experience and interactions with other agents. Magliocca et al. (2009) present an agent-based model of the exurban land market in which farmers and land developers interact and price is determined by the market power of each group, which is explicit represented. Developers determine the profitability of different types of housing and sell to consumers who are differentiated by both income and preferences. The model is calibrated using secondary data, e.g., on agricultural returns and construction costs, and with demand and supply parameter estimates from the literature. Such modeling efforts represent new and innovative work. Although it is yet unclear whether these models are able to reproduce observed dynamics of land and housing markets, these several agent-based land market models constitute a serious attempt at modeling the price formation process from the bottom up. Many challenges remain (e.g., see Parker and Filatova, 2009 for an in-depth discussion) and more work in this direction is needed.

7As 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.
4. FUTURE DIRECTIONS IN SPATIAL DYNAMIC MODELS OF URBAN LAND USE

Based on this review of the literature on urban spatial 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, and 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, Jayaprakash, and Irwin, 2008). 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. Fourth, recent empirical models provide strong evidence of the importance of agent heterogeneity in determining intrametropolitan 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 microfoundations is minimally very daunting and likely undesirable 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 has done just this (e.g., Brock and Xepapadeas, 2009; 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 technologically 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. Agent-based models should follow standard best practices for model building. Rather than modeling many aspects of the real world, the models should be tailored to the research question and incorporate only the complications that are necessary for the question at hand (Parker and Filatova, 2008). In addition, we agree that the middle road approach that Hommes (2006) and others (Brock, personal communication) have advocated is sensible in this regard: use more realistic (and thus more technically difficult) dynamic equilibrium models to then guide the development of more fully specified agent-based models.

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 spatial or agent heterogeneity) and providing guidance in constraining parameter values. That economists are well trained in empirical identification methods is certainly 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. 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 macrolevel urban land use dynamics.

6. CONCLUSIONS

We find that both dynamic equilibrium and agent-based models provide potential pathways forward in developing more realistic and comprehensive

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8Also 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.
models of urban spatial dynamics. In either case, 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 illustrates the potential complementarities of these modeling approaches. First, a structural dynamic economic model that links microscale behavior and interactions with macroscale 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 microlevel 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,\(^9\) may also be possible. An investigation of the potentially nonmarginal 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 and regional land use 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 rigorous and fully specified economic agent-based models of urban land use and the majority of the existing agent-based land use models is substantial. We have enumerated a few of the key challenges and pitfalls of this method and highlighted some of the current work that is seeking to close this gap. Continued 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.

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\(^9\)Chen, Irwin, and Jayaprakash (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.


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