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Theory, data, methods: developing spatially explicit economic models of land use change

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Abstract

Questions of land use/land cover change have attracted interest among a wide variety of researchers concerned with modeling the spatial and temporal patterns of land conversion and understanding the causes and consequences of these changes. Among these, geographers and natural scientists have taken the lead in developing spatially explicit models of land use change at highly disaggregate scales (i.e. individual land parcels or cells of the landscape). However, less attention has been given in the development of these models to understanding the economic process — namely, the human behavioral component — that underlies land use change. To the extent that researchers are interested in explaining the *causal* relationships between individual choices and land use change outcomes, more fully articulated economic models of land use change are necessary.

This paper reviews some of the advances that have been made by geographers and natural scientists in developing these models of spatial land use change, focusing on their modeling of the economic process associated with land use change. From this vantage point, it is argued that these models are primarily "ad hoc," developed without an economic theoretical framework, and therefore are susceptible to certain conceptual and estimation problems. Next, a brief review of traditional economic models of land use determination is given. Although these models are developed within a rigorous economic framework, they are of limited use in developing spatially disaggregate and explicit models of land use change. Recent contributions from economists to the development of spatially explicit models are then discussed, in which an economic structural model of the land use decision is developed within a spatially explicit framework and from which an estimable model of land use change is derived. The advantages of this approach in terms of simulating policy scenarios and addressing econometric issues of spatial dependency and endogeneity are discussed. We use some specific examples from ongoing research in the Patuxent Watershed, Maryland, USA to illustrate our points. The paper concludes with some summary remarks and suggestions for further research.

Keywords: Land use change; Spatial economic models

1. Introduction

Questions of land use/land cover change have attracted interest among a wide variety of researchers concerned with modeling the spatial and temporal patterns of land conversion and understanding the causes and consequences of these changes. Among these, geographers and natural scientists have taken the lead in developing spatially explicit models of land use change at highly disaggregate scales (i.e. individual land parcels or cells of the landscape). Significant progress has been made in acquiring spatial data sets from remotely sensed data (e.g. satellite imagery of

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land cover), conceptualizing the basic geographic and environmental processes that are associated with land use change, and developing spatial models that fit the spatial process of land use change reasonably well.

Less attention has been given in the development of these models to understanding the economic process — namely, the human behavioral component — that underlies land use change. To the extent that researchers are interested in explaining the *causal* relationships between individual choices and land use change outcomes, more fully articulated economic models of land use change are necessary. These models usually begin from the viewpoint of individual landowners who make land use decisions, either to maximize expected returns or utility derived from the land. Economic theory is used to guide the model development, including choice of functional form and explanatory variables. This approach goes beyond non-behavioral models that have sought to *fit* the spatial process of land use change by developing an underlying structural model that seeks to *explain* the human behavior that generates these patterns. In contrast, the non-behavioral models use an ad hoc approach to identifying physical variables that represent the outcomes of economic and social processes, e.g. the location of roads and urban centers, without any underlying economic theory to guide the choice of variables.

The distinction is illustrated in the next section, in which the difference between underlying structural equations, derived from a conceptual economic model of a landowner's land use decision, and the resulting reduced form estimating equations is illustrated using a simple example. The rest of the paper is then oriented towards a fuller discussion of non-economic and economic models of land use change. First, the advances that have been made by geographers and natural scientists in developing cell-based models of spatial land use change are reviewed. This review is not meant to be exhaustive, but rather illustrative of the existing approaches. While there are many contributions that these models have made to the research on land use/cover modeling, we consider them only in terms of their treatment of the economic process associated with land use change. Next, traditional economic models of land use determination are briefly reviewed. These models are developed within a rigorous economic framework, but, for reasons that we discuss, are of limited use in developing spatially disaggregate and explicit models of land use change. Finally, recent contributions from economists to the development of spatially explicit models are discussed, in which an economic structural model of the land use decision is developed within a spatially explicit framework and from which an estimable model of land use change is derived. The paper concludes with some summary remarks and suggestions for further research.

2. Structural economic models

Modeling the economic structural process that underlies land use change has several benefits. First, by modeling the human behavior directly, rather than the outcome of human behavior, the underlying spatial and temporal dynamic process associated with the economic agent can be made explicit. This allows for consideration of the cumulative effect of factors over time on an individual's land use decisions and of potential spatial interactions among economic agents. For example, if an individual's land use decision is influenced by the land use decisions of those around him/her, then this process can be explicitly modeled as a spatial lag.

Secondly, and perhaps most importantly, issues of endogeneity can be addressed using a structural modeling approach. For example, if the location of roads and land use decisions are jointly determined, then this endogeneity can be explicitly modeled using a system of simultaneous equations that includes equations explaining both land use change and the location of road-building and improvements. Such an approach is necessary for consistent parameter estimation and drawing correct policy implications.

As an example, consider the following to illustrate the estimation problem that arises with endogenous variables and the distinction that economists generally make between "structural" and "reduced form" models. Consider a county that experiences high population growth and increases their property tax rate in order to accommodate the increased demand for the local government's public services. If households migrating to the county take account of the tax rate in their location decision, then population changes and tax rates may be jointly determined. In order to represent this process, a structural model with interrelated equations representing migration and local government expenditures and revenues is needed. From this structural model, which will contain endogenous variables as explanatory variables, a reduced form model can be derived that can be estimated, in which all explanatory variables are exogenous. For example, let the following two interdependent equations represent a *highly* simplified structural model[2] of these relationships:

$$\mathrm{POP}_{it} = \beta_1\,\mathrm{EMP}_{it} + \beta_2\,\mathrm{TAX}_{it} + \beta_3\,\mathrm{PUBS}_{it} + \varepsilon_{1it} \tag{1}$$

$$\mathrm{TAX}_{it} = \gamma_1\,\mathrm{POP}_{it} + \gamma_2\,\mathrm{PUBS}_{it} + \gamma_3\,\mathrm{INC}_{it} + \varepsilon_{2it} \tag{2}$$

where POP_{it} is the total population of county i in period t, EMP_{it} the employment level within county i in period t, TAX_{it} the property tax rate of county i in period t, PUBS_{it} the measure of the quantity and quality of public services in county i in period t, INC_{it} the per capita income of households in county i in period t, ε_{1it} and ε_{2it} are error terms, and β_1, β_2, β_3, γ_1, γ_2, and γ_3 are parameters to be estimated.

Note that based on the above specification, POP_{it} and TAX_{it} are jointly determined and therefore are endogenous, whereas EMP_{it}, PUBS_{it}, and INC_{it} are exogenous variables. Because POP_{it} and TAX_{it} are endogenous variables, they will be correlated with the error terms and therefore the parameter estimates from this model will be inconsistent.

An approach to obtaining consistent estimates is to estimate the reduced form model and try to recover the structural parameters from these estimates. For example, a reduced form model can be derived from structural equations (1) and (2) via substitution to yield

$$\mathrm{POP}_{it} = \pi_1\,\mathrm{EMP}_{it} + \pi_2\,\mathrm{PUBS}_{it} + \pi_3\,\mathrm{INC}_{it} + \mu_{1it} \tag{3}$$

$$\mathrm{TAX}_{it} = \pi_4\,\mathrm{EMP}_{it} + \pi_5\,\mathrm{PUBS}_{it} + \pi_6\,\mathrm{INC}_{it} + \mu_{2it} \tag{4}$$

where

$$\pi_1 = \frac{\beta_1}{1-\beta_2\gamma_1},\quad \pi_2 = \frac{\beta_2\gamma_2+\beta_3}{1-\beta_2\gamma_1},\quad \pi_3 = \frac{\beta_2\gamma_3}{1-\beta_2\gamma_1},$$

$$\pi_4 = \frac{\gamma_1\beta_1}{1-\beta_2\gamma_1},\quad \pi_5 = \gamma_2 + \gamma_1\frac{\beta_2\gamma_2+\beta_3}{1-\beta_2\gamma_1},$$

$$\pi_6 = \gamma_3 + \frac{\gamma_1\beta_2\gamma_3}{1-\beta_2\gamma_1},\quad \mu_{1it} = \frac{\beta_2\varepsilon_2+\varepsilon_1}{1-\beta_2\gamma_1},\quad \text{and}$$

$$\mu_{2it} = \varepsilon_2 + \gamma_1\frac{\beta_2\varepsilon_2+\varepsilon_1}{1-\beta_2\gamma_1}$$

As in the example above, parameter estimates from the reduced form model are a combination of the parameters from the underlying structural equations. In order to understand the correct policy implications of a property tax increase on population change, for example, the parameter estimates from the structural model (in this case, the estimate for β_2) must be recovered from the estimated parameters of the reduced form model. In some cases it is possible to recover structural parameters from the reduced form parameter estimates using algebraic manipulation and by imposing constraints on the parameter values based on theory. In other cases, this is not possible and an alternative estimation strategy, such as indirect least-squares or an instrumental variables estimation method, must be used.[3]

3. Spatially explicit, non-economic models of land use change

Geographers and natural scientists have taken the lead in developing spatially explicit models of land use change. Numerous spatially disaggregate and heterogeneous land use change models exist in the environmental science and geography literatures, spurred by the vast amount of spatially disaggregate land use/cover data that are now available (Andersen, 1996; Batty et al., 1989; Berry et al., 1996; Clarke et al., 1997; Flamm and Turner, 1994; Hazen and Berry, 1997; LaGro and DeGloria, 1992; Ludeke et al., 1990; Mertens and Lambin, 1997; White and Engelen, 1993; White et al., 1997; Wu and Webster, 1998; Veldkamp and Fresco, 1996, 1997a,b). This body of work has contributed substantially to the development

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[2] We include this example simply as an illustration of structural and reduced form models and not as a serious model of migration and taxation. For example, in a more rigorously specified model, the endogeneity of both employment and public service levels would have to be considered.

[3] See Greene (2000) for a full discussion of simultaneous-equations models and estimation methods.

of spatially explicit land use/cover change modeling. In what follows, we briefly review these models, focusing on how they have sought to incorporate economic considerations into the modeling framework. The spatially explicit land use/cover change models can be placed in three broad categories: simulation, estimation, and a hybrid approach that includes estimated parameters with simulation. Because many of the simulation models are based on a cellular automata approach, the general form of cellular automata is briefly discussed, followed by a discussion of the specifics of particular models and methods.

3.1. Cellular automata

Cellular automata are a class of mathematical models in which the behavior of a system is generated by a set of deterministic or probabilistic rules that determine the discrete state of a cell based on the states of neighboring cells. States of individual cells are updated based on the values of neighboring cells in the previous time period. This locality of the interactions between a cell and its neighbors is a defining characteristic of cellular automata. Despite the simplicity of the transition rules, these models when simulated over many times periods often yield complex and highly structured patterns. This is due to the recursive interactions among cells: the state in period $t+1$ is determined by the state in period t, but not vice versa. Because these models are explicitly spatial, they have been used to model a variety of spatial processes mainly in the physical and biological sciences, e.g. chemical turbulence, spatial diffusion of chemical reactions, evolution of spiral galaxies, and the development of patterns in the growth of organisms (Wolfram, 1986).

Much of the literature on cellular automata is concerned with identifying local and global properties of a cellular automaton, defined by a given set of transition rules, by quantifying the resulting pattern. For example, long-range spatial correlations between the system's states in different time periods are shown to generate structure and pattern (Wolfram, 1986). These correlations can be quantified and compared to a random configuration of the same dimension and possible states to yield a measure of the relative order in a system. For example, a statistical comparison of a configuration generated by a cellular automaton vs. a random configuration can be used to illustrate the self-organizing characteristic of cellular automata, which is one of their main features.

3.2. Simulation models of urban growth

Some researchers, mainly geographers, have used cellular automata models to analyze the process of urban growth (Wu and Webster, 1998; Clarke et al., 1997; White et al., 1997; White and Engelen, 1993; Batty et al., 1989). In contrast to the standard economic models of urban structure, in which complex patterns are generated by imposing external conditions, these models demonstrate how complex structure arises internally from the interaction among individual cells. When compared to actual data from US cities, researchers argue that these models yield a good representation of actual urban form.

These models are instructive and offer a practical approach to understanding of how interaction among individual agents "aggregate up" over space to determine regional patterns of urbanization. However, conclusions about their explanatory power should not be overstated. By demonstrating a correspondence between a hypothesized interaction effect and the resulting spatial evolution of land use pattern, this approach establishes that the hypothesized interaction among cells is a *possible* explanation of the observed land use patterns. But these models are not estimated using actual data. Instead, "growth rules" are assigned that govern the land use transitions of cells based on the cell's attributes and the states of surrounding cells. In reality, a whole host of features that create extensive spatial heterogeneity across the landscape will drive actual changes in land use pattern and therefore, conclusive statements about the interaction causing the changes in actual urban form are misleading. To test the hypothesized growth rules, an empirical model is needed which deals with the identification problem that arises in distinguishing the interaction effects from other landscape heterogeneity, e.g. zoning, employment centers, and environmental features. Instead, these cellular automata models of urban growth are developed with the assumption of a simple spatial landscape and therefore are unable to differentiate the interaction effect from the variety of exogenously determined variables that may also generate the same patterns of development.

An additional shortcoming of many of these models of urban growth is the absence of an economic foundation. Rather than modeling the interaction effect as a function of economic factors, the interaction effects are imposed by the researcher. This is done with little economic rationale or empirical evidence of the hypothesized effects. Contrary to some claims made by these researchers, this limits the usefulness of these models for planning and policymaking purposes. Predictions of how land use patterns will change under alternative policy scenarios requires an understanding of how individual landowners will react under these different policy regimes. To do so requires more explicit modeling of the underlying economic spatial process of land use change.

3.3. Empirical models of land use/cover change

Geographers have also taken the lead in estimating spatially explicit empirical models using remotely sensed data on land use/cover change. Examples from this literature include Mertens and Lambin (1997), Andersen (1996), LaGro and DeGloria (1992), and Ludeke et al. (1990). Each of these examples focuses on some aspect of deforestation that is derived from the remotely sensed data for the dependent variable. These models include explanatory variables that can be "seen" from the remotely sensed data and calculated using GIS, such as, distance measures, other spatial biophysical variables (e.g. soil, slope and elevation), and occasionally socio-economic "drivers," such as population or gross domestic product measures.

In many cases, these models *fit* the spatial process and land use change outcome reasonably well. However, like the urban growth models discussed above, they are less successful at *explaining* the human behavior that leads to the spatial process/outcome of land use change. This is not to say that these models are devoid of economic considerations. On the contrary, these models usually include some variables that capture economic effects. For example, distance to urban center and variables that reflect the biophysical heterogeneity of the landscape are commonly included for economic reasons. Distance to the urban center matters because of accessibility to markets (i.e. transportation costs), whereas biophysical features of the landscape, e.g. certain soils are preferred for agricultural use, will affect the choices of individual land managers. However, there are many other features that affect choice concerning land use change. These might be characteristics of the individual land manager such as family size, off-farm income, education level, wealth and ability to bear risk. Such considerations are largely overlooked in these models since the choice of economic variables is "ad hoc," rather than being derived from a set of structural models that attempt to more fully explain the underlying economic process.

Clearly temporal dynamics are an important consideration in modeling land use/cover change. There are many external features that change over time (and not necessarily space), including variables that affect the economic returns to different land uses, e.g. agricultural and timber prices, subsidies, land tenure rules, etc., that will affect individual choices. Such considerations are often omitted from these models of land use change, most likely due to data constraints, but failure to control for temporal dynamics can bias estimation results. As discussed earlier, the presence of endogenous variables (i.e. variables that change over time due to changes in land use) can lead to inconsistent parameter estimates and misleading policy conclusions. Without an underlying structural model that could make these interrelationships explicit, these empirical models are unable to address this issue of endogeneity.

A final shortcoming of these models from an economics perspective is that the unit of analysis is either an individual pixel or some aggregation of landscape units, rather than the individual decision-maker. In modeling land use change from an economics perspective, the individual is the unit of observation rather than a landscape pixel. For this reason, having information on the boundaries of individually owned land parcels, rather than just the boundaries between two dissimilar land use pixels, is greatly preferred. For example, individuals owning large land parcels may react differently to a policy than those with small land parcels. Distinguishing the effects of a policy change among large and small landowners is important and only possible if ownership boundaries are known.[4]

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[4] This issue could potentially be more relevant in a developed country context, where property rights are well established, than in a developing country context, where land use change can be a form of gaining land tenure at the agricultural frontier.

3.4. Hybrid models of land use/cover change

Hybrid models of land use/cover change begin with an estimation model, as discussed in the previous section, but continue with the addition of a simulation model. The simulation models use the parameters from the estimation model to predict the spatial pattern of land use/cover change that could occur under different exogenously imposed scenarios.

Landscape ecologists were also early developers of spatially explicit models of land use change used to predict changes in spatial patterns of the landscape (Ives et al., 1998). The early models were simple grid-based Markov models that merely *calculated* the percent change of each land cover type during a time period and predicted future changes by assuming that these proportionate changes remained constant over time. More sophisticated Markov models were then developed that *estimated* these changes as a function of other explanatory variables and not just simply a function of previous land use changes. While many of these models have sophisticated treatment of ecological relationships that affect or a result of land use/cover change, they are very simple with respect to human behavior (for a review of these early models, see Baker, 1989).

Recent examples of these hybrid models from the natural sciences include the LUCAS model (Berry et al., 1996; Flamm and Turner, 1994; Hazen and Berry, 1997) and the CLUE model (Veldkamp and Fresco, 1996, 1997a,b). Both of these models estimate the effects of such explanatory variables as slope, soil, elevation, aspect, location, and population measures, on different types of land use/cover change. Using the estimated models, both groups of researchers then simulate the effect of different scenarios on land use change. For example, the LUCAS model is used to simulate the effect on future land use change of a moratorium on logging or road-building; the CLUE model is used to simulate the effects of urbanization, abolition of national parks extension of national parks soil erosion crop disease at certain elevations and volcanic eruption.

From an economics perspective, these models are limited for the same reasons as those discussed in the previous section. In addition, the only simulations that can be performed in these models are changes that are *imposed* on the explicit features of the landscape, such as a moratorium on road-building or certain land uses, or changes to other features of the landscape, such as soil erosion or crop disease at certain elevations. Because the underlying decision-making behavior is imposed, it is not possible to model a behavioral response to a change in any variable included in the models. For example, the impact of an agricultural policy change (e.g. a subsidy change) on a farmer's decision to farm his land cannot be predicted. The only way to simulate such a policy with these models would be to assume the land use decision of the farmer in response to the policy.

4. Economic models of land use change

4.1. Non-spatially explicit models

Traditional economic models that describe urban spatial patterns of land use can be broadly classified as either microeconomic models that describe equilibrium land use patterns within an urban area or regional economic models that describe the equilibrium flows of population, employment, or other economic factors across regions. For various reasons that we outline below, most of these models do not offer a satisfactory approach to explaining the spatial economic process of land use change at the parcel level.[5]

The traditional urban economic model of land use pattern is the bid-rent model (or monocentric model), which presumes the location of an exogenous central business district to which households commute (Alonso, 1964; Muth, 1969; Mills, 1967). All other features of the landscape are ignored, so that distance to the center is the underlying determinant of land use change. Individual households optimize their location by trading off accessibility to the urban center and land rents, which are bid up higher for locations closer to the center. In its simplest form, the resulting equilibrium pattern of land use is described by concentric rings of residential development around the urban center and decreasing residential density as distance from the urban center increases. More sophisticated versions of the model have been developed, but

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[5] For a more detailed review of these models and the spatially explicit economic models discussed in the following section, see Bockstael and Irwin (2000).

nonetheless, the model's ability to explain spatially disaggregate land use patterns is limited. In comparing the model's predictions with actual land use patterns, the model fails to explain the complexity of the spatial and temporal patterns of urban growth (see Anas et al., 1998, for a recent discussion).

The limitation of the monocentric model is partly due to its treatment of space, which is assumed to be a "featureless plane" and is reduced to a simple measure of distance from the urban center. Within this context it is not possible to represent all the heterogeneous landscape features that exist in reality and that do influence land use decisions. The Ricardian tradition explains differences in land rents due to differences in land quality that arise from a heterogeneous landscape, but abstracts from any notion of relative location leading to spatial structure. Many models that try to explain land values (namely, hedonic pricing models[6]) combine the two approaches by including variables that measure the distance to urban center(s) as well as specific locational features of the land parcel. However, these types of models, in general, have not been used in the land use change literature, except for Bockstael (1996) (discussed below).

More recent urban economic models have focused on explaining the formation of urban spatial structure as an endogenous process that is the result of "interactions" among individual economic agents distributed in space (Fujita et al., 1999; Krugman, 1991, 1996; Anas and Kim, 1996; Zhang, 1993; Arthur, 1988). These models, which are part of the new economic geography literature, hypothesize an interdependence among individual households and/or firms that leads to the location decisions of one individual affecting the location decision of others. Such interdependence can arise due to a variety of factors, e.g. demand and supply linkages between customers and firms, knowledge spillovers among firms, or congestion effects among residential land uses. Depending on the type and magnitude of these interactions, a monocentric, polycentric, or fully dispersed land use pattern may result. Because these models explain the emergence of agglomerations and urban spatial structure, they are much more robust than the traditional bid-rent models. However, in order to solve the model for an equilibrium solution that describes the urban spatial structure, much of the actual heterogeneity of the landscape is ignored. As such, these models offer a fairly abstract description of land use pattern based on equilibrium conditions. Nonetheless, because they are models based on individual agents spatially distributed within a landscape, they offer potential for incorporating the effects of spatial heterogeneity at a disaggregate scale. Some economists have developed agent-based simulation models of this sort applied to land use change and we review some of this research in a subsequent section.

An alternative approach to modeling urban spatial structure is given by regional economic models that describe population and other economic flows across regions (see Wegener, 1994, for a review). The urban region is represented as a limited number of discrete zones, in which each zone is described by an aggregate number of households and industries, and zones are connected via a transportation network. Based on the relative distance between zones and the location preferences of individuals, these models seek to describe the equilibrium flows of people across these discrete zones. While many of these models have proven quite useful for transportation planning and other regional planning applications, their spatial resolution is too coarse to capture the heterogeneity of the landscape at a parcel level.

4.2. Spatially explicit models

Recent work in environmental economics has focused on developing economic models of the individual landowner's decision within a spatially explicit framework. This work is noteworthy because of the link between the resulting empirical model and the underlying theoretical motivation for the model. In what follows, we review some of these recent contributions.[7]

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[6] The hedonistic pricing model is a method for estimating the implicit prices of characteristics of a heterogeneous good, in which the price of the good is estimated as a function of a vector of attributes that describe the good. For example, housing is a differentiated good defined by a host of structural, neighborhood, and locational attributes. A hedonic pricing model can be used to estimate the marginal value of these individual housing characteristics by estimating housing price as a function of these attributes. See Freeman (1993) for further details

[7] See Bockstael and Irwin (2000) for a fuller review of these models.

Much of the economic work in land use change has focused on deforestation in lesser-developed countries. For example, Chomitz and Gray (1996) develop a simple model of deforestation in which landowners maximize expected profits, so that the optimal use is determined by the use with the highest rents, using remotely sensed data and other spatial (GIS) data. Rents in an agricultural use are equal to returns minus costs of production, where production is a function of soil quality. The likelihood of forest conversion to agriculture is modeled as a function of soil quality and input and output prices at any given location. Accessibility to markets is used as a proxy for the spatial variation in prices, based on the argument that prices will vary at any given location depending on transportation costs to market centers. Chomitz and Gray recognize the potential endogeneity problem associated with the accessibility measure, since road location may be influenced by the location of agricultural production. In testing for this possibility, evidence of the endogeneity of roads is found, which suggests that the estimate of the influence of accessibility on deforestation is overstated.

Other examples of economic models of deforestation using remotely sensed data and GIS include Pfaff (1999) and Nelson and Hellerstein (1997). Like Chomitz and Gray, these studies demonstrate how economic theory can be applied to motivating the variables that are included in the land use conversion model and identifying potential endogeneity problems. For example, Pfaff (1999) points out that population may be endogenous to forest conversion, due to unobserved government policies that encourage development of targeted areas, or that population may be collinear with government policies. If the former is the case, then including population as an exogenous 'driver' of land use change would produce a biased estimate and lead to misleading policy conclusions. If the latter is the case, then the estimates would be unbiased, but inefficient, leading to a potential false interpretation of the significance of variables in explaining deforestation. To address these issues, he uses a temporally lagged value of population in the regression analysis.

A spatially explicit and spatially disaggregate land use change model from the urban planning literature is found in Landis (1995) and Landis and Zhang (1998a,b). The unit of observation in this model is a 1 ha cell of the landscape, and they use a discrete choice approach to model development and redevelopment in an urban setting. The choice of explanatory variables is motivated using economic theory and includes initial site use, variables to capture demand pressures, distance/accessibility measures, costs of development, returns to alternative uses, and non-conforming uses. The economic process is modeled, so that the impact of different policies that affect the returns to different land uses can be predicted from the model. However, there is no explicit model of price formation and the policies that most directly affect land uses, such as zoning and impact fees, are not included in the model, so only indirect policies can be simulated. The unit of observation is a cell of the landscape, rather than the land manager, and therefore there is no direct link between the unit of observation and the decision-maker. Lastly, because the model is estimated with only one time change, it is does not capture how changes in other variables affect land use change over a longer time horizon. For example, the influence of cumulative development pressures over time is not considered.

While these models clearly demonstrate the benefits of incorporating economic theory into land use change models, they do not go beyond estimating a land use conversion model to predicting resulting changes in the spatial pattern of the landscape. To do so requires a dynamic model of land use change and one in which individual, spatially distributed land use decisions can be aggregated to describe the resulting changes in *regional* pattern. Examples of a dynamic land use change model and one in which changes in land use patterns are simulated over time in order to predict regional outcomes are discussed in the following section.

5. Examples from the Patuxent River Watershed project

In this section we offer examples of economic spatially explicit modeling of land use change from ongoing research at the University of Maryland to further illustrate some of the benefits of a spatially explicit, economic modeling approach. This research project is an extensive effort aimed at modeling the spatial dynamic changes of land use and land use change within the counties of the Patuxent River Watershed

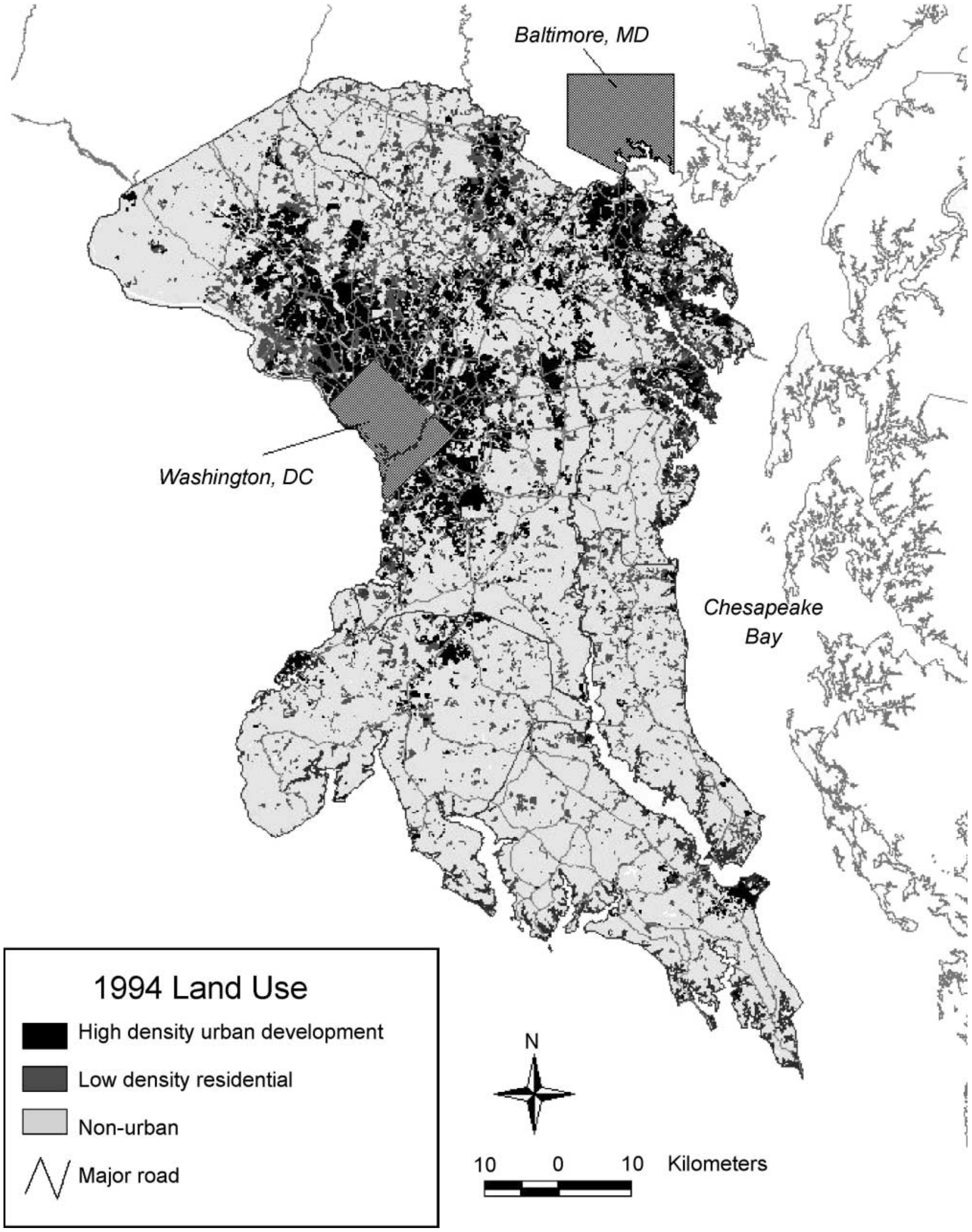

Fig. 1. Central Maryland region.

and furthering an understanding of some of the economic and ecological consequences of these changes. The Patuxent area, located in central Maryland, USA, has witnessed tremendous growth in residential land use and changes in land use patterns in recent years (see Fig. 1). Between 1973 and 1994, population in this seven county region increased from approximately 1.79 million to 2.44 million, an increase of 36%. The amount of low-density residential land use in the study area increased from approximately 92 000 acres to almost 188 000 acres during the same time period, an increase of 119%. Particularly in the urban–rural

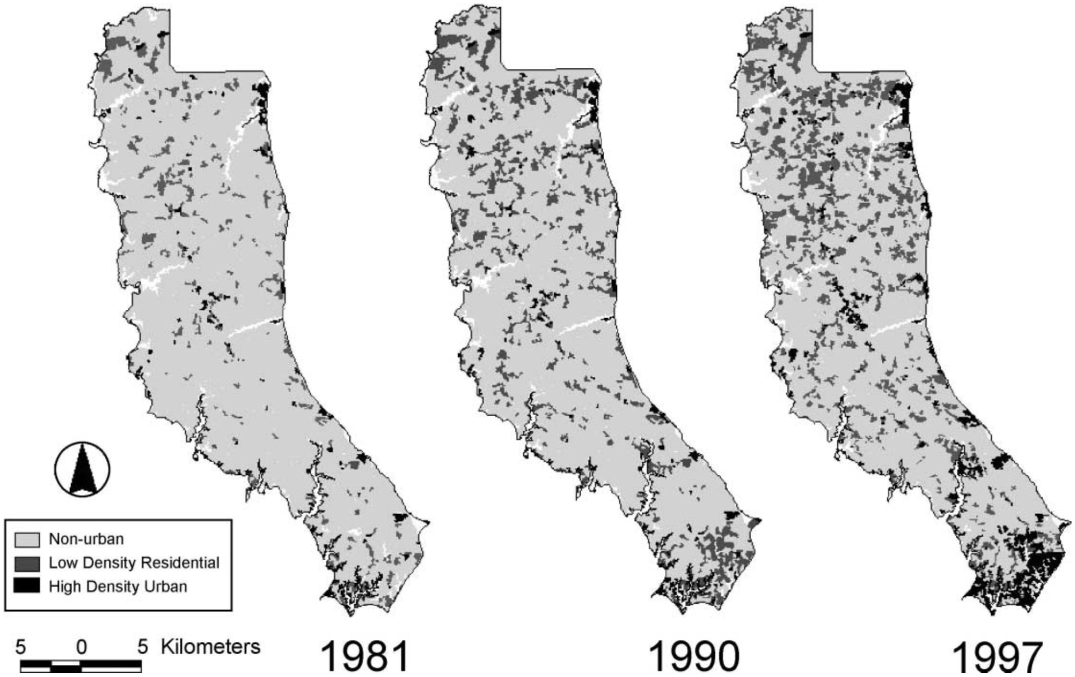

Fig. 2. Land use changes in Calvert County, Maryland, 1981–1997.

fringe areas of the region (e.g. Calvert and Charles Counties), the high conversion and population growth rates have led to an increasingly fragmented land use pattern. Fig. 2 illustrates the change in the pattern of development that has occurred in Calvert County, which is located within the study area and was one of the fastest growing counties in Maryland in the 1990s. These rapid changes have sparked concerns about the costs of providing public services, the preservation of open space, and the protection of environmental resources.

5.1. Economic spatial models of land use conversion

Because most of the land use changes occurring in this area are from previously undeveloped land to residential use, much of the work to date has focused on this residential urbanization process, in which land in agriculture, forest, or a natural state is converted to a residential use. Similar to other microeconomic models of the land use conversion decision, the underlying motivation for landowners to convert land to a developed use is assumed to be maximization of expected returns over an infinite time horizon. Based on this theoretical framework, a simple structural model describing the individual's discrete choice of land use can be developed. The simplest characterization based on profit maximization is one in which parcel *j*, which is currently in state *u*, will be converted to state *r* in time *t* if

$$W_{jrt|u} - C_{jrt|u} \geq W_{jmt|u} - C_{jmt|u} \quad \text{for all land uses}\ m = 1, \ldots, a, \ldots, M \tag{5}$$

where $W_{jrt|u}$ is defined as the present value of the future stream of returns to parcel *j* in state *r* at time *t*, given that the parcel was in state *u* in time $t-1$ and $C_{jrt|u}$ is defined as the cost of converting parcel *j* from state *u* to state *r* in period *t* (Bockstael, 1996).

Given that not all factors that affect *W* and *C* are observable, this statement can be rewritten in terms of the *probability* the parcel *j* is converted from state *u* to *r* in time *t*, in which the systematic (or observed) and random portions of *W* and *C* are explicitly modeled,

$$\text{Prob}(V_{jrt|u} - \eta_{jrt|u} \geq V_{jmt|u} - \eta_{jmt|u}) \tag{6}$$

where V represents the systematic portion of $W - C$ and η the random portion, which is unobserved to the researcher. Given a distribution for the error terms and a functional form for the systematic portion, this model can be rewritten and estimated using discrete choice modeling techniques (see Bockstael, 1996 for more details).

The first step in incorporating spatial heterogeneity of the landscape is accomplished by recognizing that the returns to converting land to a residential use, W, and the costs of conversion, C, will both be influenced by a host of spatially heterogeneous variables. In early work, Bockstael (1996) develops a two-stage approach to modeling residential land use change. A spatially explicit hedonic[8] model of residential land values is first estimated as a function of spatially varying landscape features, including lot size, accessibility measures, neighborhood zoning, and percentages of land in different uses. The estimated model of residential land values is then used to predict the value is residential use of all "developable" land in the region. This predicted residential land value is used as an exogenous variable, along with other variables representing the costs of development and the value of the land in agricultural use (estimated from a separate model) in a binary discrete choice model of land use conversion, in which the land may either be in an undeveloped or residential use. This model is estimated using observations on actual residential land use conversions and is then used to predict the probability of development of each cell for a future round of development. The output of this type of model is a probability map (Fig. 3 shows an example for the southern region of the study area) that shows the likelihood of future development of each spatially differentiated land parcel that is yet undeveloped. A limitation of this model is that it only predicts the spatial distribution of conversion probabilities and does not explain the amount of development that might occur in any given period. In addition, this model is limited to a "snapshot" representation of land use change and does not seek to explain the dynamic evolution of land use patterns over time.

This modeling approach can be used to predict the effects of different land use policies. For example, Bockstael and Bell (1998) analyze the effects of a number of alternative land use policies including the effects of different regulations concerning minimum lot size, used in land use zoning. They find that differential zoning across counties deflects development from one county to another and that the amount of increased nitrogen loadings from a constant amount of new development varies from 4 to 12%, depending on the degree of difference across counties' minimum lot size zoning.

Further development of the data and model of Bockstael (1996) is found in Irwin and Bockstael (2001) and Geoghegan and Bockstael (2000). In these papers, a dynamic model of rural–urban fringe development that is both spatially disaggregate and spatially explicit, is developed in which land use and land use change over both time and space are modeled. The temporal dimension is explicitly considered by posing the land use conversion decision as an optimal *timing* decision in which the landowner seeks to maximize expected profits by choosing the optimal time $t = T$, in which the present discounted value of expected returns from converting the parcel to residential use are maximized. In this case, the underlying dynamic structural model can be written as follows (Irwin and Bockstael, 2001). The landowner will choose to convert his/her parcel to residential use in the first period in which the following conditions hold:

$$W_{jrT|u} - CC_{jrT|u} - \sum_{t=0}^{\infty} A_{jut+T}\,\delta^{T+t} > 0 \tag{7}$$

and

$$W_{jrT|u} - C_{jrT|u} - A_{juT} > \delta(W_{jrT+1|u} - C_{jrT+1|u}) \tag{8}$$

where W and C are defined above, δ is the discount rate, and A the one period returns from the land in its undeveloped use, so that the last term in (7) represents the present value of forgone returns from the land in its undeveloped use. In words, Eq. (7) states that the agent will convert his/her parcel when the net returns from development, $W - C$, is greater than the forgone returns from keeping the land in an undeveloped use over an infinite horizon. Eq. (8) states that the agent will convert given that the expected returns from converting in period T, net the one period opportunity cost of conversion A, is greater than the discounted net returns from converting in period $T + 1$. The agent is hypothesized to develop his/her land in the first period that both of these conditions are true.

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[8] See Freeman (1993) for a review of hedonic pricing models.

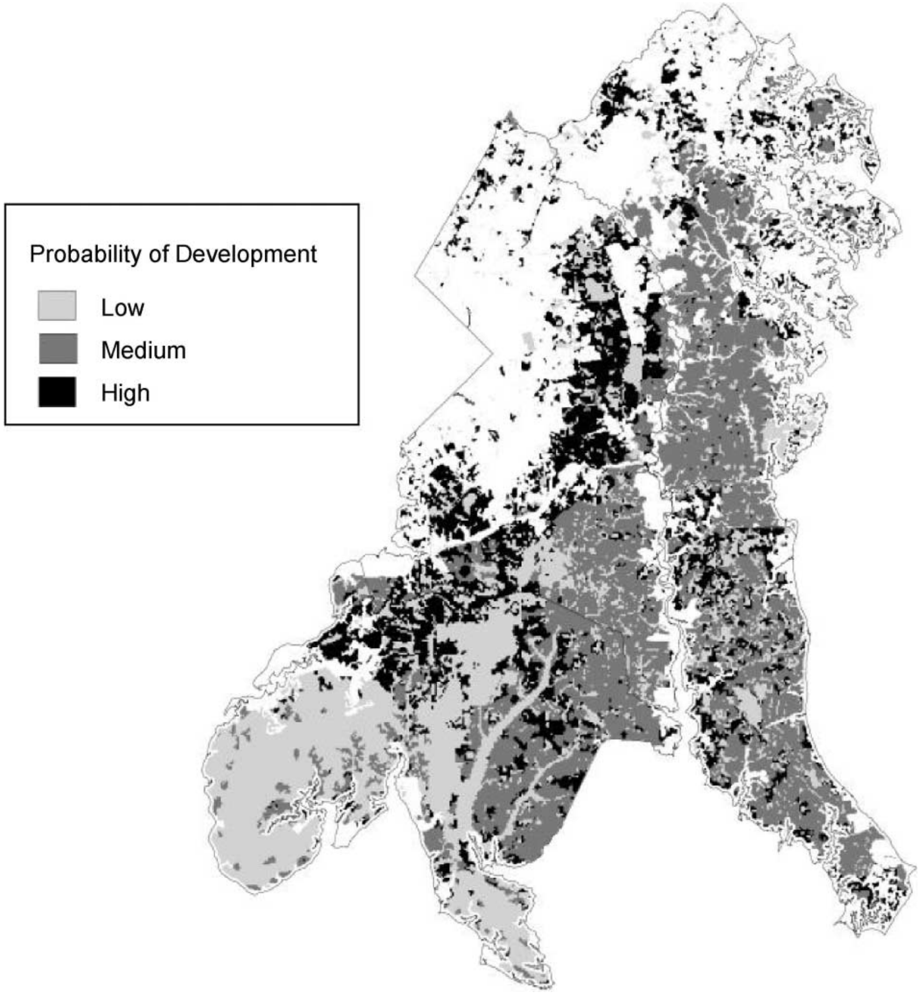


Fig. 3. Predicted probability of development.

As in the simpler model outlined in (5) and (6), the spatial characteristics of the parcel and its relative location in space are expected to influence *W*, *C*, and *A*. In both Irwin and Bockstael (2001) and Geoghegan and Bockstael (2000), historical data over time is used that tracks the conversion of land parcels from an undeveloped parcel (e.g. farm) to subdivided residential lots. This provides a direct link between the unit of observation and the land manager, who makes the land use conversion decision. The structural model outlined in (7) and (8) is operationalized using a duration model, in which the conditional probability that a parcel is developed in period t is estimated, conditional on the parcel still being in an undeveloped use in period $t-1$.

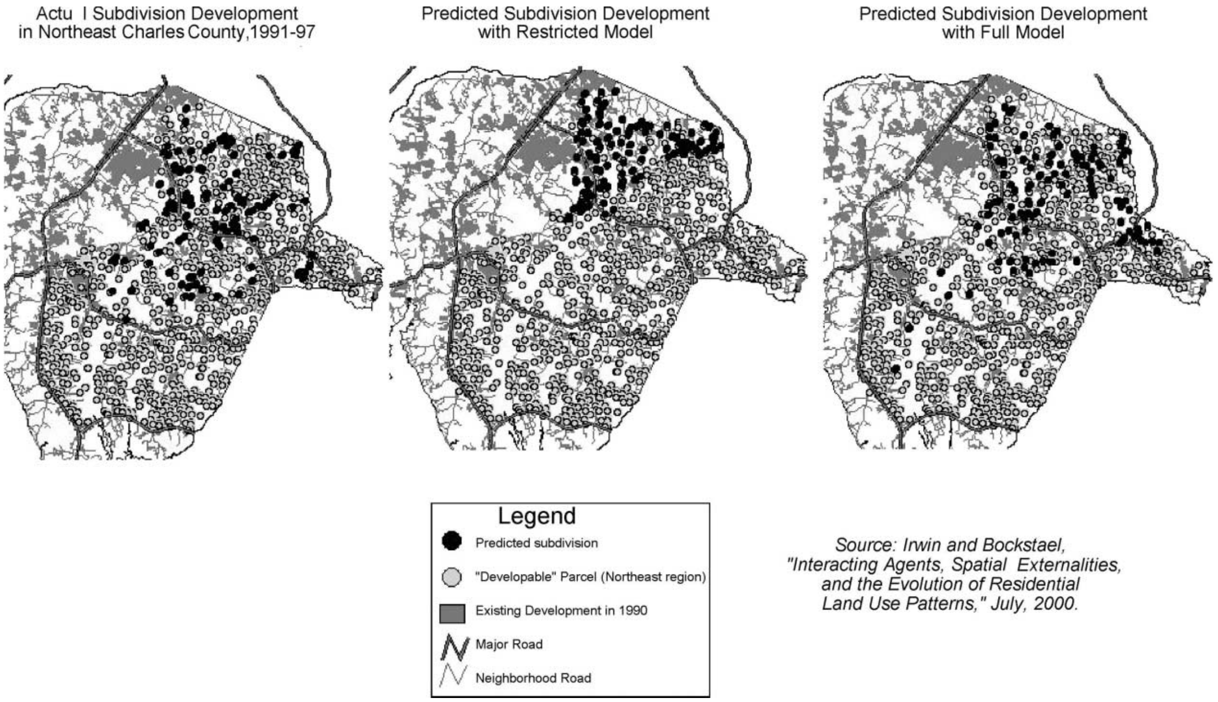
Geoghegan and Bockstael (2000) use this modeling approach to explore the effects of different land use regulations on the location and timing, of residential development and how these changes respond to land use regulations. The model includes land use policy instruments that have the potential to affect the pattern of development, such as zoning, development impact fees, adequate public facilities moratoria and provision of public sewer and water. Because the major land use regulations that affect the location of residential development are incorporated in the model, relevant policy simulations can be performed that illustrate the predicted effects of these growth control tools on land use change patterns. Given changes in one or more of the exogenous variables of the model, the model is able to predict both the *spatial location* of residential development and the *timing* of residential development. This allows for the effect of different land use policies on land use pattern to ultimately be tested.

This spatially explicit approach to identifying the variables that are significant in land use change can also provide insight into the spatial and temporal dynamics of land use change. Drawing upon the agent-based interaction models that have recently been developed in the new economic geography literature to explain urban spatial structure, Irwin and Bockstael (2001) develop a model in which exogenous features create attracting effects (e.g. central city, road, public services) among developed land parcels and interactions among land use agents create net repelling effects. They demonstrate that such a model offers a viable explanation of the fragmented residential development pattern found in many US urban–rural fringe areas. Assuming the presence of exogenous growth pressure effects that increase the likelihood of conversion over time, the time dimension is explicitly modeled by estimating a duration model of residential land use conversion. The conversion decision is treated as a function of both exogenous landscape features and a temporally lagged interaction effect among neighboring agents making a residential conversion decisions. Empirical evidence of a negative interaction effect among land parcels in a residential use is econometrically identified.

Irwin and Bockstael (2001) use a spatial simulation model to predict patterns of land use change in an urbanizing area, in which the transition probabilities are estimated as functions of a variety of exogenous variables and an interaction term that captures the effect of neighboring land use conversions. Given estimated parameters from a model of land use conversion, transition probabilities are calculated for yet undeveloped parcels and then updated with each round of development. The spatial simulation model is used to demonstrate that negative interaction effects result in the evolution of a more fragmented land use pattern that is qualitatively much more similar to the observed pattern of development than the pattern that is predicted by a more naive model in which these interactions are ignored. Fig. 4 illustrates the result of this simulation exercise for the northeast portion of Charles County, one of the exurban counties located within the study area. The actual pattern of development in this area between 1990 and 1997 is compared with the predicted pattern of development from a restricted model, in which the spatial interaction effects are ignored, vs. the full model, in which the negative interaction effects are shown to generate a much more scattered pattern of development. Comparison of nearest neighbor spatial statistics from these two different predicted patterns vs. the actual pattern show that the pattern generated by the full model is qualitatively much more similar to the pattern of actual development.

5.2. Spatial data issues

In any modeling approach that uses spatial data, there are two related issues to using these data: how to use the data “creatively” and how to use the data “correctly.” The former refers to developing ways of creating variables from spatial data that can be used in a model; the latter refers to issues of spatial econometrics. The question of using data creatively relates to finding ways in which the power of the spatial data can be used in a model to better estimate the spatial process. For example, in many of the traditional land use models, “space” is often reduced to a uni-dimensional measure of distance to city representing transportation costs to and from a central market. But the importance of location in land values and land use determination is not restricted to market accessibility. The pattern of landscape features and land uses that surround a parcel of land are likely to have a major influence on its value and use, for example, a negative influence on a residential land value that is caused by surrounding industrial land uses, and a positive influence as a result of a nearby park. That is, individuals value the *pattern* of land uses surrounding a parcel. In order to test this hypothesis for the Patuxent Watershed, Geoghegan et al. (1997) create spatial indices on land use fragmentation and diversity, borrowed from the landscape ecology literature that were calculated for each residential land parcel at different scales in a model of residential land values. These variables were found to be statistically significant in the different empirical specifications of the model. By using these spatial landscape indices, an improved model of land values was developed



Actual Subdivision Development in Northeast Charles County, 1991-97

Predicted Subdivision Development with Restricted Model

Predicted Subdivision Development with Full Model

Source: Irwin and Bockstael, "Interacting Agents, Spatial Externalities, and the Evolution of Residential Land Use Patterns," July, 2000.

Fig. 4. Northeast Charles County, Maryland. Actual vs. predicted development.

by capturing how individual value the diversity and fragmentation of the land uses around their homes.

The second modeling issue, spatial econometrics, deals with the methodological concerns that follow from explicit consideration of spatial effects in econometric models (Anselin, 1988). Such effects may take the form of spatial dependence, in which the values of observations in space are functional related, or spatial heterogeneity, in which model parameters are not stable across location. Spatial dependence may arise due to data measurement errors or omitted variables, leading to spatial error autocorrelation, or from spatial interaction, which implies a structural interdependence among observations. Analyzing a problem that is essentially location-based while ignoring the potential of interactions among the location of the observations is analogous to analyzing a time series problem without knowing the chronological order of the observations. Just as the chronological relationship of one observation to another is critical in time series analysis, so is the spatial relationship among observations in location-related problems, such as land use questions. All of the interesting statistical/econometric complications one encounters in time series analysis, such as autocorrelation, temporal dynamics, and structural change, have analogues, sometimes of greater complexity, in spatial analysis. Because of these, applying standard statistical/econometric techniques to spatial data in the presence of spatial dependence will generate inconsistent and/or inefficient estimates and lead to false conclusions regarding hypothesis tests.

Spatial dependence can result from a structural spatial relationship across dependent variables or a spatial dependence across error terms. If either form of spatial dependence occurs, specialized spatial econometric techniques can be used, where the pattern of the spatial dependence is assumed. The practice that has developed in the spatial econometrics literature uses spatial weight matrices, based either on contiguity or distance between observations, to assign the spatial structure needed to correctly estimate these models (for further details see Anselin, 1988).

Bell and Bockstael (2000) illustrate the importance of controlling for spatial error autocorrelation in a model of residential land values. Recognizing that a hedonic model of residential land values is likely to suffer from an omitted variables problem that, in a spatial setting, will lead to spatial autocorrelation, they use two different estimation methods to estimate a spatial error model. Parameter and standard error estimates from this model, in which the autocorrelated error structure is corrected using a spatial weights matrix that specifies the spatial dependent structure, are compared to estimates from a standard ordinary least-squares (OLS) model of residential land values. The results show that the significance of some of the explanatory variables changes with the spatial autocorrelation correction. In addition, the authors find that the results are dependent on the particular specification of the spatial weights matrix, e.g. whether the spatial weights are defined using a contiguity vs. distance-decay rule and the particular maximum distance cut-off that is used to delineate neighbors.

An example of spatial dependence caused by spatial interaction is found in Irwin and Bockstael (2001), in which the probability that an individual will convert his/her land parcel to a residential use is posited to be a function of the neighboring parcels' land uses. Evidence of a negative spatial interaction among developed parcels is found, implying that a developed land parcel "repels" neighboring development due to negative spatial externalities that are generated from development, e.g. congestion effects. The presence of such an effect implies that, ceteris paribus, a parcel's probability of development decreases as the amount of existing neighboring development increases. In this case, Irwin and Bockstael reasoned that this spatial lag is also temporally lagged, so that neighboring land uses in period t were hypothesized to influence a parcel's land use in period $t+1$. The authors also discuss an econometric identification problem that arises in this situation. Given the presence of unobserved spatial heterogeneity that is time invariant, temporally lagged neighboring land use states will be correlated with the error term and will introduce a positive bias in the estimated spatial interaction parameter. If this unobserved spatial correlation is not accounted for, then evidence of a positive spatial interaction effect could be found even if no spatial interaction existed in reality.

Geoghegan et al. (1997) test for the presence of spatial heterogeneity with the use of a varying parameters model (also known as a spatial expansion model), in which the coefficients on some of the explanatory variables were allowed to vary over space. Results show that for such variables as access to roads and lot size, the value of an additional unit on residential price did vary significantly with distance from the central business district, so that these did not remain stable with location.

6. Conclusions and further research

In order to improve our understanding and modeling of spatially explicit and spatially disaggregate land use change, improved datasets, improved methods, and improved theory are needed. All three of these issues are closely linked. As has been argued elsewhere (Geoghegan et al., 1998), the historical lack of spatially explicit social science data constrained spatial modeling of human behavior. As a result, interest in spatial issues in the social sciences beyond the field of geography has been limited. But, with the increasing availability of spatial social science data, there has been a renewed interest in spatial issues among other social sciences. In a recent discussion of future research issues in natural resource and environmental economics, Deacon et al. (1998) comment, "the spatial dimension of resource use may turn out to be as important as the exhaustively studied temporal dimension in many contexts." Therefore, having spatially explicit data on a decision-maker basis should result in more sophisticated modeling of spatial human behavior and hypotheses testing.[9]

However, obtaining better data that can be used to test more sophisticated theories of spatial behavior necessitates improved empirical methods, such as those being developed within the field of spatial econometrics. As argued above, not taking into account spatial dependence or spatial heterogeneity when estimating a model can lead to biased or inconsistent estimates and false conclusions regarding the sign and significance of parameter estimates. While many advances have been made in the field of spatial econometrics, it is still in its infancy when compared to its dynamic

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[9] The need for improved spatial data beyond the development of remotely sensed datasets, has been documented in LUCC Report Series No. 3 "LUCC Data Requirements Workshop: Survey of Needs, Gaps, and Priorities on Data for Land-use/Land-cover Change Research", November 1997.

counterpart, time series econometrics. A particular need for land use and land cover change modeling is the application of spatial econometric techniques to discrete choice models, since these models are particularly useful in modeling land use and land cover changes. To date, a rigorous methodology has not yet been developed that would allow for the treatment of spatial effects in a discrete choice framework, although some limited cases have been developed in the literature (for more details, see Anselin and Florax, 1995).

Lastly, the development of better economic models of land use/cover change rests on advances in the spatial economic theory of urban spatial structure that can better explain the spatial and temporal patterns of migration, employment growth, government actions, and resulting land use changes. As discussed in Bockstael and Irwin (2000), a primary challenge is in understanding how individual choices that are spatially distributed can be aggregated up to regional market outcomes, i.e. the issue of crossing from one scale of analysis to another. In general, the defining factor for economists in aggregating from individuals to markets is the distinction between what is endogenous and what is exogenous at each scale. But once spatial heterogeneity is introduced, aggregating individual land use choices to spatially articulated market outcomes becomes much more complicated. As reviewed above, new theories about the evolution of urban land use patterns have begun to take hold in the urban and regional economics literature, but this research remains almost all theoretical. More hypotheses from these new theories need to be identified and empirically tested to gauge the robustness of these theories.

Land use/cover change research *requires* an interdisciplinary approach, as has been argued in the LUCC Science Plan and Implementation Plan[10] and as has been proven on the ground in many research projects. However, until recently economists have not been active participants in the international LUCC community. We hope that this discussion paper and the examples that it includes, demonstrates some of the ways that economics can contribute to, and advance the interdisciplinary field of land use/change research.

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