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Geographically and temporally weighted likelihood regression: Exploring the spatiotemporal determinants of land use change ☆

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ABSTRACT

Urban areas possess complex spatial configurations. These patterns are produced by cumulative changes in land use and land cover as human and natural environments are influenced by market forces, policy, and changes in the natural landscape. To understand the mechanisms underlying these complex patterns, it is important to develop models that can capture the complexity of the underlying economic process. This includes spatiotemporal variation in the variables as well as spatiotemporal heterogeneity or non-stationarity in the model. The objective of this paper is to build on previous work in spatial nonparametric modeling and propose a spatiotemporal technique for nonlinear panel data models. Using a series of Monte Carlo experiments, we demonstrate how extending a geographically weighted likelihood regression (GWLR) model to account for temporal heterogeneity can improve the performance of the model when heterogeneity exists in the spatial and temporal dimensions. We also show how the technique can be used in modeling real world land use changes by applying our proposed technique to a panel of historical subdivision development from an urbanizing county in the Baltimore/Towson Metropolitan Statistical Area (MSA). Our results demonstrate that the method provides better performance than a standard parametric model. We also demonstrate how the spatiotemporal marginal effects from the model can be used to conduct policy analysis at multiple spatial and temporal scales, which is not possible using the standard global parameter estimates. Our proposed technique is simple to execute and can be implemented using any statistical software package.

1. Introduction

Metropolitan regions contain substantial heterogeneity in land use across urban, suburban, and exurban landscapes (Irwin and Bockstael, 2007; Burchfield et al., 2006; Nechyba and Walsh, 2004). These patterns are produced by cumulative changes in land use and land cover as human and natural environments are influenced by heterogeneous market forces, land use policy, and changes in the natural landscape. Much of the recent development in urban areas around the US can be categorized by low-density, scattered, and non-contiguous development. While this type of development was documented as early as the 1960s (Clawson, 1962; Bahl, 1963), it was not until the development of dynamic urban models (Ohls and Pines, 1975; Mills, 1981; Wheaton, 1982) that researchers were able to provide a theoretical explanation for these patterns.

Dynamic urban theory explains discontinuous urban spatial development by appealing to the optimal intertemporal decision making process of developers. Ohls and Pines (1975) showed that in the case of homogeneous land, atomistic land developers, taking account of intertemporal differences in land rents between parcels, will develop lower-valued parcels in more remote areas earlier than higher-valued parcels located closer to the urban center. Mills (1981) showed that the same type of pattern could be realized and sustained when land use was heterogeneous. Since that time there has been substantial theoretical work in extending dynamic urban models to account for many other aspects of the urban land development and growth such as uncertainty, development lags, competing development options, and edge city and endogenous subcenter development (Arnott and Lewis, 1979; Arnott, 1980; Capozza and Helsley, 1990; Capozza and Li, 1994; Bar-Ilan and Strange, 1996; Henderson and Mitra, 1996; Fujita et al., 1999). While dynamic urban models are extremely useful for answering many research questions, they are quite limited in explaining many of the seemingly "nonmonocentric" growth patterns witnessed in many urban areas (Irwin, 2010).

One of the key features of these so-called nonmonocentric models is their focus on more localized influences such as agent and landscape interactions and the spatially and temporally heterogeneous impact of land use and transportation policy. For example, Irwin and Bockstael (2002) use micro-level subdivision data from several Maryland counties and demonstrate that congestion effects from local agent interactions

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can lead to more urban sprawl as parcel owners attempt to internalize the negative externalities associated with urban congestion. Several other papers using similar data have shown that land use policies ranging from zoning and conservation reserve purchases (CRP) to urban growth boundaries and regulatory delay can influence the timing and location of the development (Towe et al., 2008; Newburn and Berck, 2006; Cunningham, 2007; Wrenn and Irwin, 2013). A number of other authors, using dynamic spatial econometric models, have shown how transportation access and choice over time and space can influence urban land use patterns (Wang et al., 2012; Paez, 2009; Vandenbulcke et al., 2009). Finally, there is a growing literature in structural demand modeling that explains urban spatial structure as a result of neighborhood sorting based on Tiebout's (1956) hypothesis (Klaiber and Kuminoff, 2013; Tiebout, 1956). All of these models build in heterogeneity and interactions in both space and time.

A key feature in most spatiotemporal econometric models is the specification and estimation of a parametric econometric model. This approach is valid in the cases where the researcher knows the economic process underlying the data or when he or she is willing to make some assumptions in order to test a specific hypothesis. Often, however, the researcher does not know the underlying process and must find a way to uncover it. Thus, researchers need econometric models that can flexibly capture the intricacies of the determinant processes and the potential for non-stationary equilibria over space and time. Moreover, policymakers need models that allow them to test the effects of different policies in the spatial and temporal dimensions. The focus of this paper is to extend previous empirical work in spatiotemporal parametric modeling and provide a new technique that can both tease out unknown economic relationships as well as assist researchers and policymakers in testing specific hypotheses related to the spatial and temporal impacts of land use policy.

In recent years, Geographic Information System (GIS) technology has allowed researchers to digitize historical land use maps. These maps have been combined with parcel-level GIS files to create panel data sets of historical land use change. Using these spatially explicit panel data sets, researchers can now model land conversion decisions at the same spatial and temporal scales as they occurred. In addition, to answer specific research questions and identify the most important factors impacting land conversion, these data sets have been combined with additional spatial and policy data collected from other sources to generate the necessary variables for identifying the key economic drivers determining land use patterns. While the development of these micro-level panel data sets has allowed for increased flexibility in modeling land use change, many of the models that have been applied in modeling land use outcomes have relied on restrictive parametric assumptions between the explanatory variables and the outcome of interest. What remains is to develop more flexible econometric techniques that can take full advantage of the richness of these micro-level data sets. This includes models that can capture both the spatial and temporal variations in the data as well as variation in the effect of the variables on the outcome variable, i.e., models that can account for spatiotemporal variation in both the variables and the coefficients.

Most econometric models share the same common simplification — the relationship between the outcome variable and the regressors is parametrically stationary and the coefficients in the model are homogeneous or fixed regardless of the location or time period. This implies that, while the information matrix, X, accounts for variation in the variables over space and time, the parametric assumption about the stability of the econometric relationship between the outcome variable and the regressors forces the coefficients, β, to remain fixed. This stationarity assumption, while it simplifies estimation, ignores two of the most important features of land use data and spatial econometric modeling — that heterogeneity and scale matter. Even a cursory glance at any metropolitan land cover map reveals an inherently heterogeneous built and natural landscape. Additionally, as economic agents, with heterogeneous preferences, make optimal timing decisions regarding conversion of their parcels, they further influence the heterogeneity of this pattern. Combining these two results implies that observed land use patterns are the result of spatiotemporal interactions between a heterogeneous natural environment and the heterogeneous decisions of economic agents. As a result, models that assume spatiotemporal stationarity in the underlying economic relationship may be limited in capturing the intricacies of the actual process.

Recognizing these limitations, a number of new approaches have been proposed to account for different types of heterogeneity in the coefficient values. The most popular application of this new modeling approach has been geographically weighted regression (GWR) (McMillen and Redfearn, 2010; McMillen and McDonald, 2004; Paez et al., 2002; Fotheringham et al., 2002). GWR estimates a separate econometric model, using a locally varying sample, at each geographic location in the data set. This technique produces a separate set of spatial regression parameters for each cross-sectional observation. Using this repeated estimation technique, spatial heterogeneity is accounted for by allowing the marginal effects to vary across space and local analysis is conducted by aggregating the coefficient values to the appropriate spatial scale.[1] While GWR models have been shown to represent spatial heterogeneity effectively, they do not account for heterogeneity in the temporal dimension. This creates a real limitation in applying nonparametric models to many of the most pressing questions in land use change, which are, by default, the outcome of an underlying process that is inherently intertemporal.

The objective of this paper is to build on previous work in spatial nonparametric modeling and propose a geographically and temporally weighted likelihood regression (GTWLR) technique for binary panel data. One of the main reasons for applying any nonparametric model to an economic problem, spatial or otherwise, is to allow for flexibility in capturing the potential multiplicity of the equilibria that arise in models with a non-stationary relationship between the dependent variable and the regressors. The importance of this added flexibility has been demonstrated by many previous authors in applying the GWR models to various spatial econometric problems.

We first develop a series of Monte Carlo experiments using a five-period logit panel data model and demonstrate how extending current GWR models to account for temporal heterogeneity provides better performance when variation exists in both spatial and temporal dimensions. Then we show, using a discrete-time duration model and panel data set of historical land use change from an urbanizing county the Baltimore, MD metropolitan region, how our proposed technique can be used in modeling actual land use change as well as showing that our proposed technique again achieve better performance in describing the data than a strictly parametric model. And finally, using the marginal effects from our discrete-time duration model, we demonstrate that the econometric relationship between our binary outcome variable and our measures of distance and local subdivision interactions is non-stationary. This last result is particularly important given that most spatial econometric models of land use and urban land development assume a stationary or fixed econometric relationship over space and time.

This paper makes a number of contributions to the literature on land use modeling. First, recent years have witnessed the advent GIS technology that has allowed researchers and policymakers to construct long micro-level panel data sets of historical land use change. One of the main advantages for these data sets is that they allow economists to test the basic assumptions of the traditional urban model. However, in order to test these assumptions it is necessary to have models that are flexible and do not force the assumptions on the data in a parametric

[1] While spatial nonparametric models have many advantages over more restrictive parametric models, recent research has shown that they do not address all spatial issues in the data and can even introduce issues that did not exist before including spatial-autocorrelation, multicollinearity, and sign reversals (Leung et al., 2000; Wheeler and Tiefelsdorf, 2005; Farbar and Paez, 2007).