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SCIENCE DIRECT
Regional Science and Urban Economics 34 (2004) 705–725
regional SCIENCE & urban ECONOMICS
www.elsevier.com/locate/econbase

Land use externalities, open space preservation, and urban sprawl

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Accepted 2 March 2004
Available online 18 May 2004

Abstract

Parcel data on residential land conversion are used to investigate how land use externalities influence the rate of development and modify policies designed to manage urban growth and preserve open space. Several "smart growth" policies are found to significantly influence land conversion, including a development clustering policy that concentrates development and generates preserved open space. In addition to directly affecting a parcel's hazard rate of conversion, this policy is found to affect neighboring parcels' conversion by generating a positive open space externality that hastens their development. The implication that the clustering policy could generate a more sprawled pattern of development is explored using spatial simulation.

JEL classification: R14; R52
Keywords: Land development; Urban land use patterns; Smart growth

1. Introduction

Sprawl, a term often used to describe non-compact features of urban land use patterns, is a regional-level phenomenon driven by individual choices over location and land use that are influenced by a myriad of factors, including land features, infrastructure, policies, and individual characteristics. Because it is the cumulative result of individual actions, an understanding of sprawl requires an understanding of individual

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doi:10.1016/j.regsciurbeco.2004.03.002

decision making and how these decisions "aggregate up" over time and space. However, because of a lack of spatial data on individual-level land use and location choices, most empirical studies have defined sprawl at an aggregate level, e.g., census tract or county level, and have measured it using aggregate values of population, employment, or urban development (e.g., Fulton et al., 2001; Galster et al., 2001). At this more aggregate scale of analysis, causal explanations of sprawl that link underlying individual behaviors to observed patterns are difficult to come by and empirical analyses of sprawl are most often limited to identifying characteristics that are associated with, but do not necessarily cause, sprawl. On the other hand, parcel and plot-level models of individual land use conversion decisions have been useful in identifying factors that drive changes at a disaggregate level (e.g., Bockstael, 1996; Irwin et al., 2003; Landis and Zhang, 1998; McMillen, 1989), but this approach offers an incomplete picture for understanding sprawl, which is the cumulative result of many individual decisions.

This paper uses parcel-level data on land conversion and a Geographical Information System (GIS) to explore the pattern of development as the result of several types of influences: (1) spatially varying policy variables, including several "smart growth" policies and a clustering regulation that requires developers to preserve varying amounts of open space by clustering development on a parcel; (2) other spatially heterogeneous features of land parcels, including accessibility to urban centers, soil quality, and size; and (3) interactions among neighboring landowners' land use decisions due to land use externalities. We do so by building on the optimal timing of development model developed in Irwin and Bockstael (2002), which incorporates the effects of land use externalities and is estimated using a hazard model of development. Our analysis extends the previous work by incorporating a much more extensive set of policy variables, including a variety of "smart growth" variables that are hypothesized to influence development timing, and by focusing on how the presence of land use externalities may moderate the effectiveness of these policies. In particular, we focus on whether land use externalities alter the effectiveness of a clustering policy designed to protect open space by creating a positive amenity associated with the preserved open space that, under certain conditions, may attract development and exacerbate sprawl.

To structure our analysis, we argue that policies have both direct and indirect effects. Direct policy effects are those that influence a landowner's decision by directly influencing either the costs or returns to development in some way, e.g., by constraining land use choices, limiting the allowable density of development, or improving the level of public services associated with a parcel. Indirect effects, on the other hand, arise via land use externalities from neighboring land parcels and can either increase or decrease the development value of a parcel. An indirect policy effect arises if a policy induces a land use change on one parcel that in turn affects a neighboring parcel's development value. The specific externality that we hypothesize in the current analysis is a positive amenity effect that arises from designating neighboring land as preserved open space and which may be associated with a scenic view, increased privacy, or guarantee of no neighboring future development. If present, such indirect effects would certainly complicate the task of predicting the likely impacts of a policy on land use patterns and, in some cases, may contribute to unintended consequences such as exacerbation of a sprawl pattern of development.

The rest of the paper is organized as follows. First, the influences of land use externalities and direct and indirect policy effects on the optimal timing of land development are considered. Next, detailed parcel-level data on land use change from a central Maryland region are used to estimate a hazard model of land use conversion. Results show that a variety of factors influence a parcel's hazard rate, including several "smart growth" policies as well as land use externalities from neighboring residential, commercial, and unpreserved open space lands. With respect to the clustering policy, we find that the direct effect is to either hasten or slow a parcel's development, depending on the amount of preserved open space required by the regulation. The indirect effect, which is the amenity value associated with the preserved open space that is a byproduct of the clustering policy, is found to be positive and significant. We explore the implications of this finding for sprawl by using GIS to predict the development pattern under alternative policy scenarios in which the clustering policy is applied more widely to rural lands within our study area. The results demonstrate the potential for the clustering policy to generate a more sprawled pattern of development.

2. Interaction effects and the optimal timing of development

We are interested in an individual landowner's optimal timing decision regarding the conversion of a land parcel from an "undeveloped" to "developed" state. An undeveloped state is considered to be some type of open space, e.g., agriculture, another resource producing activity such as commercial forestry, or a natural state. Given that our interest lies primarily in the evolution of residential sprawl occurring in rural–urban fringe areas, a developed state is defined exclusively as residential use. More specifically, a "developed" parcel is one that has been subdivided by the landowner and then sold to a housing developer, who subsequently build houses on individual lots and sell them individually to households.[1] Once developed, the costs of reversing development are considered to be prohibitive, and therefore the development decision is viewed as irreversible.

Because our focus is on the dynamic process of land conversion in high growth pressure regions, the relevant question for an individual landowner of a "developable"

[1] We assume that the land market is competitive and that strategic interaction among developers is absent. Such interaction has been studied as a primary cause of edge city and community formation (Henderson and Becker, 2000; Henderson and Mitra, 1996; Henderson and Thisse, 2001). While it is also possible that developers of residential subdivisions in rural–urban fringe areas would behave strategically, data on development in our particular study region suggests that this may not be the case. According to tax assessment records, just over 100 companies were active in residential subdivision development in our study region in the 1990s. Between 1993 and 2000, a total of 164 residential subdivisions were developed, suggesting that the number of developers relative to the number of exchanges in the market during this time period was large. Because it is possible that a single developer would control multiple companies to disguise their ownership of land or that a few large companies developed the vast majority of the land, this evidence does not rule out the possibility of strategic interaction, but it does provide us some reason to believe that the assumption of competitive land markets may not be entirely naive.

parcel is not so much *whether* but rather *when* to develop.[2] For this reason, we follow Irwin and Bockstael (2002)[3] and treat the relevant decision from the agent's perspective as the optimal timing of development. To formalize the landowner's decision, define A_{it} as the returns to the original, un-subdivided parcel (denoted i) in the undeveloped use (e.g., farming) in any period t. Conversion of parcel i at time D will require the agent to incur costs to record the subdivision, provide subdivision infrastructure, and pay impact, permitting, and other administrative fees. Gross returns from conversion equal the sum of the expected sales prices of the subdivided residential lots. We denote δ as the discount factor, defined as $1/(1+r)$ where r is the interest rate, and the returns from development net the costs of conversion in time D as R_{iD}. Under certain assumptions regarding the time paths of returns and costs,[4] a profit-maximizing landowner will choose the optimal period to develop by comparing the net gains from developing in period D vs. period D+1 and then developing in the first period that the net returns, minus the opportunity cost of development, outweigh the discounted returns of developing in the subsequent period (Irwin and Bockstael, 2002):

$$R_{iD} - \delta R_{iD+1} - A_{iD} \geq 0. \tag{1}$$

In this paper, we begin with this decision rule and consider the potential role of land use externalities embedded in R and how the land use surrounding a parcel may affect its value in residential use. While our empirical application focuses on the amenity effects from preserved open space that enhance the parcel's value, the potential for land use externalities is not limited to this, e.g., surrounding high density development may generate congestion effects that erode its value or surrounding residential development may generate positive community benefits. Because of temporal lags in the development process, this interaction may be a recursive process. The net direction of this effect may be positive or negative and may vary with distance between parcels, depending on the nature of the externalities and how they vary across space.

To further consider the role of land use externalities, we assume that there are only two land uses—residential development and open space.[5] Let λN_{it} represent an interaction effect, where N_{it} is the proportion of the relevant neighborhood of parcel i that is in a

[2] The exception is the decision to enroll one's land in agricultural preservation or conservation easement programs to protect it in perpetuity. The preservation decision is not studied in this analysis (although it is elsewhere, e.g., Nickerson and Bockstael, 2002). Parcels that enrolled in these programs were excluded from our data set.

[3] This model is similar to the optimal timing of development models that have been developed by a number of authors, most notably Arnott and Lewis (1979) and Capozza and Helsley (1989).

[4] Specifically, sufficient conditions are that (1) net discounted returns to development are expected to rise, but at a decreasing rate over time and (2) discounted returns to the undeveloped use are expected to remain constant or decrease over time. The first assumption will hold if growth pressures put upward pressure on residential land prices over time, but in such a way that these prices increase at a decreasing rate and/or that development costs increase over time. Increasing costs of development are often an observed reality in rapidly growing exurban areas as additional growth controls that increase the costs of development are instituted over time.

[5] This implies that developed and undeveloped land are the converse of each other and that negative (positive) development externalities are equivalent to positive (negative) open space externalities. This assumption is dropped in the empirical application.

developed state at any given time t and λ is an interaction parameter. A value of $\lambda<(>)0$ implies that negative (positive) externalities are generated by neighboring development or conversely, that there are positive (negative) externalities associated with open space. The net returns from development in period D are now given by $\tilde{R}_{iD}+\lambda N_{iD}$, where $\tilde{R}_{iD}$ is a function of all the factors affecting the net returns to development except the land use externalities. Development now occurs in the first period in which:

$$(\tilde{R}_{iD} + \lambda N_{iD}) - \delta(\tilde{R}_{iD+1} + \lambda N_{iD+1}) - A_{iD} > 0,$$

where N_{iD+1} is the proportion of neighboring land expected to be in the development state by the next time period. This condition can be rewritten as:

$$\tilde{R}_{iD}\left(\frac{r-\gamma_R}{1+r}\right) - A_{iD} > \lambda N_{iD}\left(\frac{\gamma_N - r}{1+r}\right), \tag{2}$$

where γ_R is the growth rate in net returns holding neighboring land use constant and γ_N is the growth rate in the proportion of developed area in the neighborhood of parcel i. A comparison of Eqs. (1) and (2) suggests that the effect of neighborhood interactions on the optimal timing of development is more complex than might be expected. Whether neighborhood interactions speed up or postpone the optimal timing of development will depend not only on the sign of the interactions parameter λ, but also on the rate of growth in neighborhood development. For example, if the interaction effect is negative and the growth rate of neighborhood development is less than the interest rate, then the right-hand side of Eq. (2) will be positive, indicating that development disamenities will delay the optimal time until parcel i is developed. However, negative interaction effects coupled with rapid growth in development will tend to speed up development. Intuitively, negative development externalities will hasten the optimal timing of development in fast growing areas as landowners race to convert their land in an effort to develop before the neighborhood becomes even more congested. In slow-growing areas, the costs of any development disamenities can be mitigated by allowing the undeveloped land to accrue in value over time, which makes postponement of development worthwhile. If developed uses convey positive externalities for adjacent development, then the reverse will be true, e.g., high rates of growth will tend to slow the optimal conversion timing of a parcel since it will appear worthwhile to postpone conversion until additional development within the neighborhood has occurred.

Such effects, if present, can generate unintended effects associated with policies aimed at managing land use change. For example, the direct effect of a policy that preserves open space would presumably be to prevent the development of certain parcels, which would create areas of preserved open space and would slow the growth rate of neighborhood development, γ_N. If the growth rate is below the interest rate ($\gamma_N<r$) and if positive open space externalities exist ($\lambda<0$), then the open space induced by the policy would act to hasten future development. Thus, the indirect effect of the policy would be to spur development in the neighborhood and the net effect of the policy on the rate of development would depend on the relative magnitudes of the direct and indirect effects. If the indirect effect outweighs the direct effect, a policy intended to preserve open space could actually induce more development. Whether such externalities exist and the extent to which they may induce such effects remain empirical questions, however, and it is to these questions that we turn in the next section.

3. Hazard model of land development

We begin by recasting the optimal timing of development model in stochastic terms for purposes of estimation. Because landowners are heterogeneous in income, age, preferences over owning land, and other unobservable attributes, all of which are assumed to be randomly distributed across the landscape, we treat the optimal timing of development as a realization of a random process. Let the unobservable attributes associated with the owner of parcel i be represented by the stochastic variable ε_i. Then the probability of conversion of parcel i in period D can be expressed as:

$$Prob\left\{\varepsilon_i < \left(\tilde{R}_{iD}\frac{r-\gamma_{\tilde{R}}}{1+r} + \lambda N_{iD}\frac{r-\gamma_N}{1+r} - A_{iD}\right)\right\} \tag{3}$$

where N_{iD} is now redefined as a *vector* of different types of surrounding land uses, including residential, commercial, undeveloped, and preserved open space lands, and λ is the corresponding parameter vector to be estimated.

A second source of uncertainty, which we suppress here, is the landowner's uncertainty over future returns to development. As demonstrated in the real options literature,[6] the standard net present value (NPV) rule expressed in Eqs. (1) and (2) should be modified when the future value of development is uncertain. The presence of uncertainty implies an additional opportunity cost associated with developing—the value of the "option to wait" to develop. Empirical applications of real options models of land development and of other one-time investment decisions with durable capital have shown that this option premium can be quite large (Capozza and Li, 1994; Clarke and Reed, 1989; McDonald and Siegel, 1986). However, as Grenadier (1996, 2002) has shown, the presence of competition (in this case, among developers competing for the same undeveloped land parcels) erodes the option value and makes the NPV rule a much more accurate representation of decision making.[7] Over 100 developers were active in the residential land market in our study region during the 1990s, which provides some apparent evidence that competitive forces are present in our study area. If this is true, then the omission of variables to measure the influence of an option value in Eq. (3) may not alter results. However, it is ultimately an empirical question and the empirical evidence on this point is mixed. It is quite difficult to measure the variance of the expected value of development accurately, and therefore the influence of an option value is often found to be insignificant in empirical work. Some recent work in land use change suggests that this value is significant in influencing parcel conversions between agricultural and forest land uses (Schatzki, 2003). Whether this may also be true of landowners making development decisions in our study region is unclear and is something that we do not test for in this paper.

[6] For a review of this literature, see Pindyck (1991).

[7] We thank an anonymous reviewer for pointing out this result to us.

The probability expression in Eq. (3) can be expressed as a hazard rate:

$$h(D) = \frac{F[\varepsilon^*(D+1)] - F[\varepsilon^*(D)]}{1 - F[\varepsilon^*(D)]} \tag{4}$$

where F is the cumulative distribution function for ε and ε^* is defined as the ε that makes Eq. (3) an equality—i.e., the value of ε such that the owner of the parcel is just indifferent between converting and not converting in D.

In estimating the expression in Eq. (4), a variety of assumptions regarding the error structure and functional form of $h(D)$ are possible. For a number of reasons, we choose to estimate the empirical model using Cox's partial likelihood method of estimation. It handles the influence of time-varying covariates on a parcel's hazard rate of conversion, it is not dependent on the assumption that the duration process actually began in the first period of the analysis, and the baseline hazard that depends in this case on time-varying regional growth pressures cancels out of the estimation. Adapting Cox's model to our problem, the log of the hazard is given by:

$$\ln h(D) = \frac{r - \gamma_{\tilde{R}}}{1+r}\tilde{R}_{iD} + \lambda\frac{r - \gamma_N}{1+r}N_{iD} - A_{iD}. \tag{5}$$

The partial likelihood function specifies the conditional probability that, given an event that occurs in a particular time period, it occurs to a specific individual. Only parcels that are developed within the study period make contributions to the likelihood function, but the entire set of parcels that are at risk for development at any given point in time is represented in the denominator of each contribution. Specifically, the contribution to the likelihood function of the ith parcel's conversion is given by

$$L_i = \frac{\exp(\beta' X_{iD})}{\sum_{j=1}^{J_i} \exp(\beta'_{jD})} \tag{6}$$

where $\beta' X$ is a linearization of the expression on the right-hand side of Eq. (5). The X vector contains all the measurable factors that affect $\tilde{R}$, N, and A. The set of parcels denoted by J_i is that set that is "at risk" at the time that parcel i is converted.

In this application, we treat the expressions $(r-\gamma_{\tilde{R}})/(1+r)$ and $(r-\gamma_N)/(1+r)$ as if they were constants over space. Assuming that the expected growth rate in residential land values (γ_R) is approximately constant across a relatively small and homogeneous region such as ours is not unreasonable, but expectations of localized development activity are nonetheless likely to vary. While we ultimately would like to allow for such variations over space in our empirical model by introducing a varying parameters specification, we have no suitable proxies for these varying expectations. As a result, we limit the current analysis to estimating an average development growth rate (γ_N) that is constant across the county.

3.1. Data

The model is estimated using land use change and other data from Calvert County, Maryland, an "exurban" county located approximately 30 miles southeast of the

Washington, DC, metropolitan area. Although traditionally a rural county, Calvert County has experienced rapid growth pressure within the last several decades. Between 1981 and 1997, the county experienced a 94% increase in population and a 191% increase in the number of acres in low-density residential use.

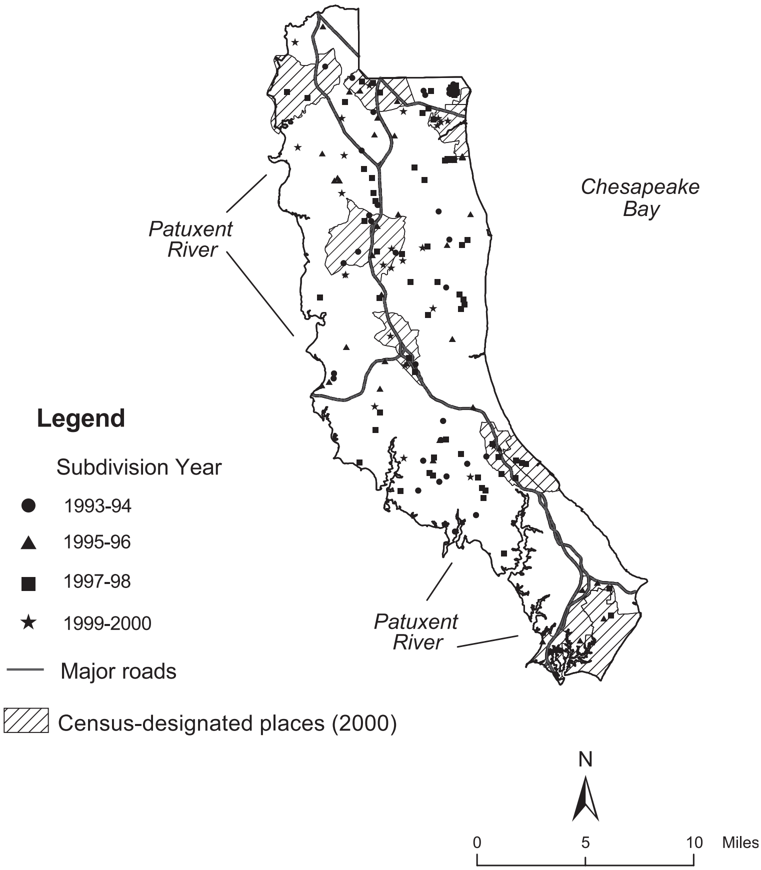
The data used in this analysis come largely from the Maryland Division of Assessment and Taxation (A&T Division). The Assessment and Taxation database includes data on every land parcel in the county and includes a legal description and categorization of the parcel, its zoning, size, current use, and the date on which it was recorded as a parcel. Unfortunately, the A&T Division overwrites this database continually. In addition, the database includes only limited information that directly relates a parcel in one year to its antecedents in previous years if the parcel was developed from a larger parcel or set of parcels. We acquired snapshots of this database in 1993, 1995, 1997, and 2001 and with considerable effort have traced the origins of parcels that appear in 2001 back to 1993.

From this historical reconstruction of the data, we identify all undivided parcels that could have been developed into at least three residential lots as of 1993, given that a minor subdivision consists of three lots. We also identify those parcels that actually experienced subdivision into at least three residential lots sometime during that time period.[8] The database is especially valuable, because the Maryland Office of Planning has digitized the centroid (but unfortunately not the boundary) of every parcel in the state starting in 1996.

Although we have calculated all of the undivided parcel characteristics from 1993 to 2000, our starting year in this analysis is 1994. This is because of the temporally lagged neighborhood variables that are included in the model. In 1994, there were 1,947 original parcels in our study area that we deemed as developable, given their size and applicable zoning. Some of these were entirely vacant land while others had at least one structure in 1994 but were large enough to accommodate further subdivision into at least three additional lots. The parcels averaged 32 acres in size, but given the variation in zoning across the county, developable parcels ranged in size from a little more than a third of an acre to almost 600 acres. Approximately 53% were forested at the beginning of the period, another 21% were in agricultural use, and the remaining 16% were already partially developed, albeit at lower than binding densities. Of the 1,947 developable parcels, 152 were subdivided into residential parcels during the time period, 1994–2000. Map 1 illustrates the location of these parcels.

We use GIS to identify a number of parcel attributes that could be expected to affect the value of the parcel in residential use, the costs of conversion, and the foregone returns from abandoning the current use. Parcels were expected to generate more valuable residential lots the shorter the commuting distances to employment centers, including both Washington, DC, and the nearest smaller employment center within the county. These distances are measured via the roads network and enter the model in log form to account for the declining influence of these centers with increasing distance. Parcels located in school districts with higher school quality indices were also expected

[8] Occasionally, large parcels are developed in waves or sections that span several years. For the purposes of this analysis, we consider development of an original parcel to have taken place when the first set of subdivided residential lots is recorded.



Map 1. Residential subdivision development, 1993–2000, Calvert County, Maryland.

to generate more valuable residential lots. The percent of students in the senior class meeting state university admission requirements was lagged by one year and included as a time-varying covariate to approximate school quality. Property tax rates are also included in the model to test whether the increased costs of ownership from higher property taxes make residential lots less desirable, ceteris paribus. Given that the eastern and southern borders of Calvert County are the Chesapeake Bay shoreline and the western border is the Patuxent River, we include a measure of access to the shorefront. This measure is greatest for parcels located directly on the waterfront and declines with distance from the shoreline, assuming the value of zero for any parcel that is beyond two miles inland.

A set of variables captures the approximate proportion of the parcel consisting of different types of terrain. These include the amount of the parcel that is made up of prime soils for agriculture. These soils are also good for excavation, so it is an empirical issue whether they will delay or hasten development. This variable is measured as the proportion of the parcel that contains prime soils and varies between zero and one. Parcels with large portions of poorly drained soils will be cost more to develop, especially if they do not have access to public water and sewer service. A dummy variable that indicates the combination of poorly drained soils and no public access to water or sewer is included to capture this. In addition, we include the proportion of the parcel that is forested to approximate clearing costs.

Policy-related variables either increase the restrictions to development or create incentives or disincentives for development in certain locations. One policy variable affects costs of development directly—whether or not the parcel is served by publicly supplied utilities. This is included as a time-varying dummy variable that indicates whether the parcel had access to public sewer and water in each time period. Additionally, a set of variables indicates the extent to which a parcel is influenced by certain smart growth policies. Smart Growth legislation has designated certain areas of each county in Maryland as Priority Funding Areas (PFAs)—sections of the county in which the state will share in infrastructure costs. Areas outside these PFAs receive no such priority treatment. This variable is measured as the approximate proportion of the parcel that falls within the boundaries of a PFA. Likewise, Rural Legacy Areas are represented by the approximate proportion of the variable that falls within these designated areas. These are locations designated for special priority when preservation moneys become available and are areas in which the State wishes to discourage development. Under earlier Critical Areas legislation, the area from the high tide line inland 1000 ft has been designated as environmentally sensitive and comes under more restrictive building constraints. Like the other two smart growth variables, this variable is also defined as the approximate proportion of the parcel that falls within these areas. A fourth policy-related variable indicates the approximate proportion of the parcel that falls within the boundaries of one or another agricultural preservation programs. Enrollment does not entirely preclude residential lots from being split off the parcel, but does limit the number of these lots that can be developed. Finally, Maryland counties are able to use adequate public facilities moratoria to postpone new development if school or road capacity is exceeded. The moratoria are at best temporary, lasting 3–5 years. We include time-varying dummy variables that equal one if a parcel is in an area under a moratorium in a given year and zero otherwise. Given the lag in the development process, the grandfathering of previously recorded developments, and the temporary nature of the moratoria, we consider it an empirical issue whether these moratoria actually depress development activity.[9]

A few variables affect both the value of the lots in residential use and the costs of development. Zoning ordinances specify minimum lot sizes, the amount of open space (if any) that must be preserved on a parcel that is developed, and the overall allowable density of development. These characteristics vary dramatically over the county, depending on zoning designation. Minimum lot size for our developable parcels can be as small as a quarter of an acre and as large as 5 acres. Overall densities range

[9] For an in-depth analysis of the effects of this policy on land development using regression discontinuity, see Geoghegan and Bockstael (2003).

from 0.2 to 6 dwelling units per acre. Some zoning categories require open space set asides of 50%, others 80%, while still others are subject to no open space requirements at all. All other things being equal, larger lots will be more valuable, but larger minimum lot sizes will reduce the number of lots that can be subdivided. Given any overall density, clustering requirements will raise the open space requirement and reduce lot sizes. This may have a positive or negative effect on lot prices, but will most likely reduce costs as fewer roads, storm drainage, and other infrastructure will need to be built. Finally, given any minimum lot size and number of lots, a larger open space requirement will likely raise the value of the lots but also raise costs since more land must be dedicated to the subdivision. We include a parcel's minimum lot size, the total number of subdividable lots that are contained on the parcel, and the amount of open space that must be preserved on the parcel to test the net effects of these constraints. To allow for the possibility that costs and returns may vary nonlinearly with the clustering requirement, we specify the amount of open space required to be withheld as a quadratic term.

Lastly, several neighborhood land use variables are included to capture the potential neighborhood interaction effects.[10] The categories of land use that we investigate are: low, medium, and high density single-family residential land use[11]; a combined measure of commercial, multi-family residential, and industrial land use; and three measures of open space: undeveloped land that is currently in agriculture or some other undeveloped use but could be developed in the future; publicly owned open space; and open space that is provided on neighboring developed parcels as required by the clustering requirement. Neighborhood land use measures were calculated for each of the 7 years (1993–1999), which yielded lagged, time-varying measures of neighboring land use for each of the four different distance measures for each of the seven land use categories (a total of 196 neighborhood land use variables). Because the landscape is fully described by these seven aggregate categories of land use and total land area is fixed, we normalize on low-density residential land use to avoid problems of perfect colinearity. Hence, land use variable X_1 would be interpreted as the marginal effect of a 1% change in the amount of neighboring land from a low density residential use to land use X_1. To minimize the identification problems discussed in the next section, these measures are lagged by one time period, so that the hazard rate in period t is a function of the neighborhood land use pattern in period $t-1$.

[10] In measuring these variables, it is necessary first to approximate the size of the parcel for which the neighborhood measures were generated in order to overcome the data limitation of having only parcel centroids rather than boundaries. To approximate the extent of each parcel, a circle whose area equaled the total acreage of the parcel was drawn around the centroid. Buffers of different widths were then drawn around the approximate parcel to represent alternative neighborhood distance rings. Neighboring parcels whose centroids were located in each of these rings were ascribed to the respective ring. Distance rings of 0–200, 200–400, 400–800, and 800–1600 m were calculated using GIS and the amount of land in each type of use associated with centroids in each distance ring was calculated as a proportion of the total neighborhood land ascribed to that ring.

[11] Residential densities are defined as follows: low density is defined as 2 dwelling units per acre or less; medium density is 2–8 dwelling units per acre; and high density is anything greater than 8 dwelling units per acre.

3.2. Identifying neighborhood interactions and the indirect policy effect

Several identification issues arise in seeking to test hypotheses regarding the influence of neighborhood interactions and indirect policy effects on the probability of land use conversion. First, there are potential problems associated with unobserved correlation.[12] In addition to unobservable attributes of landowners that will generate differences in decisions regarding the optimal timing of conversion, there are likely to be heterogeneous attributes of the parcels (e.g., physical or locational features) that are unobservable as well. If these attributes influence expected returns to development and/or returns to undeveloped uses, then they also will be captured by the error term ε_i. If these unobservable parcel features were randomly distributed across the landscape, as we assume the unobserved landowner attributes to be, then they would not cause estimation problems. However, because of the nature of these spatial data, unobservable parcel attributes are likely to be positively spatially correlated, in which case omission of such variables causes the errors to be spatially correlated.[13] As discussed in Irwin and Bockstael (2002), such spatial effects, if unobserved, will make neighboring decisions appear interrelated even if they are not. This is because the spatial error autocorrelation will be correlated with the neighborhood interaction variables and therefore will bias the neighborhood interaction estimates, thus creating the possibility that neighborhood interactions will be "observed" even when none exist.

Because the unobserved spatial heterogeneity is contemporaneous with development, using temporally lagged values of neighboring land uses provides a means for addressing this problem (Manski, 1993). However, to the extent that the unobserved spatial heterogeneity is also time-invariant, the identification problem will persist (Irwin and Bockstael, 2002). Given our relatively short time period (1994–2000), it is likely that at least a portion of the unobserved spatial heterogeneity will be constant over this period, suggesting that the coefficients associated with the lagged neighboring land measures will still be biased. Unfortunately controlling for this source of autocorrelation is difficult since the time dimension does not aid with identification in this case. Due to the positive correlation of most spatial data, the unobserved heterogeneity is most likely to bias estimates in the positive direction. Therefore, our estimates of neighborhood land use measures reported here can be interpreted as bounding the "true" estimate from above.

Secondly, success in separating direct and indirect policy effects relies on being able to identify the direct influence of a policy on a parcel's conversion probability separately from the indirect effect arising from the influence of the policy on neighboring land use

[12] This problem arises in the study of other problems as well, e.g., in identifying social interactions (Brock and Durlauf, 2001; Manski, 1993, 1995). For a more complete discussion of the problem in the land use context, see Irwin and Bockstael (2002).

[13] Spatial autocorrelation in continuous regression models leads to inefficient but unbiased estimates. In a discrete choice context, spatial autocorrelation generates inconsistent estimates. The problem has not been investigated in hazard models, but since the Cox proportional hazard model's likelihood function is a modified form of a logit likelihood function, spatial autocorrelation is likely to be a concern here as well. Corrections for spatial autocorrelation in the probit context have recently been developed, but no progress to date has been made in the hazard model framework.

decisions. Separating changes in neighboring land use pattern that are due specifically to the influence of a policy from those that are due to the myriad of other factors that influence land use decisions is difficult. However, policies for which a one-to-one correspondence exists between the policy and land use conversion, such as policies that result in the preservation of open space, provide a clear mechanism for identifying any indirect effect that may be associated with a policy. This is because no other influence other than the policy will result in this particular type of land use conversion.

For this reason, our policy of choice is a development clustering requirement. This policy requires developers in certain parts of our study area to provide open space by clustering development on a portion of the converted parcel. In Calvert County, the clustering requirement does not change the overall maximum allowable development density of a parcel, but it does change its configuration. For example, a clustering requirement of 80% open space in an area zoned for overall density of no more than one dwelling unit per 5 acres changes the allowed configuration from ten 5-acre house lots with no preserved open space to ten 1-acre house lots with 40 acres of open space. The individual lots are smaller, but they also have more preserved and accessible open space within the development and less infrastructure is needed to service individual lots. Thus, the net direct effect may be to either raise or lower net returns. To measure the direct policy effect we include the amount of open space required of each developable parcel, which depends on the cluster zoning and the size of the parcel and allow this term to vary nonlinearly.

In addition to this direct effect, an indirect effect may arise if land use externalities associated either with the resulting open space or higher density development influence the development returns of neighboring parcels. Open space provides scenic views and less congestion, but unpreserved open space does so only in the short term. Preserved open space, as provided by the clustering requirement, does so presumably in perpetuity. Because we expect preserved open space to provide open space amenities and protection against further neighborhood development, we expect a priori that more neighboring preserved open space will increase the returns to developing a parcel.

A final empirical challenge is the choice of the relevant extent of the neighborhood. We seek to identify the geographic extent of the neighborhood within which land use changes influence the optimal timing of conversion. While it is reasonable to expect that this effect will exhibit some sort of distance decay, we do not have a priori information regarding the relevant geographical extent of the neighborhood. Our task is further complicated by the fact that our concentric rings are only approximations of the truth due to our uncertainty regarding actual parcel boundaries. We incorporate multiple neighborhood distance rings that range in radius from 200 to 1600 m in the model, but emphasize that the results should be interpreted in approximate terms rather than as precise measurements.

3.3. Empirical results

The model specified in Eqs. (5) and (6) is estimated on a yearly time step from 1994 to 2000. The model is estimated with observations on all undeveloped parcels that could have been developed in a given year. Observations on parcels that were actually developed between 1994 and 2000 are censored and therefore the total number of observations used to estimate the model declines with each year as these observations are dropped from the set of "at risk" parcels. To incorporate time-varying covariates into the estimation procedure, the data are "blown up" so that for every time-varying covariate, there are seven values (one for each year) associated with the same observation. In our case, we have 29 time-varying variables, each of which has seven values that correspond to each year of the analysis, and 13 variables that are constant over the 7-year time period, yielding a total of 216 explanatory variables in the model.

Before turning to the results, we point out that the coefficients associated with the variables that affect net residential value include the term $(r-\gamma_R)/(1+r)$. Likewise, the coefficients associated with neighborhood effects include both the relevant λ_k and the term $(r-\gamma_{Nk})/(1+r)$, where k indexes the land use category. The sign of these estimated coefficients will be dependent on the relative magnitudes of the interest rate, r, the expected growth rate in net returns, γ_R, and the expected growth rate in each type of neighboring land use, γ_{Nk}. During this period, residential land values have not been growing as fast as the interest rate, so we can assume that $r-\gamma_R>0$ so that the sign of the estimated coefficients on variables affecting R will be as expected.[14] A problem arises in evaluating the signs of the expressions $(r-\gamma_{Nk})/(1+r)$. Global averages taken across the entire study region indicate that the annual rate of change in any land use category between 1994 and 2000 was smaller than the interest rate, e.g., single-family, residential development increased at an average annual rate of 1.6%, multi-family residential development increased at an average rate of 5.5%, commercial/industrial development increased at an average rate of 1.7%, and the amount of non-urban land decreased by an average annual rate of 6.2%. However, we find that in a few localized areas of the county, growth rates were above the interest rate for one or several years. Because our current analysis does not account for these potential variations in expectations over space, we limit our interpretation of this parameter to the average estimated effect associated with neighborhood land uses. On average, $r>\gamma_{Nk}$ and therefore the sign of the estimated neighborhood land use coefficients will be as expected.

Table 1 presents the empirical results from the estimation of the hazard model of land development for the Calvert County, Maryland, study area. The location of a parcel in terms of accessibility and other features is found to have varying effects on the parcel's timing of conversion. Increasing commuting distances to Washington, DC, and to the nearest town are both found to have negative and significant effects on development timing. Proximity to the shoreline is also found to have a significant effect: The closer to the shoreline a parcel is, the larger the returns to development and the shorter the time until development. On the other hand, the effect of variation in property taxes is not found to be significant. This is not surprising, since property tax rates are homogeneous across the county except in a few of the incorporated towns. In addition, it is possible that towns that charge higher tax rates also provide better services, making it very difficult to distinguish the tax penalty from the benefit of better services.

[14] The average nominal price of residential housing increased 3.4% annually between 1995 and 1999 in Calvert County, while the interest rate averaged 8% during this same time period.

Table 1
Estimation results from hazard model of residential land development

Variable	Parameter estimate	Standard error	Chi-square	Pr>ChiSq	Hazard ratio
Log(Distance to DC)	−0.99306	0.59548	2.7811	0.0954	0.37
Log(Distance to Town)	−0.27539	0.07966	11.951	0.0005	0.759
(T) School Quality Index	−0.33817	0.17504	3.7327	0.0534	0.713
(T) Property Tax	−1.78325	1.24788	2.0421	0.153	0.168
Shoreline Access	4.99629	2.27973	4.8032	0.0284	147.864
Prime Ag. Land	0.80233	0.26491	9.173	0.0025	2.231
(T) Poorly Draining Soils*Septic	−1.04762	0.53755	3.7982	0.0513	0.351
%Forest	0.40837	0.27935	2.1371	0.1438	1.504
(T) Public Sewer	1.42342	0.44973	10.0177	0.0016	4.151
Priority Funding Area	1.49515	0.43777	11.6651	0.0006	4.46
Rural Legacy Program	0.25783	0.80978	0.1014	0.7502	1.294
Critical Area	−2.48933	0.65542	14.4253	0.0001	0.083
Ag. Preservation	−0.83545	0.3956	4.46	0.0347	0.434
(T) Adequate Pub. Facilities	0.14552	0.34424	0.1787	0.6725	1.157
Minimum Lot Size	0.58595	0.07416	62.4301	<.0001	1.797
Number of Lots	0.00217	0.0007677	8.0198	0.0046	1.002
Req. Open Space	0.20501	0.05116	16.0584	<.0001	1.228
(Req. Open Space)^2	−0.00465	0.00167	7.7078	0.0055	0.995
(T) %Med Den Res (200 m)	1.52285	0.54	7.9529	0.0048	4.585
(T) %Med Den Res (2–400 m)	4.2321	1.53088	7.6424	0.0057	68.861
(T) %Med Den Res (4–800 m)	−1.53032	3.6367	0.1771	0.6739	0.216
(T) %Med Den Res (8–1600 m)	−1.88472	5.29511	0.1267	0.7219	0.152
(T) %High Den Res (200 m)	1.49057	1.02817	2.1017	0.1471	4.44
(T) %High Den Res (2–400 m)	3.51879	3.6796	0.9145	0.3389	33.743
(T) %High Den Res (4–800m)	−7.41027	13.04442	0.3227	0.57	0.001
(T) %High Den Res (8–1600 m)	−17.50667	18.57698	0.8881	0.346	0
(T) %Comm/Ind/MF (200 m)	−2.8942	1.05383	7.5425	0.006	0.055
(T) %Comm/Ind/MF (2–400 m)	−2.20747	0.95456	5.3478	0.0207	0.11
(T) %Comm/Ind/MF (4–800 m)	0.23987	0.94224	0.0648	0.7991	1.271
(T) %Comm/Ind/MF (8–1600 m)	−0.2379	1.17742	0.0408	0.8399	0.788
(T) %Undev (200m)	0.45984	0.23127	3.9536	0.0468	1.584
(T) %Undev (2–400 m)	−0.47114	0.37572	1.5724	0.2099	0.624
(T) %Undev (4–800 m)	0.07025	0.62619	0.0126	0.9107	1.073
(T) %Undev (8–1600 m)	−0.98961	0.67952	2.1209	0.1453	0.372
(T) %Clustered Open (200 m)	0.99078	0.51359	3.7216	0.0537	2.693
(T) %Clustered Open (2–400 m)	1.52421	0.81146	3.5282	0.0603	4.592
(T) %Clustered Open (4–800 m)	2.38892	1.44637	2.728	0.0986	10.902
(T) %Clustered Open (8–1600 m)	−1.19428	2.30333	0.2688	0.6041	0.303
(T) %Public Open (200 m)	0.82026	1.87105	0.1922	0.6611	2.271
(T) %Public Open (2–400 m)	−0.20877	1.58003	0.0175	0.8949	0.812
(T) %Public Open (4–800 m)	−0.88391	1.47287	0.3602	0.5484	0.413
(T) %Public Open 8–1600 m)	−0.91525	1.15768	0.625	0.4292	0.4

(T) Time-varying variable; time period: 1994–2000; no. of parcels at risk at beginning of period: 1,947; no. of events: 152.

Some of the factors influencing the costs of converting a parcel are found to be significant. The measure of prime agricultural land is found to have a positive and significant effect on the hazard rate. While this effect is not of the expected sign, it likely reflects the fact that prime agricultural land is also prime residential land in many cases. The presence of public sewer is found to hasten the timing of a parcel's conversion as expected, since this lowers the costs of development. In addition, parcels that are dependent on septic fields (i.e., with no public sewers) and that are situated on poorly drained soils are estimated to experience delayed development. There appears to be no difference, ceteris paribus, in the timing of development of agricultural vs. forested lands.

The influence of the State of Maryland's smart growth policies is evident based on the Priority Funding Area (PFA) results. Areas that are designated as PFAs are found to have a much higher hazard rate of conversion. Specifically, a 1% increase in the proportion of a parcel that is within a PFA is found to increase the parcel's hazard rate of conversion by 4.5%. In addition, the location of a parcel at least partially within the Critical Areas and the enrollment of a parcel in the agricultural preservation program are both found to significantly reduce the parcel's hazard rate of conversion, although the overall magnitude of these effects appears to be much less than the effect of the Priority Funding Area designation. On the other hand, neither the Rural Legacy designation nor the adequate public facilities ordinance is found to affect the hazard rate. The former is not unexpected. The Rural Legacy Program is more of a wish-list than a policy, as it designates areas that the State would like to see preserved. Given limited budgets since the inception of this program, the State has had little opportunity to purchase land or easements in these areas. We included the variable to determine whether the very act of designation had any effect on development timing, but found no significant effect.

The restriction on the minimum lot size, implied by zoning regulations, has a positive and significant effect on the timing of development. This is consistent with the theory of optimal timing and residential density; assuming that returns to development increase over time, a decrease in the maximum allowable density (i.e., an increase in the minimum lot size) will *hasten* the optimal timing of development since developing at a higher density in the future is not possible (Fleming, 2003). Not surprisingly, the number of allowable lots on a parcel significantly influences the hazard rate of conversion in a positive direction.

The direct effect of the development clustering policy is found to have a significant effect on the parcel's hazard rate of conversion. The hazard increases at a decreasing rate in the amount of open space required up to about 20 acres (about 62% of the average-sized parcel in our data set) and then declines with larger amounts of required open space. This suggests that there may be initial cost savings from developing at higher densities, but that as the amount of required open space increases further, these cost savings are outweighed by the loss in revenues generated by having to develop smaller lots.

The final set of results relates to neighboring externality effects. Where there are apparent interaction effects, they appear to die out by 800 m, so we can be fairly confident that we have included a sufficiently large neighborhood. The results suggest that parcels with more nearby undeveloped and medium-density land (relative to low-density residential land) will be developed sooner, suggesting that there are positive effects associated with both undeveloped (but developable) land and higher density residential development (e.g., due to the services and infrastructure that are implied). Also, parcels with less commercial and industrial land relative to low-density residential land will have a higher hazard rate of development, indicating that these land uses convey negative externalities. No significant effect is found for either high-density residential development or public open space. The first is explained by the fact that there is little variation in this measure in the data set, as there is little high-density residential development in Calvert County. The second is likely due to the nature of the errors made in calculating surrounding land use. Because public open space is likely to take the form of very large parcels, we do not tend to pick up these centroids in our neighborhood calculations.

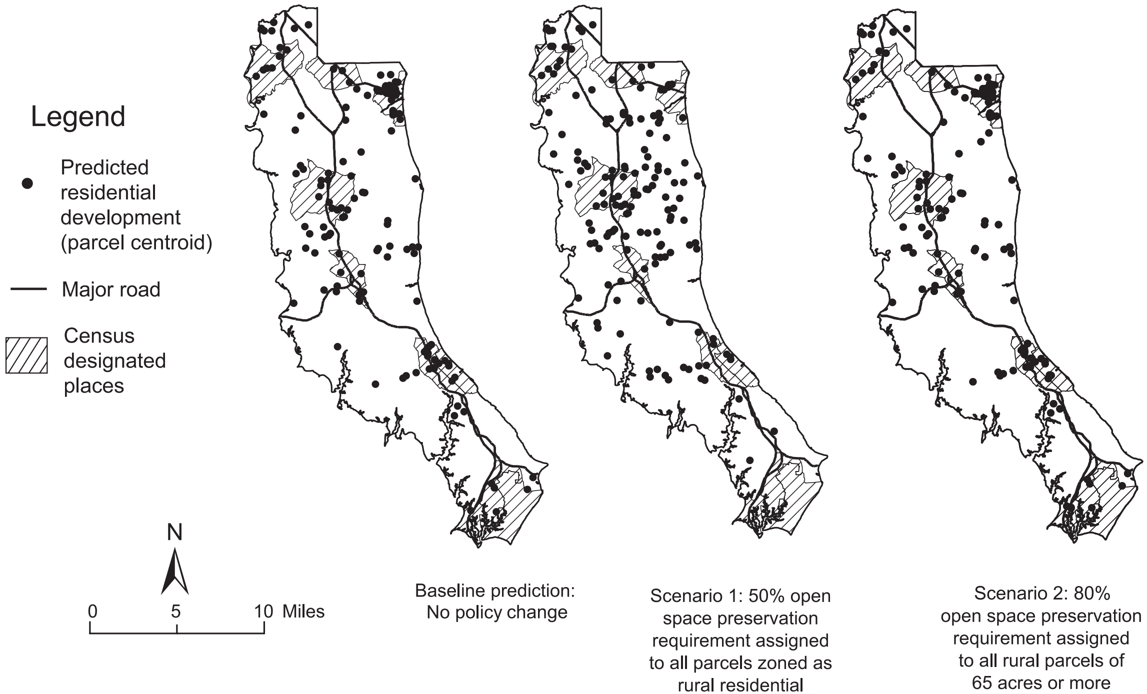
The remaining land use externality is the neighboring preserved open space that is created as a byproduct of the cluster development policy. We find that this neighboring land use has a positive and significant effect on the hazard of development, suggesting that the clustering policy will hasten neighboring development and will do so up to within a half-mile radius of the clustered development area. The results translate into the following estimated effects: the hazard rate increases by 0.29% for every additional neighboring acre within a 200-m neighborhood that is converted to preserved open space and by 0.29% and 0.22% for every additional acre of preserved open space within 200–400 and 400–800 m, respectively. Thus, we find that the clustering policy has an indirect effect on the hazard rates of neighboring parcels and that this effect is spatially persistent over a localized neighborhood.

4. Predicting the effects of preserved open space on sprawl

Cluster development policies are often promoted as an effective growth management tool for rural areas that can be used to preserve open space, protect critical natural resource areas, and promote a more efficient use of land. This view assumes that the clustering policy itself would not alter the rate or amount of growth in the regulated and immediately surrounding areas and therefore ignores the policy's direct and indirect effects on the likelihood of development.

Our results are interesting in this respect. We find that, for the particular clustering policy considered here, the direct effect of the policy increases the hazard rate if small to moderate amounts of open space are required to be preserved and slows the timing of development if larger amounts of open space are required to be preserved. In addition, we find that the indirect effect hastens the timing of development for neighboring parcels due to positive amenities from the preserved open space.

The effects of these policies on sprawl per se are difficult to predict, given that sprawl is an inherently spatial phenomenon and our empirical model is estimated at the individual unit of analysis. To explore the spatial implications of the clustering policy, we use GIS to perform the following hypothetical exercise. We assume that local policymakers, in an effort to preserve more open space land in rural areas, implement a more extensive clustering requirement that targets rural areas. We consider two versions of this hypothetical policy: (1) a policy in which 50% of the land area of all parcels zoned as rural residential is required to be preserved as open space and (2) a policy that requires 80% of the land area of only larger rural parcels (65 acres or more) to be preserved as open space. The first version is a naive policy that ignores the potential for both direct and indirect effects to speed up growth on parcels for which only a moderate amount of open space



Map 2. Predicted pattern of residential development under hypothetical clustering policies, Calvert County, Maryland. Each scenario assumes that a total of 150 parcels are converted.

must be preserved; the second is a more informed policy that attempts to take advantage of the deterrent to development that is created by imposing a relatively stringent open space requirement on larger parcels only.

To simulate these hypothetical situations, we recalculate the direct and indirect variables under the two different scenarios and use the estimated coefficients from our empirical model to predict the relative hazard rates[15] of the remaining 1799 parcels that are yet undeveloped as of 2000. We then make an assumption that the parcel with the highest hazard rate is the parcel that is actually converted. This simulation is performed for 150 "rounds" of development.[16]

The results of the policy simulations are illustrated in Map 2. They predict the evolving spatial pattern of land use change, but by the nature of their construction, they give no information about the speed of change. The naive policy (scenario 1, requiring 50% open space) actually *spurs* additional development in non-urban areas of the county relative to a baseline status quo prediction. Specifically, whereas 36.7% of the development is predicted to occur within urban areas (i.e., Census designated places) under the baseline prediction, only 17.3% of the development is predicted to occur in these areas under this policy. This result is due both to the direct effect, which are the cost savings that are possible with moderate amounts of clustering, as well as the indirect effect, which makes neighboring properties more valuable due to the preserved open space provided via the policy. On the other hand, the resulting prediction for the second policy, in which an 80% open space requirement for large parcels is assumed, is much more similar to the baseline prediction with 38% of the growth predicted to occur within the urban areas. Relative to scenario 1, this version of the clustering policy does not result in greater growth in rural areas, despite the offsetting effect associated with the indirect open space effect.

5. Conclusions: unintended consequences and sprawl

The results from the estimation model provide empirical evidence of interdependencies among neighboring landowners that influence the timing and pattern of land development. We find evidence that parcels with greater amounts of both preserved and unprotected open space nearby are more likely to have larger hazard rates of development (relative to those with more low-density development nearby), while more neighboring commercial and industrial development has a depressing effect on the hazard rate. This suggests that

[15] The baseline hazard function, which is a function of time only, drops out of the Cox model because the individual hazards are assumed to be proportional to each other. The advantage of this approach is that no assumption regarding the distribution of the duration process is required to estimate the model. The disadvantage is that, in the case of models with time-varying covariates such as ours, the baseline hazard cannot be recovered. Although we cannot generate exact predictions of the hazard rate for individual parcels, we can identify their relative hazard rates since the parameter estimates are unchanged by any monotonic transformation of the duration times. We use a logistic model to calculate these relative rates.

[16] Because the theoretical and empirical models are partial equilibrium models, we ignore general equilibrium effects in this simulation exercise. In particular, we ignore the potential for the hypothetical policies to alter the land rent functions and thus our results should be viewed within the context of this limitation.

interaction effects tend to push new development away from areas with existing high-density urban development and pull new development towards areas with yet undeveloped land. If such effects are sufficiently strong, they will foster an increasing leapfrog or sprawled pattern of development.

The finding that neighboring preserved open space hastens a parcel's timing of development is of particular interest because of its implication for open space policies. The positive amenity value associated with preserved open space created by the clustering policy suggests that open space preservation policies can alter the evolution of development patterns not only because they create an area in which development cannot occur, but also because they may create areas that attract neighboring development. In the policy case considered here, the provision of open space is a byproduct of the development process; as parcels in areas subject to clustering requirements are developed, a certain amount of preserved open space is created. If neighboring parcels are then induced to develop due to these positive externalities, then the pattern of development that emerges across space and time is one that is clustered at the micro-scale (within a parcel), but potentially fragmented at a neighborhood or more regional scale. In the hypothetical policies considered here, we explored two versions of the clustering policy and found that the net effect of the policy on land use patterns varied according to the policy specifics. In the first scenario, a moderate policy resulted in the conversion of more parcels in rural areas; in this case, the direct effect was positively augmented by the indirect effect, both of which served to hasten development of parcels in non-urban areas. In the second scenario, the direct effect was negative and sufficiently strong to deter the development of many of the larger rural parcels subject to the clustering requirement and to encourage development of more parcels in urban areas. Because many fewer rural parcels were developed, the offsetting indirect effect associated with the preserved open space was small. The end result was that less open space was preserved via the clustering policy, since fewer rural parcels subject to this policy were converted, but more developable open space was retained since this policy deflected development to urban areas.

While these results are hampered by potential problems of econometric identification, they provide some evidence of the nature of land use interdependencies that exist among neighboring agents and the manner in which these effects interact with policies and aggregate up over time and space to influence regional patterns of development. They also provide a cautionary tale for policymakers concerned with promoting a smart growth agenda: Policies that seek to promote smart growth by preserving open space may actually lead to more sprawled patterns of development.

Acknowledgements

This research was funded in part by U.S. EPA-STAR Program, Grant No. R-82801201, and NASA, Project No. NAG511149. We are grateful to Richard Arnott, two anonymous referees, Annette Kim and other participants of the 2002 Lincoln Institute of Land Policy workshop on the Analysis of Urban Land Markets and the Impact of Land Market Regulation for helpful comments. All remaining errors are our own.

References

Arnott, R., Lewis, F., 1979. The transition of land to urban use. Journal of Political Economy 87 (11), 161–169.

Bockstael, N.E., 1996. Modeling economics and ecology: the importance of a spatial perspective. American Journal of Agricultural Economics 78, 1168–1180.

Brock, W., Durlauf, S., 2001. Interactions-based models. In: Heckman, J.J., Leamer, E.E. (Eds.), Handbook of Econometrics, vol. 5. Elsivier, Amsterdam.

Capozza, D., Helsley, R., 1989. The fundamentals of land prices and urban growth. Journal of Urban Economics 26 (3), 295–306.

Capozza, D., Li, Y., 1994. The intensity and timing of investment: the case of land. American Economic Review 84 (4), 889–904.

Clarke, H.R., Reed, W.J., 1989. The tree-cutting problem in a stochastic environment: the case of age-dependent growth. Journal of Economic Dynamics and Control 13, 569–595.

Fleming, M., 2003. The economics of growth controls with spatially differentiated land. PhD Dissertation, University of Maryland, College Park.

Fulton, W., Pendall, R., Nguyen, M., Harrison, A., 2001. Who sprawls most? How growth patterns differ across the U.S., Center on Urban and Metropolitan Policy, The Brookings Institute.

Galster, G., Hanson, R., Ratcliffe, M.R., Wolman, H., Coleman, S., Freihage, J., 2001. Wrestling sprawl to the ground: defining and measuring an elusive concept. Housing Policy Debate 12 (4), 681–717.

Geoghegan, J., Bockstael, N.E., 2003. Testing for the effect of growth control measures using quasi-experimental design. Paper Presented at the 2003 Association of Environmental and Resource Economists Workshop, Madison, WI, June 15–17, 2003.

Grenadier, S., 1996. The strategic exercise of options: development cascades and overbuilding in real estate markets. Journal of Finance 51 (5), 1653–1679.

Grenadier, S., 2002. Option exercise games: an application to the equilibrium investment strategies of firms. Review of Financial Studies 15 (3), 691–721.

Henderson, J.V., Becker, R., 2000. Political economy of city sizes and formation. Journal of Urban Economics 48, 453–484.

Henderson, J.V., Mitra, A., 1996. The new urban landscape: developers and edge cities. Regional Science and Urban Economics 26, 613–643.

Henderson, J.V., Thisse, J., 2001. On strategic community development. Journal of Political Economy 109 (3), 546–569.

Irwin, E.G., Bockstael, N.E., 2002. Interacting agents, spatial externalities, and the endogenous evolution of residential land use pattern. Journal of Economic Geography 2 (1), 31–54.

Irwin, E.G., Bell, K., Geoghegan, J., 2003. Modeling and managing urban growth at the rural–urban fringe: a parcel-level model of residential land use change. Agricultural and Resource Economics Review 32 (1), 83–102.

Landis, J., Zhang, M., 1998. The second generation of the california urban futures model: part 2. Specification and calibration results of the land-use change submodel. Environment and Planning A 25, 795–824.

Manski, C., 1993. Identification of endogenous social effects: the reflection problem. Review of Economic Studies 60, 531–542.

Manski, C., 1995. Identification Problems in the Social Sciences. Harvard Univ. Press, Cambridge, MA.

McDonald, R., Siegel, D., 1986. The value of waiting to invest. Quarterly Journal Of Economics 101 (4), 707–727.

McMillen, D.P., 1989. An empirical model of urban fringe land use. Land Economics 65, 138–145.

Nickerson, C., Bockstael, N., 2002. Preservation or development: competing uses over the future of farmland in urbanizing areas. Paper Presented at the American Agricultural Economics Association Meetings, Atlanta, August, 2002.

Pindyck, R., 1991. Irreversibility, uncertainty, and investment. Journal of Economic Literature 29 (3), 1110–1148.

Schatzki, T., 2003. Options, uncertainty and sunk costs: an empirical analysis of land use change. Journal of Environmental Economics and Management 46, 86–105.