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Land conversion and market equilibrium: Insights from a simulated landscape

Rich Iovanna, Colin Vance

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Land Conversion and Market Equilibrium: Insights from a Simulated Landscape

Rich Iovanna, U.S. Department of Agriculture and **Colin Vance**, RWI and Jacobs University Bremen

Abstract

We specify a system of equations that fully reflects the supply and demand sides of the market for agricultural open space at equilibrium. Although simple, the system is exceedingly flexible and allows for household and parcel heterogeneity. We derive an empirical model directly from the structural equations and contrast this using a simulated landscape with the econometric specification most often found in the literature. We then show how the model can be used to project land-use change into the future and for policy simulation. Finally, we use the model to examine the impact of common land conservation policies in Europe.

JEL Classification R15, Q24

Keywords Land-use change, Urban sprawl, Simulation, Conservation easement

Correspondence: Prof. Dr. Colin Vance, Rheinisch-Westfälisches Institut für Wirtschaftsforschung (RWI), Hohenzollernstr. 1-3, D-45128 Essen. E-mail: vance@rwi-essen.de.

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1 Introduction

As one of the most built-up regions on the earth, Europe is increasingly grappling with the consequences of unmitigated land consumption and unbalanced development. Urban land-uses currently comprise more than a quarter of the European Union's territory, having increased by 5.4% between 1990 and 2000 (EEA, 2006). Even prior to this expansion, the European Commission (EC) designated sprawl as a priority concern. In its 1990 Green Paper on the Urban Environment, for example, the EC called for denser development predicated on mixed land-use (CEC, 1990). Nearly a decade later, the European Spatial Development Perspective recommended the promotion of "compact cities" within the framework of a regional approach to development based on increased cooperation between the city and surrounding countryside (CEC, 1999). More recently still, the European Environment Agency advocated a similar tack, emphasizing the importance of strong urban policy to steer the growth around the periphery of the city and ensure compact development (EEA, 2006).

Effectively implementing these broad principles in practice is very difficult, not least because it requires anticipating how particular policy measures interact with prevailing market conditions to alter the pattern of urban growth. While the key drivers of this growth – including residential preferences, agricultural land values, and associated commercial investment decisions – are well-known, understanding of their interplay is rudimentary. Moreover, there is a general recognition that policies directly targeted at promoting open-space may result in perverse outcomes, as in the case of the increasing environmental pressure from the state-encouraged tourism currently afflicting much of the Mediterranean region (Fernando Vera Rebollo and Baidal, 2003). Indeed, even policies unrelated to urban planning per se, such as funding to promote EU integration through transport linkages, may create inadvertent socio-economic effects that hasten sprawl (EEA, 2006).

The development of practical analytical tools to assist urban planners in understanding urban growth processes and gauging the likely effects of policy interventions has received increasing attention over the past decade, but there remain few examples of methodological approaches that are (1) firmly grounded in a utility-theoretic framework; (2) transparent; and (3) readily subjected to empirical validation. The purpose of the present paper is to present a tool embodying these features and to illustrate its usefulness for policy analysis. We begin by developing a simple theoretical model of land development that, unlike much of the work to date, captures both the supply and demand sides of the market for open space. We subsequently incorporate the derived equilibrium condition into an empirical model that integrates the decisions of land owners, households, and developers in predicting the likelihood of land-use change. Finally, after validating the estimated parameters using simulated data, we employ the model to study the effects of a land set-aside program, a common measure to protect against sprawl in the European Union.

2 Literature

Among the most influential contributions to the rapidly expanding econometric literature on land conversion is the urban growth model of Capozza and Helsley (1989), through which they develop the theory underlying the formation of land values. In their model, the magnitude of development and where it occurs are assumed rather than endogenous to the model: The former is simply the product of the number of households in the region and the fixed lot size. The latter is indicated by the circle around the city center whose area equals this magnitude.

While the model, itself, does not support empirical application in light of these simplifying assumptions, Capozza and Helsley's work has been highly influential in providing a theoretical basis for econometric land-use change models. Proceeding from the simple proposition that conversion occurs when doing so maximizes landowners' income, these models explain the observed timing of land conversion by estimating for one or more intervals the conversion probabilities that generated the pattern of land-use change that transpired. In order to specify such an empirical model, one must figure out how to render the daunting task faced by landowners of comparing a myriad of income streams - one for each period in which conversion could occur - analytically tractable.

Assumptions about the time path of offer prices collapse the task to a comparison of a period's agricultural and residential rental rates.

Offer prices and corresponding residential rental rates are determined by the market clearing achieved each period as landowners and households strive to maximize their utility or profit from the conversion of agricultural land (or, more generally, open space). Modeling this market is complicated by the fact that offer prices (or residential rental rates) are not only endogenous, but unobserved (for all of those parcels that do not convert during the interval under consideration). Although the appealing expedient of treating the offer price as exogenous avoids the need to grapple with this issue, it may lead to biased estimates.

In an ideal modeling set-up, structural equations that reflect motivations at the individual household and landowner levels (as well as contain an equilibrium condition) can be transformed into a set of reduced form equations that express parcel conversion probabilities as a function of exogenous demand and supply-side factors. Taken together, these structural equations consequently capture both the utility-maximizing behavior of households on the demand side of the market and the profit-maximizing behavior of landowners on its supply side. When the reduced form has not been explicitly derived from structural equations, which is common in the econometric literature (e.g. Iovanna and Vance 2007), the appropriateness of a model is difficult to ascertain. Such a leap of faith is most apparent when the critical aspects of the demand or supply sides are simplified to produce an analytically tractable model.

An alternative approach to econometrics with the potential to address these difficulties is agent-based modeling (ABM). ABM places emphasis on agent interactions and the outcomes that emerge from these at various scales of analysis (Evans and Manson 2007). In contrast to econometric models, market equilibrium each period does not provide the theoretical basis for ABM. Instead, decision events (choosing whether to convert) occur sequentially across parcels, rather than simultaneously, each period.[1] Agents, typically the landowners, decide in turn whether to convert. Each decision is governed by a set of rules, and informed by the state of the world as impacted by earlier decisions. Market prices are not jointly determined as equilibrium is attained, but rather formed according to some (boundedly rational) heuristic at each decision event along the sequence. Empirical modeling with ABM may be accomplished by iterating through the set of possible event sequences is required to overcome path dependence and explain observed land-use change in terms of conversion likelihoods.

The sequential - rather than simultaneous - nature of transactions among agents in ABM readily evokes complex patterns of land-use change and, accordingly, a semblance of realism. Nevertheless, the theoretical underpinnings of a model can be obscure and salient features of actual land-use change abstracted away (Parker and Meretsky 2004). For example, ABM of land-use change have equated parcels with the lots into which they risk being subdivided and assume that the parcel-lots are uniform in size (e.g. Brown et al. 2005).[2] The lack of reference to the density of development on a parcel could be taken to imply that lot size is not meaningful to household utility.

Agents act sequentially, which means that prices are effectively exogenous at each decision event and land-use change is evinced in ABM without modeling market interactions. Accordingly, agents need only represent either the supply or demand side of the market (multi-agent models are uncommon). Consider the agent-based model of the German countryside developed by Happe, Kellermann, and Balmann (2006): When agricultural production on a parcel cannot turn a profit, the farmer abandons the land and possibly exits the sector. The parcel stays vacant until picked up by someone else for the sake of returning it to agricultural production. There is no pressure to convert the parcel. Conversely, Caruso, Rounsevell, and Cojocaru (2005) assume when examining land-use

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[1] In synchronous sequencing, each agent gets to make a decision during a period in a randomly determined sequence. In contrast, asynchronous sequencing treats explicitly the time to each agent's next opportunity to make a decision (e.g., via a poisson process). This allows for an agent to make no or multiple decisions over an interval of time for which empirical data on conversion exist.

[2] Parcels are the unit of open-space land on which an agricultural enterprise is organized. Lots are what residential households live on.

change in Belgium simply that the most desirable parcels (from the standpoint of the developer) are those that convert, which implies the opportunity cost of conversion to be not only constant, but zero.

3 Our approach

To tighten the connection between the theory and empirics, we develop a regional equilibrium approach to land-use change that differs from the conventional econometric, as well as agent-based, modeling approaches. Unlike ABM, we do assume that the prices governing land-use change over each time interval for which conversion data are available result from market equilibrium. Unlike conventional econometric specifications, we first specify a system of equations that fully reflects the supply and demand sides of the market for agricultural open space and then show how the market equilibrium is readily expressed as a set of estimable reduced form equations.

Parcels in the model convert into lots as a result of utility and profit maximization on the part of households and landowners, respectively. In our simple model, an equilibrium price surface yields utility maximizing lot sizes that sum up to equal the amount of land landowners are willing to convert. We assume that direct interaction between these two groups generates an outcome not unlike one more realistically mediated by developers.

The scope of our model is limited to the dynamics of land-use change, rather than the general equilibrium of the regional or national economy. This simplification is standard to virtually all spatially-explicit land-use change models, with the FARM model of Darwin and colleagues (1996) among the notable exceptions. In our framework, regional and national factors as economic growth and the cost of credit are assumed to affect the number of household entrants into the market and their income and not the other way around.

3.1 The landowner's decision

Landowners give up agricultural production and sell their parcels for subdivision into lots when the price being offered for the land is thought to maximize their future stream of earnings. They compare the (unit) offer price for land at location *j* to its expected capitalized agricultural value in period *t*, Agr_{jt} , which is determined by expectations regarding input and output agricultural prices, as well as spatially varying agricultural productivity.[3]

Landowners sell their parcel, not when the offer price for the land exceeds its agricultural value, $Off_{jt} - Agr_{jt} > 0$, but rather when that difference is maximized. From the vantage of period *t*, what matters is that $Off_{jt} - Agr_{jt}$ is maximized over the interval $t : t \to \infty$ at *t*. Accordingly, our approach simply needs to consider the conditional probability that the maximum is attained at t, rather than explicitly model expectations. We specify this probability as a function of the current offer price Off_{jt} and the current capitalized value of the stream of agricultural returns from that period onward Agr_{jt}, as well as three parameters:

$$\Pr_{jt}\left(Sell_{jt} = 1\right) = N\left(\beta_{Off} Off_{jt} - \beta_{Agr} Agr_{jt}, \sigma^2\right) \tag{1}$$

where $Sell_{jt} = 1$ if the parcel is sold and $Sell_{jt} = 0$ if not and N refers to the cumulative density function (CDF) of the normal distribution with mean $\beta_{Off} Off_{jt} - \beta_{Agr} Agr_{jt}$ and variance σ^2. The parameters - β_{Off} and β_{Agr} - reflect the effect of parcel-attributes that determine its offer price and the opportunity cost of conversion, respectively. Note that this formulation also allows non-financial considerations to affect the conversion decision so that conversion may occur in a period in which Off_{jt} is less than Agr_{jt}.

This formulation is reminiscent of many studies in the literature (Nelson and Hellerstein 1997, Irwin, Bell, and Geoghegan 2003, Pfaff et al. 2007) that consider the dynamic conversion process. They essentially equate the conditional probability of conversion at period *t* with the probability that one-period net returns to conversion are positive. These

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[3] Such data and estimates are readily available so that the researcher can formulate an estimate for Agr_{jt}. For example, the European Environmental Agency's Corine Land Cover data set provides fine resolution data on agronomic characteristics, while the

models are operationalized by specifying net returns as a function of observable factors and a stochastic term and are incumbent upon 2nd order conditions that the observable component is increasing over time. While our approach is similar, there are key differences: Focusing on capitalized income streams at period *t*, rather than net returns, we dispense with 2nd order conditions. And as discussed below, the exogenous factors that ultimately populate the model are explicitly derived and utility theoretic.

While Off_{jt} is determined by market equilibrium and, thus, endogenous to the model, Agr_{jt} is not. This is not to say, however, that Agr_{jt} is not impacted by the demand-side drivers of land-use change. The possibility exists for net returns to agriculture in a region to be influenced by population growth. In particular, increases in population may motivate a shift by some farmers from low-value commodities whose market is national (e.g. corn) to high-value commodities demanded locally (such as fresh fruits and vegetables). Such a market is likely to be wholly demand constrained (i.e. an inelastic demand shifting outward with population growth that faces an elastic supply).

Assuming that population growth is a cause, rather than a consequence, of land-use change, agricultural returns and offer prices are not jointly determined. Thus, when satisfactory projections of agricultural returns needed to calculate Agr_{jt} are unavailable, they can be modeled separately in a first stage using population, soil quality, and other exogenous variables. When Livanis et al. (2006) do so, they embed population in a gravity index that reflects the magnitude of the local market and a farm's proximity to it.

3.2 The household's decision

Consider a landscape with an open space matrix and a set of I_t households each period who will buy land on which to establish their residence. Assume that the market entry decision is exogenously determined by macroeconomic factors, i.e., that these households are only considering the region in question for their residence. The households emigrate

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World Agricultural Outlook Board provides data on commodity price trends (see http://www.usda.gov/oce/commodity/ag_baseline.htm).

to the region or experience a change in economic circumstances while already in the region as a result of these factors.

The landscape is heterogeneous in terms of a vector of demand-side characteristics $\mathbf{A}_{jt}$ that are more or less appealing to households. These (dis)amenities may be static in the model, such as proximity to the central business district and parks, or dynamically determined in the sense that conversion can create spatial externalities when households are sensitive to the amount of development that has occurred to date near to a prospective lot. From this point on in the section, we focus on a single period and drop any time subscripts.

Household preferences are reflected in the household utility function, where utility is a function of lot size at location *j* for household *i*, S_{ij}, amenity at that location, A_j, and a numeraire good given by the difference between income, Y_i, and lot expenditure.[4] Akin to most models of land-use change that explicitly reference the household utility function (e.g. Brown and Robinson 2006), a Cobb-Douglas specification is assumed for Equation 2.

$$U_{ij} = A_j^{\beta_A} S_{ij}^{\beta_S} \left(Y_i - Off_j S_{ij}\right)^{\beta_X} \tag{2}$$

where $\beta_A + \beta_S + \beta_X = 1$.

For the sake of exposition, the model is pared down to essentials by invoking the standard assumption of homogenous household preferences and that amenity can be represented in the utility function by a single variable. The model can be relaxed to accommodate cases where amenity consists of several attributes that households care about.[5]

For any location (amenity) and price, households will maximize utility by selecting an optimal lot size. The optimal lot size for household *i* at location *j* is expressed by the utility function's first order condition (foc):

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[4] New home characteristics are considered separable to choice of lot location and size and so are subsumed under the numeraire.

$$S_{ij} = \frac{\beta_S Y_i}{Off_j \left(\beta_S + \beta_X\right)} \tag{3}$$

Thus, at a higher price, households maximize their utility by reducing lot size in order to increase the amount of the numeraire good consumed, irrespective of amenity. At equilibrium, S_{ij} and Off_j adjust so $U_{ij} = U_i \forall i, j$, i.e., each household is indifferent to where they stake out their lot. In fact, as the rearranged foc in Equation 4 indicates, the utility maximizing lot size adjusts with any change in unit price so that the cost of the whole lot is constant.

$$S_{ij} Off_j = \frac{\beta_S Y_i}{\left(\beta_S + \beta_X\right)} = \eta_i \tag{4}$$

Households bid for land. In order for the market to clear, bids rise until equilibrium prices are attained that generate just enough conversion to accommodate all households.[6] Bids also vary across space because households are willing to pay more for higher amenity land. However, because households must be indifferent to location at market equilibrium, price adjusts (and lot size with it via Equation 4) to maintain constant utility. Both utility and lot cost are now constant across location for household *i* (though they will vary across households).

To see this, we can substitute the foc back into the utility function via S_{ij} to express Off_j as a function of A_j (Equation 5). While amenity value is not explicitly referenced in the foc, the endogenously determined vector of prices is a function of amenity.

$$Off_j = \gamma_i A_j^{\lambda} = \gamma A_j^{\lambda} \tag{5}$$

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[5] The equation is, thus, a simplification of $U_{ij} = A_{j1}^{\beta_1} \ldots A_{jk}^{\beta_k} \ldots A_{jK}^{\beta_K} S_{ij}^{\beta_S} \left(Y_i - Off_j S_{ij}\right)^{\beta_X}$.

[6] Developers effectively act behalf of the households by converting open-space parcels to fulfill an expectation of aggregate demand that is informed by historical trends and macroeconomic factors such as the interest rate and changes in regional income change. Given the amount of money at stake, as well as the speed of communication and access to relevant information that exists today, landowners and developers are able to shop around with minimal transactions costs for the highest offer and lowest bid prices, respectively. Offer prices increase until the spatial extent of parcels for which bids are accepted just accommodates the aggregate demand anticipated by the most zealous developer.

where $\lambda = \frac{\beta_A}{\beta_S}$ and $\gamma_i = \left(\frac{A_j^{\beta_A}}{U_{ij}}\right)^{1/\beta_S} \left(\frac{\beta_S Y_i}{\beta_S + \beta_X}\right)\left(Y_i - \frac{\beta_S Y_i}{\beta_S + \beta_X}\right)^{\beta_X/\beta_S}$. Happily, the subscript on γ_i drops off since Off_j and A_j are constant across households.

Alonso (1964) first drew attention to the relationship between offer price and location (or more generally, amenity) that would become an abiding assumption in urban economics: The unit price for land outside the city center adjusts to enable the purchase of a lot of sufficient size to confer the same utility as a desired lot at the city center.

3.3 Market clearing

The fact that optimal lot size varies in proportion to income (see Equation 3) facilitates the task of specifying an equilibrium condition for the market. Aggregate demand can be compared to aggregate supply (at a particular price vector) by simply replacing S_{ij} in Equation 3 with the parcel size of a parcel ($Parcel_j$) and the probability it converts (obtained from Equation 1) and solving for the fraction of aggregate income that it will accommodate, Y_j.

$$Y_j = \frac{(\beta_S + \beta_X)}{\beta_S} Off_j \Pr_j(Sell_j = 1) Parcel_j \tag{6}$$

The market equilibrium condition becomes

$$\sum_i Y_i = \sum_j Y_j \tag{7}$$

Our interest is in where conversion occurs, rather than in who goes where. Fortunately, the former does not depend on the latter, i.e., the pattern of conversion is not a function of precisely where (among the parcels to convert at a given price vector) each household settles.

Significantly, we have developed a land-use change model in which the market is fully realized so that offer prices are endogenously determined. The equilibrium price surface for land is determined by regional supply and demand, as well as location-specific amenity value.

4 Empirical model

When data are available on whether parcels converted over a period of time, $Sell_{jt}$, as well as parcels' Agr_{jt} and A_{jt}, the system of structural equations can be converted into an empirical model that maximizes the likelihood that the observed conversions and non-conversions occur so as to estimate a meaningful set of statistically consistent parameters related to the β's.

Since we know which parcels converted, we can replace the CDF in Equation 6 with $Sell_j$ and plug this into Equation 7. Limiting consideration to a single period in which conversion decisions were made, we have

$$Y_j = \frac{(\beta_S + \beta_X)}{\beta_S} Off_j Sell_j Parcel_j \tag{8}$$

Inserting Equation 5 into Equation 8, we can then solve for γ:

$$\gamma = \left(\frac{\beta_S \sum_i Y_i}{\beta_S + \beta_X} \right) \sum_j \left(A_j^{\lambda} Sell_j Parcel_j \right)^{-1} \tag{9}$$

Inserting this into Equation 1, as well as converting the CDF to the standard normal, we have the following expression:

$$\Phi\left(\beta_{Off} Off_j - \beta_{Agr} Agr_j, \sigma^2\right) = \Phi\left(\beta'_{Off} \gamma' A_j^{\lambda} - \beta'_{Agr} Agr_j\right) \tag{10}$$

where $\beta'_{Off} = \frac{\beta_{Off}}{\sigma} \left(\frac{\beta_S \sum_i Y_i}{\beta_S + \beta_X} \right)$, $\gamma' = \sum_j \left(A_j^{\lambda} Sell_j Parcel_j \right)^{-1}$, and $\beta'_{Agr} = \frac{\beta_{Agr}}{\sigma}$.

Thus, the likelihood of the observed land-use change is simply

$$L = \begin{cases} \Phi\left(\beta'_{Off}\,\gamma' A_j^{\lambda} - \beta'_{Agr} Agr_j\right) \text{ if } Sell_j = 1 \\ 1 - \Phi\left(\beta'_{Off}\,\gamma' A_j^{\lambda} - \beta'_{Agr} Agr_j\right) \textit{ otherwise} \end{cases} \tag{11}$$

Specifying the empirical model in this manner facilitates comparison to models presented in the literature as having the same theoretical basis. An estimator commonly employed in the land-use context is the probit (e.g. Kline, Moses, and Alig 2001; Wang and Kockelman 2009), whose link function lacks the non-linear and recursive flavor of Equation 10 so that the probability that a parcel is sold is expressed as

$$\Pr_j\left(Sell_j = 1\right) = \Phi\left(\pi + \pi_A A_j + \pi_{Agr} Agr_j\right) \tag{12}$$

To distinguish the probit from our approach, the estimated parameters from the above equation are denoted by the $\pi's$, which measure the impact of amenities and agricultural attributes on the likelihood that parcel *j* is sold. While the probit model uses the CDF of the standard normal distribution, Φ, another common choice for modeling this likelihood is the logit, which uses the CDF of the logistic function.

Because Equation 10 is explicitly derived from the same theoretical foundations that Equation 12 is assumed to arise from, relationships estimated via the latter may be subject to mis-specification bias. While amenity contributes to the probability of conversion in both models, the fundamental difference between the two specifications is that Equation 10 makes clear that a parcel’s own level of amenity both affects the probability of conversion directly via λ and through its contribution to market supply to the aggregate amount and quality of available open space via the γ' parameter. Aggregate demand also plays a role: the β'_{Off} parameter embodies the total income of the household entrants into the market.

While the model has been presented in a single-period context, conversion data over multiple periods can be accommodated. While the parameters β'_{Off} and γ' are period dependent, obtaining $Parcel_j$ data for converted parcels, as well as data for (or an indicator of) $\sum_i Y_i$, the time-invariant portions of these two parameters can instead be estimated using all of the available conversion data.[7] Afterwards, the $Parcel_j$ and $\sum_i Y_i$ data can be then used to construct β'_{Off} and γ' for each individual period.

5 Policy analysis

The relevance of land-use change models hinges on the degree to which they support policy simulation and can forecast future change. In this section, we show how a fixed effects treatment of market supply and demand misses the opportunity to estimate a model well suited to projection and policy simulation. As a consequence of the manner by which it relates A to the probability of conversion, our one-period empirical model proves to be quite conducive to either projection or to the analysis of policies that effectively take land out of consideration, such as conservation easements. Once conversion occurrences in period t are used to yield estimates of β'_{Off}, λ, and β'_{Agr}, projection and policy simulations occur by removing relevant parcels from consideration and calculating the conversion probabilities for the remaining ones.

For projecting conversion beyond the period used for estimation, we consider the set of parcels were not converted in the following equation (adapted from the definition for γ' in Equation 10), which is numerically solved for γ':

$$\gamma' = \sum_j \left(\Phi\left(\beta'_{Off} \gamma' A_j{}^{\lambda} - \beta'_{Agr} Agr_j \right) Parcel_j A_j^{\lambda} \right)^{-1} \tag{13}$$

Plugging this back into Equation 10 yields a set of estimated conversion probabilities for those parcels for period $t+1$.

Multiple periods can be dealt with by calculating the conversion probabilities (as above) of each in turn and incorporating these into the γ' equation for the next period. Doing so adjusts for the probability that parcels have not converted before the period under consideration. This adjustment, ρ_{jt+s-1}, results in the following equation for period $t+s$:

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[7] We assume that the unknowns that motivate the specification based on likelihoods are not intertemporally correlated.

$$\gamma'_{t+s} = \sum_j \left(\Phi\left(\beta'_{Off}\gamma' A_j^{\lambda} - \beta'_{Agr} Agr_j\right)\rho_{jt+s-1} Parcel_j A_j^{\lambda}\right)^{-1} \tag{14}$$

where $\rho_{jt+s-1} = 1 - \left(\Phi_{jt+1} + \Phi_{jt+2}\left(1-\Phi_{jt+1}\right) + \ldots \Phi_{jt+s-1} \prod_{\tau = t+1 \to t+s-2}\left(1-\Phi_{j\tau}\right)\right)$.

These projections can also take into consideration future changes in regional income by adjusting β'_{Off} in proportion to the change in regional income relative to the model estimation period. In other words, the time invariant portion of β'_{Off} is combined with income estimates.

The same approach can be adopted for policy analysis: Equation 10 is solved for those parcels not protected by the proposed easement or analogous program. The landscape-level effect of the policy is assessed by comparing the amount of land under easement with the change in the expected conversion of the land not so protected.[8]

6 A Simulation

To illustrate the leap from the structural equations to the empirical model and policy analysis, we specify and utilize a simulated landscape, an inductive approach often used to present ABM (Parker et al. 2003).[9] Simulated data offer a means by which to present a model in a laboratory setting in which all the relevant supply and demand-side factors and their true parameter values are known. Simulated data eliminate the potential for mis-specification bias to obfuscate the ability of the model to estimate parameters and conversion probabilities. And while the temptation to create data that justify a model certainly exists, there is no reason to suspect it to be any greater than that of mining empirical data to do so.

The simulated landscape consists of 1,000 parcels with randomly generated amenity and agricultural productivity, where $A_j \sim U(1,10)$, and $Agr_j \sim U(1,10)$. Parcel size varies as

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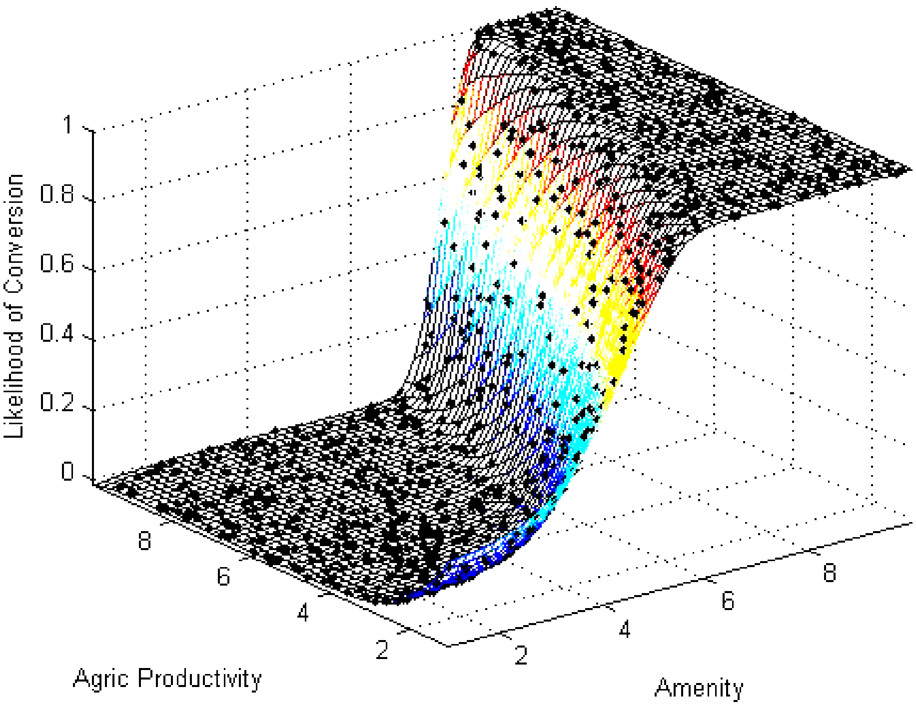
[8] If A is associated with a spatial externality, the conversion probability of parcels adjacent to the easement will be disproportionately impacted.

[9] The code used to run the simulation, written in MATLAB, is available upon request.

well, with $Parcel_j \sim U(50{,}150)$ In the simulation, developers anticipate that 10,000 households enter the market in this period in search of a suitable lot. Their income averages $500 and is randomly generated from a beta distribution. The true values of $\beta_A, \beta_S, \beta_X, \beta_{Off}, \beta_{Agr}$, and σ^2 are set at 0.3, 0.1, 0.6, 1.5, 1.0, and 4, respectively, which imply that $\beta'_{Off}\eta = 0.0154$, $\lambda = 3.0$, and $\beta'_{Agr} = 0.75$.

We ran the simulation model for a single period. The market clears with 428 of the 1,000 parcels in this simulated landscape converting into the lots sought by the 10,000 households. Figure 1 portrays how the resulting conversion probabilities relate to amenity and agricultural productivity as a result of the structural equations that define the market. The sinusoidal appearance of the surface is a consequence of the normal CDF from Equation 1. Parcels with relatively high amenity and relatively low Agr_j are relatively likely to convert. The associated vector of conversions, **Sell,** is also depicted as points.

Fig. 1 Parcel Characteristics and Associated Conversion Probability



Having generated **Sell** for our simulated landscape over a single period, we can turn around and treat for illustrative purposes the true parameters as unknown and estimate them using this vector. Proceeding with estimation, $\hat{\beta}'_{Off}\eta = 0.146$, $\hat{\lambda} = 2.98$, and $\hat{\beta}'_{Agr} = 0.677$, we ran the simulation another 999 times in order to calculate expected values and 95% confidence intervals for the parameter estimates. The results are shown in Table 1.

Table 1 Confidence Intervals for Parameter Estimates

Estimates	Lower bound	Mean	Upper bound
$\hat{\beta}'_{Off}\eta$	0.006	0.017	0.033
$\hat{\lambda}$	2.65	3.00	3.42
$\hat{\beta}'_{Agr}$	0.64	0.77	0.94

Returning to the first simulation, we assess the performance of the empirical model using receiver operating characteristic (ROC) curves and statistics. As Pontius and Schneider (2001) point out, it is inappropriate to assess the performance of an empirical model of land-use change by comparing the parcels where conversion actually occurred to parcels whose estimated conversion probabilities are above an arbitrarily selected threshold. The ROC approach circumvents this issue by considering all possible thresholds. At each point along the zero-to-one continuum, the fractions of true positives (correctly identified conversions over all actual conversions) and of false positives (wrongly identified conversions over the number of all parcels that did not convert in actuality) are calculated from the model predictions. These can be plotted and the resulting curve for the initial simulation, above, is shown in Figure 2.

The ROC statistic is the area under the curve; it will equal one if the likelihoods of all actual conversions exceed those of all other parcels. The ROC statistic for our model is 0.99. In contrast, a naïve model that randomly orders conversion probabilities across parcels will typically correspond to something close to a ROC statistic of 0.50 (and 45-degree line for the curve).[10] The model performance proves to be significantly better than

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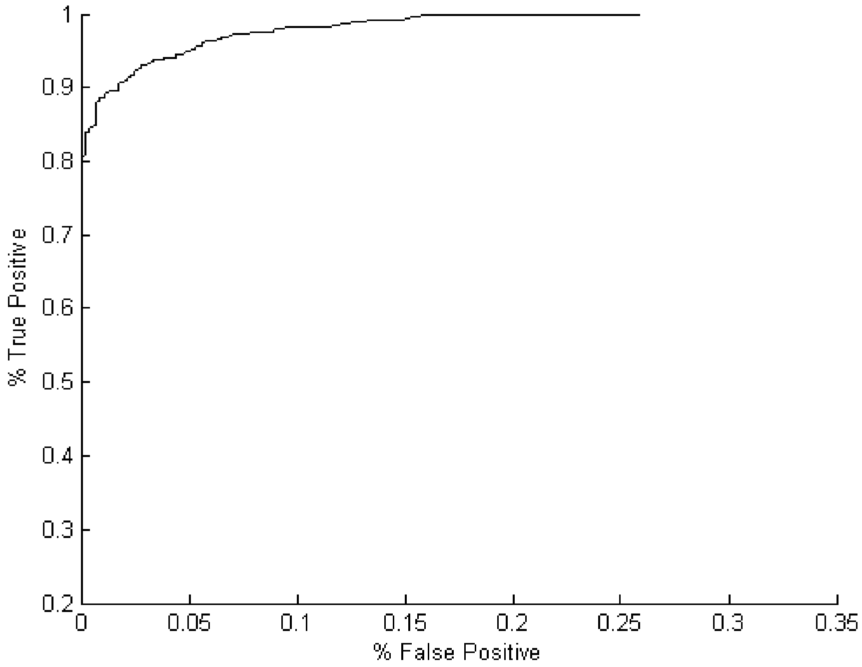
[10] Monte Carlo analysis of this ordering is used to generate the ROC curve and statistic for the naïve model.

the naïve model.

Fig. 2 Receiver Operating Characteristic Curve



We also compare the results of our model to estimates from a probit model. The latter specification may not be as compatible with economic theories of land-use change as often assumed: When conversion probabilities are estimated by both models, the log-likelihood of our approach was lower than the probit's for all 1,000 simulations, providing conclusive evidence of its superior predictive ability.

Finally, we conduct a policy analysis using the parameters estimated by the initial simulation. The policy scenario involves removing fifty percent of the landscape from consideration by way of a proposed conservation easement program. Although such programs have assumed various forms throughout Europe (see Nuissl and Couch 2007), there has been very little research in Europe or elsewhere on their associated implications for development on the surrounding landscape.[11] One exception is a recent study from the

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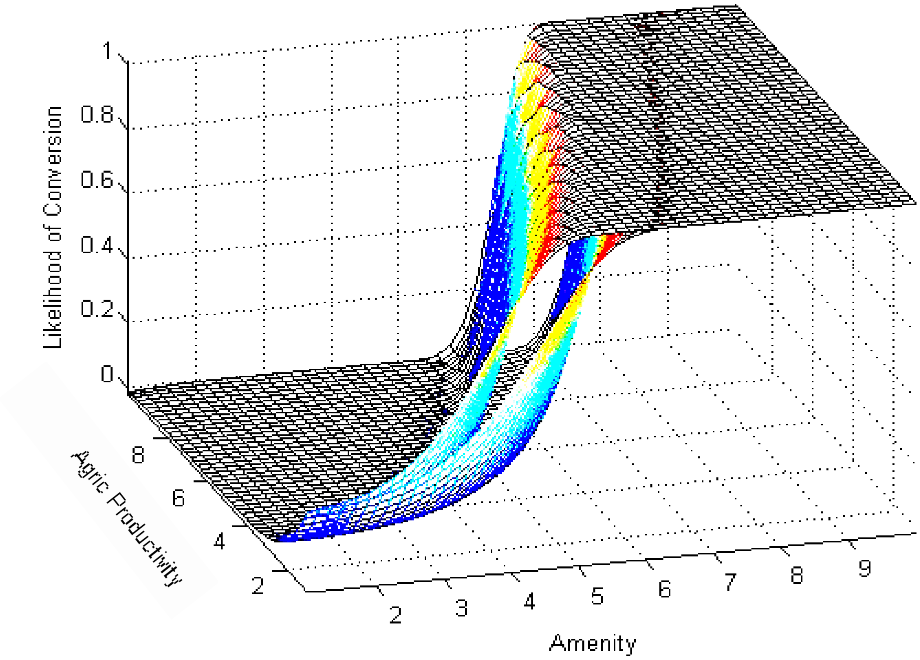
[11] Among the most extensive land protection programs in Europe is the continental-wide *Natura 2000* network of protected areas.

US, which finds for two of three sites surveyed that the development rate is significantly greater in regions with more protected land (McDonald et al. 2007).

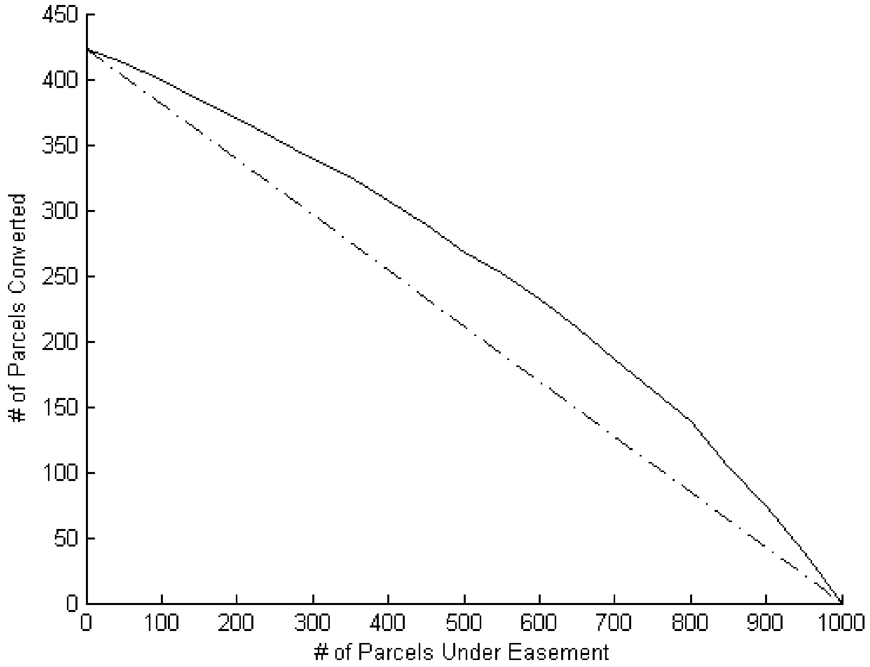
Equation 13 is used to re-assess the probability of conversion for those parcels that remain susceptible to it and calculate the aggregate, landscape-level impact of the program relative to the baseline. Figure 3 shows how the relationship between conversion probabilities, amenity, and agricultural productivity is affected by protecting fifty percent of the parcels. The lower surface pertains to the baseline scenarios, while the higher surface shows how, with fewer open space parcels available for conversion in the region, conversion probabilities rise (as η increases) across the board for parcels not participating in the program.

Fig. 3 Comparison of Baseline and Policy Conversion Probabilities



We also varied the fraction of parcels enrolled in the easement program to portray the relationship in Figure 4 between this fraction and the aggregate conversion during the period. Given how the policy affects one term of two whose difference generates the parcel-level probabilities via a normal distribution's CDF, the relationship is not a simple, linear one in which the number of parcels converted is related in a fixed proportion to the number under easement (e.g., coincident with the dashed line). While the net result of the easement program is less conversion on the landscape, irrespective of the program's scope, the ratio of the conversion reduction to easement area is initially less than 1:1. However, this result does hinge on the policy having no impact on the magnitude of *A* for any parcels not participating in the program. When easements increase the amenity of adjoining parcels, the net impact can be assessed by incorporating updated amenity values in Equations 10, 13 and 14 as parcel conversion probabilities are recalculated.

Fig. 4 Effect of Conservation Easement Program



7 Conclusion

We have tightened the correspondence between theory and empirics by deriving an empirical model of conversion directly from the structural equations characterizing the market for open space. Although simple, our specification is exceedingly flexible, allowing for household (demand-side) heterogeneity in terms of income, and parcel (supply-side) heterogeneity in terms of amenity, agricultural productivity, zoning, and parcel size. The assumptions that it does rely upon are common, if not universal, among empirical models in the literature: that landscape pattern in the region does not affect the number of households seeking a lot (the regional economy does), nor agricultural prices, and that the continuous process of conversion can be reasonably represented as a market that clears in discrete time.

Each open-space parcel is assumed to offer to each household an alternative site from which a utility maximizing lot can be carved. These prices vary systematically in accordance to the relationship of price, amenity, and lot size that underlies the household utility function. The indifference of households to where they situate their lot that results from the variation in amenity and prices establishes a necessary equivalence across dissimilar parcels. The approach, which is based on Alonzo (1964), obtains the vector of equilibrium prices (that reflect parcels' relative appeal) that clears the regional market for open space.

Contrasting the model with an empirical specification common to the literature, we suggest that it is conceivable for the latter to be at odds with standard theoretical assumptions. Further, the approach we develop is shown to offer a platform for projecting land-use change into the future and for policy simulation. Significantly, all that is necessary to develop the model for such purposes is a single period's worth of conversion data. Finally, we have shown by way of a simulated landscape what standard theoretical assumptions imply regarding the impact of a widely used policy to arrest sprawl. Removing a fraction of the landscape from the risk of conversion using easements reduces the total amount of development on a landscape, despite the relatively higher risk of conversion for unprotected parcels.

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