Optimal Land Conversion at the Rural-Urban Fringe with Positive and Negative Agricultural Externalities

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July 2000

Paper prepared for the American Agricultural Economics Association Meeting, Tampa, Florida, July 30-August 2, 2000.

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Abstract

Bid-rent curves are incorporated in a stochastic dynamic programming model of land development around a city when farmland generates both positive and negative externalities. The model delineates how the quantities of land in various uses over time should depend on the relative social weights assigned to the competing agricultural externalities.

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Land allocation has been a source of conflict between individuals, groups, and nations throughout history. Though many such disputes have been settled through violence, the modern market is often relied upon as a peaceful means to allocate land. Naturally, agriculture is a major landholder in any nation, and farm activity generates several externalities that affect nearby residents. These externalities imply that the market allocation of land may not be in society's best interest, and much of the debate concerning land policy at the rural-urban fringe has therefore focused on farmland and farm activity.

As communities grow, there can be controversy over the speed and extent to which farmland is converted to non-farm uses. On the one hand, it has long been recognized that farms generate pollution such as runoff, groundwater contamination, and offensive odors. Its nonpoint source nature and spatial variability make agricultural pollution difficult to regulate, but increasing public pressure over the past three decades has prompted several governments to enact environmental provisions for farmers, even at the national level. The U.S. Congress, for example, has acted in recent farm legislation to protect wetlands and highly erodible cropland (Heimlich; Ribaudo et al.), and has empowered the Environmental Protection Agency to regulate dangerous pesticides and animal waste (Cropper et al.; USDA/USEPA).

On the other hand, both urban and non-farm rural residents value open space and farm landscapes. Beginning in 1971 with the New York Agricultural Districts Law, all states and many communities have farmland retention programs in place (Gustafson; Heimlich). These policies include numerous institutional measures to encourage farmland retention, as well as standard remedies such as preferential property taxes, subsidies, and controls on land use, including transfer or purchase of development rights.

Although recent empirical studies have confirmed the sometimes substantial willingness for households to bear additional tax burdens in order to retain farmland (Lopez et al.; Hackl and Pruckner), we know little about the effectiveness of such policies. Their precise goals are often not well articulated, and we still know relatively little about the nature of land use decisions or the development process itself. What we do know is that as developed countries explicitly recognize the multifunctional nature of agriculture, there will surely be increased interest in similar policies around the world (OECD, 1997a, b).

When land is converted to non-agricultural uses, nearby residents avoid agricultural pollution, but the landscape amenity benefits are sacrificed, as is the option to develop later when the returns to development may be even higher. The socially optimal decision thus depends on current benefits and costs as well as option value. Yet, even if all these values can be observed or calculated, their implications for selecting a policy are not transparent. If amenity values are the only concern, agricultural land should be protected from being developed through subsidies or land use regulations. If concerns about agricultural pollution are also significant, the optimal land use strategy must include environmental regulation, or possibly the removal of some land from agriculture to provide open space as a buffer between urban and agricultural activity.

This paper proposes a framework to determine the optimal patterns of land conversion in a growing community. The model incorporates spatial features, allowing both public and private returns from various land uses to depend on location. Because development is both costly and considered irreversible, the land allocation process is viewed as a dynamic process where future events are uncertain. A spatial theory of land use that generalizes von Thünen's bid-rent curves is incorporated into a stochastic dynamic programming framework, treating the conversion process at each location as an optimal stopping problem under uncertainty. This is the first model that accommodates both positive and negative externalities in determining optimal patterns of land use over time and space.

The analysis leads to several theoretical conclusions and implications for empirical modeling. It reveals precisely how policies to affect land conversion should depend on the relative weights the community assigns to the competing agricultural externalities, and the option value associated with the uncertain private returns from delaying conversion. Because the positive and negative externalities affect the socially optimal land use configuration differently, empirical land conversion models must acknowledge the multifunctional nature of agricultural activity, and avoid specifications that focus only on the most pervasive externality or combine all external values into a single "net" measure (Ollikainen).

The most notable result is that the multifunctionality of agriculture, combined with the inherently dynamic nature of land conversion, may imply that farmland is being converted too slowly. While farmers are clearly not being rewarded for the amenity benefits they provide to nearby households, an optimal set of policies would reduce agricultural pollution and raise the external benefits even more. When this happens, the potential value of developing farmland (which is near other farmland) also increases, and the net result may be a faster rate of conversion. This possibility is formalized in the theoretical model below, and its empirical plausibility is demonstrated through numerical simulations of metropolitan areas in the United States.

The following section sets forth the theoretical model and develops the major conceptual results. Using this framework, the third section describes the specification, method, and results of empirical simulations of a typical city in the United States. The conclusions and policy implications of the results are discussed in the final section.

Theoretical Model

In a spatial economy, land at each location is a distinct commodity. From the observation that individuals usually consume land in only one place, we can infer that the tradeoffs between any two parcels are nonconvex: Given any set of relative prices for separate parcels, agents almost always choose the corner solution of consuming land at only one location. Because solutions to agents' optimization problems cannot be easily characterized under nonconvexity, spatial economic models assume that individuals consume one contiguous land plot but choose its location and size along with the consumption of non-land commodities (Fujita).

As in much of the urban economics literature, the monocentric urban model is relied upon here to explain land use. The "model city," which is assumed to be built on a featureless plain, encircles a single central business district (CBD) where all shopping and employment opportunities are located. All households, identical except for where they live, earn an annual income of y; a household living r miles from the CBD incurs a yearly transportation cost of $T(r)$, leaving a location adjusted income of $I_r = y - T(r)$.[1] By generalizing von Thünen's bid rent curves, Alonso (1964), Muth (1969), and Mills (1972) developed a unified theory of urban land use in a monocentric city, where households' bid rent curves for housing land describe their willingness-to-pay for land at each location. Solow modernized this theory by deriving bid rent functions using duality.

Because all locations at a common distance to the CBD are the same in this model, the city can be regarded as a series of concentric rings of development, where each ring is indexed by its radial distance to the city center (r). If development has proceeded out to some urban

[1] This model is clearly an abstraction; most cities have irregular shapes, heterogeneous land parcels that are equidistant to the CBD, and dispersed employment centers. Nonetheless, the model still provides a good statistical description for many urban areas in the United States (Jordan et al.).

fringe distance r_f, the goal is to determine when (if ever) the farmland in rings $r_f + 1$, $r_f + 2$, … is converted under optimal planning or free markets, assuming that development is irreversible.

If land at any location is developed, households living there will enjoy utility equal to $U(c, s, a, e)$ each year, where c is (annual) non-land consumption, s is the size of land plot for each house, a is amenities from nearby undeveloped land, and e is emissions of agricultural pollution. U is increasing in c, s, and a, and decreasing in e. Assuming that residents may move away from the area to enjoy a reservation utility of u, the Solow bid rent function for land in ring r is:

(1) $$\psi(I_r, u, a, e) = \max_{c,s} \frac{I_r - c}{s}$$

$$\text{s.t. } U(c,s,a,e) = u$$

This function represents the maximum yearly benefit per acre of land that accrues to a household with income I_r, when the target utility level is u, and environmental quality is (a, e).[2] Stated differently, $\psi(\cdot)$ is the yearly willingness-to-pay per acre of housing land in ring r.

To understand the intuition for bid rent, consider the budget constraint for a household in ring r: $I_r = c + Rs$, where R represents the rent paid (per acre) for land. Solving the budget constraint for rent, $R = (I_r - c)/s$; the problem in (1) is therefore to maximize R with respect to c and s, subject to a constraint on utility. The geometry of this maximization problem is shown in Figure 1. The utility constraint requires the choice of (c, s) to lie along the indifference curve *BDC*. If, for example, point *B* is chosen, land rent is the slope of the budget line *ABC*. Because there exist steeper budget lines (i.e., with a larger slope) that also satisfy the constraint, a point like *B* is not a solution. The solution is at point *D*, where the budget line is tangent to the

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[2] ψ is the benefit from land only; services from capital improvements (the housing structure) are part of the numeraire commodity c.

indifference curve, and bid rent ψ is the slope of the line *ADE*. In general, bid rent is the slope of the line emanating from *A* that is tangent to the indifference curve.

The envelope theorem applied to (1) implies that ψ is increasing in I_r and *a*, and decreasing in *u* and *e*; bid rent rises with income and amenities, but falls if opportunities elsewhere become better or if emissions become higher. These changes can be clearly seen from Figure 1. As I_r increases, point *A* moves upward, and the optimal budget line becomes steeper. On the other hand, an increase in *u* shifts the indifference curve outward, implying the line between *A* and a tangency becomes flatter. Because $u_e < 0$ and $u_a > 0$, an increase in *e* also shifts the indifference curve outward, while an increase in *a* shifts it inward.

If land remains in farming, it generates yearly revenue equal to $pf(z)$ per acre, where *p* is the price of farm output, $f(z)$ is the production function (assumed twice differentiable, increasing, and strictly concave), and *z* is a vector of inputs that must be chosen. A corresponding input price vector *w* represents the opportunity cost of obtaining inputs from outside the city. As a by-product of market output, agriculture generates the two externalities *a* and *e*.

In a spatial framework, the social values of these by-products depend not only on the farm production process, but also on the location of households and farms. In general, the effect on surrounding households decays with their distance from agriculture. Here, assume distance is measured so that agriculture affects only households in the adjacent ring. If "leapfrog development" is precluded, all rings out to the urban fringe are developed, and the innermost ring of farmland affects only the outermost ring of households; farm externalities at more distant locations can be ignored. Analytically, this assumption implies that the decision to expand the city into one more ring of farmland involves only the activities on two rings. A more general model includes more rings in the decision but leads to the same conclusions.

Because there is no leapfrogging, the only way a household in ring r can receive amenity benefits is if ring $r + 1$ remains undeveloped ($r - 1$ is developed by assumption). It is sufficient to regard a as a discrete variable that equals one when the next ring is undeveloped and zero otherwise. Similarly, emissions at r are a non-decreasing and convex function of farm inputs at $r + 1$; $e = g(z)$, where g', $g'' \geq 0$, and $g(0) = 0$. Bid rent for a household in a ring adjacent to agriculture is thus $\psi(I, u, 1, g(z))$, and for all other households inside the city it is $\psi(I, u, 0, 0)$. For brevity, denote these bid rent functions $\psi_1(I, u)$ and $\psi_0(I, u)$, respectively.

Observations of y and u evolve according to two (exogenous) Markov processes. Given the current year observations y_t and u_t, y_{t+1} and u_{t+1} follow the cumulative distribution functions $G_y(y_{t+1}; y_t)$ and $G_u(u_{t+1}; u_t)$, respectively. The expected values of both variables increase over time; i.e., $E[y_{t+1} \,|\, y_t] \geq y_t$ and $E[u_{t+1} \,|\, u_t] \geq u_t$. Moreover, they satisfy "positive persistence" in the sense of first order stochastic dominance: $\partial G_y/\partial y_t < 0$ and $\partial G_u/\partial u_t < 0$, which ensures that larger current values of y_t and u_t shift the distributions of y_{t+1} and u_{t+1} to the right. Note that $I_{r,t+1}$ inherits its distribution from G_y, and that incomes on r and $r + 1$ differ by transportation cost: $I_{rt} = I_{r+1,t} + [T(r+1) - T(r)] \equiv I_{r+1,t} + \Delta T$. Finally, assume that the domains of y and u are compact so that ψ_1 and ψ_0 are bounded functions.

Socially Optimal Land Use

Suppose that a social planner manages all land in the urban area. In a spatial economy, the planner could not maximize welfare by solving a Pareto-type problem because the solution will assign different utility levels to identical individuals (Mirlees). Since a market equilibrium with identical agents cannot produce such an outcome, urban models typically avoid this "unequal treatment of equals" by solving the dual of the welfare problem, where the social surplus of achieving a common utility level is maximized (and the cost is thereby minimized). In a dynamic model, the planner's goal is to maximize the stream of surpluses (i.e., the property value) when utility is set at the reservation level *u*.

In the present context, the planner must solve a recursive series of problems. In any period, he must decide whether to develop the innermost ring of farmland. To make this choice, he considers the effect on property value of the farmland if it is developed, as well as the property value change on the outermost ring of households. If he does not develop it in the current year, he faces exactly the same problem the following period; if he develops, the problem has an identical structure but involves the development choice for the next ring of farmland. Below, the planner's problem is derived for an arbitrary point in the development process, where the last ring of development is at distance *r* and the first ring of farmland is at *r* + 1.

In ring *r*, property value depends on households' bid rent, which in turn depends on the land use at *r* + 1. If ring *r* + 1 is developed in year *t*, the property value at *r* is $H_0(I_{rt}, u_t) = E_t \sum_{\tau=t}^{\infty} \beta^{t+\tau} \psi_0(I_{r\tau}, u_\tau)$, where E_t is the expectation with respect to future realizations of I_r and *u* given information in *t*. The expression for H_0 follows from irreversibility; agricultural externalities disappear forever once ring *r* + 1 is developed. If ring *r* + 1 remains undeveloped in *t*, property value in ring *r* in any period $\tau \geq t$ can be defined recursively as:

$$(2) \qquad H_1(I_{r\tau}, u_\tau) = \begin{cases} \psi_1(I_{r\tau}, u_\tau) + \beta E H_1(I_{r,\tau+1}, u_{\tau+1}) & \text{if } r+1 \text{ is undeveloped in } \tau \\ H_0(I_{r\tau}, u_\tau) & \text{if } r+1 \text{ is developed in } \tau \end{cases}$$

If development occurs in τ, property value becomes H_0. If not, households earn a current return of ψ_1 and face the possibility of development in $\tau + 1$.

Because delaying development preserves the option to develop in the future, the value of farmland in ring *r* + 1 includes agricultural value as well as an option value that depends on potential returns to housing. Assuming for simplicity that agricultural prices and technology do not vary over time, the capitalized value of farm production is a constant, and the option value of developing varies with income and reservation utility levels. Accordingly, let $F(I, u)$ represent the property value of farmland when location-adjusted income is I and reservation utility is u, where the constant value from farm production is embedded in the structure of F. In any year τ, this function satisfies:

$$(3) \qquad F(I_{r+1,\tau}, u_\tau) = \begin{cases} \pi(z) + \beta EF(I_{r+1,\tau+1}, u_{\tau+1}) & \text{if } r+1 \text{ is undeveloped in } \tau \\ H_1(I_{r+1,\tau}, u_\tau) & \text{if } r+1 \text{ is developed in } \tau \end{cases}$$

where $\pi(z)$ is the yearly profit from farming. Similar to above, if development is delayed, farm property value is the current return from farming plus the (discounted) expected value next period. If development occurs, the new residents of ring $r + 1$ have a property value of $H_1(I_{r+1,\tau}, u_\tau)$.

In addition to the development decision on ring $r + 1$, the planner must select the input level z if he chooses to farm. The combined surplus on rings r and $r + 1$ from farming $r + 1$ during the current year is $\psi(I_r, u, 1, g(z)) + pf(z) - wz$, and the input level z^* that maximizes this surplus satisfies:

$$(4) \qquad pf_z(z^*) = w - \psi_e(\cdot)g_z(z^*)$$

where subscripts denote derivatives. Denote the maximized value of surplus as $\psi_1^*(I, u) + \pi(z^*)$.

The planner's development decision can then be expressed by the Bellman equation:

$$H_1(I_r, u) + F(I_{r+1}, u) = \max\{\psi_1^*(I_r, u) + \pi(z^*) + \beta E[H_1(I_r', u') + F(I_{r+1}', u')],$$
$$H_0(I_r, u) + H_1(I_{r+1}, u) - k\ \}$$

where primes denote next period observations, and k is the conversion cost of development. The left side of this equation represents the combined social property values of the two rings at the beginning of an arbitrary year. Whether the second ring should be developed depends on which argument is larger inside the max operator. The first argument represents the value of choosing to farm; the first two terms are the (maximal) current surplus from farming, and the remaining terms are the discounted value of the farming/developing choice in the following year. The second argument is the value of developing. If this option is selected, the property values at r and $r + 1$ become H_0 and H_1, respectively, based on the arguments above, and society must incur the one-time conversion cost k.

For comparison with the competitive equilibrium below, it is convenient to subtract $H_1(I_r, u)$ from both sides of the Bellman equation. The resulting functional equation simplifies to:

(5) $$F(I_{r+1}, u) = \max\{\pi(z^*) + \beta EF(I_{r+1}', u'), H_1(I_{r+1}, u) - [H_1(I_r, u) - H_0(I_r, u)] - k\},$$

because in the first argument of $\max\{\cdot\}$, $\psi_1^*(I_r, u) + \beta EH_1(I_r', u') - H_1(I_r, u) = 0$ if development is delayed.

The planner will delay development as long as the first argument on the right side of equation (5) is greater than the second. Rearranging terms, the inequality that triggers development is:

(6) $$H_1(I_{r+1}, u) \geq k + [\pi(z^*) + \beta EF(I', u')] + [H_1(I_r, u) - H_0(I_r, u)]$$

Here, the property value at $r + 1$ after development has been isolated on the left side. For development to be optimal, this amount must be at least as large as the sum of conversion cost and the two bracketed expressions. The first of these expressions is the current and future agricultural value on ring $r + 1$, and the second is the reduction in property value on ring r due to development.

It can easily be shown that the operators on the right sides of equations (2) and (3) are contraction mappings under the development rule in (6); H_1 and F thus have unique fixed points in the space of bounded and continuous functions (Stokey and Lucas).[3] To distinguish the socially optimal fixed points from the competitive case below, denote them H_1^* and F^*, respectively. Beginning with arbitrary guesses for H_1 and F, the contraction property guarantees that a sequence of new guesses, derived by successive application of the rule in (6), will converge to H_1^* and F^*. Such a procedure is the basis of an empirical method to calculate the value functions.

Because the termination payoff H_0 is increasing in I and there is positive persistence in the stochastic process of y (and hence I_{r+1}), the development rule is equivalent to dividing the domain of I_{r+1} into two regions (conditional on u) such that development occurs the first time I_{r+1} crosses some barrier $I(u)$ (Dixit and Pindyck). Let $I^*(u)$ denote the conversion barrier for the fixed points H_1^* and F^*. From (6) and the relationship $I_r = I_{r+1} + \Delta T$, $I^*(u)$ is implicitly defined by the equation:

$$H_1(I^*(u), u) = k + [\pi(z^*) + \beta EF(I', u')] + [H_1(I^*(u) + \Delta T, u) - H_0(I^*(u) + \Delta T, u)]$$

Note that $I^*(u)$ depends only on the shapes of the functions H_0, H_1^*, and F^*, and not on r. The barrier that triggers development is thus the same at all locations; because adjusted income is larger for rings near the city center (small r), the barrier is reached earlier at these locations and they are the first to be developed. The city expands outward as income continues to grow and the development barrier is reached at more distant locations.

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[3] Consider some operator M that takes an argument from some set and returns an element of the same set; i.e., $\theta \in \Theta$ and $M(\theta) \in \Theta$. Given a function $d(\theta, \theta')$ that measures the distance between any two members of Θ, M is a *contraction mapping* if and only if $d(\theta, M(\theta)) > \beta d(M(\theta), M(M(\theta)))$, for some $\beta \in (0, 1)$. That is, the distance between θ and $M(\theta)$ shrinks as M is applied repeatedly. The contraction mapping theorem guarantees the existence of a unique fixed point of a contraction mapping in Θ: there exists $\theta^* \in \Theta$ such that $M(\theta^*) = \theta^*$ (Stokey and Lucas). In the dynamic programming context here, Θ is the set of bounded and continuous functions to which H_1 and F must belong. Blackwell established two sufficient conditions for a contraction. First, the *monotonicity* condition requires that if $d(\theta_1, 0) > d(\theta_2, 0)$ then $d(M(\theta_1), 0) > d(M(\theta_2), 0)$. Second, the *discounting* condition means that $M(\theta + \alpha) \leq M(\theta) + \beta\alpha$, where α is a scalar. Because both operators in question satisfy these conditions, functions F and H_1 that satisfy the recursive definitions in (2) and (3) exist and are unique.

Figure 2 depicts the functions F^*, H_1^*, and H_0. For all levels of income up to $I^*(u)$, land is farmed and the property value is given by F^*. Between $I^*(u)$ and $I^*(u) + \Delta T$, land is developed and is adjacent to agriculture (land on the next ring is not yet developed) with a property value of H_1^*. Finally, above $I^*(u) + \Delta T$, agricultural externalities disappear because the next ring has been developed and the property value function is H_0.

In general, I_r exceeds I_{r+1} by the marginal commuting cost ΔT, and I_{r+1} exceeds I_{r+2} by the same amount. At the levels of I_r, I_{r+1}, and I_{r+2} depicted in the figure, property on ring r is the outermost developed land with a value of $H_1^*(I_r, u)$, and both rings I_{r+1} and I_{r+2} are farmed, with property values of $F^*(I_{r+1}, u)$ and $F^*(I_{r+2}, u)$, respectively. In the year that I_{r+1} grows large enough to cross the barrier $I^*(u)$, I_r will cross $I^*(u) + \Delta T$; $r + 1$ will be developed and the agricultural externalities on ring r will be lost. In the ensuing years, $r + 1$ will be the fringe of the city until I_{r+1} reaches the barrier $I^*(u) + \Delta T$. When that happens, I_{r+2} will hit the development barrier and $r + 1$ becomes an interior ring of the city.

Competitive Equilibrium Land Use with Taxes

In a competitive equilibrium it is the farmers at $r + 1$, rather than a social planner, who must set input levels and make a development decision every year. To see what interventions are needed to restore the social optimum in light of the two externalities, consider two policy instruments: T_z, a per unit tax on agricultural inputs, and T_D, a tax on development. The development tax could take many forms (e.g., a tax on developers, a reduction in property tax liability for farmers, or a payment for the purchase of development rights).

Assume farmers are profit maximizers and solve: max $pf(z) - (w + T_z)z$. Competitive input levels z^c thus satisfy:

(7) $$pf_z(z^c) = w + T_z.$$

Let $\pi(z^c)$ denote the corresponding value of farm profits. The Bellman equation that describes farmers' development choices can then be written:

(8) $F(I_{r+1}, u) = \max[\ \pi(z^c) + \beta EF(I_{r+1}', u'),\ H_1(I_{r+1}, u) - k - T_D]$

In a competitive equilibrium where developers buy farmland and improve the land into saleable housing lots, the second argument $H_1 - k - T_D$ is the net sales price of farmland for development. The farmer will choose development the first time this sales price exceeds the value of farming. Rearranging, the development rule is:

(9) $H_1(I_{r+1}, u) \geq k + \pi(z^c) + \beta EF(I', u') + T_D$

Land is converted if development value exceeds the combined value of conversion cost, current and future returns from farming, and development taxes.

Similar to above, the development condition (9) applied to (2) and (3) defines fixed points for the value functions in competitive markets, denoted H_1^c and F^c. Given a set of taxes, these functions represent equilibrium property values of farmed and newly developed land at various income levels. Associated with these functions, there exists some barrier value of income $I^c(u)$ that triggers conversion. If the economy cannot be planned, the task of a welfare-maximizing government is to set taxes so that equilibrium allocations are socially optimal. Mathematically, the government's problem is one of solving for the combination of T_z and T_D that generate equilibrium inputs (z^c), property values (H_1^c and F^c), and a development barrier ($I^c(u)$) equal to z^*, H_1^*, F^*, and $I^*(u)$, respectively.

By comparing equations (4) and (7), the optimal set of taxes on farm inputs can be directly calculated as $T_z = -\psi_e(\cdot)g_z(z^*)$. These taxes, which are positive because ψ_e is negative, imply that each farm input must be charged by the marginal cost of the pollution it imparts on nearby households. If the cost of pollution is very high, taxes could potentially drive farm profits to zero. In this case, landowners will exit agriculture and leave their land vacant while awaiting development (or sell the land to a speculator); essentially, sufficiently strong negative effects from farming implies development should be surrounded by a "greenbelt" that places a buffer between urban and agricultural activity.

A comparison of equations (9) and (6) implies an optimal development tax of $T_D = H_1(I_r, u) - H_0(I_r, u)$. If this tax is imposed jointly with the optimal input tax (so that $z^c = z^*$), the Bellman equation and development rule in (8) and (9) are identical to the corresponding expressions under optimal planning in (5) and (6). Because there are unique fixed points for H_1 and F in each case, H_1^c and F^c must coincide with H_1^* and F^*, and it follows immediately that $I^c(u) = I^*(u)$. As one might expect, development should be taxed by the amount it reduces property value elsewhere, but a necessary condition for such a tax is regulations to correct other externalities; if inputs are not regulated, the development tax above is not appropriate.

Of particular interest are the input levels and development time in an unregulated outcome when all taxes are set to zero. Because optimal input taxes are positive, the competitive input levels in this case are strictly larger than the socially optimal ones. For the time of development, a first inspection of condition (9) may suggest that removing the development tax must speed the rate of conversion because the criterion is more likely to be met. However, the development decision also depends on the other terms in the inequality, and the net effect of policies depends on how these functions change.

Because the value functions H_1 and F are fixed points that are endogenously determined, these comparisons cannot be derived without specifying functional forms and stochastic processes for y and u. The empirical simulations below provide a way of estimating such changes for a plausible description of modern urban areas. In principle, an optimal set of policies may either speed or slow the rate of conversion because the two taxes act in opposite directions. The development tax is an extra cost of development, but the input tax reduces the return to farming and adds a benefit to developing because new households are exposed to less pollution.

A Numerical Policy Simulation of a Typical U.S. Metropolitan Area

Though a very small proportion of the land area in the United States is developed, the accelerating rate of conversion in recent decades has prompted many state and local governments to introduce land retention programs. Meanwhile, increased concern about the health hazards of agricultural chemicals and animal waste have led to new or proposed environmental regulations, usually imposed at the federal level. Because these two sets of policies are designed independently, the result is a group of piecemeal programs that are likely to work at cross-purposes. The land retention programs, typically in the form of property tax relief to farmers, have the marginal effect of raising the return to farming relative to development. On the other hand, environmental regulations necessarily impose an extra cost on farmers, and the resulting improvement in environmental quality increases the potential value of development.

Given data on land rents and estimates of non-market values for a particular urban area, the model above can be applied to estimate the optimal policy intervention and its likely effects. Theoretically, the pollution and land retention policies are related, but the empirical significance of their cross-effects would vary across cities. To investigate the likely importance of this relationship for any city, the empirical analysis here uses data from all metropolitan areas in the United States. to estimate policies for a typical city. The goal is to determine the optimal set of policies if they are chosen jointly, and compare them to the outcomes with single policies or with no regulation at all.

To accomplish this goal, the dynamic programming model developed above must be solved for the property value functions empirically. Except for very special cases, these functional equation problems cannot be solved explicitly, but may be approximated to an arbitrary degree of accuracy through numerical computation methods (Dixit and Pindyck). Such a numerical simulation procedure is developed below. In these simulations, as in the theoretical model, the development value of land is assumed to derive from households' bid rent, which in turn depends on income and the reservation utility level. Because the focus is on an "average" urban area, the model abstracts from movements between cities. Instead, urban development as a whole is explained by differences between metropolitan and non-metropolitan opportunities.

In particular, the income variable I is specified as a metropolitan household income, while the reservation utility level u is based on income and consumption in non-metropolitan counties. In short, conversion occurs because there is growth in the urban-rural wage gap. The value of farmland, newly developed land, and property inside a city all conceptually depend on the state variables I and u. By specifying functional forms in a judicious way, the two state variables are combined into a single measure that can be computed from observable data. Each property value function is then interpolated over one state variable that represents the urban-rural opportunity gap.

As the theory predicts, development occurs at some location the first time the state variable crosses some barrier. In addition to approximating the property value functions, the empirical model also generates a value of this conversion barrier that can be compared across the policy scenarios. The optimal development tax is estimated from the approximated value functions, and the pollution tax is computed from an empirical specification of farm technology.

Before the computational model is presented and its results are interpreted, the specification of functional forms and parameter values are described.

Model Specification

To develop an operational simulation model, several empirically tractable functional forms are specified and parameterized. First, a form for the bid rent function ψ is derived from assumptions on utility and income. Second, given this specification of bid rent, it is shown that the property value functions depend on a single variable, and that growth in this variable over time is the trigger for development. The stochastic process for this variable is then specified and estimated. Third, based on estimates from the environmental literature, values are chosen for the unobservable non-market parameters that affect the value of housing. Finally, a functional form for agricultural technology is specified, and its parameters are calibrated to observed data. All parameter values are summarized in Table 1.

For the components of the bid rent function $\psi(I_r, u, a, e)$ (equation (1)), gross income y is specified as metropolitan household income, and the transportation cost function as $T(r) = b_0 + b_1 r$, where b_0 is the (yearly) fixed cost of commuting and b_1 is the cost of commuting an extra mile. Location-adjusted income then becomes $I_r = y - T(r) = y - b_0 - b_1 r$. The values of b_0 and b_1 in Table 1 are based on a fixed toll/parking cost of \$5 per day and a vehicle operation cost of 30¢/mile. Households' utility functions are specified as the money-metric quasilinear form (Mas-Collel et al.): $U(c, s, a, e) = c + \varphi(s) + \gamma a - \delta e$, where c is measured in real dollars of consumption, $\varphi(s)$ is an increasing and concave function that measures the utility of land, γ is the marginal value of farmland amenities, and δ is the marginal social cost of pollution. Because there is relatively little observed variation in lot sizes, they are assumed to be technologically fixed at $\bar{s}$.

Substituting these elements into the definition of bid rent:

$$\psi(I_r, u, a, e) = \max_c \frac{I_r - c}{\bar{s}}$$

$$\text{s.t. } c + \varphi(\bar{s}) + \gamma a - \delta e = u$$

where u is the utility level available in non-metropolitan areas. Because there is only one value of c that satisfies the constraint ($c = u - \varphi(\bar{s}) - \gamma a + \delta e$), bid rent becomes the linear function:

$$\psi(I_r, u, a, e) = (1/\bar{s})(I_r - u + \varphi(\bar{s}) + \gamma a - \delta e).$$

This linear specification can be further simplified by combining I_r and u into a single variable that avoids the need to measure u or $\varphi(\bar{s})$. To accomplish this, let $\bar{c}$, $\bar{a}$, and $\bar{e}$ be the non-metropolitan levels of consumption and externalities per household. Then $u = \bar{c} + \varphi(\bar{s}) + \gamma\bar{a} - \delta\bar{e}$. Substituting this expression into ψ yields a redefined bid rent function:

$$\psi(\hat{I}_r, a, e) = (1/\bar{s})(\hat{I}_r + \gamma a - \delta e)$$

where $\hat{I}_r = I_r - (\bar{c} + \gamma\bar{a} - \delta\bar{e})$. From this redefined function, note that $\psi(\hat{I}_r, 0, 0) = (1/\bar{s})\hat{I}_r$; this specification allows the value of housing to depend on the single state variable $\hat{I}_r$, which is the metropolitan bid rent per household in the absence of agricultural externalities. Empirically, the property value functions F, H_0 and H_1 can then be defined as functions of $\hat{I}_r$, and land conversion is triggered by changes in this variable.

These stochastic changes, in turn, can be estimated from first differences in a series of observations on $\hat{I}_r$. The precise interpretation of $\hat{I}_r$ is the rent paid to land only (i.e., not including the value of housing structures) for housing developments r miles from the city center. Because a land parcel and housing structure are held by the same owner in practice, $\hat{I}_r$ cannot be directly observed, but there are conceptually two different methods for imputing an appropriate series from available data. First, a series could be calculated from the definition of $\hat{I}_r$ above, given observations on (or estimates of) metropolitan income and transportation costs (y and $T(r)$), and non-metropolitan consumption and externalities ($\bar{c}$, $\gamma\bar{a}$, and $\delta\bar{e}$). Alternatively, it may be constructed by adjusting observed metropolitan housing rents to reflect the return to land alone. The second approach is the one adopted here.

Data to estimate average yearly urban rents for two-bedroom housing is available from the Department of Housing and Urban Development for the years 1983-1998. Because typical housing in the United States has three bedrooms,[4] these average rents are adjusted by the ratio of three- to two-bedroom housing values calculated from the 1997 American Housing Survey. Finally, land rent is computed by assuming that 15% of housing rents represent the return to land (Mills and Hamilton). The yearly change in this series is assumed to be normally distributed, and the estimated mean (μ) and standard deviation (σ) of the first differences are reported in Table 1; bid rent at any location grows by an average of $36 per year with a standard deviation of $20.

Focusing on a well-documented and widespread type of agricultural pollution, Peterson et al. reviewed studies that estimate the aggregate health costs from farm chemicals in the United States. Based on population data, these estimates imply costs from about $30 to $70 for an average household, although the costs for households near agriculture are likely to be higher than average. The upper estimate of $70 is therefore taken as the value for damages at the suburban fringe, and it is varied between $50 and $90 (Table 1). Because pollution is measured in dollars of damage, the parameter δ is normalized to unity. Following Peterson et al., pollution (e) is assumed to be a quadratic function of farm inputs: $e = B_e z^2$, where B_e is a technology constant. Since reliable estimates of pollution technology are absent, this function provides a first-order

[4] According to the 1997 American Housing Survey, the median housing unit in the U.S. has 2.7 bedrooms.

approximation to the underlying relationship between marginal damages and farm inputs. The constant B_e is calibrated to the various levels of e based on the quadratic form.

Poe summarizes the estimates of non-market values for farmland amenities from the environmental literature. Studies focused particularly on benefits to households at the suburban fringe (Krieger; Halstead; Bergstrom et al.) have found a household willingness-to-pay between \$10 and \$115 per year. These estimates reflect the net external value of farmland, where survey respondents take the negative value of farm pollution into account. The evidence thus suggests a gross non-market value of \$60 to \$225; the parameter γ is set at a base level of \$150 and varied throughout this range.

Based on aggregate output, input, and price series from the USDA-ERS (Ahearn et al.), Peterson et al. calibrated a constant returns to scale production function for the aggregate U.S. agricultural sector. The calibrated function expressed agricultural output as a function of land and non-land aggregates. By constant returns to scale, the production function for a typical acre can be derived by taking the ratio of inputs and output to land. The resulting function is of the form $q = B_q z^{\alpha}$, where q expresses farm output per acre in value terms, B_q is a technology constant, and α is the production elasticity of non-land inputs. The agricultural return to land can then be written $B_q z^{\alpha} - (w + T_z)z - C$, where w is the price of non-land inputs and C is the return to productive factors other than land and non-land inputs (capital and labor). The values of the parameters α, B_q, w, and C in Table 1 are calibrated based on the USDA price and input series.

The remaining parameters in Table 1 are the conversion cost of development k and the discount factor β. The conversion cost is imputed from the difference in land rents for farming and residences in rural areas, assuming an infinite time horizon and irreversibility of development.[5] The discount factor assumes an annual discount rate of 10%.

Computational Method

Several numerical methods have been developed for approximating the value functions in dynamic programming problems. One common procedure is space discretization, where a large set of discrete points are selected for a continuous state variable, and the maximization inherent in the Bellman equation is performed at each of these points. This method can approximate value functions of any shape, but to guarantee an accurate approximation the set of state points must be very large; especially if future realizations of the state variable are uncertain, the number of computations required can be prohibitive. Another frequently used method is linear-quadratic approximation, where the value function is approximated by a second-order polynomial. Here, the number of computations is smaller, but the approximant is not flexible enough for functions with discontinuities irregular shapes.

To overcome these difficulties, Miranda and Fackler suggest that numerical functional equation problems be solved by collocation methods, which can find a close approximation to an arbitrary function with a limited number of computational steps. Here, the property value functions are approximated using a linear spline collocation procedure. To illustrate this method, consider approximating an arbitrary value function $v(x)$ that satisfies the canonical Bellman equation $v(x) = \max_X \{f(x, X) + \beta Ev(x')\}$, where $x' = h(X, \varepsilon)$, and ε is a random variable that

[5] In particular, average rents to farmland and rural developed land are calculated for the years 1985-1994 based on farm cash rent data from USDA/ERS, and the American Housing Survey, respectively. Based on new construction cost and sales data, Mills and Hamilton report that the value of land represents about 15% of rents paid for housing services. Decomposing non-metropolitan rents in this way and assuming lot sizes of 0.35 acres, developed land received an average yearly rent of \$2130 in excess of agricultural rent per acre per year. This differential represents the return to the capital investment of conversion. Assuming an infinite time horizon, irreversibility, and a discount rate of 10%, the capitalized value of this conversion cost is \$21,300 per acre, as reported in Table 1.

represents noise. Here, x is the state variable, X is the control variable, and x' is the (random) value of the state variable next period. The approximation of $v(x)$ is written:

$$(10) \qquad v(x) \approx \sum_{j=1}^{J} \phi_j(x) m_j$$

where $\phi_1,\ldots,\phi_J$ is a series of linear spline functions and $m = (m_1,\ldots,m_J)$ is a set of weights that must be determined. The approximant is thus a linear combination of J functions. Geometrically, linear splines approximate a function by a set of $J - 1$ linear segments between J uniformly spaced breakpoints in some specified interval, where the segments are spliced together to preserve continuity at all the breakpoints.[6]

In the collocation method, one begins by specifying a domain of x where the function will be approximated and selecting a set of J points in the domain, called collocation nodes, where (10) is required to hold exactly. By convention, the nodes for linear spline functions are set at the J uniformly spaced breakpoints to optimize computational cost (Miranda and Fackler). Once the weight vector m has been determined, the approximant can be evaluated at an arbitrary non-node point x_0 by calculating $\sum_{j=1}^{J} \phi(x_0) m_j$. The unique vector m that satisfies the Bellman equation at nodes $x_1,\ldots,x_J$ solves the system of J equations:

$$\sum_{j=1}^{J} \phi_j(x_i) m_j = \max_{X_i} f(x_i, X_i) + \beta E \sum_{j=1}^{J} \phi_j(h(X_i, \varepsilon)) m_j\,, \qquad i = 1,\ldots,J$$

To evaluate the expectation, a series of discrete points $\varepsilon_1,\ldots,\varepsilon_N$ in the domain of the random variable are selected, and their probabilities $P_1,\ldots,P_N$ are calculated from the relevant

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[6] For J uniformly spaced breakpoints $\omega_1,\ldots,\omega_J$ on an interval $[a, b]$, the jth linear spline function is:

$$\phi_j(x) = \begin{cases} 1 - |x - \omega_j| / d & \text{if } |x - \omega_j| \le d \\ 0 & \text{otherwise} \end{cases}$$

where $d = (a - b)/(J - 1)$.

cumulative distribution function. The expectation in the ith equation can then be written explicitly as: $\sum_{n=1}^{N}\sum_{j=1}^{J}\phi_j(h(X_i,\varepsilon_n))m_j P_n$.

The collocation method finds the m vector by successive approximations. That is, it begins with some guess $m^{(0)}$ (which in turn implies some guess for the value function), and solves the maximization on the right side of the Bellman equation for each collocation node x_i. The maximized value becomes a new guess for the value function at each node and is used to update the guess for m. Letting $x = (x_1,\ldots, x_J)$ be the vector of collocation nodes, and $v^{(1)}(x)$ represent the vector of new guesses for the value function (i.e., $v^{(1)}(x) = (v^{(1)}(x_1), \ldots, v^{(1)}(x_J))$, the updated guess of weights $m^{(1)}$ is the solution to the system: $v^{(1)}(x) = \Phi m^{(1)}$, where the (i, j)th element of Φ is $\phi_j(x_i)$. In the next iteration, $m^{(1)}$ is used as the original guess to calculate a new set of guesses for the value function $v^{(2)}(x)$, which in turn is used to find a new guess of weights $m^{(2)}$. This process continues until convergence, when the change in guesses falls below some small tolerance level. As long as $\beta < 1$ and the functions f and h meet certain technical conditions, the Contraction Mapping Theorem guarantees that such a procedure will converge to the unique value function (Stokey and Lucas).

The collocation method is used to approximate the value of housing property inside the city (H_0), the value of farmland and newly developed land (H_1), and the value of farmland (F) under four different policy scenarios: (a) socially optimal joint policies, (b) an unregulated equilibrium (no policies), (c) an input tax only, and (d) a development tax only. Each model is coded and solved the in Matlab 5.3, with a convergence tolerance level of 10^{-8}. $J = 200$ collocation nodes for the state variable $\hat{I}$ are specified over the range [0, 1000], and $N = 160$

discrete values for the normally distributed change in income and their associated probabilities are calculated by Gaussian quadrature (Gerald and Wheatley).[7]

Each policy setting is solved in three steps. First, to calculate farm input levels, the functions $B_q z^{\alpha} - (w + T_z) - C$ is maximized, where T_z is set either to the internalizing level $-\psi_e g_z = 2B_e z$ (cases (a) and (c)) or zero (cases (b) and (d)). Farm profits π are then set to the maximized value of the objective function, pollution is calculated from the optimal input level according to the quadratic emissions function $e = B_e z^2$, and the bid rent of newly developed land is set to $\psi_1 = \hat{I} - \gamma - e$. In the model, ψ_1 is represented by a $J \times 1$ vector that measures the housing return at each collocation node of $\hat{I}$.

Second, the value of property inside the city H_0 is interpolated in a loop. By definition, the fixed point of this function satisfies: $H_0(\hat{I}) = \psi_0(\hat{I}) + \beta E H_0(\hat{I}')$; like ψ_1, H_0 and ψ_0 are J-vectors that represent property value and housing returns, respectively, at each node of $\hat{I}$ (note that the $\psi_0 = \hat{I}$ by construction of $\hat{I}$). For some guess of H_0, the vector m satisfies $H_0 = \Phi m$; an updated guess can be calculated by: $H_0' = \psi_0 + \beta E H_0$, and m is updated by solving $H_0' = \Phi m'$. The process continues until the norm of $m' - m$ is less than 10^{-8}.

Third, another loop jointly interpolates the value functions for housing property on the edge of the city and farmland (H_1 and F, respectively). The fixed points of these functions must satisfy the functional equations in (2) and (3) and the development rule in (9), where T_D equals either the optimal tax (cases (a) and (d)) or zero (cases (b) and (c)). Beginning with any set of guesses F and H_1, the algorithm searches for the smallest node of $\hat{I}$ where (9) is satisfied; i.e., at this critical node $\hat{I}_{\text{dev}}$, $H_1 = k + \pi + \beta E H_1 + T_D$. In the cases where T_D is nonzero, it is set to $T_D =$

[7] Thus, $E[\hat{I}_{r+1,t+1}] = \hat{I}_{r+1,t} + \Sigma_n \varepsilon_n P_n$, where the pairs (ε_n, P_n) are points on a normal density function with mean μ and standard deviation σ.

$H_1(\hat{I}_{\text{dev}} + b_1) - H_0(\hat{I}_{\text{dev}} + b_1)$.[8] At any node less than $\hat{I}_{\text{dev}}$, the updated guess for F is determined by $F' = \pi + \beta EF$, while at and above $\hat{I}_{\text{dev}}$, $F' = H_1$.[9] Since H_1 becomes H_0 at $\hat{I}_{\text{dev}} + b_1$, the updated guess is $H_1' = \psi_1 + \beta EH_1$ at nodes below $\hat{I}_{\text{dev}} + b_1$ and $H_1' = H_0$ for those above it. As in the first loop, the fixed points of F and H_1 have been found when the changes in successive guesses is small.

Results

Table 2 provides the results for the four simulations at base parameter values. As one would expect, if policies are chosen jointly (the socially optimal case), both taxes are positive ($1.12/lb. and $730/acre for the input and development taxes, respectively). From farmers' perspective the policies are quite dramatic: Compared to the unregulated case, the tax on non-land input more than doubles the effective price, forcing farmers to reduce input levels by more than two-thirds (17 vs. 46 lbs.), and decreasing farm returns by about one-third ($29 vs. $41). If farmland were never developed, its value would be an infinite stream of discounted farm returns; for a discount rate of 10%, this capitalized use value falls by the same factor as yearly return, from about $450 to about $320 per acre. When farmland is developed, the owner would be assessed a tax that is roughly double the agricultural use value.

On the other hand, because conversion costs are so high, the substantial effects on agriculture do not have much leverage in changing the value of developed land or the time of conversion. Just before farmland is converted, nearly all its value (97%) is from the option of developing. The stopping value of household bid rent where development occurs differs by

[8] In the year that $\hat{I}_{r+1}$ reaches $\hat{I}_{\text{dev}}$ and development occurs, the amenity benefits of ring r are lost. Because $\hat{I}_r$ that year is $\hat{I}_{\text{dev}} + \Delta T = \hat{I}_{\text{dev}} + b_1$, the appropriate development tax is $H_1(\hat{I}_{\text{dev}} + b_1) - H_0(\hat{I}_{\text{dev}} + b_1)$.

[9] To avoid the large discontinuity between F and H_1, the model actually interpolates $F^+ = F + k + T_D$ so that $F^+ = H_1$ in the vicinity of conversion. The updating rule for F^+ (below $\hat{I}_{\text{dev}}$) then becomes $F^{+\prime} = \pi(z^*) + (1 - \beta)(k + T_D) + \beta EF^+$.

about $40 between the two cases; based on an expected yearly increase of $36 (Table 1), this difference implies that conversion times are expected to differ by only one or two years. Interestingly, the smaller conversion barrier under social management implies that land should be developed earlier. Even though the development tax adds another cost to conversion, it is apparently outweighed by the extra benefit of reduced pollution.

The individual effects of the policies are exposed in the last two columns. If the input tax is imposed alone, it is identical to the socially optimal case ($1.12). Accordingly, the effect on input prices, input levels, agricultural returns, and pollution is also the same. Unlike the social optimum, there is no development tax to deter conversion, and compared to the unregulated case, the development barrier is reduced by $60 to $663.

If there is no input tax but a development tax instead, inputs, farm returns, and pollution levels are the same as the unregulated equilibrium. The development tax is smaller than the joint policy case ($348 vs. $730) because higher levels of pollution reduce the return to developments near agriculture, and the loss of farm activity therefore imposes a smaller cost on those residents. Starting from an unregulated economy, this development tax raises the conversion barrier by $16 to $739. Consistent with intuition, the two taxes work in opposite directions, but the marginal effect of the development tax is smaller than that of the input tax. It is therefore not surprising that the overall effect of joint policies is to lower the development threshold.

Peterson reports the optimal and unregulated simulation results at alternative parameter values that vary over the ranges in Table 1. As one might expect, changes in environmental values have a direct effect on the size of optimal policies. The different levels of pollution damage vary by about 30% from the base case and generate input taxes that vary from the base by about 20%. The high and low amenity values represent a 50% increase and a 60% decrease from the base level, and lead to about a 70% increase and 80% decrease in development taxes, respectively. On the other hand, these substantial policy changes have relatively less effect on farm returns, pollution, and the development barrier, which differ from their base values by no more than 10%, 5%, and 15%, respectively.

Across the four cases, the optimal development barrier is only \$20 to \$60 below the free market barrier, but the policies affect farmers more than developers. Even at the lowest specification of pollution damages, the input tax rate is about 90%, causing input levels to fall by more than half; the lowest amenity value still generates a development tax that is more than half the use value farmland. Thus, the two most important qualitative results appear to be robust: a social manager will convert land earlier than free markets, but the change in development patterns is small compared to the effect on farmers.

Figures 3 and 4 show the interpolated value functions at base parameter values for the optimal and unregulated cases, respectively. When bid rent values are low, land remains in farming, but its value (F) appreciates because of the steadily increasing option value of developing. At the threshold level of bid rent where development occurs (\$683 and \$723 for the two cases, respectively), H_1 becomes the relevant value function; it measures the property value of newly developed land that is still adjacent to agriculture. The discontinuity between F and H_1 reflects conversion cost and development taxes. The second discontinuity in the functions is when the adjacent agricultural land is also developed and agricultural externalities disappear. From then on, the property value becomes H_0.

Conclusions and Policy Implications

This chapter has determined the optimal development pattern for farmland by considering both the multifunctional and dynamic nature of land use. When agriculture generates pollution as well as amenity benefits, the policy rules to correct the two externalities are standard results: polluting farm inputs should be regulated so that their marginal benefit in production equals the marginal social cost of pollution, and development should be taxed by the amount it reduces the value of nearby property.

Yet, when these rules are applied together and the irreversibility of development is taken into account, the final result can contradict conventional wisdom. In particular, this chapter has demonstrated both the theoretical and empirical possibility that unregulated markets remove land from agriculture too slowly. Conceptually, optimal policies will speed the rate of farmland conversion if the added value of developing land next to "cleaner" agriculture outweighs the burden of development taxes. Simulations based on data from major U.S. metropolitan areas predict such an outcome over a large range of environmental parameters.

In a growing city with expanding housing needs, development at some location may be optimally delayed, but not stopped indefinitely. Agricultural land just beyond the urban fringe only affect nearby developments until it too is developed; an optimal set of policies that speeds conversion thus allows new suburban residents to enjoy a higher quality agricultural landscape slightly earlier.

In practice, the multiple externalities from agriculture are addressed separately. Local zoning requirements, state land retention programs, as well as federal environmental laws regulate farmland choices in any community. Often, the environmental provisions are not targeted specifically to mitigate the forms of pollution that are most costly at the suburban fringe.

In some cases, communities attempt environmental controls of their own. In others, the private market eliminates some of the problem because low polluting operations, such as organic farms or community supported agriculture, provide outputs of high value to the surrounding community. When the environmental quality of farmland is improved, we are likely to observe a faster rate of development, and farmland retention goals may become more difficult to meet. Our results imply that such a change is not surprising, nor may it be a reason for serious concern.

Because the returns to housing are so much higher than those from farming and conversion costs are so large, farm policies in general do not have much leverage in influencing land use. Our empirical simulations suggest that even very large farm policies (taxes that are several hundred percent of pre-policy prices) will cause the development timing at any location to change by no more than a few years.

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Table 1. Parameter Values

Parameter	Symbol	Base Value	Range
Fixed cost of metropolitan commuting ($/year)	b_0	1200	
Commuting cost per mile ($/year)	b_1	144	
Mean growth in metropolitan bid rent ($/year)	μ	36.1	
Standard Deviation ($/year)	σ	19.7	
Value of farmland amenities ($/year)	γ	150	60-225
Cost of agricultural pollution ($/year)	e	70	50-90
Pollution technology constant	B_e	0.035	0.024-0.043
Production elasticity of non-land inputs	α	0.29	
Agricultural technology constant	B_q	56.33	
Price of non-land inputs ($/lb)	w	1.08	
Cost of farm labor and capital ($/acre)	C	80.67	
Conversion cost of development ($/acre)	k	21,300	
Discount factor	β	0.91	

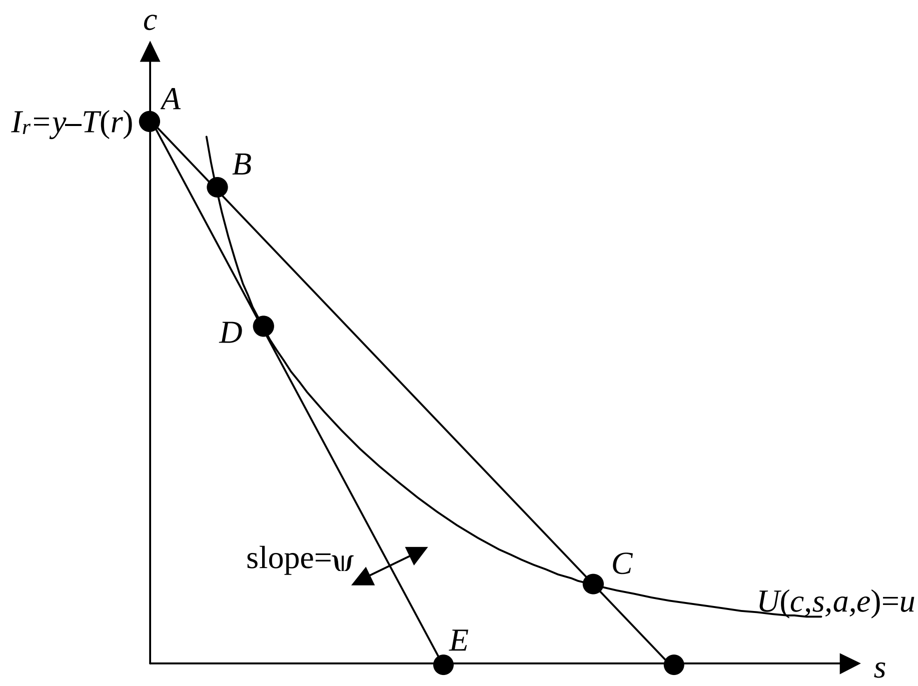

Figure 1. Geometry of Bid Rent

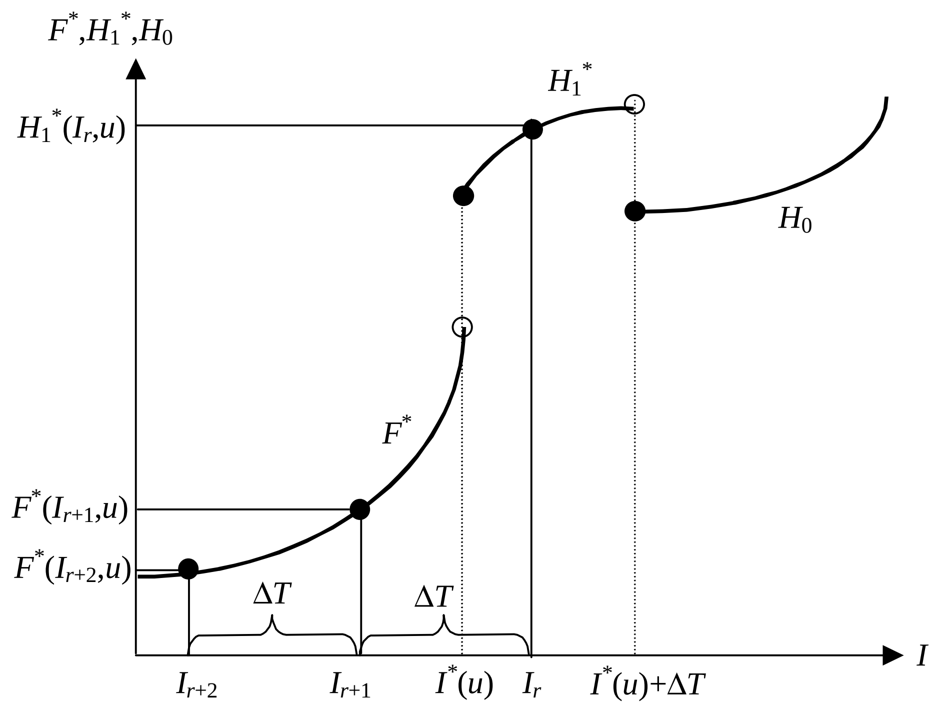

Figure 2. Fixed Point Property Value Functions

Table 2. Simulation Results, Base Parameter Values

Item	Social Optimum	Unregulated Equilibrium	Input Tax Only	Dev. Tax Only
Input tax($/lb)	1.12	0	1.12	0
Input price (including tax, $/lb)	2.20	1.08	2.20	1.08
Development tax ($/acre)	730	0	0	348
Non-land farm inputs (lb./acre)	16.9	45.9	16.9	45.9
Agricultural pollution damage ($/household)	9.43	70	9.43	70
Bid-rent conversion barrier ($/acre)	683	723	663	739
Return to farmland ($/acre)	28.92	40.66	28.92	40.66
Use value of farmland ($/acre)	318	447	318	447
Farm property value at time of conversion ($/acre)	12195	13538	12273	13639
Option value of development ($/acre)	11876	13090	11955	13192

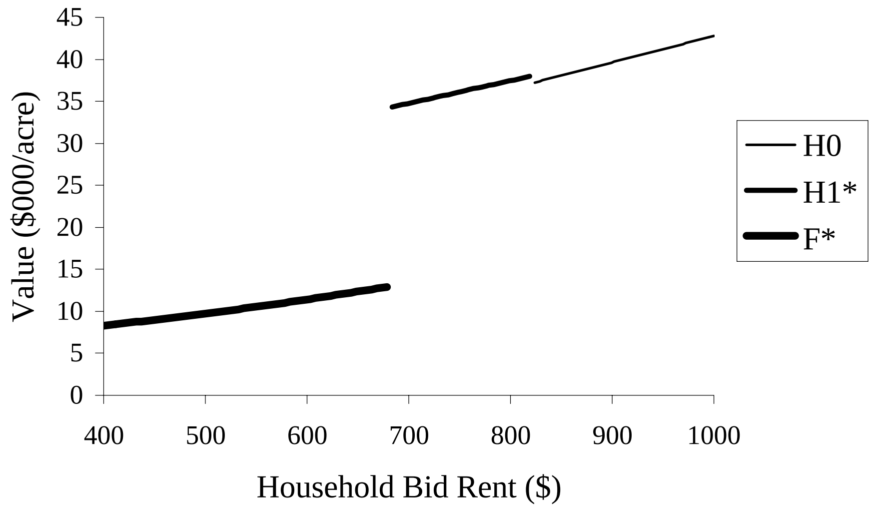

Figure 3. Socially Optimal Value Functions

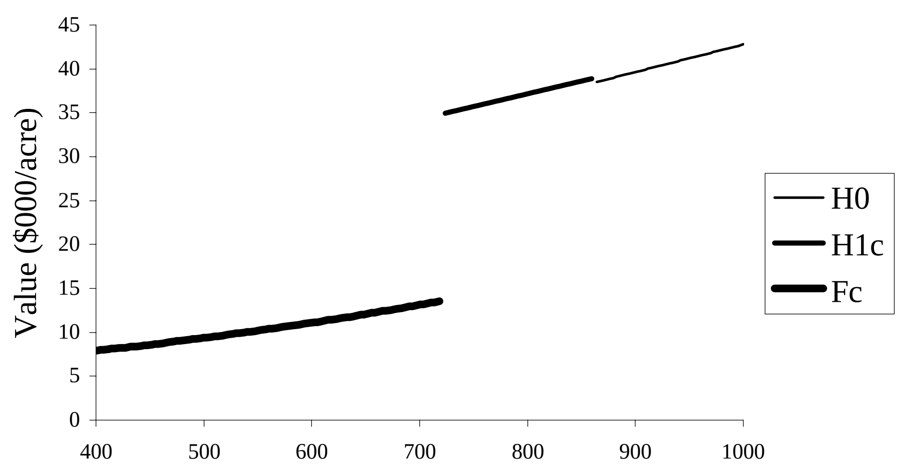

Figure 4. Value Functions in Unregulated Equilibrium