

On Exurban Development*

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Abstract

In the US, exurbia, the rural areas beyond the sewer served suburbs, is being developed with attendant denial of habitat for many species. This paper shows how exurbia can be developed for housing at the same time as the urban area, so that development occurs in widely separated areas. Exurban development is characterized by the use of septic systems so the parcel sizes are larger than average suburban parcels. The paper shows that, even absent any land heterogeneity or amenity values, consumers with higher than average income or taste for land can advantageously settle far from the suburban boundary. The paper analyzes a new case for dynamic urban models in which the high taste for land agent is in limited supply. Such agents are shown not to have to pay their whole bid rent and hence have an added advantage in exurban location.

Keywords Exurbia, Dynamic Urban Model

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1. Introduction

Empirical studies have shown that the zone of exurban development within the United States is much larger than the combined footprint of urban and suburban development (Heimlich and Anderson [11], Sutton et al. [19]). Although the majority of people in the United States live in urban and suburban areas (Nechyba and Walsh [15]), these land uses only occupied approximately 1.9% of the land area in 1992 (Burchfield et al. [5]).¹ Sutton et al. [19] recently used nighttime satellite imagery, obtained from the US Department of Defense's Meteorological Satellite Program, to detect the extent of low-density exurban development. They found that exurban development occupies 14% of the land area in the United States. Heimlich and Anderson [11] used Census data from the Annual Housing Survey and found that "nearly 80% of the acreage used for recently constructed housing is land outside urban areas. Almost all of this land (94%) is in lots of 1 acre or larger, with 57% on lots of 10 acres or larger (i.e., 10-22 acres)." Because septic systems allow individual homes to be noncontiguous, exurban development is more likely to be intermixed with agricultural uses and have characteristics associated with sprawl, such as low-density and fragmented patterns. Exurban development has also been recognized to pose a greater challenge to the protection of farmland (Heimlich and Anderson [11]) and biodiversity (Hansen et al. [10]), compared to suburban and urban development.

This paper presents a novel theory of exurban development, based upon heterogeneity of people and a relative paucity of the types who prefer exurban living. As a description of the

¹ The estimate of the urban footprint reported in Burchfield et al. [5] is based on land-cover classifications derived from LANDSAT satellite imagery. But LANDSAT imagery relies on reflected sunlight during the daytime and, thus, can only detect suburban development at higher density (> 1 unit per acre). This detection threshold, coincidentally, is the same as the density restriction for residential use with septic systems. LANDSAT imagery, therefore, cannot distinguish exurban development at lower density (< 1 unit per acre) from extensive land uses (e.g., agriculture, forestland, ranchland).

exurban phenomena, the theory depends upon two observations of the exurban phenomena. First, exurban lot sizes must be bigger than an acre and are often multiples of that. In exurbia, there is no sewer service and so public health requires substantial separation of septic and water systems. Second, exurbia is characterized by mixed usage. One finds working farms next to exurban residences and one finds this pattern even in places devoid of obvious amenities, like lakes or views. Since exurbia exists without land heterogeneity, we build our model on heterogeneity of people.

There is an extensive literature on dynamic models of urban growth to explain phenomena, such as leapfrog development, which were not possible using the static models by Alonso [1], Mills [13] and Muth [14].² The reason is that static models assume malleable capital, which means that the city is implicitly rebuilt at each period; and therefore, there can be no advantage from holding vacant land within a city.³ In contrast, early explanations of leapfrog development assumed both durable capital and perfect foresight (Ohls and Pines [17], Mills [12], Fujita [9], Wheaton [22], Turnbull [20], Braid [2, 3]). For example, Ohls and Pines [17] used these assumptions in a simple model with two land uses and two periods. They demonstrate why land inside the urban area may be withheld from early development as a result of intertemporal decision making in a growing city. Mills [12] later extends the idea in Ohls and Pines [17] by incorporating uncertainty and heterogeneity into the expectations of developers. Wheaton [22] similarly assumes perfect foresight and durable capital, but this model has multiple time periods, which allows for changing conditions in income, commute costs, and population. Interestingly,

² See Brueckner [4] for an extensive review of the urban growth models with durable capital.

³ One exception for leapfrog development in a static model is the paper by Wu and Plantinga [23]. They are able to analytically derive residential patterns of leapfrog development, resulting from the influence of public open space (e.g., parks). Essentially, public open space provides amenity values, which forms another attractant to local residents other than employment at the central business district. This paper and Turner [21] rely on household preferences for landscape amenities to explain leapfrog development patterns.

Wheaton [22] provides scenarios for urban growth in which development occurs from the edge of the city inward. This sequencing pattern of “outside-in” development occurs under conditions of sufficiently increasing commute costs or decreasing income through time. This result is significant because it shows that leapfrog development can be a pareto efficient market outcome.

Dynamic models of urban growth also have implications for the price of land. Capozza and Helsley [6] address the influence of population growth on the price of urban land. In this model, there are two land uses, agriculture and urban residential use, but lot size is fixed for residential development.⁴ They demonstrate that population growth in an urban area increases the price of urban land due to a growth premium derived from the expected future rent increases. Hence, when the growth premium is taken into account, the price of land at the urban boundary (minus conversion costs) exceeds the value in agriculture use.

In this paper, we analyze a dynamic model in which two production technologies exist for residential development—municipal sewer service for suburban development and septic systems for exurban development. Our purpose is to incorporate the cost structure of sewer versus septic production technologies in order to explain the feasibility of exurban leapfrog development. We assume that agricultural landowners have perfect foresight, and residential conversion decisions are irreversible. In this dynamic setting, agricultural landowners consider two alternatives for residential conversion. For suburban development, sewer extension costs are needed to connect a distant agricultural property to the existing sewer and water infrastructure at the city boundary. These additional sewer extension costs, or the waiting time until population growth causes the city boundary to expand and service this area, can significantly reduce the value of agricultural land in suburban use. Exurban development, while at lower density, requires

⁴ The model in Capozza and Helsley [6] is essentially a special case of the model in Wheaton [22] because the latter model allowed density to be variable. However, by assuming a fixed lot size, Capozza and Helsley [6] are able to provide interesting analytical results on urban land values.

only the onsite conversion costs. Hence, the land value in exurban use is not discounted by the waiting time until city expansion or decreased by the sewer main extension costs. Our model is closely related to Capozza and Helsley [6].⁵ However, we consider two residential alternatives and two types of households that differ only in their willingness to pay (WTP) for a larger lot size. In this manner, our model resembles the earlier works by Ohls and Pines [17], Mills [12] and Braid [2], except that we explain mechanistically why sewer versus septic production technologies are essential to understand the residential development process in the urban-rural fringe. In fact, our paper is the first, to our knowledge, to incorporate these two housing production technologies into an analytical model of residential development.

Three main results are found from the analytical model and simulation results. First, we show that the gradient of land values in suburban use is discontinuous at the municipal service boundary. Inside the boundary, the value in suburban use declines from the CBD due to commute costs only; whereas, there are both commute costs and sewer extension costs for areas outside the municipal service boundary. Hence, suburban leapfrog development, which prematurely extends sewer service beyond the city boundary, is considerably more expensive than optimal suburban development at the city boundary. Second, the land value in suburban use declines rapidly from the city boundary into the agricultural areas, especially for smaller cities and when the ratio on the discount rate to radial city growth rate is large. The WTP for exurban development may therefore exceed the agricultural landowner's reservation price on future suburban development for a range of distances from the existing city boundary. This range defines the feasible zone for exurban leapfrog development. Lastly, a household with a higher WTP for lot size can afford to live in exurbia but only during the early phases of city

⁵ Our model and Capozza and Helsley [6] both assume that rents are certain. This is a simplification of the model in Capozza and Helsley [7] in which uncertainty in rents is introduced.

development. While the city is still small, the additional land and commute costs required to live on an exurban lot, compared to a suburban lot at the city boundary, represent a relatively small portion of household income. But these additional costs increase rapidly through time as the city becomes larger, thereby decreasing the ability to afford to live on an exurban lot. Therefore, as the city evolves, there will eventually come a time when exurban development is no longer feasible at any location.

2. The model

2.1. Value of agricultural land in suburban use

In this section, we explain our baseline model, which follows the Capozza and Helsley [6] model (hereafter, CH model). In contrast to their focus on the land value within the city area, our emphasis is to derive the land value for the area outside the existing city area. We extend the CH model by considering sewer main extension costs as part of the suburban conversion costs.

The land area is located on a homogeneous plain with a monocentric city. Locations are indexed by their distance x from the central business district (CBD). There are $n^s(t)$ identical suburban households with income y , who all commute to work at the CBD incurring a constant cost per unit distance of k . Suburban households derive utility from the consumption of a composite numeraire good z and a fixed lot size q^s . The growth of future suburban development requires the centralized infrastructure, particularly sewers, to be extended radially. The radial extent of the suburban area at time t is $x^s(t)$.

The land improvement cost to convert from agriculture to suburban use has two components. First, there are the onsite improvement costs per area, C^{so} . This includes the fixed costs to establish roads, sidewalks, street lighting, and onsite sewer and water connection lines

within the property. Second, there are sewer main extension costs. Consider an agricultural parcel located at some distance beyond the current city boundary, $x > x^s(t)$. In this case, additional fixed costs are incurred to extend the sewer main lines from the property site to the existing sewer and water infrastructure at the city boundary. These costs would be

$C^{sm}(x - x^s(t))$ at location x , where C^{sm} is the cost per unit distance for extending the sewer main lines. If the property has land area, L , then the number of suburban homes being served will be $N = L/q^s$. On a household basis, the sewer main extension cost per unit distance will be $C^{sm}q^s/L$. But the rent functions, here, are expressed on a per-area basis, and therefore, the total improvement costs per area for converting land to suburban use at distance x and time t are

$$C^s(x, t) = C^{so} + \frac{C^{sm}}{L}(x - x^s(t)), \quad x > x^s(t) \quad (1)$$

and C^{so} otherwise.⁶

Suburban rent, $R^s(x, t)$, is the payment per area at time t for land improved for suburban use at location x . From the budget constraint, the consumption of the numeraire good is $z(x, t) = y - R^s(x, t)q^s - kx$. The numeraire good, therefore, includes the housing structure component; whereas, the suburban rent includes the land and improvement components.⁷ By assumption, suburban households at the city boundary must be equally well off as suburban households residing at any other location within the city area,

⁶ Note that C^{so} includes sewer main extension costs at the margin. We also assume that, if a developer decides to extend sewer lines well beyond the city boundary at the present, then they bear the full costs of this sewer infrastructure. For example, consider a developer who decides to extend the sewer lines one mile from the current city boundary. Future developers are then able to freeride on this sewer infrastructure if they eventually create infill suburban development. As shown below, it is not optimal to extend sewer lines significantly beyond the current city boundary, even if the developer today only bears part of the costs to extend sewer main lines. So a more general interpretation of C^{sm} is the portion of sewer extension costs per unit distance that the developer today must incur.

⁷ Hence, the model focuses on the expenditure required for an improved lot while the remaining income spent on other goods and housing structure is incidental to the analysis.

$U^s [z(x, t), q^s] = U^s [z(x^s(t), t), q^s]$ for $x \leq x^s(t)$. Hence, the suburban rent at any location must satisfy

$$R^s(x, t) = R^s(x^s(t), t) + \frac{k}{q^s}(x^s(t) - x). \quad (2)$$

When landowners have perfect foresight and land markets are competitive, then the price of land equals the present value of anticipated rents. The agricultural landowner's conversion decision at location x is made to maximize the present value of land. The present value, at time t_0 , of agricultural land that will be converted to suburban use is

$$V^{as}(x, t_0) = \max_t \left\{ \int_{t_0}^t R^a e^{-r(z-t_0)} dz + \int_t^\infty R^s(x, z) e^{-r(z-t_0)} dz - C^s(x, t) e^{-r(t-t_0)} \right\}, \quad (3)$$

where r is the discount rate and R^a is a constant agricultural rent. Let t^s be defined as the optimal suburban conversion time. Equation (3) is analogous to Eq. (7) in the CH model. The first term in Eq. (3) is the present value of agricultural use at time t_0 until the suburban conversion time t^s . The second term is the present value of suburban use from the time of conversion onward. The last term is the cost of suburban conversion, $C^s(x, t)$, discounted to the present. The suburban conversion decision is assumed to be irreversible (i.e., no redevelopment).

The optimal conversion time is either t_0 or is given by the first-order condition for the maximization of the value in Eq. (3) with respect to time t

$$R^s(x, t) - R^a - rC^s(x, t) = 0, \quad x \geq x^s(t). \quad (4)$$

Because the suburban rent in Eq. (2) decreases with distance and the sewer extension costs in Eq. (1) increase with distance, the left-hand side of Eq. (4) must decrease with distance x . Therefore, it is only optimal to develop at a single distance at a given time. If that location of suburban development were to occur beyond the city boundary, then it would have been optimal to have

developed at the boundary earlier. This is a contradiction, and thus, suburban development occurs optimally at the current city boundary, $x^* = x^s(t)$.⁸ In other words, suburban leapfrog development is always suboptimal.

Given that suburban development occurs at the boundary, then Eq. (4) simplifies and defines the implicit function for the optimal growth path of the city boundary, $x^s(t)$. The suburban rent at the city boundary is

$$R^s(x^s(t), t) = R^a + rC^{so} \quad (5)$$

indicating that it equals the foregone agricultural rent plus the cost of borrowing capital for onsite land improvements.

Sewer main extension costs also create a discontinuity in the suburban rent gradient at the city boundary. By substituting the boundary condition from Eq. (5) into Eq. (2), the suburban rent function within the city area is

$$R^s(x, t) = R^a + rC^{so} + \frac{k}{q^s}(x^s(t) - x), \quad x \leq x^s(t). \quad (6)$$

In contrast, the returns to land in suburban use for a developer who wants to convert a distant agricultural parcel beyond the city boundary at the present time t is

$$R^s(x, t) = R^a + rC^{so} + \left(\frac{k}{q^s} + \frac{rC^{sm}}{L} \right) (x^s(t) - x), \quad x > x^s(t). \quad (7)$$

The new term, rC^{sm}/L , is the developer's opportunity costs of capital on sewer extension, which reduces the returns in suburban use. When taking the derivative of these functions with respect to distance x , we obtain the suburban rent gradients $-k/q^s$ for $x \leq x^s(t)$ and $-k/q^s - rC^{sm}/L$ for

⁸ This condition would be met even if one solely considers the commute costs because the suburban lot size is fixed. Nonetheless, as will be shown below, it is important to recognize that the land value in suburban use declines more steeply with distance when the sewer extension costs are taken into account.

$x > x^s(t)$. The fundamental result is that the suburban rent gradient is steeper outside the city boundary because there are both sewer extension costs and commute costs. Suburban leapfrog development, therefore, will be considerably more expensive compared to optimal development at the city boundary.

In order to determine the maximum value of agricultural land in suburban use, we substitute the suburban rent function from Eq. (6) into the value function in Eq. (3). This suburban rent function increases as the city boundary increases, which, in turn, must expand to accommodate the exogenous population growth of suburban households, $n^s(t)$. Because suburban households each consume lot size q^s , the land area needed to accommodate all suburban households is $n^s(t)q^s$. Let η represent the proportion of the city area in suburban use.⁹ In equilibrium, the radial extent of the city boundary, assuming a circular city, would be equal to

$$x^s(t) = \left(\frac{n^s(t)q^s}{\eta\pi} \right)^{1/2}.$$

In the CH model, they derive the closed-form solution for land value, rent, and the city boundary for the case of exponential population growth at rate g . While their primary aim was to determine the value within the city area, our purpose below is to derive the land value for the area outside the city area. The population of suburban households is

$$n^s(t) = n^s(t_0)e^{g(t-t_0)}, \quad (8)$$

where $n^s(t_0)$ is the initial suburban population at time t_0 . The radial growth path of city boundary is

⁹ Here, we consider that there is only one type of residential use (i.e., suburban development), which occupies the entire city area $\eta = 1$. Later in this paper, when we discuss exurban development, we will consider cases in which the proportion of the city area in suburban use is less than one.

$$x^s(t) = x^s(t_0) e^{g(t-t_0)/2}, \quad (9)$$

where the initial city boundary is $x^s(t_0) = \left(\frac{n^s(t_0) q^s}{\eta \pi} \right)^{1/2}$. The suburban rent function in Eq. (6) is

made explicit by substituting the exponential city growth path from Eq. (9). Because new suburban households optimally locate at the city boundary, the city growth path in Eq. (9) may be inverted to determine the optimal conversion time

$$t^s(x) = t_0 + (2/g) \ln(x/x^s(t_0)), \quad x \geq x^s(t_0). \quad (10)$$

Hence, the maximum value of agricultural land in suburban use at time t_0 for the optimal city growth path is

$$V^{as}(x, t_0) = \frac{R^a}{r} + \left(\frac{x}{x^s(t_0)} \right)^{-2r/g} \frac{kgx}{2q^s r(r-g/2)}, \quad x \geq x^s(t_0). \quad (11)$$

This expression has two components for the net present value of exclusively agricultural use (first term) and the value of development rights in suburban use (second term), labeled the “growth premium” in the CH model. The growth premium is largest at the city boundary. But it declines away from the boundary, particularly when there is a large ratio between the discount rate to the city radial growth rate.¹⁰ Note that the factor $\left(x/x^s(t_0) \right)^{-2r/g}$ is the discount factor, $e^{-r(t^s-t_0)}$. But here we have substituted the optimal suburban conversion time in Eq. (10) so that the discount factor is written in terms of distance x . The intuition is that the growth premium depends on distance x in two ways, the commute costs and also the time until the city expands and provides municipal services into this area.

¹⁰ It is a necessary condition that the discount rate exceeds the radial growth rate, $r > g/2$, in order for the land value in suburban use to be bounded.

We now determine the land value for suburban leapfrog development, as a comparison to the maximum value in suburban use. In this case, a developer must incur additional sewer extension costs, according to Eq. (1), in order to convert a distant agricultural parcel, located at $x > x^s(t_0)$, at the present time. Additionally, the suburban households at this distant location x would have to pay additional commute costs, relative to suburban rent in Eq. (5) for new suburban development at the city boundary. Taking into account these additional costs, the value of suburban leapfrog development is

$$VN^{as}(x, t_0) = \frac{R^a}{r} + \frac{kgx^s(t_0)}{2q^s r(r-g/2)} - \left(\frac{k}{q^s r} + \frac{C^{sm}}{L} \right) (x - x^s(t_0)), \quad x \geq x^s(t_0). \quad (12)$$

Hence, at the city boundary, the value of suburban leapfrog development in Eq. (12) is equal to the maximum value in suburban use in Eq. (11). However, it declines sharply from the city boundary due to both additional sewer and commuting costs. The simulations in Section 3.1 demonstrate the magnitude of the effect from these two costs.

2.2. Willingness to pay for agricultural land in exurban use

Although it is not optimal to develop land for suburban use before time $t^s(x)$, the land may be developed for residential use without extending municipal sewer and water infrastructure. Residential development beyond municipal services is accomplished with septic systems and groundwater wells. Because privately serviced septic systems and wells are established on each individual property, exurban homes do not need to be physically connected to the centralized wastewater treatment facility. However, a larger lot size, q^e , is required for exurban use compared to the suburban lot size because public-health regulations mandate adequate spacing of septic systems and wells. The exurban lot size represents the minimum lot

size allowed with septic technology (i.e., 1 unit per acre), and for simplicity, we assume that exurban lot size is fixed.

Here, we also consider households that are identical to the suburban households, except they have a higher WTP for a larger lot.¹¹ First, we formulate the model for the case in which there is a single household of this type. This represents the CH model but incorporates the marginal change of one additional household. Our purpose is to determine the conditions for which exurban development would be feasible. Later in the paper, we then extend this logic to the scenario in which there are multiple households of this type.

In order to compare utility, and ultimately rent, across households that live on the suburban and exurban lots, we must make an explicit assumption on utility. Assuming a Cobb-Douglas utility function with share parameter α^s on lot size, the suburban households have utility, $U^s(z^s(x,t), q^s) = (y - R^s(x,t)q^s - kx)^{1-\alpha^s} (q^s)^{\alpha^s}$. The exurban household is assumed to have a Cobb-Douglas share parameter on lot size, $\alpha^e > \alpha^s$, reflecting their higher WTP for a larger lot. When making their residential location decision, this household compares two options. They can live on either an exurban lot q^e at location x , or they can live on a suburban lot q^s at the city boundary $x^s(t)$. Define $R^e(x,t)$ as the rent that makes this household indifferent between living on an exurban lot at location x versus living on the suburban lot at the city boundary. This means that $R^e(x,t)$ is the maximum amount that this household is willing to pay to live on an exurban lot. The equal utility condition may be stated as

$$(y - R^e(x,t)q^e - kx)^{1-\alpha^e} (q^e)^{\alpha^e} = (y - R^s(x^s(t),t)q^s - kx^s(t))^{1-\alpha^e} (q^s)^{\alpha^e}. \quad (13)$$

¹¹ Here we could have considered different incomes as well as different WTP for a larger lot. But we demonstrate below that, even with the same income, we find the conditions under which households would live in exurban development. Additionally, we consider only the benefits of private open space (i.e., yard space); and therefore, exurban development would be even more likely if the benefits from landscape amenities were taken into account.

After substituting the suburban rent at the city boundary from Eq. (5) into Eq. (13), we obtain

$$R^e(x, t) = \frac{1}{q^e} \left[(1-Q)y - kx + Q \left((R^a + rC^{so})q^s + kx^s(t) \right) \right], \quad (14)$$

where $Q = \left(\frac{q^s}{q^e} \right)^{\frac{\alpha^e}{1-\alpha^e}}$. The value of Q lies on the unit interval because q^s is less than q^e , and the exurban rent is increasing in α^e . The exurban rent gradient is $-k/q^e$ for all locations because exurban use depends only on commute costs, not sewer extension costs. The commute cost component of the exurban rent gradient is less steep than the suburban rent gradient because the difference in lot sizes means that the savings in commute costs per unit of land are much smaller for exurban density than for suburban density.

The maximum WTP for agricultural land to be developed into exurban use at time t_0 is

$$W^{ae}(x, t_0) = \int_{t_0}^{\infty} R^e(x, z) e^{-r(z-t_0)} dz - C^{eo}. \quad (15)$$

The first term in Eq. (15) is the value of exurban use for immediate conversion at the present time t_0 and thereafter. The second term is the onsite land improvement costs for exurban conversion, C^{eo} , which is an upfront cost made at the present time. The exurban conversion decision is assumed to be irreversible (i.e., no redevelopment).

We now determine the conditions on the optimal location for exurban use at the present time. The present value $W^{ae}(x, t_0)$ in Eq. (15) represents the maximum WTP for agricultural land for conversion to exurban use. Meanwhile, the value $V^{as}(x, t_0)$ in Eq. (3) represents the agricultural landowner's reservation price on the value of agricultural land with future suburban development. The feasible locations for exurban use at the present is the set of distances where

the value in exurban use exceeds the agricultural landowner's reservation price on future suburban use

$$\{x \mid W^{ae}(x, t_0) - V^{as}(x, t_0) \geq 0\}. \quad (16)$$

Does the exurban household pay $W^{ae}(x, t_0)$ or do they only pay the agricultural landowner's reservation price $V^{as}(x, t_0)$? If the household would pay $W^{ae}(x, t_0)$, then they would find that every agricultural landowner in the feasible region would be willing to sell and, thus, there would be an excess supply of land. So the household may offer $V^{as}(x, t_0)$, plus any small amount, and still find a willing seller. For instance, consider a small town in the early phases of its evolution with a growing suburban population, but the town is only one mile in radius. The commutershed around this small town may easily extend radially for 10 or 20 miles. Hence, there would likely be a large feasible zone of agricultural landowners that could accommodate an exurban household. As will be shown later, this logic extends beyond a single exurban household.

However, not all members of this feasible set in Eq. (16) yield the same utility for this household. The location that maximizes the difference between the WTP minus the amount needed to compensate the agricultural landowner is

$$x^e(t_0) = \arg \max_x \{W^{ae}(x, t_0) - V^{as}(x, t_0)\}. \quad (17)$$

The optimal location for exurban use must satisfy Eq. (16) and also satisfy the first-order condition on Eq. (17) with respect to distance ¹²

¹² When evaluating this first-order condition, we have made use of the envelope theorem for the optimal conversion time, $\partial V^{as}(x, t) / \partial t^s = 0$. The second-order condition is satisfied as well, $-re^{-r(t^s - t_0)} \partial t^s / \partial x < 0$. One can also derive this rule for the optimal exurban location directly from the maximization of discounted utility if the rate of interest and the rate of time preference are the same.

$$-\frac{k}{q^e r} + e^{-r(t^s - t_0)} \frac{k}{q^s r} = 0. \quad (18)$$

The first term is the marginal cost of commuting if the exurban household locates one unit distance farther from the CBD. The second term is the marginal benefit of lower land value in suburban use if the exurban household locates one unit distance farther from the CBD. That is, the agricultural landowner's reservation price on future suburban use decreases with distance according to the value of suburban commute costs, but discounted by the time until city expansion. When making their residential location decision, the exurban household considers these countervailing effects.

We now derive a closed-form solution for the optimal location of exurban development with exponential population growth. Substituting the exponential form for the city growth path from Eq. (9) into the exurban rent function in Eq. (14), we can calculate the WTP for agricultural land in exurban use in Eq. (15). The value for immediate conversion to exurban use at the present time is

$$W^{ae}(x, t_0) = \frac{1}{q^e r} \left[(1-Q)y - kx + Qq^s (R^a + rC^{so}) \right] + \frac{kQx^s(t_0)}{(r-g/2)q^e} - C^{eo}. \quad (19)$$

Note that the value in exurban use is linear in distance x . Specifically, the derivative of the value in Eq. (19) with respect to x is $\partial W^{ae}(x, t_0) / \partial x = -k / q^e r$. This indicates that the value in exurban decreases linearly according to the loss in land value from the additional commuting costs. In contrast, the agricultural landowner's reservation price for the value in future suburban development, according to Eq. (11), declines most steeply at the city boundary but then becomes flatter as the time until suburban development is much longer. The optimal location on exurban development must satisfy the first-order condition on Eq. (17) with respect to x , which, after taking these derivatives, yields

$$\frac{-k}{q^e r} + \left(\frac{x}{x^s(t_0)} \right)^{-2r/g} \frac{k}{q^s r} = 0 \quad (20)$$

This result is analogous to Eq. (18), except that the discount factor due to the time until city expansion, $e^{-r(t^s-t_0)}$, is expressed in terms of distance. Solving Eq. (20) for the optimal exurban location x in terms of the current suburban boundary yields

$$x^e(t_0) = \left(\frac{q^e}{q^s} \right)^{g/2r} x^s(t_0). \quad (21)$$

Note that $x^e(t_0) - x^s(t_0) > 0$ because $(q^e/q^s)^{g/2r} > 1$. The fundamental result is that optimal exurban development always leapfrogs beyond the current city boundary. The second-order condition with respect to x is

$$\frac{\partial^2 [W^{ae}(x, t_0) - V^{as}(x, t_0)]}{\partial x^2} = \left(\frac{x}{x^s(t_0)} \right)^{-(2r+g)/g} \left[\frac{2k}{q^s g x^s(t_0)} \right] > 0 \quad (22)$$

indicating that the exurban location in Eq. (21) is a global optimum.

This logic above extends beyond a single household. We now consider the scenario in which there is a population of these households. Our aim is to determine the proportion of the city area in suburban and exurban use, respectively, η and $1 - \eta$, which incorporates the population of exurban households. The population of exurban households is $n^e(t) = n^e(t_0) e^{g(t-t_0)}$, where $n^e(t_0)$ is the initial exurban population at time t_0 and the growth rate g is the same rate as for suburban households. As described above, the land area needed to accommodate the population of suburban households is

$$n^s(t) q^s = \eta \pi [x^s(t)]^2. \quad (23)$$

Because exurban households each consume lot size q^e , the land area needed to accommodate the exurban households is

$$n^e(t)q^e = (1-\eta)\pi[x^e(t)]^2. \quad (24)$$

To accommodate both suburban and exurban populations, the closed-city assumptions must be satisfied in both Eqs. (23) and (24). After substituting the optimal location of the exurban boundary from Eq. (21) into Eq. (24), the proportion of the city area in suburban use can be solved as

$$\eta = \frac{\left(\frac{q^e}{q^s}\right)^{g/r}}{\left(\frac{n^e(t)q^e}{n^s(t)q^s}\right) + \left(\frac{q^e}{q^s}\right)^{g/r}}. \quad (25)$$

Hence, if the exurban population is zero, then the proportion of the city land area that is reserved for the suburban population is one. But as the relative population of exurban households increases, then a smaller wedge of the land area is reserved for the suburban population. Therefore, conditional on accommodating the same number of suburban households, the city boundary must extend farther out according to Eq. (9). In this case, it causes the present value of agricultural land in suburban use to increase because the growth premium component in Eq. (11) is directly proportional to the radius of the suburban area, which, in turn, is inversely related to η . Similarly, the value of agricultural land in exurban use in Eq. (19) must also increase because it is indirectly related to the radius of the suburban area. The simulations in Section 3.2 demonstrate how the proportion of exurban households influences the land allocation between suburban and exurban households.

3. Simulations on agricultural land values in suburban and exurban use

3.1. Land value in suburban use for contiguous versus leapfrog development

In this section, we compare the value of agricultural land when suburban development occurs optimally at the city boundary versus suburban leapfrog development. In the latter case, sewer main extension costs are required to connect a distant agricultural parcel to the existing sewer and water infrastructure at the city boundary. Here, we also demonstrate the effect of agricultural property size on the land value for suburban leapfrog development. This is important because a larger property size for the distant agricultural parcel would allow the additional sewer extension costs to be shared amongst more suburban households.

As for the simulation parameters, household income is \$50,000 per year and annual commute costs are \$500 per roundtrip mile. The costs of extending the sewer main line are \$750,000 per mile, which is approximately \$150 per linear foot (Speir and Stephenson [18]). For onsite land-improvement costs, we use the service costs on streets and utilities in Table 8 from Frank [8]. These land-improvement costs are \$122,600 per acre for suburban development at 5 units per acre (in terms of 2006 dollars). The suburban lot size is 0.2 acres. Agricultural rent is \$1000 per acre, and the discount rate is 5%. Hence, the value of remaining in agriculture exclusively is \$20,000 per acre. The simulation results explained below are dependent on the specific functional forms and parameter values that were chosen. Hence, these simulations are illustrative of some, but not all, potential effects of residential development on the value of agricultural land.

Figure 1 shows the maximum value in suburban use, $V^{as}(x, t_0)$ from Eq. (11), when new suburban development occurs contiguously at the city boundary. We profile how this value declines from the existing city boundary to the outlying agricultural areas. The existing city radius is 3 miles in Fig. 1, which corresponds to a population of roughly 100,000 households. The annual population growth rate is 4% and, thus, the city boundary expands radially at half this

rate. Figure 1 also includes the land value for suburban leapfrog development, $VN^{as}(x, t_0)$ from Eq. (12), which is repeatedly calculated for three different property sizes on the distant agricultural parcel: 1, 10, and 100 acres.

The maximum value in suburban use is \$120,000 per acre at the city boundary in Fig. 1. This value declines to the value in agriculture exclusively as one travels farther from the city boundary. That is, the maximum value of development rights in suburban use is largest at the city boundary and approaches zero for outlying areas that have a long time until conversion.

The land value for suburban leapfrog development is also \$120,000 at the city boundary in Fig. 1. But it declines much more steeply than the maximum value and, thus, suburban leapfrog development is suboptimal at all locations. For example, consider the medium-sized agriculture property with 10 acres, which is located outside the existing city boundary. As seen by a prospective developer who wants to convert this distant agricultural parcel, the land-value gradient is $-\$125,000$ per mile due to the additional sewer extension costs and commute costs from premature development. Within 1 mile of the city boundary, the value for suburban leapfrog development would, therefore, be driven below even the value for agriculture exclusively. When decomposing the land-value gradient, the commute costs and sewer extension costs decrease the land value per acre by \$50,000 and \$75,000, respectively, for each additional mile from the city boundary. The component of the land-value gradient attributable to sewer extension costs will become less steep when the agricultural property size is large. This sewer main component on the land value gradient in Fig. 1 is $-\$750,000$, $-\$75,000$, and $-\$7,500$ per mile for properties of 1, 10, 100 acres, respectively.

In reality, sewer extension costs are likely to be even higher. In order to connect the distant agricultural property to the existing sewer infrastructure at the city boundary, a developer

would either have to compensate the intervening agricultural landowners for right-of-way access (i.e., easement precluding any future development along the sewer lines to provide access for maintenance equipment) or have to extend sewers over a possibly longer distance along the existing road network in order to avoid right-of-way access issues. Topography is another important consideration. Pumping stations along sewer lines would require additional costs in order to traverse any elevation changes in areas with even moderate slopes.

3.2. WTP for exurban use

We now calculate the WTP for exurban development at the present for locations outside the city area. The aim is to assess the range of locations for which the WTP for exurban development exceeds the agricultural landowner's reservation price on future suburban use. We also evaluate how different city sizes influence the land value in suburban use and the feasible range of exurban use. In these scenarios, smaller (larger) city sizes are used to represent earlier (later) phases in the evolution of cities.

First, we assume that the population of exurban households is very small compared to the suburban households and, thus, would occupy a negligible amount of the agricultural land. Hence, this first case represents the baseline CH model but with a small number of exurban households. Later, we consider a second case with a relatively larger population of exurban households. In the second case, the exurban households occupy a significant portion of the agricultural area as explained in Eq. (25). This results in a reduction of the land supply available for future suburban development, which would accelerate the city growth path in order to accommodate the suburban households. Specifically below, the total population in the first case has 0.1% exurban households while the second case has 10% exurban households.

The following simulations have the same parameters as described in Fig. 1, which were used to calculate the maximum value in suburban use. The exurban lot size is one acre due to the density limit on households serviced by septic systems. Exurban households have preferences defined by a Cobb-Douglas utility function with the alpha parameter on lot size of 0.1. Onsite land improvement costs are \$57,500 per acre (in terms of 2006 dollars) for exurban development at one unit per acre (Frank [8]). Onsite exurban conversion costs are lower on a per area basis than the onsite suburban conversion costs, $C^{eo} < C^{so}$. The reason is that exurban development has less intensive site improvement costs, often including narrower and lower quality roads, lack of sidewalks, and other differences.

Figure 2 shows the WTP for exurban development at the present, calculated according to Eq. (19). The figure also includes the maximum value in suburban use, which, again, has been calculated for a small-sized city with a three-mile radius. This value represents the agricultural landowner's reservation price on future suburban development because, as noted in Fig. 1, suburban leapfrog development would yield a lower value.

The optimal location for exurban development in Fig. 2 can be viewed as a tradeoff between higher commute costs farther from the CBD versus higher reservation price on future suburban use close to the city boundary. Exurban development, while feasible, would not be optimal when located close to the city boundary. In this vicinity, the agricultural landowner's reservation price is higher because the time until suburban development is relatively short. At much greater distances, the reservation price has flattened out and approaches the value of agriculture exclusively. The WTP in exurban use declines linearly and, eventually, drops below the landowner's reservation price at approximately 14.2 miles (Fig. 2). This location defines the upper bound on feasible exurban development at the present.

The optimal exurban location can be seen intuitively from the difference in value between the WTP for exurban use and the agricultural landowner's reservation price (Fig. 3). Exurban development would be optimally located at approximately 5.7 miles (i.e., 2.7 miles from the existing city boundary). It corresponds to the city boundary reaching this location approximately 32 years later.

It is informative to compare the relative costs for locating exurban development at the optimum versus at the city boundary. In Fig. 2, the agricultural landowner's reservation price is only \$120,000 per acre at the city boundary because the city radius is still relatively small. The WTP for exurban use is approximately \$140,000 per acre at the city boundary. When this amount is represented as an annualized mortgage payment, using the interest rate of 5%, it would mean the household is willing to spend up to \$7,000 per year on land (i.e., 14% of household income). Hence, while the size of the city is still small, the household with a high WTP for a larger lot could afford to purchase an acre lot at the city boundary. This household, however, is better off by locating away from the city boundary. At the optimum, the agricultural landowner's reservation price decreases by \$62,000 per acre, relative to the city boundary, because municipal services would not extend into this area for several decades. Meanwhile, the exurban household only incurs an additional \$27,000 in commute costs (i.e., \$10,000 per mile), thereby resulting in a net savings.

As the city becomes larger, however, the agricultural landowner's reservation price sharply increases. Figure 4 shows the WTP for exurban use and the reservation price for a medium-sized city with a radius of five miles. This represents a city population of approximately 250,000 households. One reason for the larger reservation price is that the growth premium at the city boundary increase proportionally to the city radius, according to Eq. (11). Specifically, the

land value in suburban use at the city boundary increased from \$120,000 to \$187,000 per acre for a city with radius of three and five miles, respectively (Figs. 2 and 4). Additionally, the reservation price in Fig. 4 declines more slowly with distance because a larger city will expand into outlying agricultural areas faster than a smaller city, *ceteris paribus*.

The WTP for exurban use therefore becomes less able to exceed the reservation price on future suburban use as the city evolves through time. In fact, the agricultural landowner's reservation price exceeds the WTP for exurban use at any distance less than 6.4 miles (Fig. 5). This location defines the lower bound on feasible exurban development. An "exurban dead zone" therefore exists between the city boundary at 5 miles and the lower exurban bound at 6.4 miles. In this zone, agricultural landowners are better off waiting for imminent suburban development, and thus, would never sell to an exurban household. The optimal location for exurban development is now located even farther away at 9.5 miles from the CBD (i.e., 4.5 miles from the city boundary).

The expenditure required to live on an exurban lot has increased through time for two reasons. First, the commuting costs have increased because the optimal location for exurban development has become more distant from the CBD. Second, the landowner's reservation price at the optimal exurban location is higher for the larger city. Specifically, it increased from \$58,000 to \$84,000 per acre for a city with a radius of three and five miles, respectively (Figs. 2 and 4). Therefore, as the city evolves, there will come a time when exurban development is no longer feasible at any location.

To investigate this, we map the trajectories of the city boundary, the optimal exurban location, and the upper and lower boundaries on feasible exurban development as a function of time. Figure 6 shows the trajectories of these four boundaries, based on an initial city radius of 1

mile. During the early stages of city growth, the land area within the feasible zone for exurban development is much larger than the city area. Consider the city when the radius has grown to 3 miles, for instance. This translates into a city with an area of only 28 square miles. The feasible exurban zone, which spans a ring between the city boundary at 3 miles and the upper exurban boundary at 14.2 miles, has an area of approximately 605 square miles. Hence, while the municipal sewer and water service area is still relatively small, the commutershed contains a large number of available sites that would be feasible for exurban development.

An exurban dead zone emerges once the city reaches about 4 miles in radius (Fig. 6). As the city size increases, the exurban dead zone will continue to grow because the agricultural landowner's reservation price has become much larger at the boundary and extends farther into countryside. Eventually, after approximately 90 years, the radius of the city boundary reaches more than 6 miles (i.e., 350,000 households) and exurban development is no longer feasible at any distance.

Up to this point, we have assumed that the city expands, according to the CH model, but with a small number of exurban households that occupy a negligible amount of the agricultural area. We now explicitly calculate the land allocation between exurban and suburban use for two cases. The total population is comprised of 0.1% exurban households in the first case and 10% exurban households in the second case. In the first case, exurban development occupy more than 0.1% of the developed land area because the exurban lot size is five fold larger than the suburban lot size. However, at each given city radius, exurban development is optimally located further away from the city boundary. Equilibrium conditions to accommodate both populations, as stated in Eqs. (23)–(25), indicate that exurban and suburban households, respectively, occupy 0.14% and 99.86% of the city land area. Consider again the city with a radius of 3 miles with roughly

100,000 households. The suburban population is 99,900 households and new suburban development occurs at the city boundary. Meanwhile, there are 100 exurban households, occupying only a minor portion of land area, and new exurban development occurs optimally at 5.7 miles.

At first glance, it may seem optimal for exurban development to fill a thin ring entirely at its present location, as the city continues to expand. However, exurban development continues to move out through time because the optimal location is a tradeoff to minimize both the commute costs to the CBD and the amount needed to compensate the agricultural landowners (i.e., reservation price on future suburban use). If exurban development completely fills a thin ring at one location, it would minimize the commute costs for these exurban homes. But the land costs would increase by a greater amount. Therefore, the exurban development occurs in small pockets at the optimal distance, leaving the majority of surrounding land in agricultural use.

This sparse exurban settlement pattern can be understood by considering the city expansion from 3 miles to 4 miles. At a 4% population growth rate, it would take 14 years for the city boundary to expand this additional mile, and the suburban population would increase from 99,900 households to 175,000 households. The optimal exurban boundary would increase from 5.7 miles to 7.6 miles during this time, tracing out a ring of available sites for exurban development equal to 250,000 acres. But, the exurban population has only increased from 100 to 175 households. So these 75 additional exurban households could occupy a thin ring at 5.7 miles over the intervening 14 years, but a more efficient pattern of exurban development would be to keep locating further away as the city boundary expands.

We next consider the second case in which the exurban population comprises 10% of the total population. Because exurban development now occupies a significant portion of the

agricultural area, it would take a smaller suburban population to reach the same city radius. In this case, the equilibrium conditions to accommodate both populations indicate that exurban and suburban households occupy 13% and 87% of the city land area, respectively. For instance, the city with a radius of three miles previously corresponded to roughly 100,000 suburban households; however, in this case, the same city radius would be reached when there are approximately 87,000 suburban households. Meanwhile, there are 8,700 exurban households that occupy a significant portion of land extending out to the optimal exurban boundary at 5.7 miles. However, the municipal service boundary and, thus, the land value in suburban use, continues to increase with or without a significant exurban population. The main difference is that, with a significant population of exurban households, the time until when exurban development is no longer feasible occurs earlier.

Some caveats must be noted regarding the finding that exurban use may eventually become infeasible. First, a larger city might not be able to sustain a high population growth rate, such as 4% used in the simulations above, and may slow down as it grows. The land value in suburban use at the city boundary is proportional to the population growth rate. With a slower growth rate, the reservation price would also decline more rapidly with distance because the time until suburban conversion would be much longer. Second, the exurban upper bound would extend farther with lower commute costs. Exurban development as a vacation home, or with telecommuting, would reduce the commute costs and, thus, would extend the exurban boundary much farther. It is also implicitly assumed that the exurban household would continue to commute to the CBD for employment; however, as the city area expands, it may be more realistic to assume the exurban household could commute to the edge of the city. Third, the annual income of \$50,000 was chosen to represent a median income household in the United

States. Hence, the simulations demonstrate that, while the city size is still relatively small, a median income household would be able to afford the expenditure required to live on an exurban lot. But only higher income households would be able to afford the amount needed for exurban development as the city becomes larger. Lastly, the exurban upper bound would extend farther with lower agricultural rents. We used an agricultural rent of \$1000 to reflect the returns from intensive agriculture. However, if ranching or forestry was the existing use, then the annual rents may be an order of magnitude less. In this case, it would be relatively easy for an exurban household to outbid even larger acreage (5 or 10 acre lots) rather than the maximum density of one acre allowed by septic systems.

4. Conclusion

Understanding the mechanisms for leapfrog patterns of residential development has been an important topic of inquiry in urban economics. In this paper, we incorporate the cost structure of sewer versus septic production technologies in order to provide an intuitive explanation for exurban leapfrog development. One insight from our model is that, at the municipal service boundary, the gradient of land values in suburban use is steeper outside than inside. The influence of commute costs on the land value gradient is the same on both sides of the boundary. However, suburban development in outlying agricultural areas imposes an additional cost of contiguity because sewer main lines must be physically extended from the existing municipal service boundary. Exurban development has the advantage that it can occur without either requiring the costly investment of sewer main lines into the countryside or waiting for the municipal service boundary to expand. But the spacing requirements between septic systems and

private groundwater wells, due to public health concerns, acts as an implicit maximum-density restriction on exurban development.

These fundamental differences between suburban and exurban development are important to recognize because the vast majority of the land area in the United States lies outside existing municipal sewer and water service areas. As pointed out by Burchfield et al. [5], the urban and suburban footprint detected from LANDSAT imagery only occupied 1.9% of the entire United States in 1992. This indicates that the existing municipal sewer and water service areas are scattered over a small portion of the land area nationwide. Meanwhile, if one considers the land area within reasonable commuting distance around each town and city, these commutersheds would together occupy a much larger area. Exurban development may not necessarily occupy the entire feasible zone because septic systems easily allow this form of residential development to be noncontiguous. But even a small exurban population, therefore, would be able to cause a high degree of fragmentation in the urban-rural fringe (e.g., losses in farmland, wildlife habitat, and ecosystem services) and increase the costs per household of providing some types of public services (e.g., protection of exurban homes from wildfires).

As further explained in our model, areas around smaller towns and cities are the most likely places for exurban leapfrog development. For example, a small city with a population on the order of less than 100,000 inhabitants would have a radial extent of only a few miles. In this case, the speed at which the municipal service boundary travels is relatively slow, and agricultural landowners located several miles from the existing boundary may have to wait decades before suburban development can occur. Hence, the agricultural landowner's reservation price on future suburban use declines rapidly from the municipal service boundary into the agricultural area. The WTP for exurban development may exceed the agricultural landowner's

reservation price on future suburban use over a range of locations. Specifically, households with a higher WTP for a larger lot size can easily afford the additional land and commute costs needed to live on an exurban lot in the vicinity of a small city. The optimal exurban location is a tradeoff to minimize the commute costs to the CBD versus agricultural landowner's reservation price farther from the municipal service boundary.

However, exurban development is less affordable in the vicinity of a large metropolitan area. As a city becomes larger, the agricultural landowner's reservation price increases significantly for two reasons. First, the growth premium at the city boundary is proportional to the city radius. Second, the reservation price declines more slowly because the municipal service boundary for a large city travels faster into the agricultural area, *ceteris paribus*. Therefore, the minimum expenditure required for exurban development increases through time as the city becomes larger. The effect of city size on the feasibility of exurban development is important to understand because, according to Census data, the number of urbanized areas with relatively small populations is much greater than the number of large metropolitan areas. In conclusion, we hope that this study draws attention to analyzing the dynamics of residential development in the urban-rural fringe, particularly in areas surrounding smaller towns and cities.

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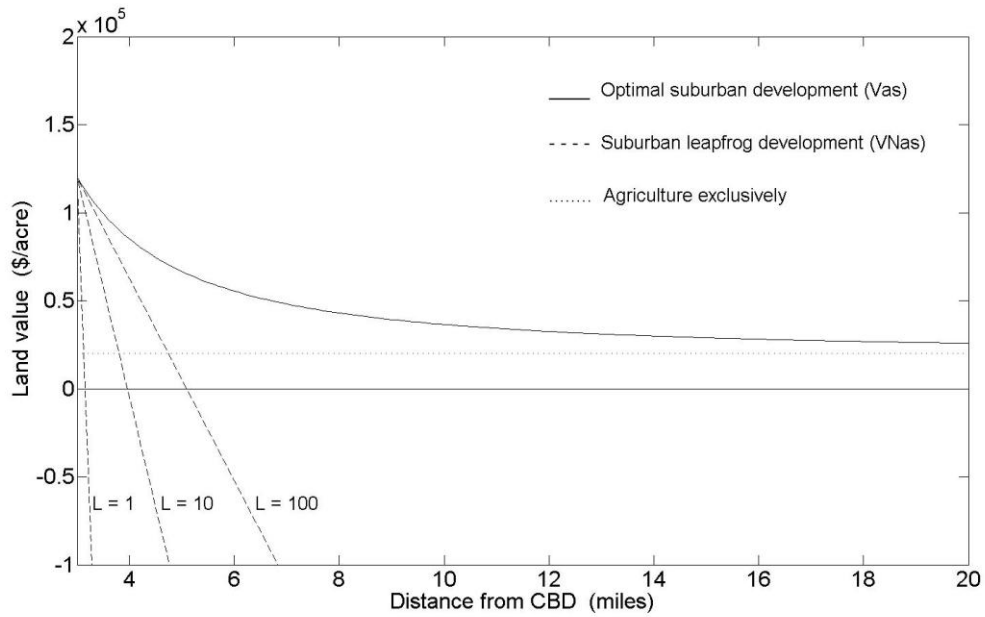


Fig. 1. The value agricultural land for optimal suburban development and for suburban leapfrog development. Suburban leapfrog development includes premature sewer extension costs to a distant agricultural property with lot size (L) of 1, 10, and 100 acres. The x-axis is the distance from the CBD, starting from the current city boundary at three miles.

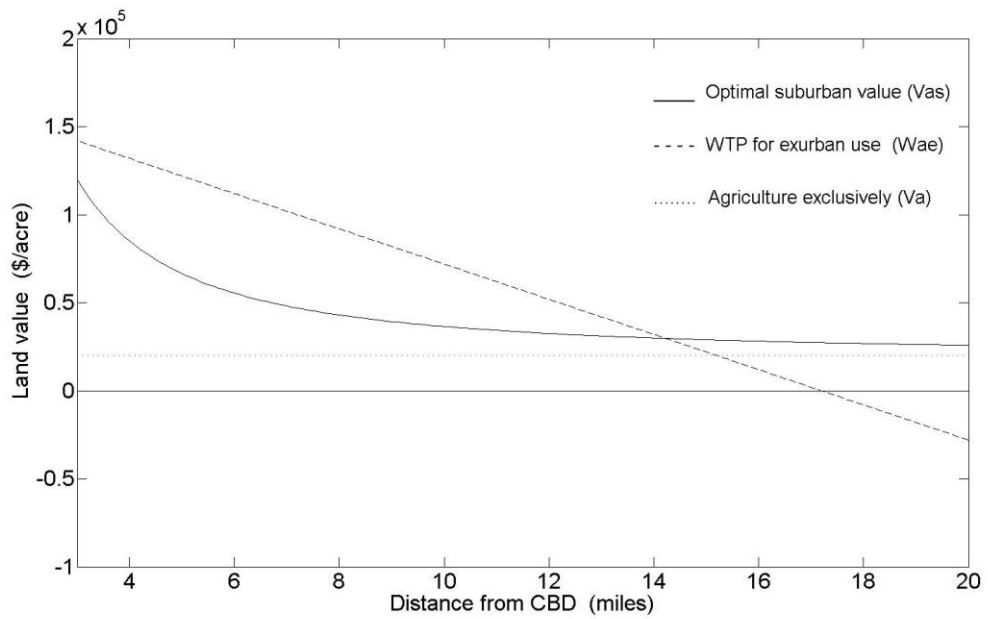


Fig. 2. WTP for exurban use and agricultural landowner's reservation price on future suburban use. The x-axis is the distance from the CBD, starting from the current city boundary at three miles.

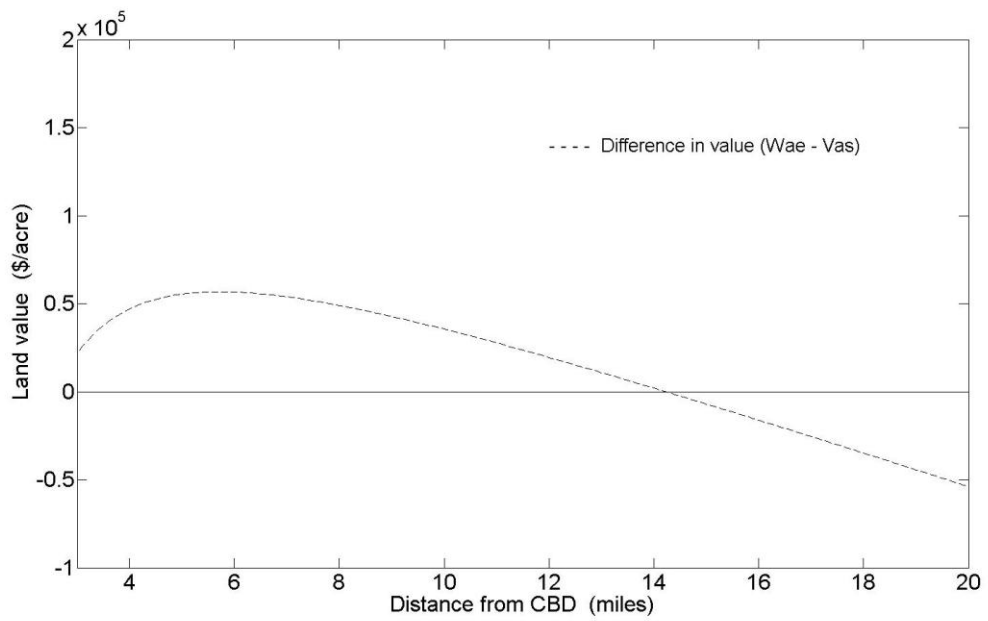


Fig. 3. The difference in value between the WTP for exurban use and the agricultural landowner's reservation price on future suburban use. The x-axis is the distance from the CBD, starting from the current city boundary at three miles.

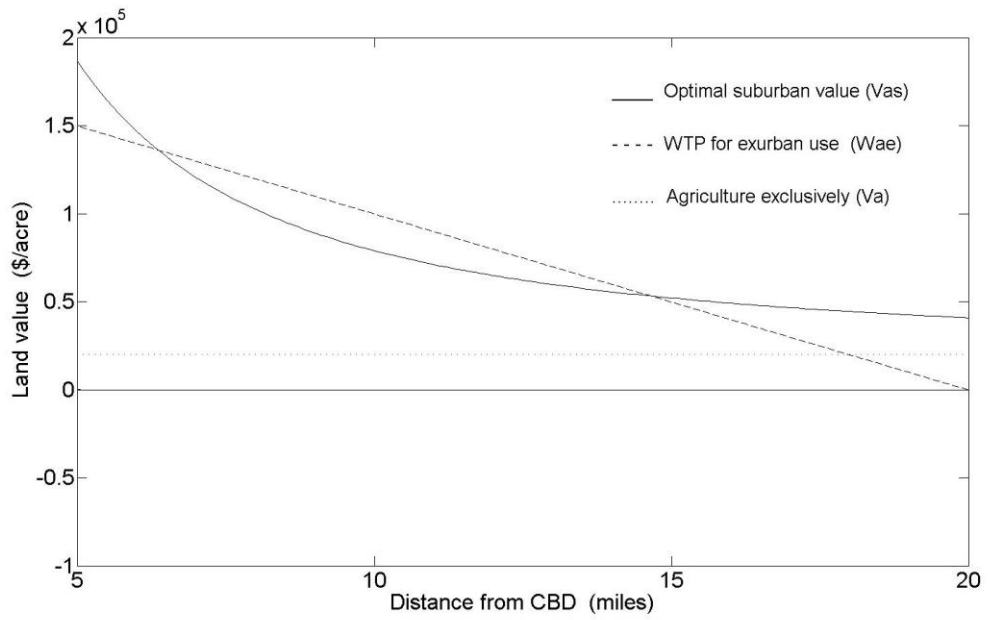


Fig. 4. WTP for exurban use and agricultural landowner's reservation price on future suburban use. The x-axis is the distance from the CBD, starting from the current city boundary at five miles.

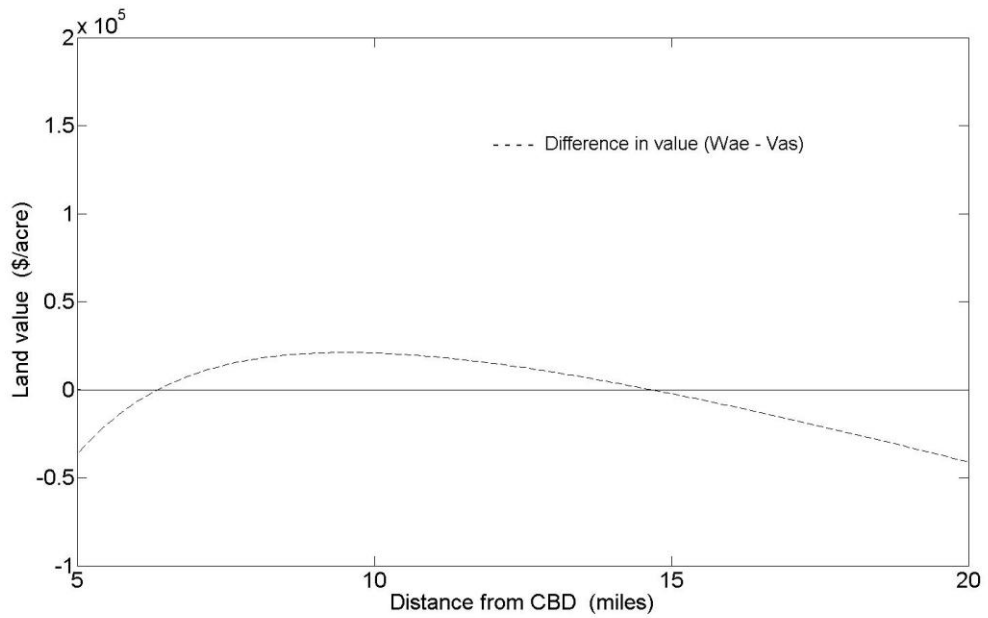


Fig. 5. The difference in value between the WTP for exurban use and the agricultural landowner's reservation price on future suburban use. The x-axis is the distance from the CBD, starting from the current city boundary at five miles.

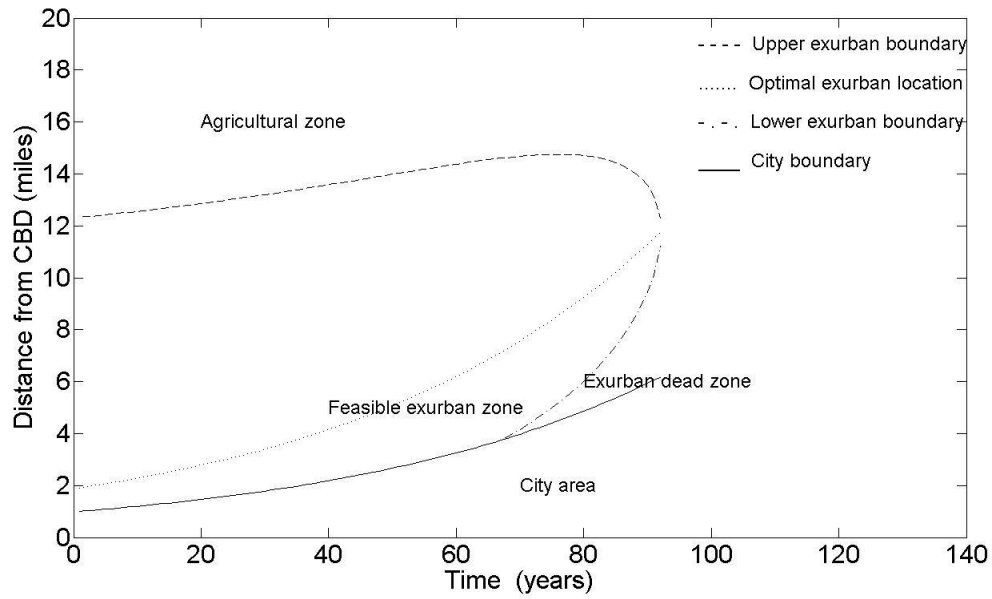


Fig. 6. Trajectories for the city boundary, optimal exurban location, and the lower and upper bounds on feasible exurban development.