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Market thinness, income sorting and leapfrog development across the urban-rural gradient

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ABSTRACT

This paper investigates the conditions under which thin residential land markets generate an incentive for leapfrog development. We provide empirical evidence that suggests the presence of thinly traded land market in exurban areas. We develop a spatial model of an exurban land market that incorporates this key feature and show the conditions under which leapfrog development emerges. Specifically, given increasing market thinness with distance and a limited number of heterogeneous buyers, higher income households are able to bid down land prices at farther away locations. This creates an incentive for leapfrog development and leads to a positive income gradient, which we also confirm empirically.

1. Introduction

Urbanization patterns characterized by low density, scattered development have led to extensive consumption of land resources and raised serious questions about the efficiency and sustainability of this type of urbanization (Pickett et al., 2011). Given strong demand for agricultural land, e.g., due to growing biofuels markets and growing global demand for agricultural crops, understanding the economic factors that may threaten agricultural land and lead to greater fragmentation of agricultural land use patterns is critical for guiding policies that seek to improve the sustainability of urbanizing agricultural regions.

The canonical monocentric model of urban land development by Capozza and Helsley (1989, 1990) demonstrates the fundamental effects of future growth on current land rents, prices and development decisions. However, this model is unable to explain leapfrog development, the one-dimensional variant of scattered development in which vacant land is skipped over while land farther from the city center is developed first. These authors conclude that some other source of heterogeneity in land, land use or in expectations is necessary to generate leapfrog development. On the land supply side, intertemporal decision making of landowners or developers with heterogeneous returns to development can result in optimal leapfrog development. Ohls and Pines (1975) and Mills (1981) demonstrate that with multiple types of development that differ in their expected returns, land developers have the incentives to withhold land closer to the city from development at lower density for lower returns in return for future development at higher density for higher returns. This can generate temporary leapfrog development that will decrease over time as the region fills up. Bar-Ilan and Strange (1996) show that leapfrog can occur when lags exist in the urban development process, which generates heterogeneous uncertainty in land rents that increases with distance. Newburn and Berck (2011) consider the heterogeneous production costs of higher-density suburban versus low-density rural development and how these heterogeneous costs combined with heterogeneous household preferences for rural lots can lead to leapfrog development.

Demand-side explanations of leapfrog and scattered development focus on spatially heterogeneous amenities and how household preferences over these amenities can lead to leapfrog patterns of residential land use. Irwin and Bockstael (2002, 2004) illustrate that leapfrog patterns can emerge due to land use spillovers. Wu and Plantinga

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(2003) introduce natural amenities into the urban economic bid-rent models. The spatial separation of the urban boundary and the center for natural amenities results in the concentration of development around these two centers. The land between these two centers is less desirable to households and is therefore developed at a later time. Turner (2005) considers the case in which open space is endogenous to household location decisions. Because of this endogeneity, the location of one household imposes negative externalities on its close neighbors by reducing the amount of open space available. Leapfrog development can emerge due to this preference for endogenously determined open space. Caruso et al. (2007) extend Turner's analysis by showing that scattered development can occur when both the open space and social interactions are endogenous to households' location decisions. Irwin and Bockstael (2002) provide empirical evidence of interaction effects from neighboring development and their influence on scattered residential patterns. Wrenn and Irwin (2015) and Zhang et al. (2017) show that spatially heterogeneous zoning could also contribute to the leapfrog development.

This paper proposes an alternative explanation to the puzzling phenomenon that people are willing to incur higher transportation costs to live at more distant locations when there is unoccupied land closer in. We start with the premise that household location choices in growing rural areas located within the commuter shed of urbanizing regions reflect the basic economic conditions of exurban land markets, which may differ from those of large urban and suburban areas. One striking difference is in the relative supply of land. As of 2010, there were an average of 22.4 households per square mile living in rural counties compared with averages of 146.4 and 121.9 households per square mile in urban and suburban counties respectively. Thus, the relative abundance of land is a key feature of exurban land markets. This finding, together with heterogeneity that further divides the market, e.g., in land or households, suggests the potential for thinly traded exurban land markets in which households may have some bargaining power to bid down prices. The standard urban model, in which land is scarce and households pay their maximum willingness to pay for any given location, does not account for this market feature.

Because thin markets are characterized by infrequent trading (Rostek and Weretka, 2008), we measure the market thinness by the time on the market for housing properties. Using the Multiple Listing Service (MLS) data for the Baltimore region, we find that as distance to urban center increases, the time on the market becomes longer. This suggests that land markets may become thinner along the urban-rural gradient.

To explore the potential linkage between thin markets and leapfrog development, we develop a model of household location choice in which households maximize utility by formulating the optimal bids and choosing the optimal locations. Landowners maximize expected payoffs by choosing the optimal reserve prices in a private-value first price auction. Leapfrog development emerges if at least some households maximize their utility by choosing more distant locations that are not contiguous to more proximate locations that are occupied. Our main result shows that, with heterogeneous income and moderate transportation costs, an incentive to leapfrog exists due to the gains from bargaining that emerge from a smaller number of households that are in the market at greater distances. Households that can afford more distant locations make an optimal location choice by trading off the higher travel costs with the benefits of bargaining. Leapfrogging emerges if these gains outweigh the increase in transportation cost. This result is reinforced by variations in land supply that increase with distance. Finally, while all households with sufficient income are able to locate at more distant locations, the richer households are more likely to outbid competing buyers and reap the potential gains from trade. This income sorting is also consistent with the empirical evidence from our study region.

We contribute to the literature in several ways. First, we provide empirical evidence that suggests the presence of thinly traded land market in exurban areas. Second, we develop a theoretical model about household location decisions in a thinly traded land market. Last but not the least, we propose a new mechanism of leapfrog development that arises from thinly traded exurban land markets with abundant land supply and limited household demand. While some have hypothesized that urban land markets are characterized by thin markets (e.g., Arnott, 1989, Harding et al., 2003) and that thin markets may generate sprawl (Clawson, 1962), ours is the first paper to formalize this hypothesis and demonstrate the conditions under which such leapfrog development may occur. To the extent that these conditions are fundamental characteristic of exurban land markets, the implication is that leapfrog development is a natural consequence of exurban growth in the short run. The result depends critically on the thinness of exurban land market, which is due to the scarcity in land demand and the abundance in supply. Therefore our model explains leapfrog development as a short-run outcome when population is constrained, e.g., by moving or search costs. In the long run, population growth in exurban areas may gradually increase land scarcity and market competition, which will reduce incentives for leapfrog development.

The remainder of the paper is as follows. First, we empirically investigate the thinness of exurban land market. We then develop a spatial model of household location decisions that incorporates the key features of exurban land markets. We model optimal household bids for location and optimal landowner reserve prices. We then derive a set of analytical results that focuses on the role of income heterogeneity and the resulting spatial variations in demand. Under the assumption that market thinness increases with distance to urban areas, our model is able to generate leapfrog development. The paper concludes with a discussion of the implications of thin markets for exurban regions.

2. Thin market: some empirical evidences

One salient feature of exurban areas is that population density (U.S. Census Bureau, 2012) and housing density decrease with the distant to urban area while land supply increases. To control for the differences in lot sizes along the urban-rural gradient, we define relative demand as the number of approved mortgage applications divided by the number of available zoned residential lots per census tract. Using data from the Baltimore metropolitan region, Fig. 1a and b illustrate the effect of distance on the availability of zoned residential lots and the relative demand for residential housing using data from the Home Mortgage Disclosure Act (HMDA) and Maryland Property View on a census tract level. It reflects a simple reality: as distance to urban areas increases, the supply of zoned lots increases and the relative demand for housing decreases. In other words, market thinness tends to increase with distance.

Because thin markets are characterized by infrequent transactions, we use a property's time on the market (TOM), the number of weeks on the market, as a quantitative measure for market thinness. Using Multiple Listing Service (MLS) listing data for Baltimore metro region (Anne Arundel, Baltimore, Carroll, Harford, Howard, and Queen Anne Counties),[1] we are able to calculate TOM for all houses listed for sale. The MLS listing data also includes some structural attributes and the physical location of the houses. After removing houses that have missing values in key structural attributes such as house size, number of bathrooms, and parcel size, the remaining dataset include 66,545 houses for sale in the Baltimore region from 2008 through 2015. The summary statistics are reported in Table 1.

In order to investigate the correlation between market thinness and distance to urban center, we run the following regression:

$$\boldsymbol{TOM_{ij}} = \boldsymbol{\beta_0} + \boldsymbol{\beta_{DIST}} \boldsymbol{Dist_i} + \boldsymbol{\beta_X} \boldsymbol{X_i} + \boldsymbol{\beta_Y} \boldsymbol{Year_t} + \boldsymbol{\gamma_J} \boldsymbol{County_j} + \boldsymbol{\varepsilon_I} \tag{1}$$

[1] Baltimore City is not included because of our focus on the housing market outside of the city proper. Inclusion of Baltimore City does not change the key conclusions of the empirical analyses.

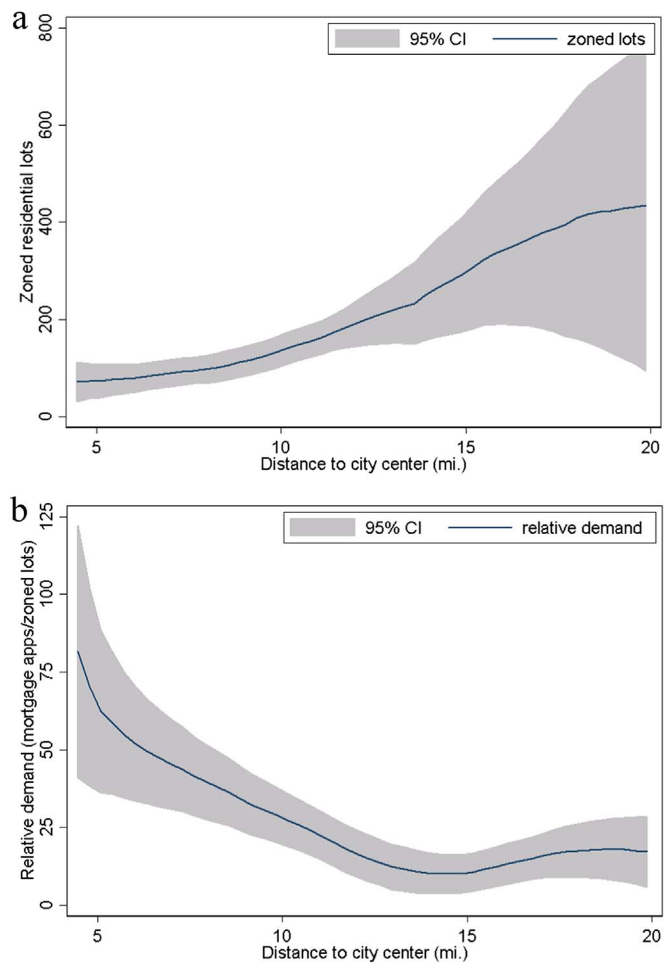

Fig. 1. a: Zoned residential lots by distance to Baltimore CBD. b: Relative demand for residential housing by distance to Baltimore CBD.

Table 1
Summary statistics for MLS data.

Variable	Mean	Std. Deviation	Min	Max
Weeks on market	19.553	20.637	0	200
Number of bedrooms	3.754	0.875	1	9
Number of bathrooms	2.773	1.054	1	7
House sqft	2636.929	1325.657	500	7000
Parcel size (acres)	0.887	2.709	0.01	218
Year built	1974	22.2533	1907	2007
Distance to city (mi.)	16.368	8.054	4.033	46.503

where $\boldsymbol{TOM_{ij}}$ is the time on the market for house i in county j. $\boldsymbol{Dist_i}$ is the distance between house i and the Baltimore City. $\boldsymbol{X_i}$ is a vector of housing characteristics like the number of bedrooms, number of bathrooms, house size, parcel size, year built. A year fixed effect and a county fixed effect are included. This later term helps to mitigate unobserved county-level spatial correlation that could correlate with our market thinness measure. As expected, TOM is positively correlated with the distance to city. On average, every five-mile increase in the distance to Baltimore city increases TOM by one week (see Table 2). This is consistent with our hypothesis that land market becomes thinner as distance to urban center increases.

One limitation of the above analyses is that household characteristics (such as income) are missing. To address this issue, we turn to the mortgage application data from HMDA. We focus on the originated (approved) HMDA mortgage applications in the Baltimore region from 2008 to 2015.[2] The HMDA dataset provides a yearly list of all mortgage applications with income and socio-demographic data on all applicants and the status of the application, i.e., approval status and loan information. Because HMDA provides only the census tract (CT) but not the physical address for houses associated with the mortgages, we geolocate each mortgage loan into the appropriate CT. We also calculate the average income in each CT by year for all approved buyers and the yearly variance in income from region wide average in each CT.

Table 2
Market thinness regression.

Variable	Time on Market
Distance to city (mi.)	**0.186***** (0.0572)
(Distance to city)^2	**0.000904** (0.00142)
Bedrooms	0.278** (0.125)
Bathrooms	0.539*** (0.133)
House sqft	-0.000288 (0.00032)
(House sqft)^2	0.0000*** (0.0000)
Lot size (acres)	0.546*** (0.0717)
(Lot size)^2	-0.00416*** (0.000902)
Age	-0.0990*** (0.0147)
(Age)^2	0.00173*** (0.00016)
Constant	8.14
R-squared	0.062
Number of observations	66,545
Year Fixed Effects	Yes
Fixed Effects Level	County

Note: ***, **, * indicate significance at the 1, 5, and 10 percent level, respectively.

Because HMDA data do not include housing characteristics, we calculate the CT average characteristics (including lot size, house size, number of bathrooms, average stories, garage, pool, and public water/sewer) for houses sold in each year using housing transactions data from Corelogic. Foreclosures are excluded. Table 3 reports the summary statistics. We then estimate the following equation using OLS with robust standard errors:

$$\boldsymbol{Ln(Income_{it})} = \beta_0 + \beta_X X_{it} + \beta_{DIST}\boldsymbol{Dist_i} + \beta_Y \boldsymbol{Year_t} + \gamma_J \boldsymbol{County_j} + \varepsilon_I \quad (2)$$

where $\boldsymbol{Income_{it}}$ is the mean income of CT i and year t. $\boldsymbol{X_{it}}$ is a vector of housing characteristics mentioned above. $\boldsymbol{Dist_i}$ is the distance from the centroid of CT to the CBD of Baltimore city. Year-fixed effects and county-fixed effects are included. We find that household income increases with the distance to the CBD of Baltimore city (see Table 4)[3]. This suggests households are sorting along the urban-rural gradient.

In sum, this evidence suggests that as distance to urban center increases, the land market becomes thinner and households seem to

[2] 2016 data is not yet available.

[3] The significance of the quadratic term suggests that the income increases at a decreasing rate.

Table 3
Summary data for income sorting.

Variable	Mean	Std. Deviation	Min	Max
Mean income ($)	110,015	40,621	47,000	344,861
Distance to city (mi.)	13.323	7.647	4.017	38.728
House sqft	3563.754	1260.981	624	6955
Parcel size (acres)	1.63	1.793	0.101	10
Bath	2.779	0.734	1	6
Stories	2.026	0.217	1	3
Garage	0.943	0.173	0	1
Pool	0.359	0.319	0	1
Public sewer	0.845	0.35	0	1
Public water	0.808	0.384	0	1

Table 4
Income sorting regression (mean income).

Variable	Ln Mean Income
Distance to city (mi.)	**0.0274***** (0.00305)
(Distance to city)^2	**-0.000546***** (0.0000)
House sqft	0.000166*** (0.0000)
(House sqft)^2	0.0000** (0.0000)
Lot size (acres)	0.0349*** (0.00714)
(Lot size)^2	-0.00447*** (0.000866)
Bathrooms	0.0504*** (0.00962)
Stories	0.135*** (0.0237)
Garage	-0.0713*** (0.0267)
Pool	0.0426*** (0.0142)
Public sewer	-0.0779*** (0.0129)
Public water	-0.00736 (0.0163)
Constant	10.55
R-squared	0.652
Number of observations	3,207
Year Fixed Effects	Yes
Fixed Effects Level	County

Note: ***, **, * indicate significance at the 1, 5, and 10 percent level, respectively.

sort along the urban-rural gradient. In the next section, we develop a theoretical land market model that formalizes the idea of thin land markets and show that the presence of thin market can generate leapfrog development and income sorting along the urban-rural gradient.

3. An exurban land market model with market thinness

In this section, we develop a structural model of thinly traded exurban land market based on the premise that land demand decreases while the land supply increases with the distance to urban area. We show that this fundamental feature of exurban land market, in combination with a limited number of heterogeneous buyers, can provide households with an incentive to leapfrog. In this model, a limited number of utility-maximizing households formulate optimal bids for all parcels they can afford, but only choose the one parcel that maximizes their utility. Given the limited number of buyers, not all landowners will be able to sell their parcel for development and therefore, landowners formulate an expected payoff from the land that accounts for the possibility that the land may be unsold at the end of the period. Any unsold land is assigned a salvage value, which reflects agricultural returns and the landowners' expectations over future growth. Landowners choose the so-called reserve price that maximizes their expected payoff from the land. A landowner reserves the right to not sell the land if the bid price is lower than the reserve price (Krishna, 2002).[4] To reflect the reality that developable land is more abundant in exurban than suburban and urban areas, we assume that the number of land parcels increases with the distance to urban boundary. Leapfrog development occurs when a household chooses to locate at a more distant location while a more proximate location is left vacant. To maintain analytical tractability, we assume initially that income is distributed uniformly. We show that households have the incentive to leapfrog if the gain from increased bargaining power exceeds the increased transportation cost. We then relax this assumption and use an empirically calibrated log-normal income distribution. The results are qualitatively unchanged. We summarize the notations used in this section in Table 5.

3.1. Household bidding for location

Because household bidding prices depend on both the private value of a parcel and the market conditions represented by supply and demand conditions, we first explain how the private value for land parcels is derived from the household budget constraint. Treating the land parcels at different locations as differentiated goods, we explain how supply (the number of substitutable parcels) and demand (the expected number of competing buyers) conditions for each parcel are modeled. Finally we formulate the household's optimal bidding strategy and show how the bidding strategy depends on the private value of the parcel and the market conditions.

We begin with a discussion of the income distribution and consumption profiles of households. Household income Y is a random variable uniformly distributed on the interval $[0, Y_{max}]$ with cumulative distribution function (cdf) denoted by $F(Y)$. For simplicity, we normalize the maximum income $Y_{max} = 1$. Income is allocated to travel costs, the consumption of a numeraire good C and land L to maximize the household utility $U = CL$. To further simplify the analysis, we assume that all the parcels have the same constant size normalized to be $L = 1$. This transforms the utility into a linear function of numeraire good consumption C. As a result, the reservation consumption of a household is fully determined by its reservation utility, which is the utility that the household would get if it does not migrate into the exurban region. We call C the reservation consumption. We assume that richer households have a higher reservation utility and that this reservation utility increases linearly with income. This implies reservation consumption C also increases linearly with income. We represent this as $C = c_1 Y (c_1 > 0)$. According the 2010 Consumer Expenditure Survey (U.S. Bureau of Labor Statistics, 2000), households on average spend half of their annual expenditure on commodities other than housing and transportation, so we set $c_1 = 0.5$.

[4] Although this behavior appeals to the idea of the landowner formulating expectations over future growth, we do not formally model the formation of these expectations in order to maintain model tractability. We leave the development of a dynamic model with explicit representation of forward-looking behavior for future work.

Table 5
Model variables and parameters.

Symbols	Definition
z	Distance to urban boundary
z^*	The optimal location for a household
$M(z)$	Number of substitutable parcels at z
$N(z)$	Average number of bidders
N_0	Expected number of bidders for parcels at the urban boundary
Y	Household income
$Ymax$	Maximum income for the income distribution
$Ymin(z)$	Minimum income to afford parcel at distance z
$E(z,Y)$	Minimum expenditure at distance z with income Y
$V(z)$	Household private value of parcel
U	Household utility
L	Household consumption of land
C	Household consumption of the numeraire good
c_1	Marginal increase in reservation consumption for income increase
T	Household transportation cost per unit of distance
t_0	Travel cost per unit distance independent of income
t_1	Marginal cost per unit distance for income
F	Cdf of income distribution
G or g	cdf or pdf of the parcel value
H or h	cdf or pdf for winning a parcel
$b(V, r)$	Bid function
$S(z)$	Consumer surplus at z
$r(z)$	Landowner's reserve price at distance z
$V_0(z)$	Salvage value of land
π	Landowner's expected return from the land

The travel costs[5] of the households are specified as follows. Space within the exurban region is defined in one dimension as the distance z from the urban boundary. Travel cost per unit distance, T, includes fixed travel expenses t_0 and the opportunity cost of time. The former includes the fuel cost and fixed costs of owning and operating a car. The latter is assumed to be a fixed proportion of the household's income, $t_1 Y$.[6] At a location with distance z from the urban boundary, the minimum expenditure of the household is defined as the sum of the minimum consumption expenditure and travel cost at z:

$$E(z, Y) = C + Tz. \quad (3)$$

The household income Y must be at least as much as this minimum expenditure level in order for the household to be considered as a potential buyer for the land at this distance.

We refer to the household's maximum willingness to pay for a parcel at a distance z as the household's private value of the parcel, $V(z)$. The household's maximum willingness to pay equals its income Y minus the minimum consumption and minus the travel cost:

$$V(z) = Y - C - Tz = Y(1 - c_1 - t_1 z) - (t_0 z). \quad (4)$$

The private parcel value for a household with income Y=0.8 is plotted in Fig. 2. Only households with income higher than the minimum expenditure will participate in the auction for the parcel, i.e. $E(z, Y) \le Y$ or equivalently $V(z) \ge 0$. This implies that for any bidder, the private values of his competitors are randomly drawn from a uniform distribution on the interval $[-t_0 z,\ (1 - c_1 - t_1 z)Y_{max} - t_0 z]$. Denote the corresponding cdf by $G(V)$.

In the formulation of the bid, each household will also consider the market competition conditions, i.e. the number of substitutable parcels (M) and the expected number of bidding households (N) at location z.

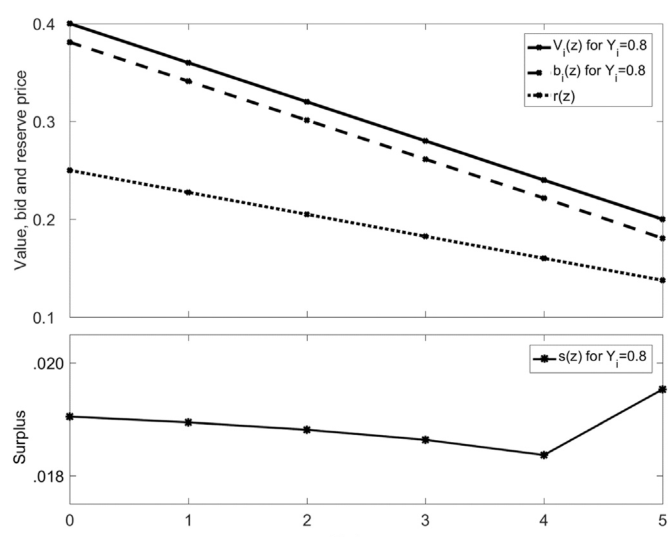

Fig. 2. Private value, optimal bid price, landowner reserve prices and utility surplus as a function of distance from the urban boundary.

[5] Here we adopt the conventional assumption of a monocentric model that households commute to a central business district for work. This excludes the rural households who do not need to commute to the CBD for work. The inclusion of those households will not eliminate the variation of market thinness along the urban-rural gradient and therefore will not invalidate the arguments.

[6] To specify t_0, and t_1, we assume that the average one-way commute to an exurban location takes 30minutes, which is somewhat higher than the national average of 25minutes in 2009. This implies that it takes six minutes to travel from distance z to $z + 1$ in our model. According to 2010 Consumer Expenditure Report (U.S. Bureau of Labor Statistics 2010), average transportation expenditures on gasoline and other vehicles expenses is around 10% of the average household annual expenditure. Because the average two-way commuting distance in our model is 5, we set $t_0 = 0.02$. Parameter t_1 measures the opportunity cost of time. If one works eight hours a day, the opportunity cost of one-hour roundtrip commuting time is 0.125 multiplied by one's income or $\frac{0.125}{60} * Y$ per minute. Because we assume that it takes six minutes to travel from z to $z+1$, we calculate t_1, which is the parameter that determines the opportunity cost of time per unit of distance, as $t_1 = 0.025 = (\frac{0.125}{60}) \times 6 \times 2$.

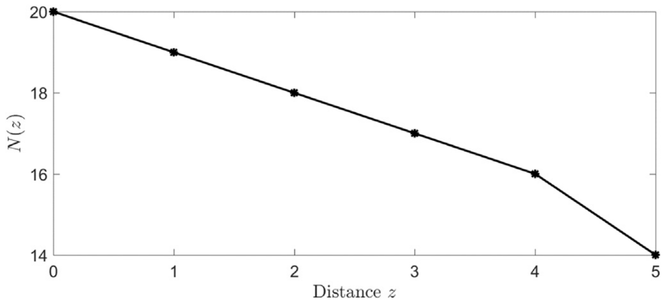

Fig. 3. Expected number of bidders as a function of distance from the urban boundary.

To reflect the reality that land availability increases with the distance to urban boundary, we assume $M(z) = z$, so that $\sum_z M(z)$ is proportional to the area z^2. Let N_0 represent the expected number of bidders for parcels at the urban boundary and $N(z)$ the expected number of bidders at distance z. Households use N_0 as a benchmark to calculate the expected number of bidders for parcels that are farther away from the urban boundary. Denote the minimum income necessary for a household to afford a parcel at location z as $Y_{min}(z) = min\{Y|Y \geq E(z, Y)\}$. Given the assumption of a uniform income distribution, we can solve for this value analytically:

$$Y_{min}(z) = \frac{t_0 z}{1 - c_1 - t_1 z}. \tag{5}$$

As distance z increases, both the transportation cost and the minimum income $Y_{min}(z)$ will increase, which reduces the probability that a randomly selected household will be able to afford the parcel. That is, $\mathrm{Prob}(Y \geq Y_{min}(z))$ decreases with distance z. Note that Eq. (5) implies that all the households can afford land parcels at distance z=0. The expected number of bidders on a parcel at distance z can therefore be determined as:

$$N(z) = Floor(N_0 \cdot Prob(Y \geq Y_{min}(z))), \tag{6}$$

where *Floor(x)* gives the largest integer less than or equal to x. It is obvious that $N(z)$ is nonincreasing in z, i.e., $N(z + 1) \leq N(z)$ as illustrated in Fig. 3.

Next consider how households formulate their optimal bid for land at a given location. The bid of a household depends on its private value of the parcel and market conditions. Importantly, we assume that land transactions are conducted through a first-price sealed-bid auction, and follow Krishna (2002) to derive the optimal household bid function $b(V, r)$ for a land parcel at a given location, where r is the reserve price of the landowner, Because a landowner will not sell the land if the bid is lower than the reserve price, the household bid b is a function of both V and r. A household chooses its bid function $b(V, r)$ to maximize the expected payoff conditional on winning one of the M parcels at the distance.[7] Let there be $M(z)$ parcels and $N(z)$ bidders at distance z. We can rank the $N(z)$ bids in ascending order. To win one of the $M(z)$ parcels, a bidder needs to ensure that his bid should have a rank number no less than $J(z) = N(z) - M(z)+1$, which we refer to as the rank number of the bids. For instance, among 10 bids ranked in ascending order, in order to win one of the 3 parcels, a bid has to be ranked no less than 8 (= 10-3+1). The household's optimal bidding strategy will depend on its private value of a parcel at a given location relative to the landowner's reserve price (r). If the bidder's private value of the parcel is less than the reserve price of the landowner, the bidder will bid zero and will not receive the parcel. If the private value equals the reserve price, the bidder will bid the reserve price, that is $b(r) = r$. For those with private value higher than the reserve price, the bidder with private value V wins a parcel at distance z if his bid is among the *M(z)* highest bids at the distance, that is, when the highest private value of the remaining *N-M* bidders is less than V. Because the bids are independent, the probability this event occurs is given by

$$H(V) = G(V)^{N-M} \tag{7}$$

where $G(V)$ is the cumulative distribution function of the value V. Denote the inverse function of the optimal bid $b = b(V, r)$ with respect to parcel value V as $V = \nu(b, r)$.[8] A bidder takes the reserve price r as given and tries to maximize the expected payoff, the payoff $[V(z) - b(V, r)]$ times the probability of winning $H(V)$, that is:

$$\max_{b(V,r)} [V(z) - b(V, r)]H(V), \tag{8}$$

where $H(V)$ is the probability that household optimal bid $b(V, r)$ wins a parcel with a total of N expected competing bidders. Intuitively, an increase in the bid will increase the chance of winning but it will also decrease the payoff from auction $V - b(V, r)$.

To derive the optimal bidding strategy $b(V, r)$, we take the derivative of Eq. (8) with respect to $b(V, r)$. This yields the first order condition,

$$-H(\nu(b, r)) + (V - b)h(\nu(b, r))/b'(\nu(b, r)) = 0$$

where $h(x) = H'(x)$. Since $\nu(b, r)$ is the inverse function of the bid function $b(V, r)$, we have

$$H(V)b'(V, r) + h(V)b(V, r) = Vh(V)$$

Rearranging the terms yields:

$$\frac{d}{dV}(H(V)b(V, r)) = Vh(V)$$

Since $b(r, r) = r$, the optimal bid function is given by:

$$b(V, r) = rH(r)/H(V) + \int_r^V vh(v)dv/H(V) \tag{9}$$

This can be reformulated as:

$$b(V, r) = V - \int_r^V \frac{H(\xi)}{H(V)} d\xi \tag{10}$$

Substitute Eq. (7) into (10) and use the L'Hôpital's rule, it is easy to show that $\lim_{N\to\infty} \int_0^V \frac{H(\xi)}{H(V)} d\xi = 0$ and $\lim_{N\to\infty} b(V, r) = V$. Taking the limit describes the long term property of this model under conditions of growth. A growing population gradually increases competition for land and reduces the bargaining power of households. As $N \to \infty$, all households bid their maximum willingness to pay. All winning households receive the reservation consumption. Differences in the transportation cost across space are fully capitalized into land price. Thus with sufficient population growth, the motivation for leapfrogging is eliminated and the land use pattern is fully contiguous and expands from the inside out.

The optimal bidding strategy $b(V, r)$ will be higher if private value of the parcel (V) is higher or if more households are competing for the parcel (i.e., N increases) or if fewer substitutes are available (i.e., M decreases). Under the assumption that household income is uniformly distributed, the optimal bid function has an analytical form:

$$b(V, r) = V - \frac{V(z)}{J(z)}\left\{1 - \left[\frac{r(z)}{V(z)}\right]^{J(z)}\right\} \tag{11}$$

where is $J(z) = N(z) - M(z)+1$, is the rank number of bids. Eq. (10) specifies the optimal bidding strategy for a household given his information set, which includes the knowledge of the overall income distribution and the rank number of bids at distance z. Substituting the household's private value of the land parcel in Eq. (4), we can express

[7] Because the bidders are risk neutral, the optimal bidding strategy derived from maximization of the expected payoff is identical to the bidding strategy derived from utility maximization. Risk aversion will increase the optimal bids in a first-price auction. For detailed discussion, please refer to Krishna (2010, p38-41).

[8] The inverse exists since the bid is a monotonically increasing function of the value.

the optimal bid β as a function of income Y, distance z and reserve price r. In Fig. 2, we plot the optimal bidding function for a household with income Y = 0.8. [9] The optimal bid price $b(V,\ r)$ of a household declines with distance, but not at the same constant rate. This is because the decrease in the optimal bid price is a result of two forces. First, the monotonic decrease in bid price reflects the monotonic decline in land value due to transportation costs. Second, it reflects the fact that bidders' market power increases with distance because the rank number of bids decreases with distance. These effects allow the household to bid down its optimal price and thus, in addition to transportation costs, the slope of the optimal bid price is determined by the relative demand and supply of land at each location.

3.2. Landowner reserve prices

A landowner optimally chooses the reserve price to maximize the expected payoff. If the parcel is sold, the landowner receives the winning bid. Otherwise, the landowner keeps the land to the next period, which gives a salvage value $V_0(z)$. The salvage value represents the value the landowner assigns to the land, which depends on the landowner's expectation of future growth, which we leave unspecified given our static model framework. If the landowner is pessimistic about future growth, the salvage value V_0 would be equal to agricultural returns. If the landowner is more optimistic, then the salvage value should also include a growth premium as discussed in Capozza and Helsley (1990). If the landowner is able to put the land up for auction in the future when the auction in the current period fails, then the salvage value V_0 becomes the discounted expected payoff from the future auction. This salvage value is private information known only to the landowner, which reflects the reality that potential buyers typically are ignorant of this piece of information.

Following Krishna (2002), the expected return to a landowner from a parcel located at distance z that could be developed can be written as:

$$\pi = \frac{1}{M(z)}G(r)^{J(z)}V_0 + \frac{J(z)}{M(z)}E[H(V)b(V,\ r)]. \tag{12}$$

The preceding expression contains two terms, representing the probability weighted payoffs when the auction fails and succeeds respectively. A parcel at distance z has $M(z)$ substitutable parcels and $N(z)$ bidders. If the $M(z)$-th highest bid is below the reserve price r, which happens with probability $G(r)^{J(z)}$, any one of the $M(z)$ parcel could be unsold and generates salvage value V_0. The expected payment in this case is captured by the first term on the right hand side of the Eq. (12). If the $M(z)$-th highest bid exceeds the reserve price r, the parcel is sold. The second term captures the consequent *ex ante* expected payment for the landowner. The expected payment by a bidder with private value V is simply the expectation of the product of the bid and the winning probability, $E[H(V)b(V,\ r)]$. Because a winning bidder randomly chooses one of the $M(z)$ parcels at distance *z,* the *ex ante* expected payment received by a landowner from a bidder is $E[H(V)b(V,\ r)]/M(z)$. Because among the $M(z)$ bidders with highest bids, $M(z)-1$ of them will choose other parcels at distance z, the number of bidders of relevance to the landowner is $N(z)-M(z)+1$, which is the rank number of bids $J(z)$. Following Krishna (2002, p.22), the second term is multiplied by $J(z)$. It is obvious that the expected return π is an increasing function of N. Other things equal, a landowner would prefer to have more bidders competing for the parcel. Therefore, a landowner would avoid private negations that limit the number of competing bidders, such as a bilateral negotiation.

Maximizing the expected return π with respect to the reserve price r yields the first order condition:

[9] The optimal bids are conditional on the optimal reservation prices set by the landowners, which is discussed in the next section.

$$\frac{\partial \pi}{\partial r} = \frac{J(z)}{M(z)}G(r)^{J(z)-1}[1 - G(r) - (r - V_0)g(r)] = 0. \tag{13}$$

The optimal reserve price solves the above equation, which is public information released to all potential bidders. As an illustration, we plot the reserve price for each location $r(z)$ in the baseline scenario in Fig. 2. Under a uniform income distribution, the optimal reserve price is given by $r(z) = (V_{max}(z)+V_0(z))/2$, where V_{max} is the private value of a household with the highest income Y_{max}.

It is important to note that the value of the land parcel for the landowner is the expected return (π) not the reserve price (r) because the reserve price is only a tool used to maximize the value of its land parcel (π). By raising the reserve price (r), a landowner can increase the expected return (π) from the auction because it would exclude those bidders with private values lower than the reserve price and therefore increases the winning bid on average. However, raising the reserve price (r) also increases the probability of failing to sell the parcel because the probability that the highest bid is lower than the reserve price becomes larger. The optimal reserve price balances these two effects. This reserve price (r) is different from the reservation price of the land, which is the lowest price a landowner is willing to sell the land. To avoid the potential confusion between the reserve price and the reservation price, in this paper the reservation price of the land is referred to as the salvage value V_0.

3.3. Optimal locational choice

Define the utility surplus $s(z)$ that a household can expect to obtain from locating at any given distance z as the difference between the household's private value of the parcel, $V(z)$, and the household's optimal bid for that location $b(z)$, that is $s(z) = V(z) - b(z)$. Given the expression for $V(z)$ in Eq. (4) and for $b(z)$ in Eq. (10), the utility surplus for a household at location z is:

$$s(z) = \frac{V(z)}{J(z)}\left\{1 - \left[\frac{r(z)}{V(z)}\right]^{J(z)}\right\}. \tag{14}$$

It is straightforward to show that for any given location z, $s(z)$ increases with income Y and number of parcels $M(z)$, but decreases with transportation cost Tz and the number of bidders $N(z)$. In Fig. 2, the utility surplus for a household with income Y = 0.8 is plotted at the bottom of the figure.

A bidder will choose only one land parcel at a location that maximizes his utility surplus. Denote this optimal location as z^*. Then for all locations $z \neq z^*$, we have $s(z^*)-s(z) = V(z^*) - V(z) - [b(z^*)-b(z)] \geq 0$. As shown in Fig. 2, for a household with income Y = 0.8, his optimal location is at z=5 because his utility surplus reaches the maximum. Note that household's private value of locations z and z^* differ only in the transportation costs and therefore we can write:

$$s(z^*) - s(z) = T(z - z^*) - [b(z^*) - b(z)] = T\Delta z - \Delta b(z^*,\ z) \tag{15}$$

Eq. (15) captures the key to optimal household location decision: the trade-off between transportation cost and bargaining gains. The first term on the right hand side is simply the difference in the parcel value, which equals the household's transportation cost between the two locations $T\Delta z$. The second term represents the change in the household's utility surplus that arises from the different bidding prices at these two locations, $\Delta b(z^*,\ z)$.

For $z^* < z$, transportation costs at location z^* are lower and the corresponding number of competing bidders is higher $J(z^*) \geq J(z)$. Given that the closer location z^* is optimal, the savings in the transportation cost $T\Delta z$ must outweigh the loss from the foregone bargaining benefits $\Delta b(z^*,\ z)$. On the other hand, suppose $z < z^*$. In this case, the gain from the increased bargaining power at the more distant location z^* exceeds the loss from the higher transportation cost at z^*. Such a situation exactly describes the conditions under which leapfrog development will occur in our model.

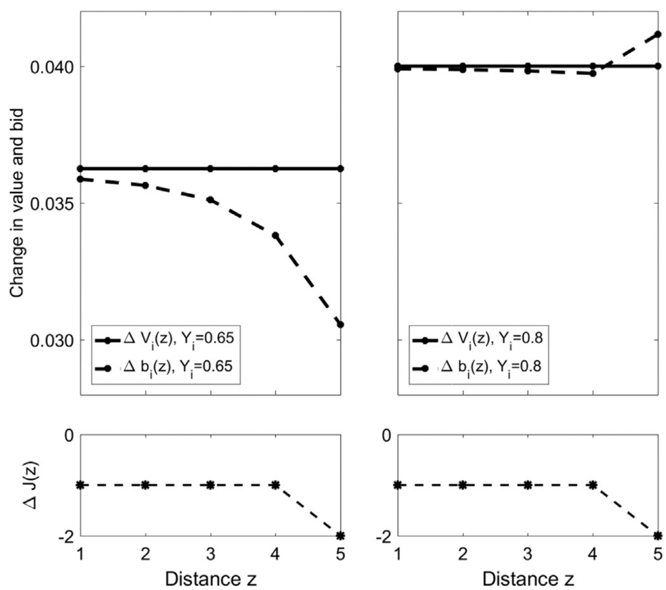

Fig. 4. Changes in parcel value, bid and effective bidder number over income and distance.

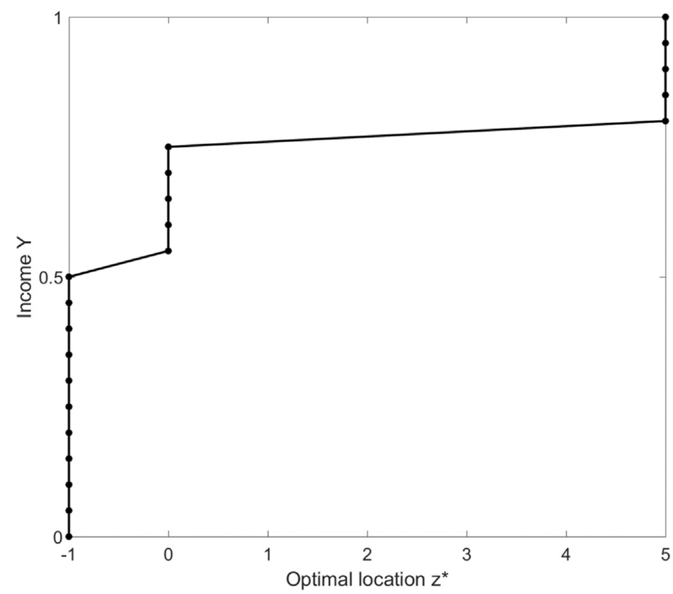

Fig. 5. Optimal household location choice as a function of income.

To illustrate this decomposition of utility surplus, we plot the two components of the utility surplus at nearby locations $\Delta s(z) = s(z-1) - s(z)$ for households with income equal to 0.65 and 0.8 in Fig. 4. The change in private parcel value equals the incremental travel cost T from location $z-1$ to z, illustrated as the solid line. The travel cost is higher for households with higher income as shown in the figure. The incremental change in bid prices $\Delta b(z) = b(z-1) - b(z)$ is illustrated as the broken line. As shown in the left column of Fig. 4, with income equal 0.65, the saving in the bid price by locating one step away from urban boundary is always less than the increase in the commuting cost. Therefore, the optimal location for this household is at z = 0. For a household with income equal 0.8, plotted on the right column of Fig. 4, he faces the same situation for distances z = 0 to 4. This makes location z = 0 preferable to locations at z = 1 to 4. However, as the household increases the commuting distance further to z = 5, the decrease in bid price exceeds the increased transportation cost and the increase in magnitude can cover all the incremental losses as the household moves from z = 0 to 4. Therefore, the optimal location for this household is at z = 5.

In Fig. 4, $\Delta b(z)$ does not monotonically decline with distance. This is due to the non-monotonic changes in the rank number of bids. To illustrate the cause of the non-monotonicity in $\Delta b(z)$, we plot the corresponding incremental changes in the rank number of bids over distance $\Delta J(z) = J(z) - J(z+1)$ at the bottom of the figure. At locations with a bigger decrease in the number of competing bidders, the marginal benefits maybe much bigger, such as with household income equal 0.8 and at distance $z = 5$.

Decompose $\Delta b(z^*, z)$, we have

$$\Delta b(z^*, z) = \left[\frac{1}{J(z)} - \frac{1}{J(z^*)}\right]V(z^*) + [1 - 1/J(z)][V(z^*) - V(z)] + \left\{\frac{V(z^*)}{J(z^*)}\left[\frac{r(z^*)}{V(z^*)}\right]^{J(z^*)} - \frac{V(z)}{J(z)}\left[\frac{r(z)}{V(z)}\right]^{J(z)}\right\} \tag{16}$$

Eq. (16) shows that changes in the bidding prices can be decomposed into three components. The first term on the right hand side gives the change due to the changes in the bargaining power at the two locations. The second term captures the changes in bidding prices due to the different private values as driven by the travel cost. The third term reflects the difference in bidding prices due to differences in the reserve prices. Altogether, this expression captures the difference in the benefits of bargaining that are reflected in the differences of both the optimal bid prices and optimal reserve prices at these two locations.

To determine how the optimal location decision varies with income, we calculate the optimal location for a range of income levels. Fig. 5 illustrates the plot of optimal location z^* as a function of income.[10] Because the bid price should be no less than the reserve price set by the landowners, households with income below this level will be forced out of the market. When this occurs, we set their optimal location as $z = -1$. For households with income levels just above this minimum level ($Y \in [0.55, 0.75]$), our model predicts that they prefer to live at city center close to the urban boundary. With income $Y \in [0.80, 1.0]$, household would jump further away from the urban boundary because the gain from reduced market competition exceeds the increased transportation cost.

Another interesting outcome of this model is the prediction of income sorting. The model predicts that households with a medium to high range of income are the households that will leapfrog to the more distant places where land market is thinner. In contrast, more moderate income households are either priced out of the exurban region or confine themselves to a location close to the urban boundary. As shown in Fig. 5, household income is positively related to the thinness of land market in exurban areas.

3.4. Information update

The optimal location outcome in the previous section does not consider the fact that households and landowners may modify their decisions based on the updated observable information like winning bid prices of households and reserve prices of landowner. In this section, we consider the outcome when this information update is incorporated. The unobservable information like household income and the salvage value of land remains private information.[11]

[10] Although optimal location is dependent on income, we switch the vertical and horizontal axes so that we can maintain a consistent set of plots with distance on the horizontal axis.

[11] Even though, it is mathematically possible to back out the household income from bid price in Eq. (10) and the salvage value from the reserve price in Eq. (13), we think it is unrealistic to assume that ordinary people in reality are sophisticated enough to do the calculation. Alternatively, if we assume that the formulation of the optimal bid and reserve prices (Eqs. 10 and 13) is private information, then the household income and landowner's salvage value can remain to be private information after observing the bid and reserve price.

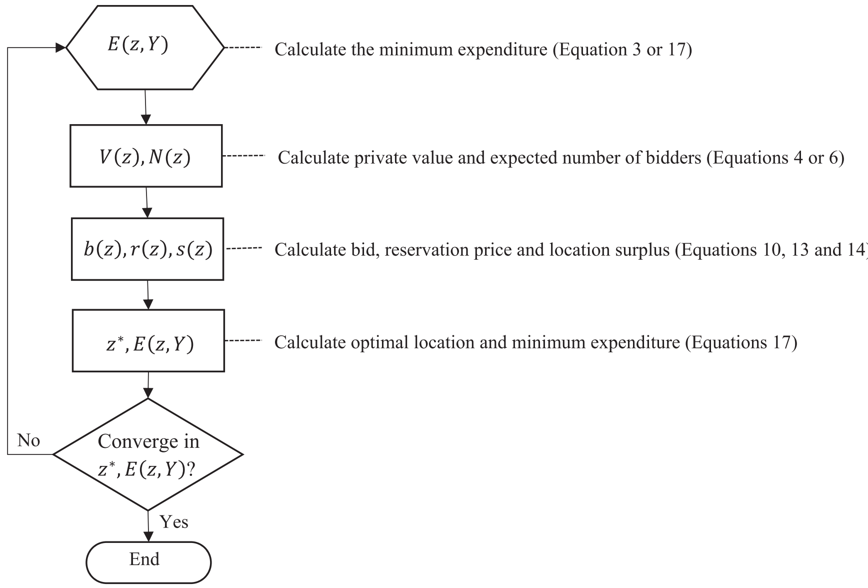

Fig. 6. Calculation of the equilibrium.

Given the optimal location choices of households (Fig. 5), the bid and reserve prices at each location, households can update their information about the minimum expenditure required for each location. For an unchosen location like $z = 1, 2, 3$ and 4, the minimum expenditure should now include the reserve price $r(z)$. For a location that is chosen by some households like z = 0 and 5, the minimum expenditure should include the minimum winning price at that location. Formally,

$$E(z, Y) = \begin{cases} C + Tz + \min(b(z)), & \text{if } z \text{ is optimal for some income } Y, \\ C + Tz + r(z) & \text{otherwise.} \end{cases} \quad (17)$$

With this updated information about the minimum expenditure level for a given location, we then update the private value of the land $V(z)$, or the maximum willingness to pay, for all households and the expected number of bidders $N(z)$ at all locations according to Eqs. (4 and 6) respectively. Landowners then update their reserve prices and households update their optimal bid prices and location choices. This generates a new set of location choices z^* and a new set of minimum expenditure $E(z, Y)$. If the updated location choices z^* and new minimum expenditure $E(z, Y)$ are the same as those from the previous iteration, an equilibrium is reached. Such a process is illustrated in Fig. 6. The resulting equilibrium location choice is plotted in Fig. 7. While Fig. 7 looks different from Fig. 5, the two basic features are maintained: leapfrog and income sorting.

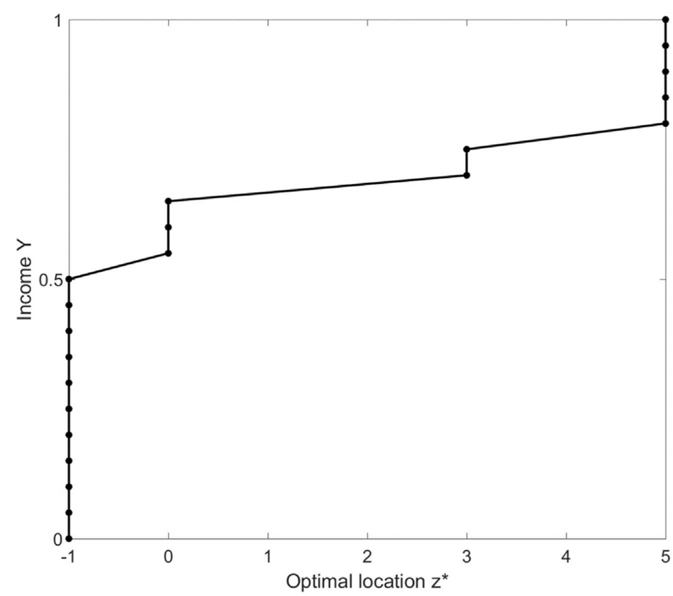

Fig. 7. Optimal household location choice with updated bidding and reserve price information.

At first sight, it is counter-intuitive that a household would not approach the landowner of the undeveloped parcel and offer to buy the parcel at a price slightly above the reserve price of auction. Such an offer is inconsistent with the household incentives. If the household is willing to pay such a price, it would have won the parcel in the auction because the landowner is willing to accept any offer higher than the reserve price. Moreover as explained in Section 3.2, it is not in the landowner's best interest to engage in private negotiations that exclude other competing bidders, such as in a bi-lateral negation, because such private negotiations lower the expected return from the land. Second, the reserve price of the auction is only a tool for the landowner to maximize the expected return from the land. It is not the actual reservation price of the land. The actual reservation price of land is determined by the expected return of land as expressed in Eq. (12) in Section 3.2, because it captures the true value of the land to the landowner. So long as landowners believe that they can put the undeveloped land up for auction in some future period, they will reject any private offer that is less than their the expected return, subject to some discount given the inherently dynamic nature of the problem. If some landowner were willing to accept an offer that was slightly above the reserve price of the auction, the household that bought the land could leave the land empty and list it for auction in the next period. This is expected to generate a positive profit. Similar to the discussion of speculation in Ols and Pines (1975, p. 232): "As long as several potential owners are aware of this possibility of future profit, they will, in competing for the land, bid its current price up to a value which is high enough to reflect its future profitability." This high speculative price of the land discourages landowner to sell the land cheap.

The emergence of leapfrog development depends on two conditions: First, the number of available parcels increases with distance and/or the number of potential buyers decreases with distance. which is likely to be a characteristic along the urban-rural gradient. Compared with their urban counterparts, exurban land markets have more abundant land supply and more limited land demand. The second condition is a consequence of thin markets when only the *ex ante* expected market conditions are known and the thinness of the market

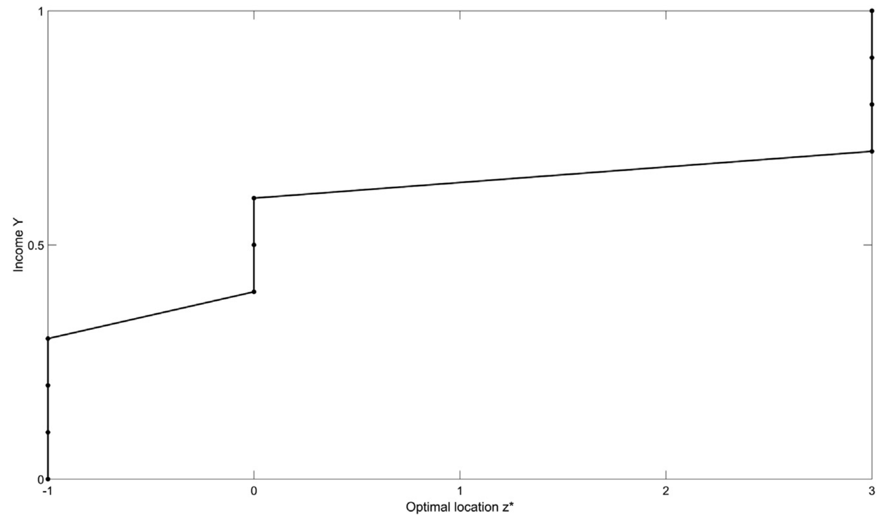

Fig. 8. Optimal household location choice assuming a log-normal income distribution.

obscures a meaningful market signal. In our model, the optimal prices that households submit to landowners reflect the *ex ante* bargaining power of a limited number of heterogeneous households in which the income levels of other bidders is unknown and only the income distribution is known. Using this same information, landowners formulate their optimal reserve prices based on their *ex ante* expected payment if the parcel is successfully sold or not. Transacted prices reflect both the individual household's private value of the location as well as these *ex ante* expectations about market competition for that location.

If these conditions hold, then the development pattern will be determined by the optimal locational choices of households and optimal leapfrog development may emerge. The outcome of our model is therefore an equilibrium in whichlandowners and households do not deviate from their optimal strategies assuming that both the ex ante expectations and the market conditions remain unchanged. This is clearly a static equilibrium and one that is subject to the constraints that generate thin markets. As population grows and more households find it optimal to locate at a given location z, the number of households bidding on the location will increase, land will become relatively less abundant and conditions of land scarcity will set in. As households compete with more bidders, their ability to bargain erodes and with it their incentive to locate farther away. New development will gradually fill in the locations that were leapt over. However, at more distant locations, incentive for leapfrog development may continue to exist especially if transportation cost decreases. Finally, if we apply to an open-city assumption, i.e., there is a sufficiently large number of potential households for every location, then competition among households will result in perfectly elastic demand and a contiguous development pattern.

3.5. Robustness

To test the sensitivity of our results to parameter values, we vary the key parameters in our model. Firstly, we increase the number of substitutable parcels at each distance by setting $M(z) = 2z$ and double N_0. Secondly, by increasing the transportation costs, either the fixed expenditure T_0 or the unit time cost T_1, more households choose optimal locations closer to the urban boundary as compared to the baseline case. When transportation costs are high enough, leapfrog development disappears. Thirdly, by increasing the number of bidders at the urban boundary, which increases the rank number of bids (J) at all locations, we find similar results. Leapfrog development and income sorting are still observed.

Finally, we relax the assumption of uniform income distribution and replace it with a more realistic log-normal distribution. In order to reflect reality, we calibrate the income distribution using household income data from the 2010 U.S. Census. Because the last income category in the census is the number of households with income over $200,000, we calibrate the income distribution with a censored log-normal distribution using Matlab function lognfit. To be consistent with the discussion in the baseline case, we normalize the income using $200,000, the cap of the reported income in census, so that the simulated income is a censored log-normal distribution on the interval [0, 1]. Denote the expectation and variance of the log(income) by μ and σ^2 respectively. The calibration yields estimates of $\mu = -1.5$ and $\sigma = 1.0$. The private value at distance z given household income Y_i is defined the same way as in the previous section: $V = Y - E(z, Y)$. Because Y follows a log-normal distribution, the private value for land V follows a shifted log-normal distribution with a cumulative probability function of $G(V)$:

$$\log(V + c_0 + t_0 z) \sim Normal(\mu + \log(1 - c_1 - t_1 z), \sigma).$$

As in the baseline case, a household will choose to leapfrog if the gain from the reduction in parcel price exceeds the increase in transportation cost. Income sorting is also observed (Fig. 8).

4. Conclusion

This paper contributes to the literature in two ways. Empirically, we provide evidence suggesting that the thinness of land markets increase along the urban-rural gradient. This highlights the often neglected reality that exurban areas contain many fewer households and an abundant supply of developable land, which is in sharp contrast to the land-scarce urban areas. Theoretically, we develop a model that captures the thinness of rural-urban land markets. Moreover, we illustrate for the first time how spatial variation in market thinness, along with a limited number of heterogeneous buyers, can generate leapfrog development. We show that this systematic variation in the relative land demand and supply with distance results in a trade-off between transportation costs and gains from bargaining. It is this tension that provide the incentive for leapfrogging. If the net benefits of this trade-off are positive, households will have the incentive to choose a more distant location over one that is closer to the urban boundary. Given heterogeneous incomes, households vary in how they make this trade-off. When multiple households compete for locations with a utility surplus, a rational landowner always picks the one with the highest offer. But at the same time, a rational household always chooses the location that maximizes the utility surplus that is positively correlated with market thinness. As a result, richer households tend to sort to farther away locations.

Whether leapfrog patterns actual emerge depends not only on the incentive for households to leapfrog, but also on the total number of households bidding for exurban location, the total supply of exurban land at each location and whether market participants have an incentive to deviate from their *ex ante* optimal choices. In our model, the relative abundance of substitutable land in exurban regions implies that each household that optimally chooses a location will win that location, so long as their bids are at least as high as the reserve price. A testable hypothesis that emerges from our theoretical model is that the differences in leapfrog development patterns across exurban regions are related to the degree of thinness of local land markets, and that exurban markets with less heterogeneity or greater numbers of households will exhibit less leapfrog development and more contiguous development.

A central insight of our model is the important role that heterogeneity plays in influencing exurban development patterns. Heterogeneity is a common characteristic of thinly traded markets. Although we focus on the role of heterogeneous income, other sources of heterogeneity may also generate these same conditions. For example, if open space amenities increase with distance and households are heterogeneous in their preferences over open space, then fewer households will compete for more distant locations and systematic variations in the relative number of bidders for any given location. Alternatively, if the cost of information is higher for more distant locations or there is larger uncertainty associated with these parcels, then fewer households will bid on these locations and the incentive for leapfrog development can emerge. Regardless of the specific mechanism, the essential conditions for leapfrog development are those that appear typical of exurban land markets: an abundant land supply, limited and heterogeneous household demand, and systematic variation in these across space. The implication is that leapfrog development is a natural early consequence of exurban land markets when demand for new residential land development is limited and land supply is abundant.

Acknowledgements

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