Spatial Heterogeneity, Accessibility, and Zoning: An Empirical Investigation of Leapfrog Development

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Abstract

Using data on subdivision development from 1960-2005 in the Baltimore, Maryland region, we develop a new, subdivision-specific measure of leapfrog development. Applying this measure, we find that about 80% of developable land that was more accessible to the urban center than newly built subdivisions remained undeveloped as of 1960. This amount declined by more than 50% over our 45-year study period to 36% in 2005. We compare this pattern with a hypothesized pattern generated by a parameterized intertemporal urban growth model and find that the observed pattern is consistent with urban economic theory, including the implied effects of zoning. Specifically, by fixing the allowable development density, low-density zoning eliminates the incentive to withhold more accessible land and thus reduces leapfrog development, a prediction we confirm empirically. The results illustrate the efficacy of the urban growth model and the substantial influence of spatially heterogeneous zoning on urban land development patterns.

Keywords: Urban Spatial Structure, Leapfrog Development, Zoning, Landscape Metrics

JEL Codes: R14, R12, R52

1. Introduction

Low-density, scattered, and non-contiguous residential development is the dominant form of land use in most urban areas of the U.S. (Heimlich and Anderson, 2001; Burchfield et al., 2006; Irwin and Bockstael, 2007). A key feature of this type of development – leapfrogging – is the spatiotemporal evolution of urban land development such that more accessible land parcels are withheld for development in later periods and more remote parcels are developed in earlier periods. Leapfrog development was first observed in the 1960s (Clawson, 1962; Lessinger, 1962; Bahl, 1963; Ottensmann, 1977), but it was not until the 1970s that the first theoretical models were developed (Ohls and Pines, 1975; Mills, 1981; Wheaton, 1982).

Urban economic theory explains leapfrog development as the result of optimal intertemporal decision-making by developers who choose the timing, type, and location of development. Given sufficient growth, developers find it optimal to reserve land located closer to the urban center for future higher-valued (e.g., as higher-density residential (Ohls and Pines, 1975; Wheaton, 1982) or industrial (Mills, 1981)) development and to first pursue lower-valued development (e.g., lower-density residential) in locations that are farther away. The emergence of leapfrog development depends critically on several factors: forward-looking developers that anticipate future prices and optimize over time; a choice between at least two development options that differ in their net returns; and sufficient growth in land values over time.

While the process of leapfrog development is well understood theoretically, its presence and persistence over time is an empirical question. Empirical evidence of leapfrog development requires spatially disaggregate data on land development over time. Given the difficulties of assembling such data, rigorous empirical evidence is scarce. To the best of our knowledge, Pieser (1989) provides the only empirical investigation of the urban economic model's predictions of leapfrog development. Using data on platted subdivisions from selected urban gradients in Washington, D.C. and Dallas, TX, he finds some support for the hypotheses that density declines with distance and that later development is higher density than earlier development. However, the study does not provide a direct measure of leapfrog development and instead relies on an analysis of age and distance regressed on lot size to draw inferences about changes in the density of infill development over time.

In contrast, many studies have implemented more general measures of urban sprawl (Brueckner and Fansler, 1983; Malpezzi, 1999; Galster et al., 2001; Burchfield et al., 2006; Irwin and Bockstael, 2007; Jiang et al., 2007; Frenkel and Ashenzi, 2008; Hashim et al., 2010) or infill development (Farris, 2001; Steinacker, 2003; Landis et al., 2006; Wiley, 2009; McConnell and Wiley, 2010) using spatial data on population density and urban land use. Others have foregone an explicit spatial measure of urban development and instead focused on the factors that influence low-density, exurban development, including the role of local open space and other land use externalities (Irwin and Bockstael, 2002; Wu and Plantinga, 2003; Turner, 2005), lower public service costs (Newburn and Berck, 2011), spatial differences in subdivision regulations (Wrenn and Irwin, 2015), and other zoning policies (McConnell et al., 2006; Newburn and Berck, 2006; Lewis et al., 2009; Towe et al., 2015). However, because they are not focused on the combined spatial and temporal aspects of development, these approaches fall short of considering leapfrog development.

The objective of this paper is to develop and apply a subdivision-specific measure of leapfrog development to examine whether the evolution of new residential development in a growing urban region is consistent with urban economic theory. In doing so, our goal is not to directly test the intertemporal optimization or expectations formation of developers, but instead to examine whether observed spatial and temporal patterns of land development are consistent with the patterns implied by a model of intertemporal residential growth. We are particularly interested in the role of zoning and whether regulations that impose a maximum allowable development density on residential development influence leapfrog development in ways that are consistent with theory. To examine these questions, we make use of original datasets on housing sales and residential subdivision development over a 45-year time period, from 1960-2005, in a three-county region of the Baltimore, Maryland metropolitan region. All three counties implemented a significant downzoning policy between 1976 and 1978. These downzoning policies, which impacted about 75% of the developable land in the metro region, converted land that was previously zoned to accommodate one house per acre to several new zoning classes ranging from one house per three acres to one house per 50 acres.

We use these data to develop a new measure of leapfrog development that calculates the amount of leapfrog development that is created by each new subdivision developed at a particular time and location in our study region, and track the changes in these subdivision-specific measures over time as additional development occurs. The amount of leapfrog development associated with a specific subdivision is measured as the percentage of developable vacant land that is more accessible to the city center than the subdivision itself and located within a given buffer along the most expedient commuting route to the outer boundary of Baltimore City. The leapfrog measure is expressed in percentage terms relative to the total amount of developable land that is either developed or vacant within each subdivision-specific buffer and varies between zero (no remaining developable land) to one (all land is developable).

We use the intertemporal model of urban growth developed by Wheaton (1982) and data on housing values to develop a prediction of hypothetical leapfrog development in the absence of zoning for our study region. This seminal paper derives the conditions under which different patterns of urban growth emerge over time, including inside-out, outside-in, and leapfrog development. Outside-in development emerges in a growing city with sufficiently low discount rates when the demand for density increases at a sufficient rate over time. Using a long time series on housing sales, we estimate the key reduced-form parameters of the model and apply these estimates to our parcel-level data to generate a theoretically based hypothetical pattern of leapfrog development without zoning and assuming a discount rate. We also generate predictions of random urban development and then use our measure of leapfrog development to compare the observed evolution of leapfrog development with the evolution predicted by these two hypothesized processes.

Our analysis reveals a pattern of leapfrog and infill development that is consistent with urban economic theory and that underscores the influence of zoning on the evolution of these patterns. We find that the relative amount of leapfrog development is high, but declines over time from 80% in 1960 to 36% in 2005. In other words, about 80% of developable land deemed more accessible than existing subdivisions was undeveloped in 1960. This amount declined by more than 50% over our 45-year study period at an annual rate of approximately 1%. In comparing this observed pattern to the unconstrained hypothetical pattern predicted by the basic intertemporal urban growth model, we find that it closely matches the predictions, but only in the early years before the downzoning policy. After the downzoning, the observed amount of leapfrog development is significantly less than the unconstrained predicted pattern. We further explore the role that zoning may have had on the evolution of leapfrog and infill patterns using a series of first difference models. The results show that after controlling for distance to urban centers, the spatial pattern of infill development is significantly influenced by local variations in the maximum allowable development density. Specifically, we find that the downzoning policies enacted in the late 1970s significantly slowed the rate of infill development in more rural areas of the metro area and increased the rate of infill development in areas closer to the urban centers.

This paper makes several contributions to the literature on urban growth and spatial structure. First, we use a dataset on residential subdivision development activity over time to develop a spatially disaggregated measure of leapfrog development that corresponds to the scale of the microeconomic unit of behavior (the land developer), is based on commuting time to the urban center, and is sufficiently precise to capture the essential spatial-temporal aspects of leapfrog development. Second, we provide evidence that the evolution of leapfrog development is consistent with urban economic theory, including the hypothesized effect of zoning. Specifically, Wheaton's model of intertemporal residential growth emphasizes the role of increasing demand for density over time as a necessary condition for leapfrog development. Zoning fixes the allowable development density and therefore eliminates the incentive for leapfrog development and encourages more infill development. We find that the observed leapfrog development pattern is consistent with the hypothetical unconstrained pattern predicted by theory in the pre-downzoning period. Given that zoning removes the incentive to withhold development, the divergence of the observed and predicted patterns in the post-downzoning period is also consistent with theory. Lastly, we provide direct empirical evidence of the significant effect of zoning on leapfrog and infill development patterns. These findings underscore the importance of spatially heterogeneous regulations and indicate that the spatial process of exurban growth is more complex than one that is determined solely by transportation costs.

The organization of the remainder of the paper is as follows. In section 2, we introduce the methodology, and in section 3 we describe our data. Results regarding leapfrog and infill development are presented in section 4; section 5 provides additional discussion and concludes.

2. Methodology

2.1 Quantifying Leapfrog Development

An accurate measure of leapfrog development accounts for the timing and location of development based on accessibility as well as the corresponding amount of leapfrogged land. Moreover, given the dynamic predictions of the urban economic models, the measure should account for changes in these quantities over time. We operationalize these ideas by first, defining what it means for a parcel to be leapfrogged; second, developing a measure of the relative amount of leapfrog development that is generated by an individual subdivision development; and third, updating this measure for each over time.

To identify the set of leapfrogged parcels for each subdivision, we first determine the shortest travel time route, via the metro road network, to the center of Baltimore City. Then, we create a series of buffers – 250, 500, and 1000 meters – around each route (Figure 1) and intersect each of these subdivision-specific buffers with a series of land use maps created in five-year increments from 1960 through 2005.[1] Each land use map provides a temporal snapshot of the types of land use – subdivision, non-subdivision residential, commercial/industrial, public facilities, utilities, transportation, preserved/protected, and all other undeveloped land – occurring in the region.

[1] All GIS calculations are performed using ArcGIS 10.2 and the Network Analyst extension.

We count a parcel that falls within each buffer as being leapfrogged if it is undeveloped land that is neither preserved agricultural nor protected land (i.e., all other undeveloped land). We then construct a measure of the relative proportion of leapfrog development by calculating the total area of the set of leapfrogged parcels and dividing it by the total area of all developable land that falls within the buffer, which includes the total area of undeveloped land (the numerator) and the total area of developed land (all types of residential and other urban land). This statistic is calculated for each subdivision that was developed from 1960 through 2005.

A subdivision's first leapfrog measure is calculated using the land use map that corresponds to the end of the five-year time period during which the subdivision was first created; we then calculate the measure for each subsequent five-year time period through 2005. For example, a subdivision platted between the years 1965 and 1970 in Baltimore County is treated as a new subdivision as of 1970, and we use the 2005 land use map to calculate the 2005 leapfrog measure associated with this subdivision (Figure 1). This subdivision has a total of eight leapfrog measures that describe the evolution of leapfrog development associated it as a result of land use changes that occurred between 1970 and 2005.

[Insert Figure 1]

Formally, the leapfrog measure associated with subdivision j, platted in year t, and with subsequent land use of time s is defined as

$$LF_{jts} = \frac{Undeveloped\ Land\ in\ Time\ s\ in\ Buffer\ j}{Developable\ Land\ in\ Time\ s\ in\ Buffer\ j}, \tag{1}$$

$$LF_{jts} = 1 - \frac{Developed\ Land\ in\ Time\ s\ in\ Buffer\ j}{Developable\ Land\ in\ Time\ s\ in\ Buffer\ j}, \tag{2}$$

$$LF_{jts} = \frac{Undeveloped\ Land\ in\ Time\ s\ in\ Buffer\ j}{All\ Undeveloped\ and\ Developable\ Land\ in\ Time\ s\ in\ Buffer\ j}. \tag{3}$$

In sum, the leapfrog measure varies continuously between zero and one with higher values indicating a greater degree of leapfrog development. This relative measure is comparable across space and time and has an easy interpretation as the relative amount of leapfrogged land that is associated with a specific subdivision, location and time period. Intertemporal comparisons illustrate how the leapfrog and infill development associated with a specific subdivision change with changes in all types of land use that fall within the subdivision-specific buffer.

2.2 Quantifying Infill Development

Because residential development is generally considered as irreversible, our measure of leapfrog development is non-increasing over time. Differing over time provides a subdivision-specific measure of infill development – i.e., the relative amount of additional development that occurred within a given buffer between two subsequent time periods. We define the amount of infill development associated with buffer j that occurs between years s and r as the change in the leapfrog measure over these years or, equivalently, as the total area of infill development relative to the total area of all developable land within the buffer. Specifically:

$$InFill_{jsr} = LF_{jts} - LF_{jtr} \tag{4}$$

where $t \leq s \leq r$.

2.3 Quantifying Downzoning

To explore the impact of downzoning on residential development patterns, we construct a subdivision-specific measure of the zoning change within each buffer. To do this, we first intersect each buffer with a series of zoning maps (Figure 2) and calculate the are percentage of each zoning class – agriculture, conservation, and urban – relative to the total land area within the buffer, and we calculate the zoning percentages before and after the changes in zoning policy in the mid-1970s. The change in agricultural and conservation zoning within each buffer is calculated as the increase in the proportion of each zoning class after the downzoning occurred.

[Insert Figure 2]

3. Study Region and Data Description

Our study area comprises three counties – Baltimore, Carroll, and Harford – within the Baltimore, Maryland metro region (See Figure 1). These three counties represent a combination of urban, suburban, exurban, and rural land use, with residential densities varying from 16 houses per acre in areas near Baltimore City to one house per 50 acres in areas in Northern Baltimore County.[2]

The Baltimore metro was one of the first to enact sweeping land use restrictions in the mid-1970s. Much of the outlying areas in this region remained rural through mid-20th century, but faced increased population growth beginning in the 1950's as the result of a number of decentralizing factors, including construction of interstate highways and the desegregation of public schools in Baltimore City. The growth rate reached a peak of 40% in 1980 before declining to a growth rate of 10% in 2010.

As a result of this early growth, all three metro counties enacted large-scale downzoning policies in the mid-1970s, which effectively rezoned around 75% of the land area. Each county designated a significant portion of their rural land as either agriculture or conservation. Agriculture zoning reduced the maximum allowable density from one house per acre to one house per 20 acres in Carroll and Harford and one house per 50 acres in Baltimore County; conservation zoning limited development density to one house per three to five acres. The remaining developable land in each county was zoned for various higher-density classes of urban development (Figure 2).[3] The intent of the

2 According to Berube et al. (2006), this area serves as one of the most representative examples of exurban growth areas in the U.S. with both high population growth and a significant amount of low-density, non-contiguous residential development across the entire metro area. We selected the three counties used in this paper based on the availability of parcel-level subdivision data.

3 Zoning policy in the Baltimore metro region is established at the county level. Thus, each county has a different set of zoning classes and names. Since our research focuses on how broad, yet large, zoning changes have impacted leapfrogging and spatial development patterns in our study region, we do not differentiate between all of these zoning classes and reclassify the many zoning classes across counties as agriculture, conservation, or urban based on the development densities described above.

1970's downzoning was to reduce development in rural areas and concentrate development in development corridors. Apart from several small adjustments made in the early 2000s, these same restrictions have been in place since 1976.[4]

Of the total amount of land in our three-county study region, over 22.5 percent was residential as of 2005. The overall location of the subdivision development activity, through 2005, is relatively scattered throughout the region (Figure 1), but a greater concentration of development is in areas closer to Baltimore and Washington DC and around suburban subcenters.

To implement our leapfrog metric, we construct a spatially-explicit dataset of historical subdivision development for all three counties from 1960 to 2005 by matching current parcel boundary GIS shapefiles to historical plat maps obtained from the Maryland Historical Archives. Subdivision development comprises about 75% of overall residential development area in each county and has been the dominant residential land use type since 1960. From 1960 through 2005, a total of 7,528 subdivisions were developed across all three counties. These developments range in size from as small two- or three-lot minor developments to large commercial developments with more than 1,000 lots. Our final set of GIS datasets for each county contain information about the

[4] This downzoning change, while extreme, does not appear to be unusual for rapidly urbanizing counties. More generally, downzoning is the most common growth control tool used by urban and urban-rural fringe counties to control growth (Adelaja and Gottlieb 2009; Gyourko and Molloy, 2015). Using a series of statistical test, shown in Appendix, Section A.1, we show that zoning is strictly enforced in our study region.

physical attributes of parcels, their structural characteristics, purchase dates and prices, development timing, the number of lots created in each subdivision, and land use and preservation information.[5]

4. Results

4.1 Descriptive Pattern Analysis

Each subdivision is associated with a separate set of buffers based on the year in which the subdivision was approved. Thus, subdivisions that were developed in early periods have more leapfrog values associated with them. To develop an initial assessment of how leapfrogging has changed across time in our study region, we take the average value of our leapfrog metric in each time period for all subdivisions platted in 1960.

The results of this process for a 500-meter buffer size are shown in Figure 3.[6] This figure shows the average leapfrog metric for each of three counties as well as the average measure for the entire metro. The red line in Figure 3 shows that the average value of our leapfrog measure across all of the 89 subdivisions platted in the Baltimore metro in 1960 is 0.80—i.e., an average of 80% of developable land deemed more

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[5] See Wrenn and Irwin (2015) for details about how these types of data were constructed for each county

[6] We examined the robustness of our results by calculating the metric using 250 and 1,000 meter buffers, and this figure is available from the authors upon request. We compared the three-county average leapfrog metric values to that of the 500-meter buffer and found the results to be almost identical. The average leapfrog metrics calculated using only newly platted subdivisions at five-year increments, as opposed to all existing subdivisions, yield similar results. Thus, we feel confident in using the results from the 500-meter buffer for all subsequent analysis and discussion.

accessible than the existing subdivisions in 1960 remained vacant. The lines for the individual counties are interpreted similarly and show similar patterns.

There are three things worth highlighting about this figure. First, leapfrog development declines over time in all three counties due to infill developments, which is consistent with basic theory. Furthermore, the leapfrog metric values are substantially lower for Baltimore County, which is mainly due to the fact that more development occurred in suburbanized Baltimore as compared to the more exurban counties of Carroll and Harford. It also likely stems from the fact that more of Baltimore County is zoned for conservation and higher-density residential development. Finally, note that the average leapfrog measure declines over time to 36% in 2005, which implies a more than 50% drop in leapfrog development. We find that infill development systematically occurs over time and that about 1% of the land that was previously leapfrogged is developed, over average, each year.

[Insert Figure 3 Here]

To further examine the statistical relationship between our leapfrog measure and the location and timing of subdivision development, we construct a panel dataset of subdivision development based on the year that each of our subdivisions was created. We then use these data to estimate a series of regression models. In the first model, we estimate a simple pooled OLS regression model; for the second model, we estimate a random effects model with the random effects at the subdivision (buffer) level.

The dependent variable in each model is the leapfrog measure associated with each subdivision in each year following the year in which it was platted – up to 2005.

Thus, the panel is unbalanced as subdivisions platted in later years have fewer observations. The time-invariant variables in each model include the total acreage of the subdivision, an indicator for whether the subdivision is a minor development (2-3-lot subdivisions), the driving distance, in miles, to Baltimore City along the most expedient route, and the square of this driving distance variable. In addition to these time-invariant covariates, we also include a set of time-varying variables that account for changes in the zoning. These variables are defined as the percentage of total land area in each 500-meter buffer that is zoned as agriculture, conservation, or urban (see Figure 2 and Section 3 for an explanation). Since these zoning percentage variables sum to one, we estimate each model with just agriculture and conservation and interpret our results relative to the excluded urban class. Each model also includes a full set of time fixed effects associated with our five-year time increments with 1960 as the excluded dummy.

The results from this regression analysis (Table 1) show that the coefficients on all of the year dummies are negative and significant, which again confirms the basic intuition that leapfrog development should decrease over time. In addition, the magnitude of these coefficients increases over time indicating that the difference between the leapfrog patterns in 1960 and more recent years is greater than the difference between 1960 and earlier years.[7] The coefficients associated with distance to the city indicate that the incidence of leapfrogging increases at a decreasing rate with distance, suggesting that the influence of proximity to urban centers has a diminishing marginal

[7] A series of F-tests confirms that these differences in coefficient values are statistically significant in all cases.

effect. Finally, leapfrog development is positively associated with the percentage of agricultural zoning in each buffer and negatively impacted by the percentage of conservation, relative to the percentage of urban zoning. The results for the agricultural zoning variable are intuitive: the lower development density artificially creates more undeveloped yet developable land and thus a higher leapfrog metric. Conservation zoning on the other hand was largely designed to be a "happy medium" between the very restrictive agriculture zoning classes and less-restrictive urban classes and is mostly located on the border with urban zoning. The estimated negative effect of conservation zoning on leapfrog development is therefore consistent with the spatial pattern of this zoning class.

[Insert Table 1 Here]

4.2 A Test of the Significance of the Leapfrog Development Pattern

Given a consistent empirical measure of leapfrog development, we now turn to developing a predicted leapfrog development pattern based on a parameterized version of the intertemporal model of urban residential growth developed by Wheaton (1982). We estimate reduced-form parameters using hedonic analysis and historical housing sales data from the Baltimore region to capture the macro conditions of our study region. Historical land use regulations are used to determine the allowable density of development in each time period and use them to generate a predicted landscape for our study region based on the theoretical model.

Wheaton develops a basic intertemporal model of urban growth under perfect foresight in which leapfrog development patterns can occur when market conditions – rising income, population growth, falling transportation costs, and increased demand for land – combine with lower discount rates to make it profitable for developers to withhold land close to the urban center and develop more remote land in early periods. The intuition is that at lower discount rates land rents closer to the urban centers, which are projected to be higher in the future, are sufficiently large to make it worth holding them for future development. This underscores the key behavioral mechanism in the model: that landowners have the incentive to withhold land in earlier periods so that they can develop at greater densities in the future.

The model follows a standard urban bid rent specification, positing that land, located d miles from the city center in period t with transportation cost equal to k_t has the following rent function in equilibrium:

$$R_{\mathrm{t}}(y_{\mathrm{t}}, k_{\mathrm{t}}, u_{\mathrm{t}}, d, q) = y_t - k_t d - u^{-1}(u_t, q), \tag{5}$$

where the rent in period t depends on household income y_t, transportation costs $k_t d$, the amount of the numeraire good purchased, and household preferences for land, q. Given perfect foresight, a landowner contemplating the development of a specific parcel in period t will develop that parcel in order to maximize per-period profits, Π_t, as follows:

$$\max_q \Pi_t = \sum_{\mathrm{s=1}}^{\mathrm{t-1}} D_{\mathrm{s}} A_{\mathrm{s}} + \sum_{\mathrm{s=t}}^{n} D_{\mathrm{s}} \frac{R_{\mathrm{t}}(y_{\mathrm{t}}, k_{\mathrm{t}}, u_{\mathrm{t}}, d, q)}{q}. \tag{6}$$

The first summation is the present discounted value of holding agriculture land, A_s, from the first period up to the beginning of period t, and the second summation is the present discounted value of rent, per acre, from period t onward, where q represents the density of development and D_s is the per-period discount factor. The entire expression in equation (6) represents a "hold until the beginning of period t and then develop" strategy.

Combining equations (5) and (6) expresses how rent per acre of land, r_t, varies with distance to urban center and over time as follows:

$$\max_q r_t = \left[\sum_{s=1}^{t-1} D_s A_s + \sum_{s=t}^{n} D_s \frac{y_t - u^{-1}(u_t, q)}{q}\right] - \sum_{s=t}^{n} D_s \frac{k_t d}{q}. \tag{7}$$

The bracketed terms in equation (7) represent a set of time-varying intercepts, which are defined by the predictable market parameters in period t, including income, population growth, and preferences for density. The last term is determined by transportation costs to the city center. The entire equation is defined on a per-unit-of-land basis. Thus, a parcel's rent per acre in each time period is based on its distance to the city center and market parameters and all parcels at the same distance have the same value. Given these time varying parameters and the discount rate, an owner maximizes land rents by choosing the optimal density and timing of development for a given location. Assuming a competitive market and development that is unconstrained by zoning, the spatial and temporal ordering of development is determined by the highest rent value in a given time period at a location that is not yet developed.

To empirically implement Wheaton's model, we observe that equation (7) is simply an equation for the rental value per acre of land in each time period. Thus, if we had a dataset for these per-acre values over time and space within our study region, then we could regress them on a set of time-period fixed effects and a distance variable to get reduced-form estimates for the time-varying and spatial terms in equation (7). While this type of detailed data is not available for land values, it is available for housing values, which we are able to collect over almost a 50-year period from 1956 to 2005. These housing sales data, collected as part of the Maryland Property View Database (MDPV), provide information on the nominal sales values, sales dates, type of transaction, housing and lot characteristics, and location for this large sample of housing sales; we use them to extract a spatially and temporally explicit estimate for the rent per acre of land.[8]

To generate rent estimates, we regress historical housing sales on a set of housing and location characteristics for house i:

$$lnp_{it} = lnq_{it}\alpha + X'_{it}\beta + \sum_{t=1}^{T} \tau_t + \sum_{j=1}^{J} \delta_j + \varepsilon_{it}, \quad (8)$$

[8] These housing sales data were extracted from old sales databases obtained through the Maryland Department of Taxation. As expected, the sample sizes for the early periods are considerably smaller than those in more recent years, but we were still able to get yearly sample sizes in the 1960s of around 200-400 sales. By pooling these samples over time we achieve a very large sample (70K) of historical sales.

where lnp_{it} is the natural log of the real price of housing, X_{it} is a set of housing characteristics, τ_t is a set of time fixed effects, δ_j is a set of census tract (2000 boundaries) fixed effects, and lnq_{it} is the natural log of lot size. The housing characteristics used in the model include structure size, number of bedroom, number of bathrooms, housing quality, age of the structure, and indicators for whether the house had a garage, a basement, air conditioning, and whether it was located in a large subdivision. Housing prices are converted to 2013 dollars using CPI-U-RS price index.

After estimating equation (8), we use the coefficient value on land, α, and the real sales prices and lot sizes for each housing transaction to generate a prediction for the marginal price per acre of land, r_{it} – i.e., we apply the following formula to each of the housing transactions in our dataset: $r_{it} = \left(\frac{p_{it}}{q_{it}}\right) * \alpha$. This process, while admittedly imperfect, effectively produces a quasi-rent-per-acre predication at the same spatial and temporal scale as the housing data and mimics the rental value, r_{it}, from equation (7). If we assume that the housing market is competitive in each period and that land developers have perfect foresight, the rent-per-acre estimates should reflect the present discounted value of all future rents at the location and period of the observed housing transaction.

The final step in implementing equation (7) is to estimate the time-varying and spatial components of the rent-per-acre values to construct average rental values for a given time period and location.[9] This is achieved by regressing our predictions for the

[9] While it is true that real transportation costs changed over time, we constrain their effect to be constant by only including a single variable for distance. This is in line with the proofs in the

rent per acre, r_{it}, on a variable for the commuting distance to Baltimore City from each housing sales and on a set of time-period fixed effects for each of our five-year time periods (Table 2).

[Insert Table 2]

Intuitively, the time fixed effects capture the effects of income and population growth that determine the future growth of residential rents and, in combination with the discount rate, the potential benefits from withholding land today for higher density development at a later date. We use these estimates to generate present value predictions of rent per acre for each time period and for each location, defined by commuting distance that corresponds to different distance rings. By combining these predictions with different discount rates we can effectively rank order the timing and location of development in our study region – i.e., we can determine the timing of a series of development rings and produce a leapfrog pattern by altering the discount rate. Importantly, we do not include the effect of a density constraint from zoning when calculating our final per-acre estimates of rent. Therefore, this value can be interpreted as the hypothetical rent per acre in the absence of an explicit constraint on density. The implication is that the intertemporally optimal pattern that is implied by these rents is the

Wheaton paper. We also implemented our simulations using a set of time-varying distance coefficients and did not find qualitatively different results. These results are also reported in Table 2.

pattern that would have emerged in the absence of zoning that would otherwise have restricted development density.[10]

To understand how the coefficients estimated in Table 2, travel distance from Baltimore City, and a given discount rate impact the spatial ordering of development, and thus leapfrogging, in Table 3 we present the predicted rent-per-acre values for each time period and at varying distances using the coefficient estimates from Table 2 and a 0% discount rate. In Wheaton's model, the width of each development ring, or annulus, is determined by the size of the population in a given time period. We adopt this approach below, but in Table 3 we simplify the calculation by assuming that population size is constant and each ring is 5,000 meters in width.

Inspection of Table 3, and the ranking of development in terms of location and timing that are indicated in last row of the table, shows that with no discounting the ordering of development in this hypothetical scenario occurs in an outside-in manner. This result is consistent with Wheaton's paper in that at very low discount rates development can occur from the urban boundary inward.

Table 4 considers the same intertemporally optimal ranking with a discount rate of 3%. In contrast to the first case, we observe that a 3% discount rate produces a leapfrog pattern of development.[11] We use this discount rate, which is the same discount

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[10] Of course the effect of the zoning constraint may be capitalized into housing values, but we use census tract fixed effects to control for this in the hedonic estimation of the marginal value of land.

[11] If we increase the discount rate from 3% to 6% the ranking switch to an inside-outside pattern with no leapfrogging.

rate that is used in Wheaton's analysis, to simulate an intertemporally optimal pattern of leapfrog development given the observed historical conditions of our region and assuming that the downzoning constraint was not imposed.

[Insert Table 3 Here] [Insert Table 4 Here]

The final step in generating our predicted landscape is to generate the size of the development rings using our actual parcel data. We follow the logic laid out by Wheaton to create rings using the actual number of lots created in each time period as a proxy for the amount of housing needed to meet a growing population. Since we already know the order in which the rings will get developed based on the predictions from Table 4, we simply need to adjust the size of the rings to accommodate all lots created in each time period. Thus, for periods with a lot of development activity the ring size will be larger than for those periods with fewer houses built.

We assign lots to parcels within each development ring by matching the subdivision sizes from the actual data to developable land parcels in each ring based on the development capacity of each parcel to accommodate a specific sized subdivision.[12] For single-family houses – one-lot subdivisions – we randomly assign them to the remaining developable land in each ring using a simple random-assignment algorithm

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[12] The reduced form rent calculations assume that density is unconstrained and lot sizes are optimally determined. However, extracting an explicit expression for optimal lot size would require many more assumptions, including a specific functional form for utility and specified values for the housing cost, transportation cost and other key variables in each time period. In the absence of these data and given the lack of guidance from theory in specifying a utility function, we use current zoning to determine the development capacity of each parcel. To the extent that zoning is binding and optimal lot sizes are smaller, this will result in annuluses that are larger in width than what theoretically would be the case.

that puts space between parcels such that it mimics the actual development density in that time period from the actual data. To make sure we can accommodate all of the subdivision and rural-residential development in each period, we adjust the algorithm to keep adding additional land to the ring until all of the subdivisions and single-family lots created in a given period had been accommodated. The results from the process and the development rings produced from the entire Wheaton (1982) simulation are shown in Figure 4.

[Insert Figure 4 Here]

In addition to this theoretically-based hypothetical pattern of leapfrog development, we also compare the observed pattern of leapfrog development to a random landscape, reflecting the naive belief that the observed pattern in our study region was produced by a fully random process. We implement the random simulation by starting with the observed landscape in 1955 and randomly picking developable parcels that were not yet developed in 1955 and designating them as developed in 1960. We continue this random assignment process in the first period until the total number of developed lots from both subdivisions and rural residential developments (single-lot developments) match the actual amount of development activity across all three counties from 1956 through 1960. Conditional on the predicted 1960 landscape, we continue the random assignment process for each of the subsequent five-year periods up to 2005 with each step's total lot quantity based on the actual number of lots observed in the data. This randomization process is repeated 250 times to account for idiosyncratic discrepancies across iterations, which results in 250 evolutions of a randomly generated landscape over our study period.

Figure 5 compares the results of the leapfrog metric calculations based on the actual data, the theory-based predictions, and the land development trajectory based on the random-assignment algorithm. The box and whisker plots in the top portion of the figure indicate the mean and standard deviation of the average leapfrog measures from the 250 randomly-generated landscapes. The lower part in Figure 5 provides a comparison of the individual-level leapfrog metrics applied to one of the random landscape (out of the 250 random simulations), the theory-based landscape and the actual landscape.

[Insert Figure 5 Here]

In comparing these, we observe that, like the actual pattern of leapfrog development, both the theoretical and random patterns exhibit initially high levels of average leapfrog development, followed by declining average values over time. This suggests that the trend of declining leapfrog values may be more related to a general "filling up" process than any particular type of infill process. In addition, we note that both the theoretical and random patterns exhibit relatively similar average values of the leapfrog metric and that, based on the box and whisker diagram, the average value of leapfrog development generated by the theoretical model is not significantly different from a random pattern. This is interesting, given the different processes that underlie these simulated landscapes. However, this may also be a result of the fact that both landscapes are constrained by the same historical land use regulations that determine the set of developable parcels.

Finally, and most relevant for this investigation, we note that the actual pattern of leapfrog development diverges over time from both the theoretical and random patterns. The lower part of Figure 5 shows that from 1960 to 1980 the actual pattern of leapfrog development is not significantly different from a randomly generated pattern and cannot be distinguished from the theory based pattern. After 1980, however, we find that the observed pattern is indeed characterized by significantly lower leapfrog values than the two simulation-based metrics, which reflects greater infill development than in the case of either the random or theoretical landscapes. Given that the theoretical landscape does not reflect the effect of density constraints on the per-acre rent values, this divergence suggests that downzoning may indeed have reduced the relative amount of leapfrog development over time. This is entirely consistent with Wheaton's analysis, which shows that increasing demand for development density over time is a necessary condition for leapfrog development. Zoning fixes the allowable development density and therefore eliminates the incentive for withholding more accessible land to be developed at a higher density at a later date. Thus, we find that this theory of urban residential growth is consistent with the observed leapfrog development patterns in both the pre- and post-downzoning periods.

4.3 First Difference Estimation

Our previous results provide some evidence of a structural break in development patterns before and after the 1970s downzoning. To further investigate the hypothesis that the zoning change led to a substantial reduction in leapfrog development, we employ a first difference estimation technique using only those subdivisions that existed before the downzoning policy took effect.[13] By taking the first difference of the infill development measure, we are effectively controlling for any time-invariant factors that may have influence the decision of the landowner to develop their parcel such as unobserved attributes about the parcel not included in the data or unobserved information that the landowner may have had about the approval process in the county (Wrenn and Irwin, 2015).

We estimate three separate first-difference models using existing subdivisions from 1960, 1965, and 1970, respectively. The dependent variable in each model is the difference in infill development between the five-year periods before and after the downzoning occurred – i.e., $(Infill_{j81-85} - Infill_{j71-75})$. To examine the role of downzoning, we include a measure of the increase in the relative amount of land within each subdivision-specific buffer that is zoned for agriculture and conservation. We also control for the confounding impact of time-varying factors by including interest rate changes and changes in populations interacted with parcel-specific variables[14].

[Insert Table 5 Here]

[13] While we agree that sample selection may be present, the fact that we use a first-difference model to account for the time-invariant unobservables that may make development on some parcels occur before others at least, to some extent, accounts for the selection process. We chose to use the existing subdivisions because their locations are not endogeneously determined by downzoning, and it provides a comparison for amount of infill development before and after downzoning.

[14] Specifically, we interact interest rate changes with lot quantity as previous research has shown that larger subdivisions with more lots could have a longer regulatory approval process (Wrenn and Irwin, 2015), and thus potentially affecting the developers' ability to lock in a certain interest rates. In addition, we interact population change with subdivision acreage because increased demand through population growth could impact the optimal size development that is needed.

The results from our first-difference model, shown in Table 5, reveal a negative and significant impact on the rate of infill development as the percentage of agricultural zoning increased following the 1970s downzoning. Downzoning significantly slowed the rate of infill development in more rural areas of the metro area, which have a higher percentage of increased agricultural zoning. This result implies that development was shifted away from rural areas and towards areas closer to urban centers. Indeed, we find a positive and significant coefficient value on the conservation zoning variable, which, as we explained in section 4.1, likely is due to the location of conservation zoning adjacent to urban areas in our study region. This result provides further evidence that zoning changes shifted development patterns by spurring infill development and reducing leapfrog development in areas closer to the urban center. Note that the results are quite similar across three models (all three time periods).

Given the similarity in the results across all of the models in Table 5, we focus our robustness checks on the sample that contains all existing subdivisions developed from 1956-1970. Table 6 presents a series of robustness checks that test the specifications of our main model. These tests include dropping the interaction terms for population and interest rates (model 1), adding parcel characteristics (model 2), using log-linear and log-log specifications for the infill and zoning variables (models 3 and 4), dropping border parcels – parcels 2 miles on either side of the new zoning boundaries (model 5), and finally, accounting for any nonlinear effect from the changes zoning changes by adding square root terms. The results from each of these models are similar to those in Table 5 and confirm the overall effect of downzoning policy on slowing development in the exurban and rural areas and shifting it towards urban centers.

One issue that may impact our ability to isolate the causal effect of zoning changes on infill development is presence of an endogenous zoning outcome. However, we do not think that reverse causality is a concern in our particular context for several reasons. First, the downzoning policy was part of a regional institutional policy change in Maryland which impacted all of the counties in the region. Second, the zoning boundaries for each county were primarily determined by the existing distribution of the public sewer system that was in place at this time the zoning law was passed. And finally, even if the boundaries were somewhat endogenous at a very local level or certain landowners had prior knowledge of these boundaries, our series of robustness checks and the first-differencing process should be sufficient to account for this potential endogeneity.

5. Conclusions

The urban economic model explains leapfrog development as a result of the optimal intertemporal decision-making on the part of developers in which the key source of heterogeneity is the relative accessibility to urban centers (Ohls and Pines, 1975; Mills, 1981; Wheaton, 1982). Despite this longstanding theory, its predictions regarding the timing and location of land development have not been formally tested due to a lack of data. Using detailed data on historical subdivision development and housing sales from the three counties in the Baltimore, Maryland metropolitan area, which provide accurate spatial and temporal detail on the unit of microeconomic behavior, we offer the first formal test of the spatial and temporal predictions of the urban economic model using a new measure of leapfrog development. Based on a subdivision-specific measure of accessibility calculated using the actual road network in the region, our new measure captures the leapfrog and infill outcomes that are hypothesized to result from the intertemporal decision-making behavior of land developers.

Our analysis provides evidence that the spatial and temporal evolution of leapfrog and infill development is consistent with the predictions of the basic intertemporal urban growth model (Wheaton 1982) and highlights the significance of zoning in determining this evolution. Within our study region, the observed pattern of leapfrog development declines over time as predicted by urban economic theory. In addition, the observed pattern of leapfrog development closely matches predicted patterns of unconstrained development based on a parametrized intertemporal urban growth model in the early years before the downzoning policy. After the downzoning, the observed amount of leapfrog development is significantly less than the amount predicted by the theoretical model prediction of unconstrained urban growth, a result that is also consistent with urban economic theory. Specifically, zoning fixes the allowable development density and therefore eliminates the incentive for withholding land to develop at a higher density in a later period. Results from a series of first-difference models confirm that spatially heterogeneous regulations create systematic differences in the net returns to urban development, leading to a decrease infill development in exurban downzoned areas and increase in areas closer to the urban center.

Our results highlight the critical role of local land use regulations in influencing residential growth. A primary implication is that, in outlying areas of a growing urban region, the underlying mechanism of land development may have more to do with land use regulations than commuting costs. By virtue of being farther away from urban areas, exurban areas have relatively smaller differences in commuting costs than their suburban counterparts. In contrast, downzoning, agricultural preservation, and other commonly used policies that restrict development introduce large changes in the relative returns to land development in these areas. Our findings corroborate this intuition, showing that the spatial process of exurban growth is more complex than one that is determined solely by transportation costs and underscoring the important role that spatially heterogeneous zoning plays in influencing leapfrog and infill patterns of development.

References

Adelaja, A.O., Gottlieb, P.D. (2009) The political economy of downzoning. *Agricultural and Resource Economics Review*, 38(2): 181-199

Bahl, R. W. (1963) *A Bluegrass Leapfrog*. Lexington: Bureau of Business Research, University of Kentucky.

Berube, A., Singer, A., Wilson, J. H., Frey, W. H. (2006) Finding exurbia: America's fast-growing communities at the metropolitan fringe. Brookings Institution, Metropolitan Policy Program, Washington D.C.

Brueckner, J. K., Fansler, D. A. (1983) The economics of urban sprawl: theory and evidence on the spatial sizes of cities. *Review of Economics and Statistics*, 65(3): 479-482.

Burchfield, M., Overman, H., Puga, D., Turner, M. A. (2006) Causes of sprawl: a portrait from space. *Quarterly Journal of Economics*, 2: 587-633.

Chen, Y., Irwin, E. G., Jayaprakash, C. (2011) An agent-based model of exurban land development. Selected paper prepared for presentation at the Agricultural & Applied Economics Association's 2011 AAEA & NAREA Joint Annual Meeting, Pittsburgh, PA, July 24-26, 2011.

Clawson, M. (1962) Urban sprawl and speculation in suburban land. *Land. Economics*, 38: 99-111.

Farris, J. T. (2001) The barriers to using urban infill development to achieve smart growth. *Housing Policy Debate*, 12: 1-30.

Frenkel, A., Ashenzi, M. (2008) Measuring urban sprawl: how can we deal with it? *Environment and Planning B: Planning and Design*, 36: 56-79.

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

Gyourko, J., Molloy, R. (2015) Regulation and Housing Supply, in *Handbook of Regional and Urban Economics*, Vol. 5, ed. By Gilles Duranton, J. Vernon Henderson, and William Strange. Amsterdam: Elsevier Publishers, 1289-1333.

Hashim, M., Mohd Noor, N., Marghany, M. (2010) Modeling sprawl of unauthorized development using geospatial technology: case study in Kuantan District, Malaysia. *International Journal of Digital Earth*, 4: 223-238.

Heimlich, R. E., Anderson, W. D. (2001) Development at the urban fringe and beyond: impacts on agriculture and rural land. Agricultural Economic Report No. 803, Economic Research Service, U.S. Department of Agriculture, Washington D.C.

Irwin, E. G., Bockstael, N. E. (2002) Interacting agents, spatial externalities and the evolution of residential land use patterns. *Journal of Economic Geography*, 2: 31-54.

Irwin, E. G., Bockstael, N. E. (2007) The evolution of urban sprawl: evidence of spatial heterogeneity and increasing land fragmentation. *Proceedings of National Academy of Sciences USA*, 104: 20672-20677.

Jiang, F., Liu, S., Yuan, H., Zhang, Q. (2007) Measuring urban sprawl in Beijing with geo-spatial indices. *Journal of Geographical Sciences*, 17: 469-478.

Landis, J., Hood, H., Li, G., Rodgers, T., Warren, C. (2006) The future of infill housing in California: opportunities, potential, and feasibility. *Housing Policy Debate*, 17: 681-726.

Lessinger, J. (1962) Urban sprawl and speculation in suburban land. *Journal of the American Institute of Planners*, 28: 159-169.

Lewis, D. J., Provencher, B., Butsic, V., Rodgers, T., Warren, C. (2009) The dynamic effects of open-space conservation policies on residential density. *Journal of Environmental Economics and Management*, 57: 239-252.

Lohse, K. A., Newburn, D. A., Opperman, J. J., Merenlender, A. M. (2008) Forecasting relative impacts of land use on anadromous fish habitat to guide conservation planning. *Ecological Applications*, 18: 467-482.

Malpezzi, S. (1999) Estimates of the measurement and determinants of urban sprawl in U.S. metropolitan area. University of Wisconsin Madison, Madison Center for Urban Land Economics Research.

McConnell, V. D., Wiley, K. (2010) Infill development: perspectives and evidence from economics and planning. Resources for the Future. RFF Disccussion Paper 10-13.

McConnell, V., Walls, M., Kopits, E. (2006) Zoning, TDRs and the density of development. *Journal of Urban Economics*, 59: 440-457.

Mills, D. E. (1981) Growth, speculation and sprawl in a monocentric city. *Journal of Urban Economics*, 10: 201-226.

Newburn, D., Berck, P. (2006) Modeling suburban and rural-residential development beyond the urban fringe. *Land Economics*, 82: 481-499.

Newburn, D., Berck, P. (2011) Exurban development. *Journal of Environmental Economics and Management*, 62: 323-336.

Ohls, J. C., Pines, D. (1975) Urban development and economic efficiency. *Land Economics*, 51: 224-234.

Ottensmann, J. R. (1977) Urban sprawl, land values, and the density of development. *Land Economics*, 53: 389-400.

Peiser, R. (1989) Density and urban sprawl. *Land Economics*, 65: 193-204.

Steinacker, A. (2003) Infill development and affordable housing: patterns from 1996-2000. *Urban Affairs Review*, 38: 492-509.

Towe, C. A., Klaiber, H. A., Wrenn, D. H. (2015) Not My Problem: Growth Spillovers from Uncoordinated Land Use Policy. Manuscript.

Turner, M. A. (2005) Landscape preferences and patterns of residential development. *Journal of Urban Economics*, 57: 19-54.

U.S. Census Bureau (2010) Carroll County, Maryland QuickLinks (People QuickLinks). Available at: http://quickfacts.census.gov/qfd/states/24/24013lk.html

Wheaton, W. C. (1982) Urban residential growth under perfect foresight. *Journal of Urban Economics*, 12: 1-21.

Wiley, K. (2009) *An exploration of the impact of infill on neighborhood property values*. Ph.D. Dissertation. The University of Maryland, Baltimore County (UMBC), Publication No. 10221.

Wrenn, D.H. (2012). *Three Essays on Residential Land Development*. Ph.D. Dissertation. The Ohio State University.

Wrenn, D.H., Irwin, E. G. (2015) Time is Money: A Empirical Examination of the Spatial Effects of Regulatory Delay on Residential Subdivision Development. *Regional Science and Urban* Economics, 51: 25-36.

Wu, J., Plantinga, A. J. (2003) The influence of public open space on urban spatial structure. *Journal of Environmental Economics and Management*, 46, 288-309.

Tables

Table 1. Panel Data Models of Leapfrog Development 1960-2005

	(1) Pooled OLS			(2) Random Effects		
Variables	Coef.		St. Err.	Coef.		St. Err.
Other Controls						
Area (Acres)	2.5E-06	*	1.6E-05	2.9E-05	*	1.7E-05
Minor (0-1)	0.007	***	0.002	0.009	***	0.002
Dist. (Miles)	0.018	***	0.001	0.023	***	0.000
Dist. Sqrd	-2.9E-04	***	1.1E-05	-3.7E-04	***	9.2E-06
Zoning Percentages within Buffers						
Agriculture	0.034	***	0.004	0.035	***	0.001
Conservation	-0.024	***	0.004	-0.131	***	0.001
Year Fixed Effects						
1965	-0.043	***	0.000	-0.043	***	0.001
1970	-0.082	***	0.000	-0.082	***	0.001
1975	-0.125	***	0.001	-0.125	***	0.001
1980	-0.178	***	0.002	-0.140	***	0.001
1985	-0.221	***	0.002	-0.183	***	0.001
1990	-0.291	***	0.002	-0.253	***	0.001
1995	-0.331	***	0.002	-0.294	***	0.001
2000	-0.385	***	0.002	-0.348	***	0.001
2005	-0.439	***	0.002	-0.402	***	0.001
Constant	0.553	***	0.006	0.504	***	0.004
N	79760			79760		
R^2	0.787			0.720		

Notes: The dependent variable in each model is the yearly leapfrog metric value associated with each residential subdivision. Area is the total acreage of each subdivision; minor is an indicator for whether a subdivision is a minor development (2 or 3 lots created); and the distance variables are miles traveled from each subdivision to the center of Baltimore City along the most expedient route. The zoning variables are in percentage terms and represent the percent of total area of each zoning class in each subdivision-specific buffer. Since these percentages sum to 1 for each buffer, we present only results for the agriculture and conservation zoning classes and each is understood as being relative to the percentage of the urban zoning class. The standard errors are robust and clustered at the subdivision level.

* Significant at 10% level. ** Significant at 5% level. *** Significant at 1% level.

Table 2. Coefficient Estimates from Rent Hedonic

	(I) Time-Varying		(II) Time-Invariant	
Variables	**Coef.**	**Std Err.**	**Coef.**	**Std Err.**
Dist. (Miles)			-5.6E-05***	4.0E-07
Dist. (Miles) * 1960	-6.8E-05***	4.0E-06		
Dist. (Miles) * 1965	-5.9E-05***	3.4E-06		
Dist. (Miles) * 1970	-5.9E-05***	2.4E-06		
Dist. (Miles) * 1975	-6.7E-05***	1.9E-06		
Dist. (Miles) * 1980	-6.9E-05***	1.7E-06		
Dist. (Miles) * 1985	-7.2E-05***	1.2E-06		
Dist. (Miles) * 1990	-5.7E-05***	9.6E-07		
Dist. (Miles) * 1995	-5.2E-05***	8.8E-07		
Dist. (Miles) * 2000	-5.0E-05***	8.8E-07		
Dist. (Miles) * 2005	-4.9E-05***	9.6E-07		
Time Periods				
1960	11.505***	0.070	11.314***	0.028
1965	11.503***	0.060	11.449***	0.023
1970	11.559***	0.039	11.521***	0.015
1975	11.918***	0.031	11.756***	0.013
1980	12.030***	0.028	11.832***	0.012
1985	12.099***	0.020	11.844***	0.010
1990	12.145***	0.017	12.127***	0.009
1995	12.060***	0.015	12.131***	0.008
2000	12.046***	0.015	12.148***	0.008
2005	12.330***	0.017	12.442***	0.009

Note: *** indicate that all regression coefficients are statistically significant at the 1% level.

Model (I) allows the coefficients on the commuting distances to Baltimore City to vary over time through interactions with time dummies, while model (II) kept the distance parameters to be time-invariant.

Table 3. Spatial Ordering of Leapfrog Development with No Discounting

	Development Period									
	1960	1965	1970	1975	1980	1985	1990	1995	2000	2005
Distance (1K Meters)	Total Rent Per Acre									
5	$61,884	$70,847	$76,145	$96,304	$103,920	$105,165	$139,641	$140,125	$142,589	$191,233
7.5	$53,786	$61,576	$66,181	$83,702	$90,321	$91,404	$121,368	$121,788	$123,930	$166,209
10	$46,748	$53,518	$57,521	$72,749	$78,502	$79,443	$105,486	$105,851	$107,712	$144,459
12.5	$40,630	$46,515	$49,994	$63,229	$68,229	$69,047	$91,682	$92,000	$93,617	$125,555
15	$35,313	$40,428	$43,451	$54,955	$59,301	$60,011	$79,684	$79,961	$81,367	$109,125
17.5	$30,692	$35,138	$37,765	$47,764	$51,541	$52,158	$69,257	$69,497	$70,719	$94,845
20	$26,676	$30,540	$32,823	$41,513	$44,796	$45,333	$60,194	$60,403	$61,465	$82,434
22.5	$23,185	$26,543	$28,528	$36,081	$38,934	$39,401	$52,317	$52,499	$53,422	$71,647
25	$20,151	$23,070	$24,795	$31,359	$33,839	$34,245	$45,471	$45,629	$46,431	$62,271
27.5	$17,514	$20,051	$21,550	$27,256	$29,411	$29,764	$39,521	$39,658	$40,355	$54,122
30	$15,222	$17,427	$18,730	$23,689	$25,562	$25,869	$34,349	$34,468	$35,074	$47,040
32.5	$13,230	$15,147	$16,279	$20,589	$22,217	$22,484	$29,854	$29,958	$30,484	$40,884
35	$11,499	$13,165	$14,149	$17,895	$19,310	$19,541	$25,947	$26,037	$26,495	$35,534
37.5	$9,994	$11,442	$12,297	$15,553	$16,783	$16,984	$22,552	$22,630	$23,028	$30,884
40	$8,686	$9,945	$10,688	$13,518	$14,587	$14,762	$19,601	$19,669	$20,015	$26,843
42.5	$7,550	$8,643	$9,290	$11,749	$12,678	$12,830	$17,036	$17,095	$17,396	$23,330
45	$6,562	$7,512	$8,074	$10,212	$11,019	$11,151	$14,807	$14,858	$15,119	$20,277
47.5	$5,703	$6,529	$7,017	$8,875	$9,577	$9,692	$12,869	$12,914	$13,141	$17,624
50	$4,957	$5,675	$6,099	$7,714	$8,324	$8,424	$11,185	$11,224	$11,421	$15,317
52.5	$4,308	$4,932	$5,301	$6,704	$7,235	$7,321	$9,721	$9,755	$9,927	$13,313
55	$3,744	$4,287	$4,607	$5,827	$6,288	$6,363	$8,449	$8,479	$8,628	$11,571
Ranking	10	9	8	7	6	5	4	3	2	1

Notes: This table displays the predicted spatial ordering of development over time for a set of fixed 5,000-meter spatial rings, or annuli, around Baltimore City with no discounting. The values in the table represent predicted total rent per acre based on estimates from the hedonic models estimated using historical housing price data. The rent values are in real 2013 dollars and based on the CPI-U-RS price index. The ranking in the final row shows the ranking, over time, of the development rings with a 0% discount rate.

Table 4. Spatial Ordering of Leapfrog Development Based on 3% Discount

	Development Period									
	1960	1965	1970	1975	1980	1985	1990	1995	2000	2005
Distance (1K Meters)	Total Rent Per Acre									
5	$61,884	$60,826	$56,129	$60,948	$56,465	$49,060	$55,929	$48,184	$42,097	$48,472
7.5	$53,786	$52,867	$48,784	$52,972	$49,076	$42,640	$48,610	$41,879	$36,588	$42,129
10	$46,748	$45,949	$42,400	$46,040	$42,654	$37,060	$42,249	$36,399	$31,800	$36,616
12.5	$40,630	$39,936	$36,851	$40,015	$37,072	$32,210	$36,720	$31,636	$27,639	$31,825
15	$35,313	$34,710	$32,029	$34,779	$32,221	$27,995	$31,915	$27,496	$24,022	$27,660
17.5	$30,692	$30,168	$27,838	$30,228	$28,005	$24,332	$27,739	$23,898	$20,878	$24,041
20	$26,676	$26,220	$24,195	$26,272	$24,340	$21,148	$24,109	$20,771	$18,146	$20,895
22.5	$23,185	$22,789	$21,029	$22,834	$21,155	$18,380	$20,954	$18,053	$15,772	$18,160
25	$20,151	$19,807	$18,277	$19,846	$18,387	$15,975	$18,212	$15,690	$13,708	$15,784
27.5	$17,514	$17,215	$15,885	$17,249	$15,981	$13,885	$15,829	$13,637	$11,914	$13,718
30	$15,222	$14,962	$13,807	$14,992	$13,889	$12,068	$13,757	$11,852	$10,355	$11,923
32.5	$13,230	$13,004	$12,000	$13,030	$12,072	$10,489	$11,957	$10,301	$9,000	$10,363
35	$11,499	$11,303	$10,430	$11,325	$10,492	$9,116	$10,392	$8,953	$7,822	$9,007
37.5	$9,994	$9,823	$9,065	$9,843	$9,119	$7,923	$9,032	$7,782	$6,799	$7,828
40	$8,686	$8,538	$7,879	$8,555	$7,926	$6,886	$7,850	$6,763	$5,909	$6,804
42.5	$7,550	$7,421	$6,848	$7,435	$6,889	$5,985	$6,823	$5,878	$5,136	$5,914
45	$6,562	$6,450	$5,952	$6,462	$5,987	$5,202	$5,930	$5,109	$4,464	$5,140
47.5	$5,703	$5,606	$5,173	$5,617	$5,204	$4,521	$5,154	$4,441	$3,880	$4,467
50	$4,957	$4,872	$4,496	$4,882	$4,523	$3,930	$4,480	$3,859	$3,372	$3,883
52.5	$4,308	$4,235	$3,907	$4,243	$3,931	$3,415	$3,894	$3,354	$2,931	$3,374
55	$3,744	$3,680	$3,396	$3,688	$3,417	$2,968	$3,384	$2,915	$2,547	$2,933
Ranking	1	3	5	2	4	7	6	9	10	8

Notes: This table displays the predicted spatial ordering of development over time for a set of fixed 5,000-meter spatial rings, or annuli, around Baltimore City based on a single 3% discount rate. The values in the table represent predicted total rent per acre based on estimates from the hedonic models estimated using historical housing price data. The rent values are in real 2013 dollars and based on the CPI-U-RS price index. The ranking in the final row shows the ranking, over time, of the development rings for the 3% discount rate.

Table 5. First Difference Regression of the Increase in Infill Development Before and After the 1970s Downzoning

	(1)			(2)			(3)		
	Subdivision Development: 1956-1960			Subdivision Development: 1956-1965			Subdivision Development: 1956-1970		
Variables	Coef.		St. Err.	Coef.		St. Err.	Coef.		St. Err.
Acres-X-Population Change[a]	-3.0E-06	*	1.5E-06	-2.1E-09		1.1E-06	-4.2E-07		8.9E-07
Lot Quantity-X-Interest Rate Change	-2.8E-06		3.1E-06	-5.1E-06	*	2.6E-06	-4.0E-06		2.6E-06
Zoning Change Variables[b]									
Changes in % Ag Zoning in the buffer	-0.010	*	0.006	-0.032	***	0.004	-0.293	***	0.004
Changes in % Consv Zoning in the buffer	0.027	***	0.007	0.014	***	0.005	0.014	***	0..004
Constant	-0.003		0.002	0.006	***	0.002	0.006	***	0.002
N	306			660			1092		
R^2	0.0558			0.083			0.0578		

Notes: The dependent variable in each model is the incremental increase in the amount of infill development that occurred in 1980-1985 compared to that in 1970-1975. The standard errors are robust and clustered at the subdivision level.

a. The Acres-X-Population Change variable is an interaction between the total acres of each subdivision and the increase in population in each county from 1970 to 1980. The Lot Quantity-X-Interest Rate Change variable is an interaction between the total quantity of lots in each subdivision and the increase in the average 10-year treasury rate from 70-75 to 80-85.

b. The Zoning Chnange Variables represent the change in the percentage of the total area of each subdivision-specific buffer that is made up of each zoning class.

* Significant at 10% level. ** Significant at 5% level. *** Significant at 1% level.

Table 6. First Difference Regression: Robustness Checks

	(1)		(2)		(3)		(4)		(5)		(6)	
	Zoning Only		Parcel Characteristics		Log-Linear		Log-Log		Drop Parcels Near Boundary		Nonlinearity in Zoning Change	
Variables	Coef.	St. Err.	Coef.	St. Err.	Coef.	St. Err.	Coef.	St. Err.	Coef.	St. Err.	Coef.	St. Err.
Acres-X-Population Change[a]					1.0E-05	4.6E-05	8.5E-05 *	5.0E-05	-8.0E-07	9.6E-07	-3.6E-07	8.8E-07
Lot Quantity-X-Interest Rate Change					-1.8E-04	1.6E-04	-2.0E-04	2.0E-04	-3.3E-06	2.6E-06	-4.6E-06 *	2.5E-06
Acres			-1.0E-05	2.0E-05								
Lot Quantity			-2.0E-05 *	1.0E-04								
Zoning Change Variables[b]												
Changes in % Ag Zoning in the buffer	-0.028 *	0.004	-0.029 ***	0.004	-1.755 ***	0.225			-0.027 ***	0.004	-0.090 ***	0.013
Sqrt(Changes in % Ag Zoning in the buffer)											0.048 ***	0.010
Changes in % Consv Zoning in the buffer	0.014 ***	0.004	0.014 ***	0.004	-0.471 **	0.232			0.023 ***	0.005	0.008 *	0.004
log(Changes in % Ag Zoning in the buffer)							-0.276 ***	0.038				
log(Changes in % Consv Zoning in the buffer)							-0.015	0.056				
Constant	0.005 ***	0.001	0.006 ***	0.002	-4.101 ***	0.084	-5.228 ***	0.124	0.004 ***	0.002	0.004 ***	0.002
N	1092		1092		618		485		1003		1092	
R^2	0.055		0.0578		0.0951		0.1044		0.0509		0.0759	

Notes: The dependent variable in each model is the incremental increase in the amount of infill development that occurred in 1980-1985 compared to that in 1970-1975. The standard errors are robust and clustered at the subdivision level.

a. The Acres-X-Population Change variable is an interaction between the total acres of each subdivision and the increase in population in each county from 1970 to 1980. The Lot Quantity-X-Interest Rate Change variable is an interaction between the total quantity of lots in each subdivision and the increase in the average 10-year treasury rate from 70-75 to 80-85.

b. The Zoning Change Variables represent the change in the percentage of the total area of each subdivision-specific buffer that is made up of each zoning class.

* Significant at 10% level. ** Significant at 5% level. *** Significant at 1% level.

Figures

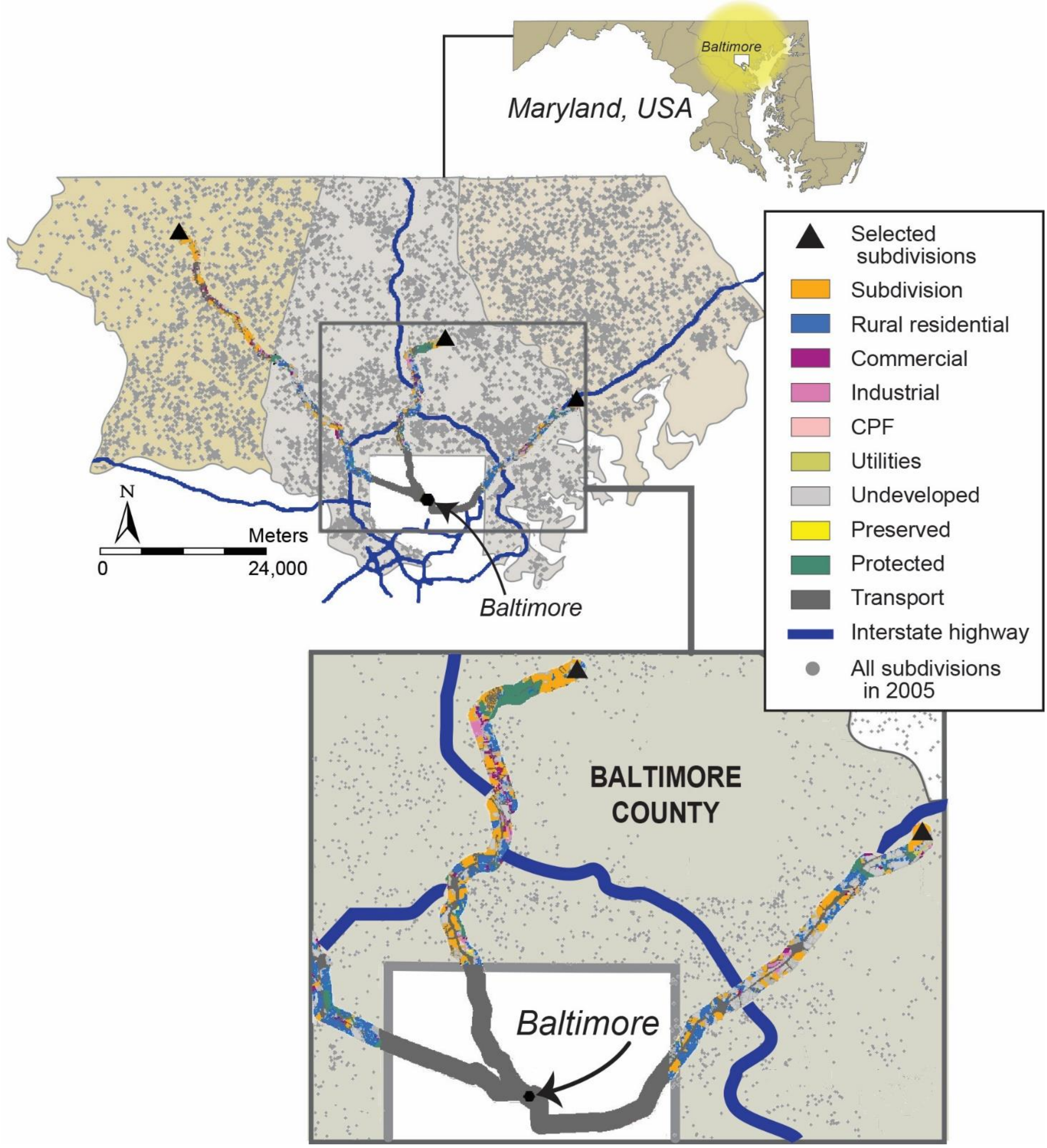

Figure 1. Illustration of 500-meter Subdivision-Specific Buffers and Leapfrog Metric Calculations for Selected Subdivision Developments

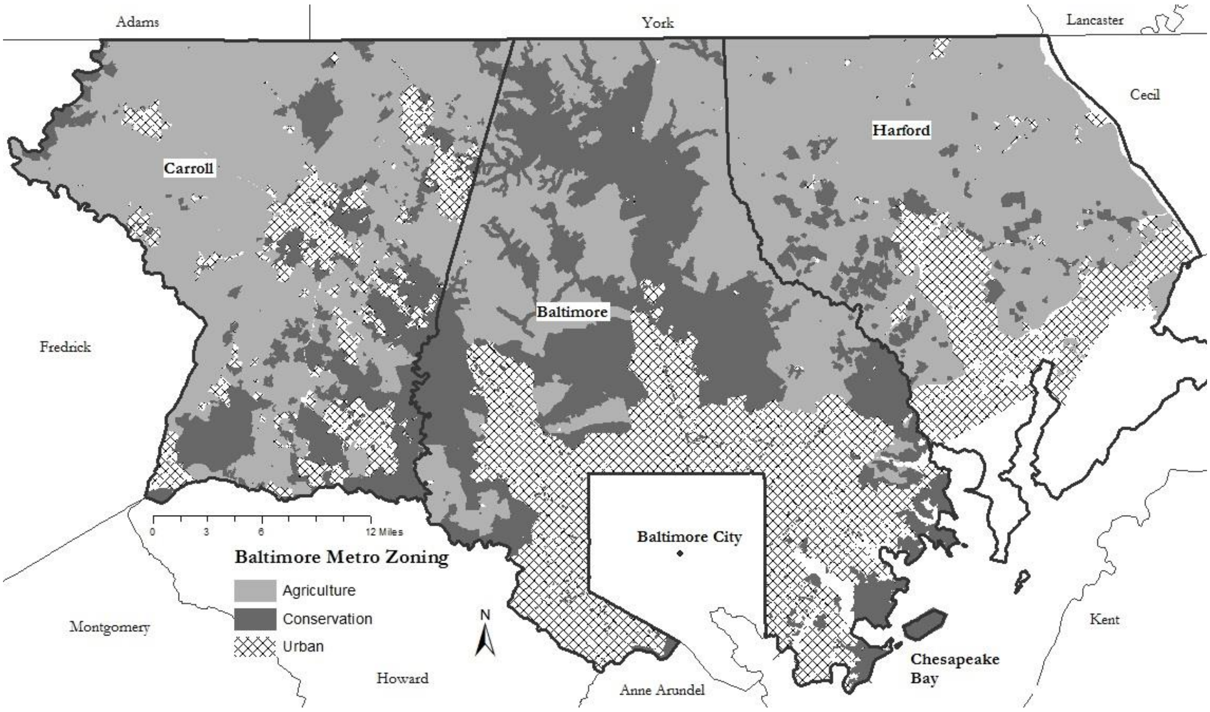

Figure 2. Zoning Map of Baltimore Metro in 2005

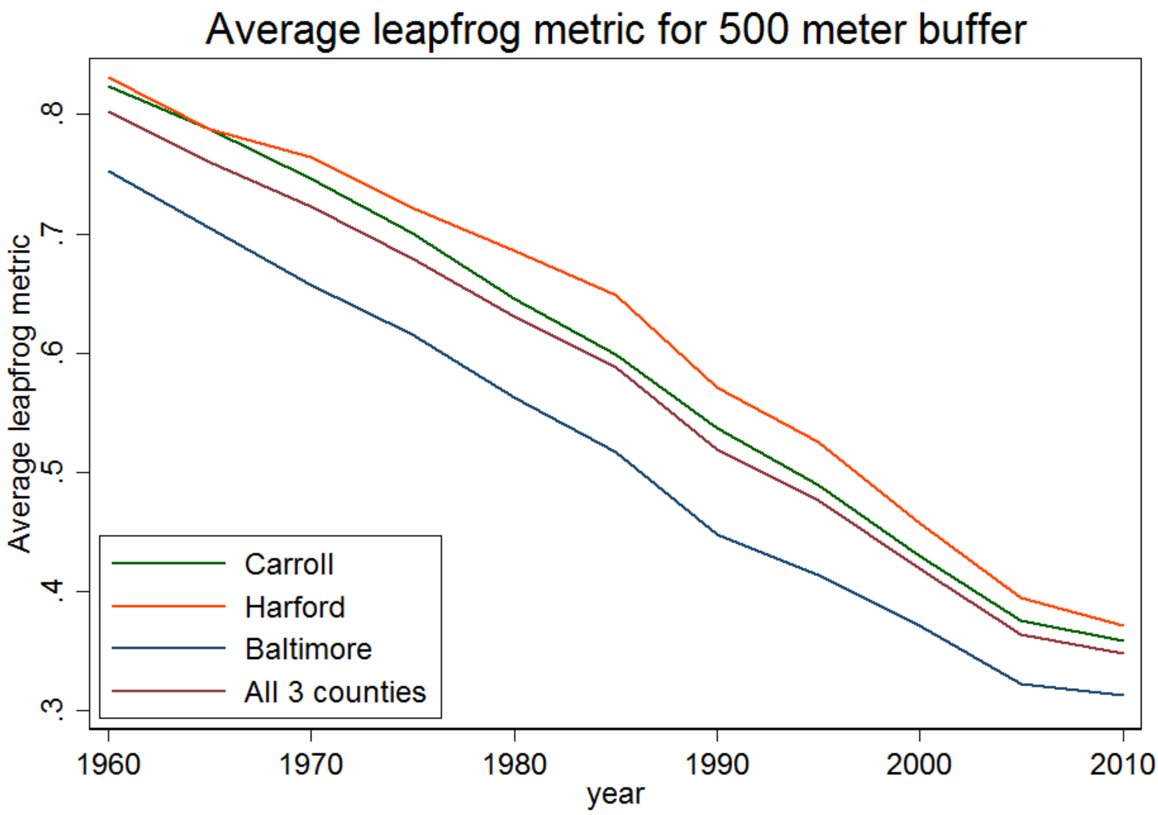

Figure 3. Comparison of Average Leapfrog Measures for the Individual Counties and a Three-County Average Baltimore Metro

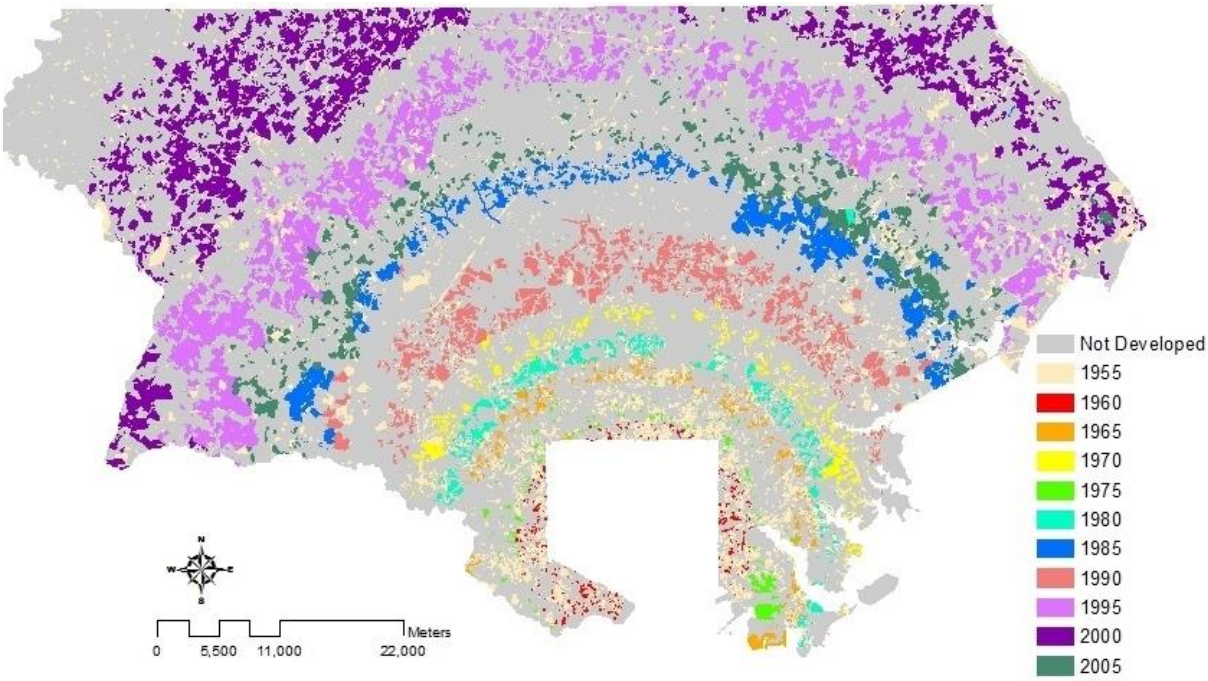

Figure 4. Predicted Development Pattern from Theory-Based Simulation Using a 3% Discount Rate

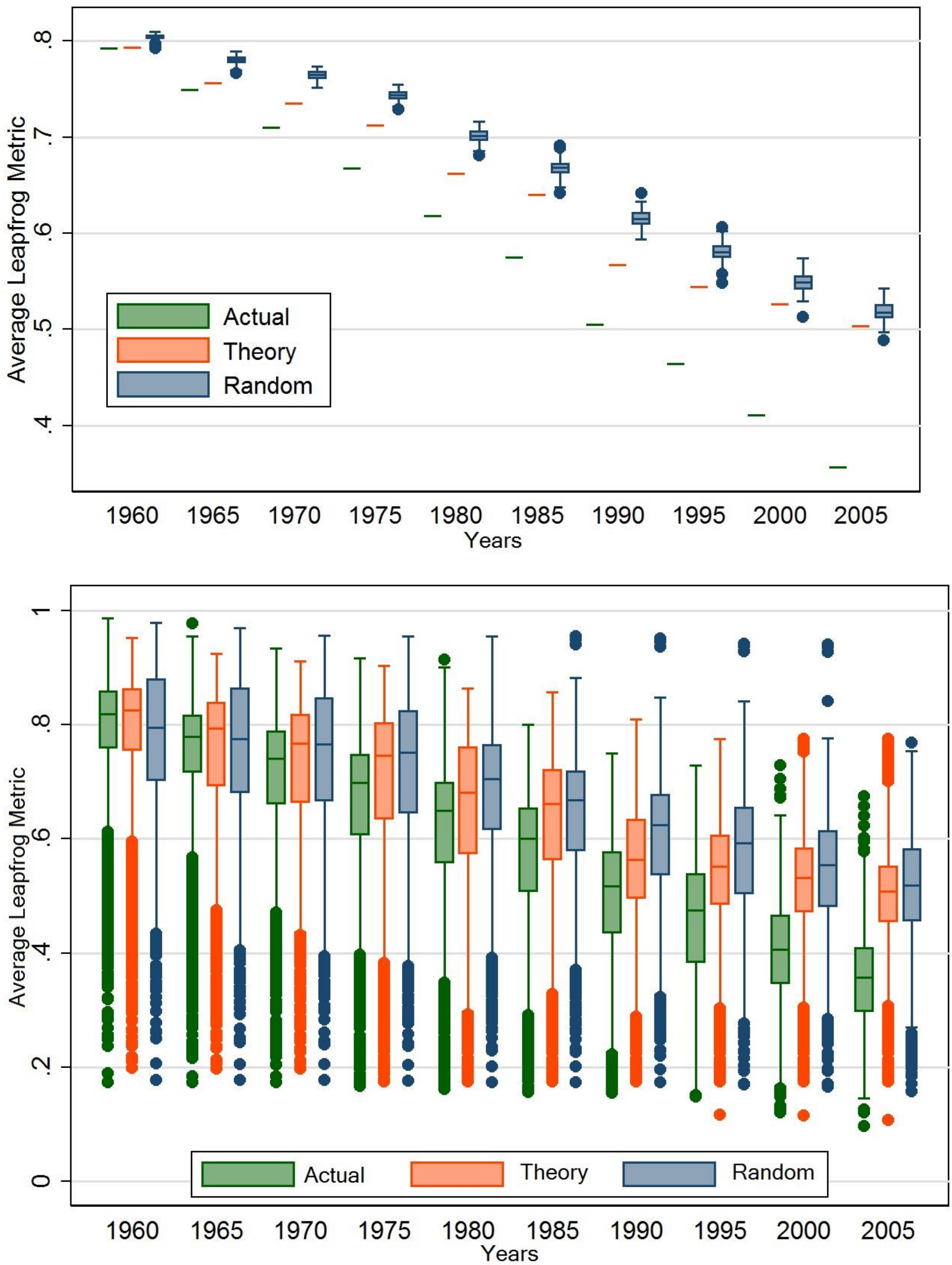

Figure 5. A Comparison of Average Leapfrog Measures for Actual, Random, and Theory-Based Simulated Development Patterns

Appendix

A1. Test of the Restrictiveness of Zoning Laws

This section provides a test of the restrictiveness of zoning in our study region. Specifically, we are concerned with how rigid the zoning laws are in terms of allowing subdivision development density – the number of lots created within a given parent parcel – to go above the threshold specified by the interaction of the zoning designation on the original parent parcel and its size in acres. To test this statistically, we combine our historical zoning maps with the actual size of the original parcel from which each subdivision is created to generate a variable (ZndLtQnt) for the total number of allowable development rights on the original parcel. Then, we take the logged ratio of the actual number of lots created over this new zoned-capacity variable. If zoning laws hold in our region, then we would expect this ratio to be close to one and for the logged value of this ratio to be statistically equal to or less than zero.

The results from these statistical tests for the subdivisions in each of our counties from 1960 through 2005 are shown in Table A1. The second column shows the mean value for our logged ratio variable and the third column shows the results of a one-tailed test that this value is less than or equal to zero. (Figure A1 shows the kernel density distribution based on the data used in Table A1.) From these results, while we see that there is variation in this ratio variable, we can statistically reject the null hypothesis that this variable is greater than one which indicates that across our study period and region zoning restrictions, in terms of the number of lots created, appear to hold.

Table A1. One-Sample Test of Logged Zoning Capacity Variable

County	Subdivision Count	Mean	t-Stat
Baltimore	3571	-0.19915	-10.5515
Carroll	1787	-0.08566	-3.8433
Harford	2518	-0.15538	-8.3666

Notes: This table presents the results of a set of one-sample t tests between the log of the ratio of the number of lots created in each subdivision over the zoned capacity allowed by the zoning laws in the county and time period the subdivision was created and an assumed mean of zero. The t-Stat are for the test that this logged ratio is statistically greater than zero, which indicates zoning variances are the norm in the metro area.

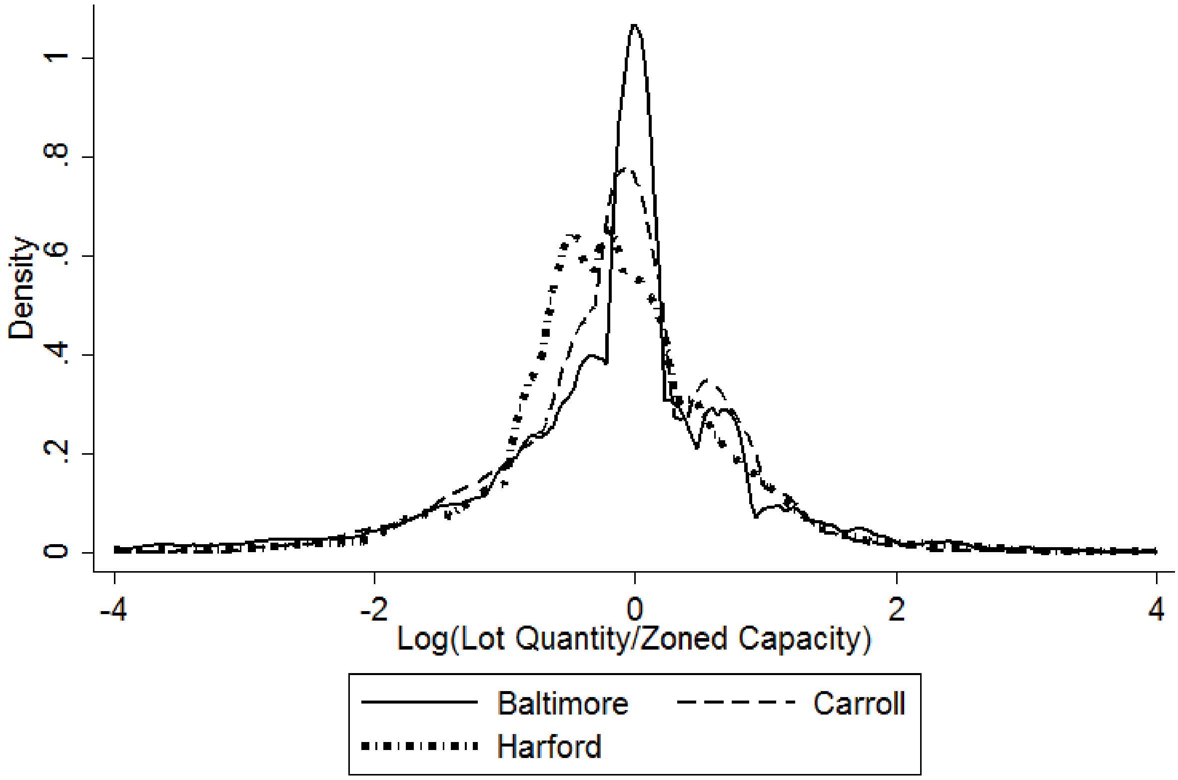

Figure A1. Kernel Density Plots of Logged Zoning Capacity Variable

A2. Robustness Checks for Regression and Simulation Results based on a Rent Hedonic with Time-Varying Distance Parameters

Table A2. Regression Coefficients for Equation (8) – A Hedonic Model of Housing Prices to Generate Rent Estimates

	Coef.	Std. Err.
Intercept	7.8640***	0.0915
Log (Lot Size in Acres)	0.0998***	0.0049
Log (Square Footage)	0.4755***	0.0094
Age of Structures	-0.0046***	0.0002
Dummy - Has Air Conditioner	0.1151***	0.0071
Dummy - Has Basement	0.0402***	0.0059
Dummy - Has Garage	0.0728***	0.0057
Year Dummy - 1960	0.0180	0.0625
Year Dummy - 1961	0.1226*	0.0653
Year Dummy - 1964	0.0828	0.0555
Year Dummy - 1965	0.1233**	0.0539
Year Dummy - 1966	0.2159***	0.0561
Year Dummy - 1969	0.2712***	0.0524
Year Dummy - 1970	0.2631***	0.0465
Year Dummy - 1971	0.3640***	0.0462
Year Dummy - 1974	0.5055***	0.0462
Year Dummy - 1975	0.5828***	0.0460
Year Dummy - 1976	0.6580***	0.0455
Year Dummy - 1979	0.6777***	0.0446
Year Dummy - 1980	0.6681***	0.0454
Year Dummy - 1981	0.6357***	0.0471
Year Dummy - 1984	0.5834***	0.0441
Year Dummy - 1985	0.6740***	0.0438
Year Dummy - 1986	0.7793***	0.0439
Year Dummy - 1989	0.9141***	0.0434
Year Dummy - 1990	0.7409***	0.0433
Year Dummy - 1991	0.5573***	0.0436
Year Dummy - 1994	0.9512***	0.0431
Year Dummy - 1995	0.9245***	0.0432
Year Dummy - 1996	0.8918***	0.0432
Year Dummy - 1999	0.9426***	0.0432
Year Dummy - 2000	0.9643***	0.0432
Year Dummy - 2001	0.9785***	0.0436
Year Dummy - 2003	1.1860***	0.0434
Year Dummy - 2004	1.3232***	0.0433

202 Census Tract Fixed Effects	Yes
N	70.439
R^2	0.35

Note: *, **, and *** mean that coefficients are significant at 10%, 5% and 1% level.
The dependent variable is the real housing prices adjusted for inflation to 2013 dollars using Bureau of Labor Statistics CPI_U_RS series.
The census tract fixed effects are based on the 2000 census tract boundaries.

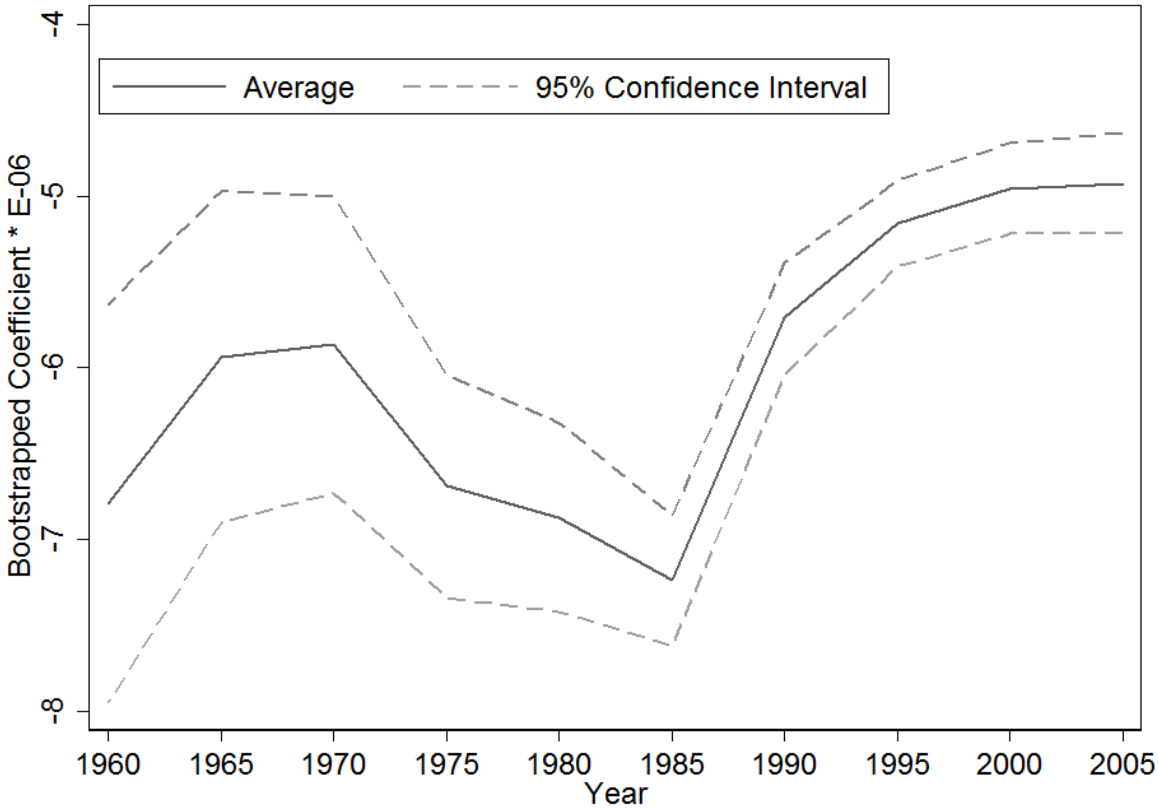

Figure A2. Bootstrapped Distance Coefficients and 95th Confidence Interval over Time for the Wheaton Model with Time-Varying Coefficients

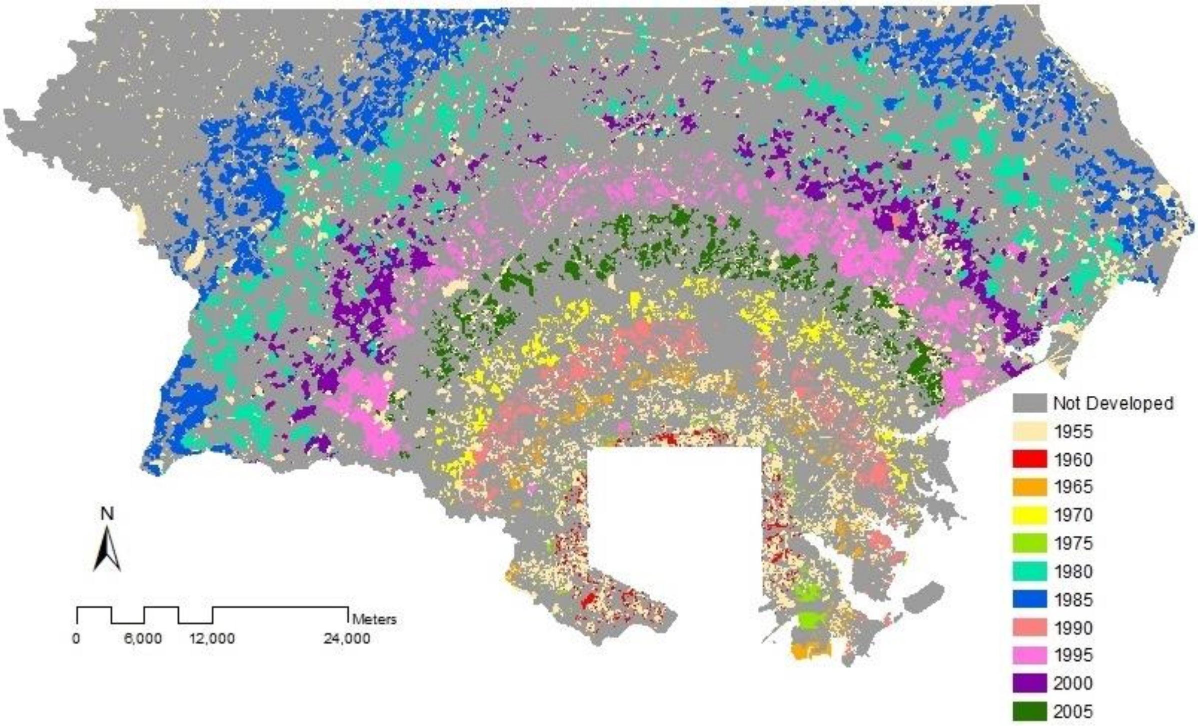

Figure A3. Predicted Development Pattern from Theory-Based Simulation Using a Wheaton Model with Time-Varying Distance Coefficients and a 3% Discount Rate

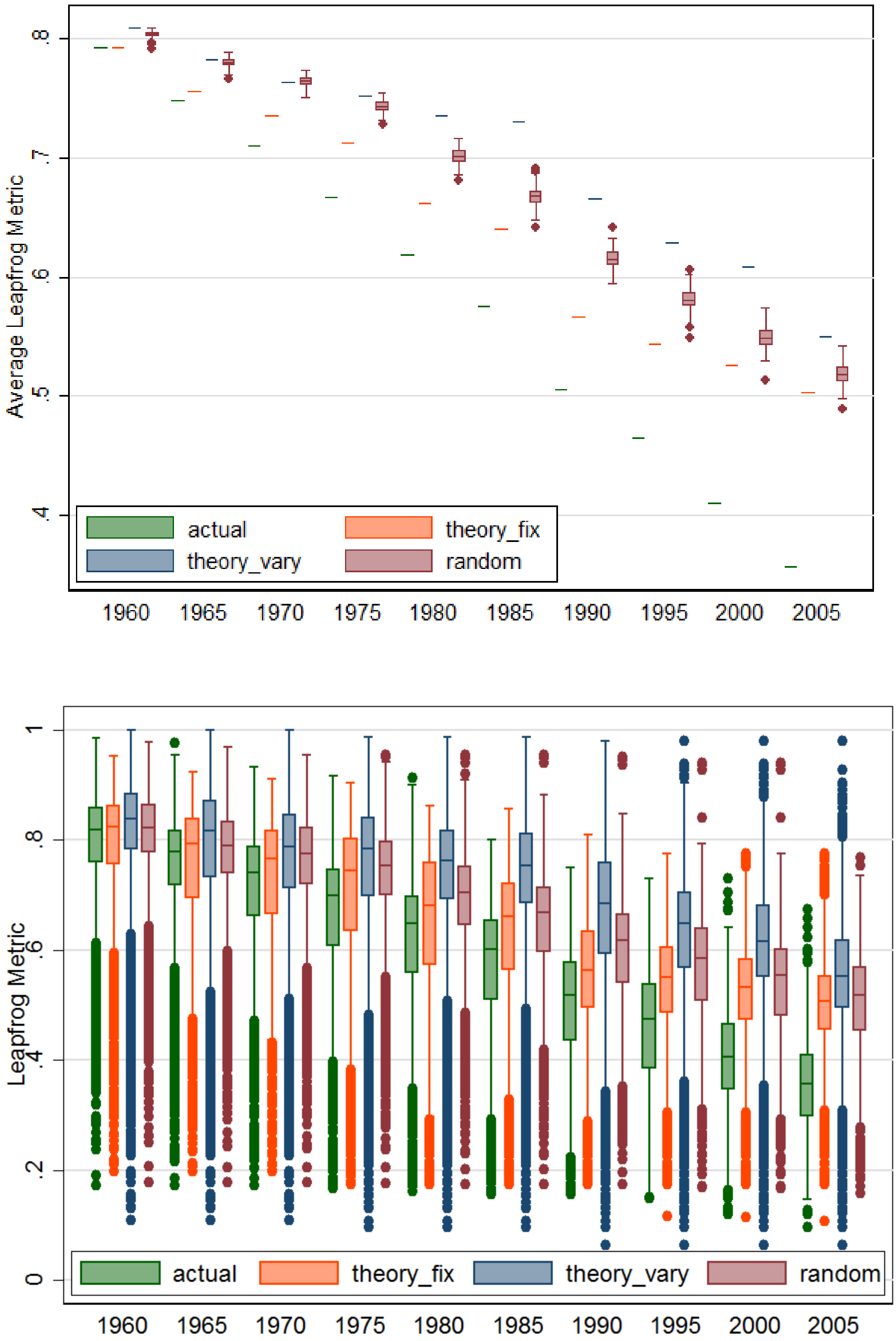

Figure A4. Comparison of Average Leapfrog Measures for Actual, Random, and Two Theory-Based Simulated Development Patterns