A DYNAMIC LAND USE MODEL WITH LOCATION EXTERNALITIES AND ZONING REGULATIONS

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ABSTRACT: This paper develops a dynamic spatial general equilibrium model to enable more land use detail, population growth, and transitional dynamics for integrated land use and transportation research. The new model specification tracks not just different parcel sizes and access attributes, but also various location externalities that affect household and firm decisions. The model also allows for three sources of spatial dynamics, including demographic change, building stock conversion subject to zoning regulations, and evolving location externalities. The model is calibrated for 38 zones across Austin, Texas; and simulations highlight changes in land use, housing demand, and rents, under four scenarios with different assumptions on land-use preferences and regulations.

Key words: Land use model, spatial dynamics, equilibrium, location externalities, zoning.

INTRODUCTION

Many land use models (LUMs) have emerged in different disciplines, including economics, planning, geography, and civil engineering (see Wegener's [2004; 2014] reviews). Among them, spatial equilibrium models (SEMs) and agent-based (microsimulation) models (ABMs), are widely discussed and applied in planning practice. Both models have their own merits and deficiency and recent progress illuminate how to incorporate the advantage of one model into the other one (Irwin, 2010). For example, the lack of market mechanisms is a major critique of ABMs. Many research efforts have included market interaction and rent-biding mechanisms in (e.g., Parker and Filatova, 2008; Magliocca et al., 2009; Filatova et al., 2009; Zhou and Kockelman, 2011). On the other hand, several recent SEMs reflect more spatial heterogeneity and transitional dynamics (e.g., Anas and Liu, 2007; Martínez and Henríquez, 2007; Jin et al., 2013), as done in ABMs. This paper attempts to enrich the literature by developing a dynamic SEM and focusing on the behavioral and policy implications of added complexity and dynamics.

While land use representation has improved in recent SEMs, such models still not reflect the land use realities. In theoretical urban economic models, the monocentric model endogenizes residential lot size (or housing size) and distance to workplace in residents' utility functions, in order to solve for the spatial distribution of residential densities (Alonso, 1964; Brueckner, 1987). Non-monocentric models can simulate an additional land use feature, employment density (Fujita and Ogawa, 1982; Lucas and Rossi-Hansberg, 2002; Zhang and Kockelman, 2014), by recognizing that firms often prefer locations closer to each other. Such agglomeration effects generate different technology benefits across locations. In applied SEMs, urban spatial structure is often organized and represented by zones and thus more land use characteristics can be considered. For example, some models allow for different building types (or land use types) and access to daily goods and services (measured via time and money costs) (Anas and Liu, 2007).

Many empirical studies find that land use or building environment attributes affect people's activity and travel choices of households and business. These land use characteristics are often summarized as three *D*s: density, diversity, and design (Cervero and Kockelman, 1997), later extended to five *D*s, by adding distance to transit and destination accessibility (Ewing and Cervero, 2001), and then seven *D*s, by adding demand management and demographics (Ewing et al., 2010). Such land use characteristics are regularly included in residential mobility studies and the hedonic analysis of property values (e.g., Song and Knaap, 2004; Löchl and Axhausen, 2010). Thus, it is important to include more land use characteristics in applied SEMs, to avoid mis-estimation of local travel decision, land use patterns, and community welfare.

In addition, urban dynamics is often ignored by SEMs. Many SEMs are static equilibrium models (e.g., monocentric models): they assume that market-clearing processes simultaneously resolve in one shot and external factors and shocks are absent. To address such limitations, the dynamic SEM developed here emphasizes land use complexity and dynamics. The starting point is Anas and Liu's (2007) zone-based computable general equilibrium model called "RELU"[1], for Regional Economy, and Land Use. In RELU, a consumer's utility is associated with his/her home neighborhood's land use features, including home floor space (the inverse of residential density) and access to workplace and daily goods and services. In RELU, a firm's output is a function of floor space and the access to the intermediate inputs from basic industries. RELU also summarizes other land use information and zonal features into an exogenous variable, representing the constant "inherent" attractiveness of each zone to consumers and firms. In addition, RELU endogenously models the dynamics of real estate development and treats developers as having perfect-foresight and thus able to perfectly predict future asset prices (e.g., looking forward 1 year). The RELU model is thus a stationary dynamic equilibrium model, in which all the exogenous variables have no change over time.

Spatial dynamics in the model proposed in this extension of RELU come from three key factors. The first is a change of demographics and zonal attractiveness, which are exogenously given.

[1] An updated version, RELU-TRAN2, is developed in Anas and Hiramatsu (2012). When compared to RELU-TRAN, RELU-TRAN2 adds the choice of vehicle fuel economy into consumers' utility functions and so internalizes people's gasoline use.

Many U.S. cities are experiencing falling household sizes and population growth, which will affect present and future housing, neighborhood, and community preferences (Nelson, 2006; 2013). Moreover, each location's attractiveness will vary with improvements in or degradation of local amenities, such as public transit infrastructure, bicycling and walking facilities, parks, and schools. The second feature relates to building stock conversions. Unlike RELU, our model assumes that building stocks evolve, changing year to year; they do not stay constant. The third feature is the endogenous change of locational (zone-based) externalities. Here, we define two types of positive location externalities that affect households and firms, respectively. The "externality" affecting households' residential location choices is assumed to be land use diversity (in the form of land use mixing and job-population ratios), and the externality affecting firm location choices is an innovation-based agglomeration economy. These externalities are evolve in a dynamic context, due to the relocation of households and firms; over time, they tend to stimulate new relocation and re-development.

This dynamic SEM was calibrated in the metropolitan city of Austin, Texas, with 38 zones, and used to explore changes in land use and rent dynamics from year 2010 to 2035. The applications are based on four scenarios, with different land use preferences and zoning regulations in place. The following three sections introduce the model's specification, calibration, solution algorithms, and simulation results. The paper concludes with a discussion of findings.

THE MODEL

Spatial and Temporal Context of the City

The city is divided into N_z model zones, representing districts of the considered region. Land use in the city is categorized into N_r types of residential use (e.g., low- and high-density single- and multi-family residential use), N_f types of land use for firms (e.g., low- and high-density commercial and industrial uses), and N_o types of other uses, including land use for civil, transportation, and open-space functions. Thus, there are in total N_{lu} $(= N_r + N_f + N_o)$ types of land use. The land used for residences and firms is endogenously determined, while the amounts used for other functions are exogenously given and will stay constant if no specific regulations or policies leading to land use change are imposed.

Urban subsystems evolve at different rates (Wegener, 2004). For example, land uses and transport networks change relatively slowly, while household locations choices, wages, and rents move faster. To reflect some of this diversity, two time scales are used here (Figure 1). The first scale, representing relatively slow change, is indexed by T, while the second scale, representing faster change, is indexed by t. Following the first scale, new construction and demolition are finished at the end of period T-1 and realized by households at the beginning of period T. Thus, households are assumed to update their understanding of the land use diversity of their neighborhood at the beginning of period T, relying on the changed land use stocks. During the period T, both the land stocks and the households' understandings of neighborhood diversity stay constant, until a new update at the early period of T+1 occurs. Meanwhile, technology diffuses locally at the beginning of period T. During the period T, firms determine their investments in innovation, leading to a new technology at the end of period T. In the second scale, each period T is divided into several time steps, from t_T to $t_T + \mathcal{T}$. Households in each time step t_T decide whether to move and/or change jobs and where to relocate. Meanwhile, job distribution, goods prices, land rents, asset prices, and wages are altered and adjusted by the market in each time step, until they reach market equilibria.

[Figure 1 about here]

Households

While the RELU model categorizes households (or consumers) based on skill levels only, the model in this paper develops a more detailed typology of households, relying on both households' lifecycles and their skill levels. Compared to skill levels, the household's lifecycle is probably more sensitive to their housing and neighborhood preference and demographic changes. For example, Nelson (2013) defined three types of households that may have different housing and neighborhood preferences, including starter-home, peak-demand, and downsizing households. Specifically, the starter-home households (whose household deads are under 35 years of age) often have higher demand for homes with smaller floorspaces or townhouses and apartments. The peak-demand households (35–64 years old), who have growing families and need more space, often prefer larger-lot single-family housing. The downsizing households (over 65 years old) likely no longer need large homes and thus may prefer smaller houses or apartment. Also, while the share of the population with different skill levels may not change much in future, the share of households in different lifecycles may significantly change in the future. Nelson (2013) predicted that the starter-home and downsizing households will account for about 84% of the new housing market from 2010 to 2035; these types of households prefer more mixed-use, walkable, amenity-rich neighborhoods and multi-family housing types than do those peak-demand households.

Households in the city are thus subdivided into n_h types relying on their lifecycle (e.g., starter-home, peak-demand, and downsizing). Every household activity is assumed to be performed by a single representative household member, which is a potential worker with s $(s = 1, \dots, N_s)$ level of working skill. In total, there are n_{hs} $(= n_h \times n_s)$ household types. The number of households Ω_{hs}^T of type *hs* in the city and its development over the first scale T $(T = T_0, T_1, \dots)$ are exogenously given. In each time step t $(t = t_T, t_{T+1}, \dots, t_{T+\mathcal{T}})$ of the period T, each household type *hs* choosing zone i $(i = 1, \dots, n_z)$ for residences, zone j $(j = 1, \dots, n_z)$ for workplace, and housing building type k $(k = 1, \dots, n_r)$ will generate a flow utility, $U_{ijk|hs}^t$, as follows:

(1) $$U_{ijk|hs}^t(C^t, q^t, D_i^T) = \alpha_{hs} \ln\left(\sum\nolimits_{\forall z} \iota_{z|ijhs} (C_z^t)^{\eta_{hs}}\right)^{1/\eta_{hs}} + \beta_{hs} \ln q^t + f\left(D_{i1}^T, D_{i2}^T \mathbb{A}_{\boldsymbol{i}}^{\boldsymbol{T}}\right) + I_{ijk|hs} + \varepsilon_{ijk|hs}^t$$

where

C_z^t is the quantity of retail goods the consumer purchases from zone *z*, in time step *t;*

q^t is the size of floor space in the chosen type *k* housing in zone *i*, in time step *t*;

D_{i1}^T, D_{i2}^T are the endogenously determined variables of land use mix and job-population ratio, representing the locational externalities in zone *i* in period *T*;

$\mathbb{A}_{\boldsymbol{i}}^{\boldsymbol{T}}$ is a vector of exogenous local amenity variables of zone *i* in period *T*;

$I_{ijk|hs}$ is exogenous inherent attractiveness of the residence-workplace-housing choice (i, j, k);

α_{hs}, β_{hs} are the elasticities of utility with respect to the retail goods and housing floor space (which are constant over time) and α_{hs} + β_{hs} =1; and

$\varepsilon_{ijk|hs}^t$ is the random error term of choice (i, j, k).

The utility function shown in Eq. (1) is similar to that of the RELU model. One major difference is that Eq. (1) introduces the land use mix variable as a proxy for the location externality and local amenity of residential zones, better tackling land use complexity. Specifically, the vector of local amenities $\mathbb{A}_{\boldsymbol{i}}^{\boldsymbol{T}}$ can include variables representing the natural advantage or disadvantage of each location (such as proximity to lakes and rivers, and site topography), open space, school quality, public transit infrastructure, and other civil and cultural facilities. The formation and evolution of a neighborhood's land use diversity is a dynamic process. Figure 1 illustrates the dynamics defined in this paper. The land use diversity of zone *i* during period *T* is assumed to be a function of land stocks of various land use types formed at the beginning of period *T*, S_{ik}^{T}:

(2) $$D_{id}^{T} = f_D(S_{i1}^{T}, \dots, S_{iN_{lu}}^{T}) \text{ and } S_{ik}^{T} = S_{ik}^{T-1} + \Delta S_{ik}^{T}$$

Type-*hs* households currently living in zone *i* and dwelling type *k* and working in zone *j* in period *t-1* will have two choice alternatives in time step *t*:

1) continue living in zone *i* and dwelling type *k* and working in zone *j*, and obtain a one-time-step utility $U_{ijk|h}^{t}$.
2) change i, j, and/or k at the beginning of period t to (i', j', k'), $(i, j, k) \notin \{(i', j', k')\}$. In the current period, *t*-1, the household pays all associated relocation costs, including moving and search costs (financially and physiologically), $\mathcal{U}_{RL}^{t-1}$. If households relocate only their residences, the relocation costs $\mathcal{U}_{RL}^{t-1}$ are assumed to relate less to their new residence than to a function of land rents of neighborhoods they are living in, i.e., R_{ik}^{t-1}[2].

The forward-looking households would maximize their expected utilities from time step t_T with a utility discount rate, μ, by making a sequence of residence-workplace-building type decisions $\{(i, j, k)\}_{t_T}^{t_T+\mathcal{T}}$, under a budget constraint on income and time, in each time step *t* in period T. The optimization problem is as follows:

$$\max_{\forall\{(i,j,k)\}_{t_T}^{t_T+\mathcal{T}}} E \sum_{t=t_T}^{t_T+\mathcal{T}} \mu^{t-t_T} U_{ijk|hs}^{t}\left(C^t, q^t, \mathcal{U}_{RL}^{t-1}, \varepsilon_{ijk|hs}^{t}\right)$$

subject to the budget constraint:

(3) $$\sum\nolimits_{\forall z} \mathcal{P}_{z|ijhs}^{t}\left(p_{n_f z}^{t}, w_{jhs}^{t}, g_{iz}^{t}, G_{iz}^{t}\right) C_z^t + q^t R_{ik}^{t} = \mathcal{M}_{ijhs}^{t}\left(w_{jhs}^{t}, \mathcal{W}_{hs}^{t}, g_{iz}^{t}, G_{iz}^{t}\right)$$

where

$p_{n_f z}^{t}$ is the price of outputs from four producer types n_f (i.e., agriculture, retail, construction, and service sectors) produced in zone *z* in time step *t*,
w_{jhs}^{t} is the hourly wage rate paid to labor from household type *hs* in zone *j* in time step *t*,
$\mathcal{W}_{hs}^{t}$ is the non-wage annual income per household that belongs to *hs* types in time step *t*,
g_{iz}^{t} is the round-trip monetary cost per person-trip from zone *i* to *z* in time step *t*.
G_{iz}^{t} is the round-trip travel time per person-trip from zone *i* to *z* in time step *t*.
$\mathcal{P}_{z|ijhs}^{t}$ is the full delivered price of a retail good *z* for a type-*hs* household residing in *i* and working in *j* in time step *t*, which is a function of $p_{n_f z}^{t}, w_{jhs}^{t}, g_{iz}^{t}, G_{iz}^{t}$, and

[2] This assumption can be also found in the empirical studies on the dynamic housing location choice models, such as Bishop (2008) and Bayer et al. (2011), since an important moving cost is the share paid to the real estate agent (e.g., 6% of the sales price, to split between seller's and buyer's agents).

$\mathcal{M}^t_{ijhs}$ is the full income of household type *hs* residing in zone *i* and working in zone *j*, which is a function of $w^t_{jhs}, \mathcal{W}^t_{hs}, g^t_{iz}, G^t_{iz}$.

The one-period optimization problem represents that households' current decisions are made relying not only on current-time-step utility but also on future-steps utility. Assuming the behavior of a household demonstrates perfect foresight, the decision-making outcome at the end of each period would fully reflect the future and a household can be modeled as looking forward one period at a time (e.g., a household's current decision in period *t* will be affected by their expected utility in time step *t+1*, but not affected by those after the time step *t+1*). This assumption makes the optimization problem tractable and solvable. Thus, the lifetime expected utility can be represented by the value function in Eq. (4), which obeys the Bellman equation (1957):

$$(4)\ V^t_{ijk|hs} = max_{d_{ijk}}\left(v^t_{ijk|hs} + \varepsilon^t_{ijk|hs}\right)$$

where

$$(5)\ v^t_{ijk|hs} = u^t_{ijk|hs} + E\left\{max\left[U^{t+1}_{ijk|h}\left(u^{t+1}_{ijk|hs}, \varepsilon^{t+1}_{ijk|hs}\right), U^{t+1}_{i'j'k'|h}\left(u^{t+1}_{i'j'k'}, \varepsilon^{t+1}_{ijk|hs}\right) - \mathcal{U}^t_{RL};\ (i,j,k) \notin \{(i',j',k')\}\right]\right\}$$

The first part of the RHS in Eq. (5), $u^t_{ijk|hs}$, represents the realization component of the utility function in period *t*, while the second part represents the expected utility maximization in period *t* by choosing (or not choosing) to relocate. Assuming that the idiosyncratic error term $\varepsilon^{t+1}_{ijk|hs}$ is a distributed as an *i.i.d.* Type 1 Extreme Value term, Eq. (5) can be written as follows:

$$(6)\ v^t_{ijk|hs} = u^t_{ijk|hs} + \mu ln\left\{exp\left(u^{t+1}_{ijk|hs}\right) + \sum\nolimits_{\forall d_{i'j'k'} \neq d_{ijk}} exp\left(u^{t+1}_{i'j'k'} - \mathcal{U}^t_{RL}\right)\right\}$$

Solving Eq. (4) under the budget constraint (3), one can derive the direct utility function $\bar{U}^t_{ijk|hs} = \bar{u}^t_{ijk|hs} + \varepsilon^t_{ijk|hs}$ at the optimized choices for floor space and retail quantities produced. $\hat{u}^t_{ijk|hs}$ is thus calculated as follows:

$$(7)\ \bar{u}^t_{ijk|hs} = \alpha_{hs} ln\alpha_{hs} + \beta_{hs} ln\beta_{hs} + ln\mathcal{M}^t_{ijhs} - \beta_{hs} lnR^t_{ik} + \frac{\alpha_{hs}(1-\eta_{hs})}{\eta_{hs}} ln\left(\sum\nolimits_{\forall z} \iota_{z|ijhs}^{\frac{1}{1-\eta_{hs}}} \left(\mathcal{P}^t_{z|ijhs}\right)^{\frac{\eta_{hs}}{\eta_{hs}-1}}\right) + I^t_{ijk|hs}$$

In each period *T*, the model assumes that the city evolving over the time steps t_T to $t_{T+\mathcal{T}}$ will reach a stationary state general equilibrium. Let $\bar{v}^T_{ijk|hs}$ be the *stationary* state value function in period *T*:

$$(8)\ \bar{v}^T_{ijk|hs} = \bar{u}^T_{ijk|hs} + \mu ln\left\{exp\left(\bar{u}^T_{ijk|hs}\right) + \sum\nolimits_{\forall i'j'k' \neq ijk} exp\left(\bar{u}^T_{ijk|hs} - \mathcal{U}^T_{RL}\right)\right\}$$

Given that $\varepsilon^{t+1}_{ijk|hs}$ follows an *i.i.d.* Gumbel distribution, the stationary state choice probability in period *T* is of a multinomial logit form:

(9) $P_{ijk|hs}^{T} = \frac{exp\left(\lambda_{hs}\bar{u}_{ijk|hs}^{T}\right)\left[exp\left(\bar{u}_{ijk|hs}^{T}\right)+\sum_{\forall i'j'k'\neq ijk} exp\left(\bar{u}_{i'j'k'|hs}^{T}-\mathcal{U}_{RL}^{T}\right)\right]^{\lambda_{hs}\mu}}{\sum_{\forall(a,b,c)}\left\{exp\left(\lambda_{hs}\bar{u}_{abc|hs}^{T}\right)\left[exp\left(\bar{u}_{abc|hs}^{T}\right)+\sum_{\forall i'j'k'\neq ijk} exp\left(\bar{u}_{i'j'k'|hs}^{T}-\mathcal{U}_{RL}^{T}\right)\right]^{\lambda_{hs}\mu}\right\}}, \sum_{\forall(i,j,k)} P_{ijk|hs}^{T} = 1$

If one ignores the model's relocation disutility term (i.e., $\mathcal{U}_{RL}^{T} = 0$) and the exogenously and endogenously changing variables (of land use mix and population) between time points, the household-side model is the same as that of RELU.

Firms

The model assumes that a firm's decision of how much to innovate in current period *T* is affected by other firms' technological diffusion, and can affect a firm's future innovation decisions (Figure 1). This setting refers to Desmet and Rossi-Hansberg (2014), who modeled spillovers and agglomeration externalities in an endogenous growth model based on abstract space. This type of dynamic mainly stems from the changing endogenous agglomeration externalities that arise from knowledge spillover varying over space (across locations) and between periods[3]. This type of agglomeration economy and dynamic are apparently not discussed in existing *applied* land use and transportation models, though the agglomeration economies from knowledge spillover and proximity to people (rather than intermediate goods) become increasingly important in understanding the location choices of firms and workers (Glaeser, 2010).

There are $\mathcal{R}$ types of basic industries, including agriculture, manufacturing, business, and retail. Firms thus can be categorized as $\mathcal{R} + 2$ types, by adding construction and demolition firms[4]. The production function of the type-*r* (*r*=1,…, $\mathcal{R}$+2) firm with output X_{rj} in zone *j* in period *T* is shown in Eq. (10):

(10) $X_{rj}^{T} = \left(A_{rj}^{T}\right)^{\gamma} F\left(K_{rj}^{T}, L_{hs|rj}^{T}, B_{k|rj}^{T}, Y_{rj}^{T}\right)$

where

A_{rj}^{T} is the technology level of type-*r* firm in zone *j*;

K_{rj}^{T} is the capital used as an input in production by type-*r* firm in zone *j*;

$L_{hs|rj}^{T}$ is labor of skill group *s* used as an input in production by type-*r* firm in zone *j*;

$B_{k|rj}^{T}$ is floor space of type *k* ($k = n_r + 1, \dots, n_k$) used as an input in production by type-*r* firm in zone *j*; and

Y_{rj}^{T} is the intermediate input in production by type-*r* firm in zone *j*.

As shown in Figure 1, technology diffuses between time periods. This diffusion *h* is assumed to be local and to decline exponentially with distance. Let A_{rj}^{T-1} be the technology used in type-*r* firms in zone *j* in period *T-1*. In the next period *T*, the type-*r* firms in zone *j* have access to (but do not necessarily use) technology $\mathcal{A}_{rj}^{T}$:

(11) $\mathcal{A}_{rj}^{T} = max_{\forall i}\left\{\exp\left(-\delta g_{ij}\right)A_{ri}^{T-1}\right\}$

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[3] Other sources of agglomeration externalities are endogenized in the model, as they are in the RELU model (Anas and Liu, 2007), including those that come from reducing the costs of moving intermediate goods over space and those that come from reducing the costs of accessing workers (via commuting costs).

[4] RELU has a more detailed category of construction and demolition firms than used here, based on different building types.

Assuming the type-r firm in zone j can access the new technology $\mathcal{A}_{rj}^T$ at the beginning of period T, this firm can decide to invest in a probability $\theta_{rj}^T \leq 1$ of innovation at cost $Z(\theta_{rj}^T, w_{js}^T)$. After the investment in innovation, the firm has a probability of θ_{rj}^T to obtain an innovation and a probability of $(1-\theta_{rj}^T)$ to obtain no effect. Thus A_{rj}^T is the expected technology level during the period T, conditional on $\mathcal{A}_{rj}^T$, as follows (Desmet and Rossi-Hansberg, 2014):

(12) $A_{rj}^T(\theta_r, \mathcal{A}_{rj}^T) = E(innovation|\mathcal{A}_{rj}^T,) + E(no\ effect|\mathcal{A}_{rj}^T) = \frac{\sigma_r \theta_{rj}}{\sigma_r - 1}\mathcal{A}_{rj}^T + (1-\theta_{rj})\mathcal{A}_{rj}^T = \left(\frac{\theta_{rj}}{\sigma_r - 1} + 1\right)\mathcal{A}_{rj}^T$, for $\sigma_r > 1$

Firms maximize the expected present value of profits with discount factor φ. The optimization problem of a type-r firm in zone j at time T is therefore:

$$\max_{\left\{K_{rj}^T, L_{s|rj}^T, B_{k|rj}^T, Y_{rj}^T, \theta_{rj}\right\}_{T_1}^{\infty}} E\sum_{T=T_1}^{\infty} \varphi^{T-T_1}\left\{p_{rj}^T\left[A_{rj}^T(\theta_r, \mathcal{A}_{rj}^T)\right]^{\gamma} F(K_{rj}^T, L_{hs|rj}^T, B_{k|rj}^T, Y_{rj}^T) - \rho K_{rj}^T - \sum_{s=0}^{S} w_{js}^T L_{s|rj}^T - \sum_{k=0}^{S} R_{jk}^T B_{k|rj}^T - \sum_{r'=1}^{\mathcal{R}-1}\sum_{j'=0}^{N_z}\left(p_{r'j'}^T + \vartheta_{r'} g_{j'j}^T\right) Y_{r'j'|rj}^T - Z(\theta_{rf}^T, w_{rj})\right\}$$

subject to a target output X_{rj}^T given by the production function (10).

Land Developers

Following RELU, land developers are modeled as looking forward 1 year at a time. In the model, the developers can perfectly foresee the capital gains of two types of investment decisions: construction (keeping the land undeveloped *versus* constructing a type-k building) and demolition (keeping the land use unchanged *versus* demolishing an existing building). In addition, the investment decisions pertaining to land use are closely related to citywide real estate policies and land use regulation. For example, many U.S. metropolitan areas have zoning ordinances that typically limit building heights and lot coverage, in favor of building low-density, single-use neighborhoods. Some high-density and mixed-use neighborhoods thus are "zoned out" under such zoning regulations (Levine, 2006). To model such zoning effects, we define an alternative set $\mathbb{z}_i$ that includes the building types that are allowed in the modeled zone i under the zoning regulations.

Market Clearing within Each Period

The model in this paper assumes that the markets of products, labor, and real estate rental are clearing in each period T. First, when the three markets of basic industrial products (e.g., agricultural, manufacturing, and business) are clearing, the aggregate output of type-r (r=1,…, $\mathcal{R}$-1) basic industry in zone i X_{ri}^T can be used as an intermediate input to any other type-r' (r=1,…, $\mathcal{R}$+2) industries in zone i' or exported outside the modeled city, $\mathbb{E}_{ri}^T$.

(13) $\sum_{r'=1,\dots,\mathcal{R}+2}\sum_{i'=1,\dots,N_z} Y_{ri\to r'i'}^T + \mathbb{E}_{ri}^T = X_{ri}^T, \forall\, r = 1, \dots, \mathcal{R}-1$

Under the condition of product market clearing, the aggregate output of the retail industry equals the aggregate demand of retail goods:

(14) $\sum_{\forall hs} \mathbb{N}_{hs} \sum_{\forall i',j,k} P_{i'jk|hs}^T C_{i|i'jk}^T + \mathbb{E}_{\mathcal{R}i}^T = X_{\mathcal{R}i}^T$

The equilibrium outputs of the construction and demolition industries will equal the demand for construction and demolition in land development:

(15) $X^T_{\mathcal{R}+1,i} = \sum_{\forall k \in \mathbb{Z}_i} m_k S^T_{i0} Q_{i0k}\left(Y^T_{i0}, Y^T_{i1}, \dots, Y^T_{iN_z}\right)$

and

(16) $X^T_{\mathcal{R}+2,i} = \sum_{\forall k=1,\dots,n_k} S^T_{ik} Q_{ik0}(Y^T_{i0}, Y^T_{ik})$

where Q_{i00}, Q_{i0k}, and Q_{ik0} are the probabilities of keeping land undeveloped, developing the vacant land to a type-*k* building ($k \in \mathbb{Z}_i$), and demolishing a type-*k* building ($k = 1, \dots, n_k$). Second, when the real estate rental markets are clearing, the demands for residential and commercial floor space need to equal their supplies in each zone *i*, respectively.

(17) $\sum_{\forall hs} \mathbb{N}^T_{hs} \sum_{\forall j} P^T_{ijk|hs} b^T_{ijk|hs} = S^T_{ik} \frac{r_o(R^T_{ik}, \mathbb{O}^T_{ik})}{r_v(\mathbb{V}^T_{ik}) + r_o(R^T_{ik}, \mathbb{O}^T_{ik})}, k = 1, \dots, n_r$

(18) $\sum_{\forall hs} B^T_{k|ri} = S^T_{ik} \frac{r_o(R^T_{ik}, \mathbb{O}^T_{ik})}{r_v(\mathbb{V}^T_{ik}) + r_o(R^T_{ik}, \mathbb{O}^T_{ik})}, k = n_r + 1, \dots, n_k$

Third, the labor market clearing also requires that the annual demand and supply for the labor hours of skill-*hs* groups needs to be equal:

(19) $\sum_{r=1}^{\mathcal{R}+2} L^T_{hs|rj} = \mathbb{N}^T_{hs} \sum_{\forall i,k} H^T_{ijf} P^T_{ijk|f}$

Transitional Dynamics

From periods *T* to *T+1*, the land stocks of type-*k* buildings and the production technology level of type-*r* firms at zone *i* will change endogenously, and the population numbers of type-*hs* residential groups are given exogenously. For example, the construction and demolition activities are assumed to be finished at the end of period *T* and the land stocks are updated at the beginning of period *T+1*, as follows:

(20) $S^{T+1}_{ik} = \begin{cases} S^T_{i0} Q_{i00} + X^T_{\mathcal{R}+2}, & if\ k = 0 \\ S^T_{ik} - S^T_{ik} Q_{ik0}, & if\ k \notin \mathbb{Z}_i \\ S^T_{ik} - S^T_{ik} Q_{ik0} + m_{ik} S^T_{i0} Q_{i0k}, & if\ k \in \mathbb{Z}_i \end{cases}$

Eq. (20) shows that the amount of vacant land of type-*k* building in zone *i* in period *T+1* equals to the amount of the undeveloped vacant land kept in period *T* and the demolished building. For those land use types excluded by zoning regulation in period *T*, their new land stocks in period *T+1* may decrease due to the possible demolition activities. For those "zoned-in" land use types, their new stocks equal the old stocks plus the new construction minus demolition stocks in the previous period. These settings differ from those in the RELU model. The model here assumes that building stocks change incrementally over time, while the RELU model solves for equilibrium building stocks so that the construction stocks equal the demolition stocks in the long term. In addition, this setting of building stock conversion here allow for modeling the effects of policy intervention.

The changes in stocks of different buildings lead to new zone-based land use characteristics, such as land use mix. Here, we use the index of land use mix entropy that is widely used in the planning field to measure the zone-based land use mixture, D^{T+1}_{i1}:

(21) $D^{T+1}_{i1} = -\sum_{\ell=1}^{\mathbb{L}} \mathcal{L}^T_{i\ell} \ln \mathcal{L}^T_{i\ell} / \ln \mathbb{L}$

where $\mathcal{L}_{i\ell}^T$ ($\ell = 1,2, \ldots, \mathbb{L}$) represents the proportion in type-ℓ land use area in total land area. Notice that the land use area is not equivalent to the floor space outcomes, S_{ik}^T, but can be calculated by them. In the following simulation, we define six types of land use in a zone ($\mathbb{L} = 6$), including single-family, multi-family, industrial, commercial, open space, and civil uses. Among them, the land areas of open space and civil uses are exogenously given, and those of the rest are calculated by S_{ik}^T and the FAR m_{ik}.

Meanwhile, as shown in Figure 1, the technology levels of type-*r* firms at zone *i* (Eq. 12) are assumed to be updated at the beginning of period *T+1*, due to innovation diffusion (Eq. 11) and the firms' investment in innovation during period *T*. Both the transitions in technology level and land use characteristics can affect the wage levels, product and asset prices, and land rents, leading to new zone-based job-housing ratios, D_{i2}^{T+1}:

(22) $D_{i2}^{T+1} = \sum_{\forall\, h,s} \mathbb{N}_{hs}^T \sum_{\forall i',k} P_{i'ik|hs} / \sum_{\forall\, h,s} \mathbb{N}_{hs}^T \sum_{\forall j,k} P_{ijk|hs}$

CALIBRATION AND SIMULATION

The model is calibrated and applied in the Texas capital metropolitan area, including 38 Multiple Listing Service (MLS) neighborhoods (covering the City of Austin and Travis County) as modeled zones and 4 outer zones (representing 4 counties near the Travis County). The MLS neighborhoods have been defined based on real estate traditions, school zones, zip codes, housing stock consistencies, and natural boundaries (like rivers). Figure 2 shows the geographical distribution of the 38 MLS neighborhoods in the urban core (12 zones), inner suburbs (16 zones), and outer suburbs (10 zones).

[Figure 2 about here]

The starting period for simulation is 2005–2010, and the starting parameters are mainly calibrated using 2008 land use data from City of Austin, 2005 travel diary and OD data from Capital Area Metropolitan Planning Organization, demographic data from the 2010 census, and estimated population projection data (until 2050) from the Texas Data Center. While these data sets cannot fully support the parameter calibration for the model here, some parameters (e.g., filmographies) refer to existing literature (e.g., Anas and Rhee, 2006; Zhou and Kockelman, 2011; Desmet and Rossi-Hansberg, 2014) and come from empirical estimates. In each policy scenario, the simulation includes five periods (from 2010 to 2035) and each period covers 5 years.

The applied model here consists of nine population groups: three lifecycle stages (defined by the household head, who is the household's one worker) across three skill levels. The numbers of households (or housing units) in each of these groups are exogenously given and estimated using data from the 2010 Census and the Texas Data Center's population projections data (through 2050). The shares of starter-home households (with household heads up to 34 years old) and peak-demand households (35–64 years old) will decrease, while the share of downsizing households (older than 65 years) will almost double, from 2010 to 2035. In addition, we define four types of residential buildings (low- and high-density single-family and multi-family uses) and calculate the occupied and vacant land stocks and floorspace based on the future zoning maps obtained from the City of Austin (COA, 2010).

The algorithm used to solve for 1,110 within-period equations refers to Anas and Liu (2007), while the calculation of transitional dynamics follows equations (26)-(28). The population numbers $\mathbb{N}_{hs}^{T}$ are exogenously given at the beginning of each period. The variables S_{ik}^{T}, D_{i1}^{T}, D_{i2}^{T}, A_{rj}^{T} are given at the starting period and calculated at later periods based on corresponding updates inform prior periods. Within each period, the endogenous variables, such as product prices and output levels, land rents, wages, and property values and rents, are solved recursively to clear product, labor, and real estate markets. The Newton-Raphson algorithm is used recursively to find the fixed point solutions of those endogenous variables. The run time for finding such spatial equilibria within a period on a standard personal computer ranges from 5 to 10 minutes, depending on the initial values used.

LAND USE AND RENT DYNAMICS UNDER FOUR SCENARIOS

This section compares the land use, housing demand, and rent dynamics from 2015 to 2035 every 5 years, under four scenarios with different assumptions. The first scenario (S1) assumes that the household groups have variant preferences for housing size but no preference for a neighborhood with mixed-use features. For example, the peak-demand group's utility elasticity of housing size is higher than that of the starter-home and downsizing groups. The second scenario (S2) assumes that the household groups have variant preferences for both housing size and a neighborhood with mixed use features (including land use mixture index and job-population ratios). By comparing S1 and S2, one can determine how demographic trends affect city land use and housing demand. The third and fourth scenarios (S3 and S4) add a low-density zoning regulation to S1 and S2, respectively. This low-density zoning regulation is assumed to exclude the development of high-density residential property in the 10 MLS neighborhoods in the Austin's outer suburbs. By comparing S1 and S3 and S2 and S4, one can examine how the supply constraints on high-density development affect land use, housing demand, rents, and property values.

Land Use Dynamics from Demographic Changes and Zoning Regulations

Simulation results suggest that city land use dynamics are closely connected with people's changing preference for various land use features, changing demographics, and changing land use supply as affected by land use regulations and planning. These changing preferences can be either exogenously given or endogenously determined and probably cannot lead to a stationary dynamic spatial equilibrium even in the long term, especially when location externalities on consumption and production sides and land development policies exist and vary over location and time.

[Figure 3 about here]

First, we compare the land use dynamics under Scenarios 1 and 2. S1 includes only the exogenous population growth as the source of urban dynamics. The simulation results show that the household densities across most of the 12 inner core neighborhoods significantly increase from 2015 to 2035 (Figures 3a). In S2, when residents prefer to live in more mixed-use neighborhoods (introducing another location externality, as a source of dynamics, as shown in Figures 3b), future population appears more centralized (than those of S1). Table 1 summarizes the land use difference in the inner core, inner suburban, and outer suburban neighborhoods of

S1 and S2. These findings suggest that a rising demand for mixed-use environments may increase core population and levels, while lowering them in the suburbs, yet improve land use diversity in the suburban areas at the same time.

[Table 1 about here]

Second, we examine the “zoned-out” effects by comparing the land use dynamics before and after low-density zoning regulations in the outer suburban areas. Here, the land use regulation can be regarded as an exogenous constraint on urban development. The comparison of Figures 4a and 4c appears to show that such a zoning regulation may increase urban population densities at the early stage but will not greatly affect the density distribution over longer periods. In contrast, the zoning regulation appears to have more significant effects on the spatial distribution of employment densities. Table 1 also provides a summary of land use change after zoning regulation. When households have no mixed-use preference, at the early stage (2015–2020) the low-density zoning regulation will centralize more households in the urban core and inner suburban areas and decrease population in the outer suburbs. At later stages of development (2025–2035), both urban and outer-suburban household counts fall, as these households move to the inner suburban area. Meanwhile, many potential employment opportunities would be zoned out by such a regulation, especially in the outer suburban areas. But such regulations may reinforce urban agglomeration economy by attracting more firms and employment. In summary, the predicted demographic trends suggest that the low-density zoning regulation may encourage population decentralization alongside employment centralization, causing citywide job-housing mismatch and urban sprawl.

If demand for smaller houses and mixed-use neighborhoods rises but their supply is constrained by land use regulations, do these trends aggravate urban sprawl? These simulations, comparing S2 and S4, yield some mixed results. Households seem to still centralize in the urban core, though the shares of households in the inner suburbs grow from 2015 to 2035. The employment distribution also shows a centralization trend. Compared to S2, more jobs in the inner suburbs will move to the urban area than from the outer suburbs. Though high-density residences are regulated by the zoning ordinances, the mixed-use demand may increase the supply of mixed-use neighborhoods with job-housing balance, thus leading to relatively matching trends of population and employment distribution. These findings suggest that when the real estate market realizes residents’ preferences for mixed-use neighborhoods, the negative sprawling effects of land use regulation may be mitigated.

Trends of Housing Demand and Rent

Table 2 shows the projected trends of housing demand, rent, and property price from 2015 to 2035 in Scenario 1. When the demographic change is the only dynamic factor, the growth rates of low-density single-family (LDSF) housing units are higher than those of other housing types before 2025. But after that, the demand for high-density multi-family and single-family housing increases at a faster rate. Table 3 compares the trends of housing demand from four scenarios. By comparing S1 and S2, one can find that the demand for LDSF housing decreases when the mixed-use preference is realized in the market. The demand for other housing types will rise, with the demand for high-density multi-family (HDMF) homes increasing the most. The effects of zoning regulation on housing demand seem much smaller than the realization of mixed-use preference. At the early periods, the constraint on high-density development will decrease the LDSF demand. But in the long term, such a land use regulation will increase LDSF demand and lower other housing demand. After comparing S2 vs. S1 and S4 vs. S2, we find that the low-density zoning may mitigate the decreasing trends of LDSF housing demand.

[Tables 2 & 3 about here]

In S1, the housing rents of four building types will increase initially and drop later, while their property price will keep increasing from 2015 to 2035, though the growth rate will decrease (Table 3). Table 3 also compares the housing rent trends between S2 and S1 and S3 and S1. Differing from housing demand, the demand for mixed-use neighborhood will significantly increase the rents of low-density multi-family (LDMF) and high-density single-family (HDSF) housing. The zoning regulation will raise the HDSF housing rent most. These findings suggest that the supply constraint on high-density development may raise the housing rents of such high-density housing.

CONCLUSIONS

This paper developed a dynamic spatial equilibrium model to compare changes in land use patterns, housing demand, and rents over a 20-year period for the Austin, Texas metropolitan area under four distinctive scenarios, assuming different agent preferences and land use policies. When compared to existing dynamic SEMs (e.g., Anas and Liu, 2007; Martínez and Henríquez, 2007), this new model introduces more land use details and more dynamics for land use change. For example, the specification tracks not just different housing sizes and access attributes, but also several location externalities (e.g., land use diversity, job-housing balance, and production externalities emerging from innovation diffusion) that affect agent (household and firm) decisions. In addition, the model allows for three dynamics that affect spatial choice, including exogenously provided demographic details, building stock conversion (as constrained by zoning regulations), and endogenously evolving location externalities. These modeling improvements help respond to many agent-based modelers major critiques (e.g., Simmonds et al., 2013), and demonstrate the ability of applied SEMs to reflect more realistic land use complexity and urban dynamics.

The scenario analyses mainly explore the effects of demographic trends, land-use preferences, and low-density zoning regulations on the dynamics of land use, housing demand, and rents, and their related welfare implication. Simulation results suggest that people's rising demand for mixed-use neighborhoods may improve land use diversity in suburban areas and lower demand for low-density single-family housing across a region. Low-density zoning regulations in Austin's outer suburbs may lead to citywide job-housing imbalances and urban sprawl (with population decentralizing and jobs potentially centralizing) while raising high-density housing rents. But such regulations do not appear to affect housing demand much, especially in the longer term. When existing low-density zoning regulations cannot be changed (in the short term), promotion of mixed-use development may increase households' preference for mixed-use environments and thus moderate tendencies towards more excessive urban sprawl.

Several modeling limitations still merit further exploration. First, further simulation analyses should discuss the effects of transitional costs (e.g., residential moving costs) and innovation diffusion on scenario results described above. Although this study focuses on methodological innovation, more sensitivity analyses are needed, to support the realistic land use policy analysis. Second, this paper does not quantify welfare effects (or their distribution) across different scenarios. Ideally, future research will extend these calculations to provide efficiency information and welfare outcomes of various land use policies (including changes to zoning regulations and subsidies for alternative development).

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Table 1 Land use comparisons between scenarios

	Land Use	2015	2020	2025	2030	2035
With and without mixed-use preference (S2 vs. S1)						
Urban Core	HH. NO.	45.69%	22.66%	26.73%	23.25%	24.11%
	Emp. NO.	1.88%	1.32%	1.38%	1.33%	1.43%
	LU Mix	-0.88%	-0.04%	-0.54%	0.26%	-0.31%
	JHR	-36.38%	-19.69%	-28.60%	-23.02%	-25.87%
Inner Suburbs	HH. NO.	-14.87%	-6.61%	-7.70%	-6.56%	-6.80%
	Emp. NO.	-4.32%	-2.19%	-3.30%	-2.99%	-3.32%
	LU Mix	0.15%	0.12%	-0.15%	0.16%	0.06%
	JHR	5.98%	0.11%	0.84%	0.24%	0.40%
Outer Suburbs	HH. NO.	-12.77%	-7.34%	-8.81%	-7.99%	-8.40%
	Emp. NO.	-4.72%	-4.55%	-4.11%	-4.18%	-4.37%
	LU Mix	4.77%	5.84%	5.97%	6.28%	6.36%
	JHR	5.08%	2.37%	5.05%	4.87%	5.28%
With and without exclusionary zoning regulation (S3 vs. S1)						
Urban Core	HH. No.	0.37%	0.16%	-0.02%	-0.12%	-0.20%
	Emp.No.	7.75%	7.61%	7.48%	7.57%	7.69%
Inner Suburbs	HH. No.	0.28%	0.28%	0.27%	0.22%	0.18%
	Emp.No.	-1.53%	-2.58%	-3.18%	-3.36%	-3.49%
Outer Suburbs	HH. No.	-0.64%	-0.49%	-0.34%	-0.20%	-0.09%
	Emp.No.	-34.44%	-35.96%	-37.11%	-37.57%	-37.91%
With and without exclusionary zoning regulation (S4 vs. S2)						
Urban Core	HH. No.	2.79%	2.18%	2.24%	2.31%	2.27%
	Emp.No.	1.19%	1.53%	1.69%	1.65%	1.56%
Inner Suburbs	HH. No.	-0.42%	0.20%	0.38%	0.52%	0.59%
	Emp.No.	-5.91%	-7.36%	-7.51%	-7.54%	-7.34%
Outer Suburbs	HH. No.	-2.78%	-2.34%	-2.73%	-2.94%	-3.03%
	Emp.No.	-0.45%	-0.94%	-2.01%	-1.79%	-1.46%

Note: The proportions were calculated using a rate of change: (land use variables of S2 – variables of S1) / variables of S1

Table 2 Changes in housing demand, rent, and property prices from 2015 to 2035 under Scenario 1

	2015 (no. of housing units)	**2020 (% change in 2015-20)**	**2025 (% change in 2020-25)**	**2030 (% change in 2025-30)**	**2035 (% change in 2030-35)**
Housing Demand					
Low-Density Single-Family	246,041	10.02%	8.50%	6.81%	5.69%
High-Density Single-Family	90,922	9.80%	8.33%	7.17%	5.98%
Low-Density Multi-Family	74,581	9.70%	8.23%	7.08%	5.92%
High-Density Multi-Family	23,739	9.69%	8.27%	7.42%	6.18%
Housing Rents					
Low-Density Single-Family	4.20	8.60%	6.51%	-0.21%	-0.50%
High-Density Single-Family	5.10	9.73%	8.11%	0.53%	-0.80%
Low-Density Multi-Family	7.50	8.63%	6.32%	-0.35%	-0.30%
High-Density Multi-Family	10.81	10.64%	9.14%	1.30%	-0.49%
Property Prices					
Low-Density Single-Family	178.75	10.12%	8.59%	6.87%	5.73%
High-Density Single-Family	97.79	9.71%	8.24%	7.10%	5.93%
Low-Density Multi-Family	82.36	9.58%	8.12%	7.01%	5.87%
High-Density Multi-Family	142.53	9.38%	8.03%	7.30%	6.09%

Table 3 Percentage changes in housing demand across paired scenarios

	2015	2020	2025	2030	2035
Housing Demand Comparisons					
With and without mixed-use preference (S2 vs. S1)					
Low-Density Single-Family	-6.99%	-4.27%	-4.81%	-4.44%	-4.61%
High-Density Single-Family	9.39%	5.22%	5.96%	5.23%	5.48%
Low-Density Multi-Family	3.57%	2.77%	3.38%	3.38%	3.53%
High-Density Multi-Family	25.25%	15.71%	16.66%	15.38%	15.61%
With and without exclusionary zoning regulation (S4 vs. S2)					
Low-Density Single-Family	-1.25%	-1.02%	-1.08%	-1.14%	-1.14%
High-Density Single-Family	1.24%	1.13%	1.34%	1.44%	1.47%
Low-Density Multi-Family	1.01%	0.87%	0.78%	0.80%	0.76%
High-Density Multi-Family	2.84%	2.43%	2.39%	2.48%	2.46%
Housing Rent Comparisons					
With and without mixed-use preference (S2 vs. S1)					
Low-Density Single-Family	-1.31%	5.51%	3.07%	4.89%	3.92%
High-Density Single-Family	16.97%	27.30%	26.22%	28.76%	27.79%
Low-Density Multi-Family	76.04%	82.70%	74.64%	77.68%	75.61%
High-Density Multi-Family	-2.41%	8.91%	4.93%	5.87%	4.87%
With and without exclusionary zoning regulation (S3 vs. S1)					
Low-Density Single-Family	-3.01%	-0.24%	1.94%	2.58%	3.13%
High-Density Single-Family	19.61%	22.87%	25.08%	25.42%	26.21%
Low-Density Multi-Family	-3.75%	0.34%	4.64%	6.72%	7.21%
High-Density Multi-Family	-4.26%	-1.79%	-0.24%	-0.35%	0.02%

Note: The proportion numbers are calculated by change rate. For example, the numbers in S3 vs. S1 are calculated as (land use variables of S3 – variables of S1) / variables of S1.

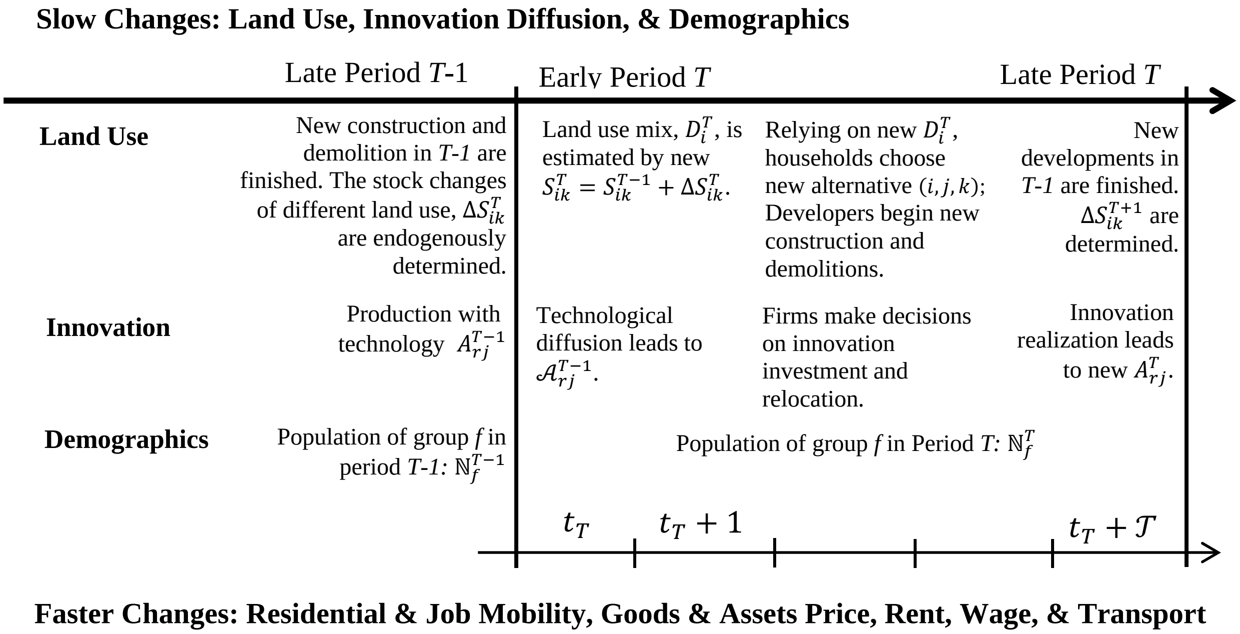


Figure 1 Model dynamics

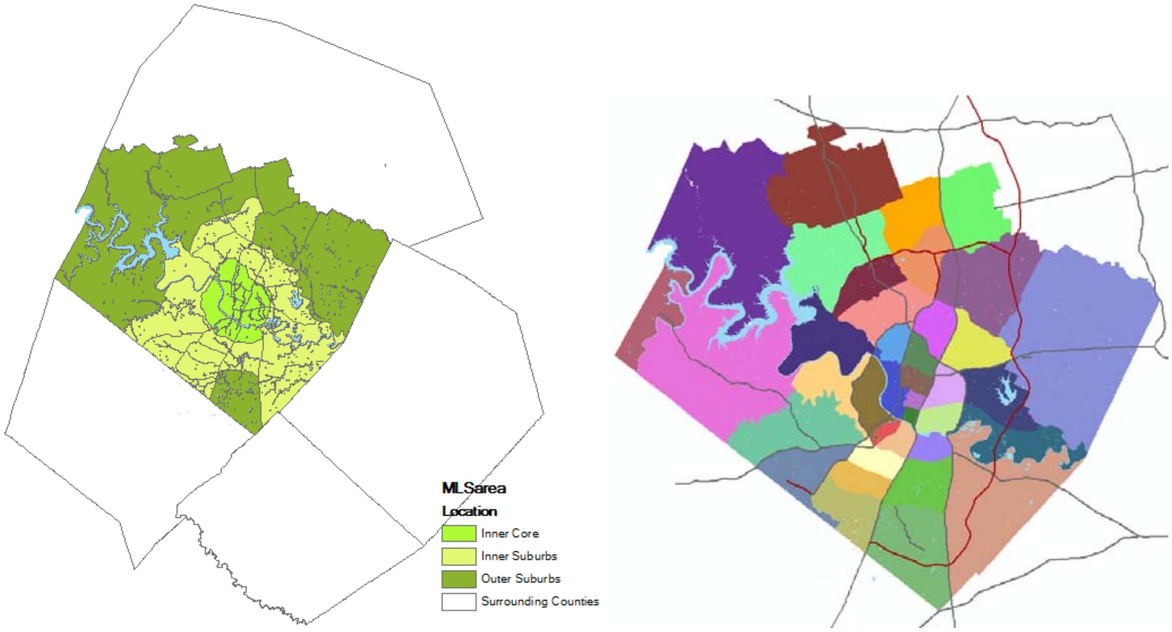
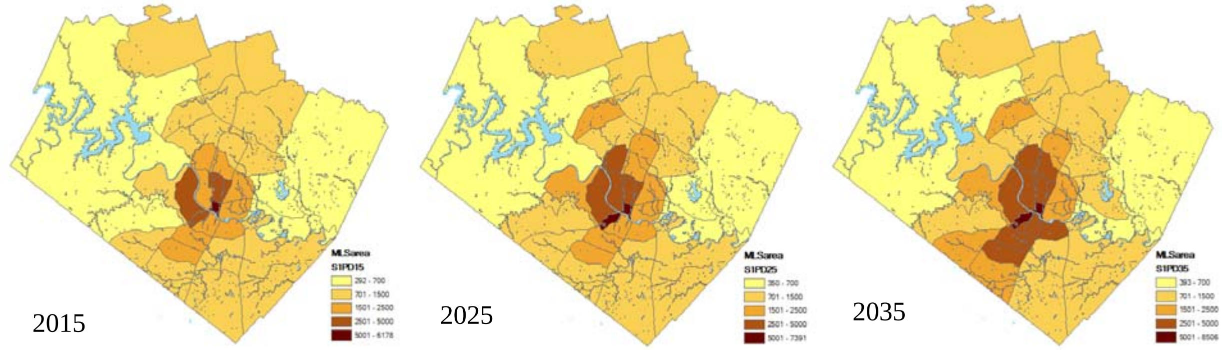
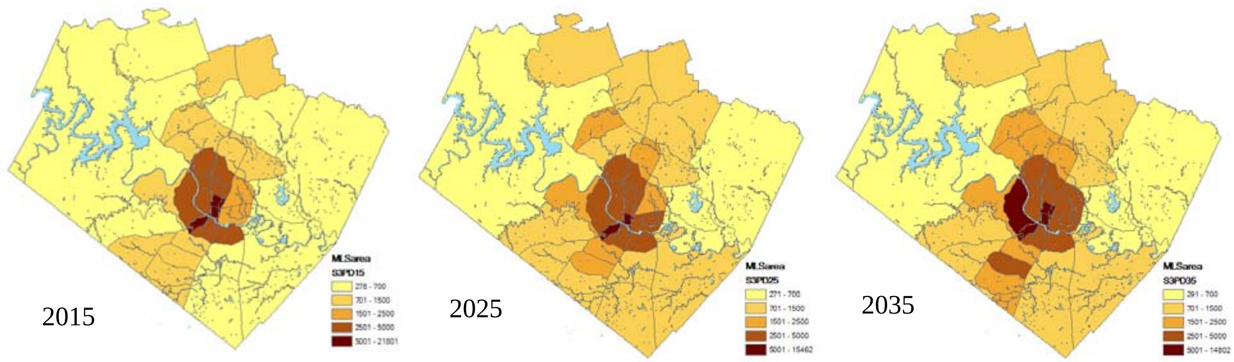


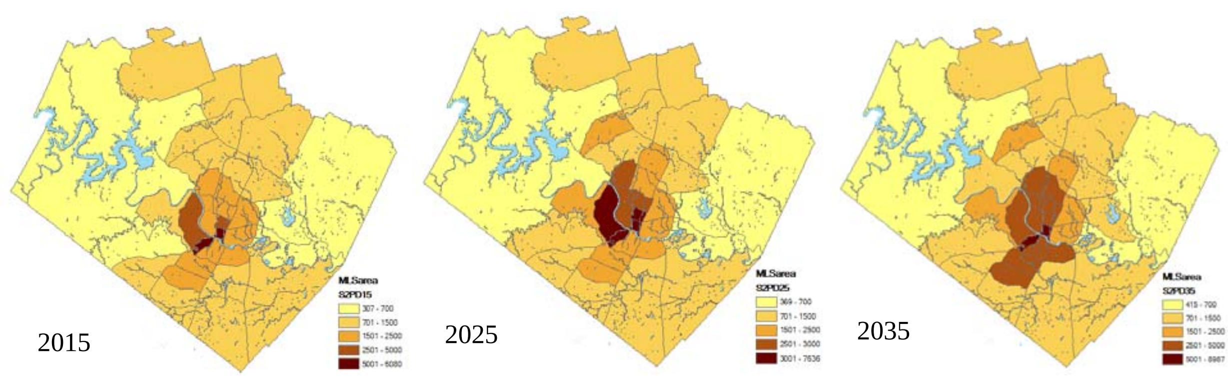
Figure 2 Austin, Texas' 38 MLS areas



(a) Household density in S1 (with exogenous population growth only)



(b) Household density in S2 (S1 + preference for mixed-use environments)



(c) Household density in S3 (S1 + low-density zoning regulation)

Figure 3 Differences in household density over time (year 2015 to 2035), across three scenarios (S1 vs. S2 and S1 vs. S3)