Modeling the Effects of Greenbelts at the Urban-Rural Fringe

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Abstract: We present and evaluate an agent based model (ABM) of land use change at the rural-urban fringe, comparing its performance to a mathematical model of the same process. Our simplified model was developed in Swarm using agents with heterogeneous preferences and a landscape with heterogeneous properties. The context of this work is a larger project that includes surveys of the preferences of residents and data on historical patterns of development. Our broader goal is to use the model to evaluate the ecological effects of alternative policies and designs. We begin by evaluating the influence of a greenbelt, which is located next to a developing area and in which no development is permitted. We present results of a mathematical model that illustrates the necessary trade-off between greenbelt placement and greenbelt width on its effectiveness at delaying development beyond. Experiments run with the ABM are validated by the mathematical model and illustrate analyses that can be performed by extending to two-dimensions, variable agent preferences, and multiple, and ultimately realistic, patterns of landscape variability.

Keywords: land use change, urban sprawl, agent-based modeling, landscape ecology

1 Introduction

Land use and cover change at the urban-rural fringe are implicated in a variety of negative ecosystem impacts, including habitat destruction and fragmentation, loss of biodiversity, and watershed degradation. A variety of approaches have been proposed to minimize the ecological impacts of development, including establishment of greenbelts of preserved lands [Mortberg and Wallentinus, 2000], clustered or ”new urbanism” designs [Arendt, 1991], purchase or transfer of development rights [Daniels, 1991], and alteration of tax or investment policies [Boyd and Simpson, 1999] among others. In order to select among these alternative strategies, the costs of implementing them need to be considered [Boyd and Simpson, 1999], as do the long term conservation benefits obtained.

To evaluate the benefits of any given option, the dynamics of development at the urban-rural fringe and their linkages to ecological impacts need to be understood. Because the impacts are driven in large part by the where development occurs, this understanding needs to be spatially explicit. Traditional models of land use change have limited abilities to support policy evaluations of this sort because they: usually explain dynamics that are spatially aggregated to the point that evaluating habitat destruction and fragmentation is not possible, do not account for feedbacks between development and the quality of life factors that drive future development, and do not account for heterogeneity in either the environment or the urban population.

In this paper we present and evaluate a foundational agent-based model (ABM) of land use change at the rural-urban fringe, which is designed to explore the interactions between locations of land development (in this case, relative to a green belt) and ecological impacts. Our longer term project will develop links between surveys of the preferences of residents, the agent-based models, and historical data on patterns of development. We intend the modeling approach developed to be useful for land planners and policy makers as they evaluate alternative land management, design and policy scenarios. The study focuses on modeling land use change at the urban-rural fringe in the Detroit Metropolitan Area, USA, but our analysis here involves a hypothetical area.

We use a mathematical model to validate our ABM results with respect to the effects of greenbelt placement and width on the locations of development. Following a description of the model, we present both the mathematical model that describes the effects of greenbelt width and placement on preservation of open space outside a hypothetical developed area, and contrast this with experimental results from our initial agent-based model.

2 AGENT BASED MODEL

The ABM presented here is designed to evaluate the dynamics arising from residential preferences, variations in natural beauty, and feedbacks associated with spatial locations of services provided to the residential population (e.g., retail, schools, etc.). The structure is fairly similar to that of Otter et al. [2001]. We call this model SLUCE (**S**patial **L**and **U**se **C**hange and **E**cological effects).

The current model is simplified for initial presentation, and involves agents (residents and service centers) that locate themselves on a two-dimensional lattice that has a set of heterogeneous attributes. Agents choose their locations based upon these attributes.

The model was developed using Swarm[1] and has three major elements: the agents, the environment in which the agents live, and the way in which the agents interact with the environment and each other.

Environment. The environment is a two-dimensional lattice of size $XSize$ by $YSize$. For the results presented below $YSize$ is always 80, and $XSize$ has a minimum of 80 but can increase to allow equivalence between runs with various settings of greenbelt parameters (described below).

The landscape is described by attributes that affect agent behavior. The only attribute we use in this paper is natural beauty (nb_{xy}), with range [0,1], but the model allows for the inclusion of other attributes, e.g., soil and ecological quality. The attributes can be generated randomly or read in from a GIS-based file.

The service center distance (sd_{xy}) can also affect an agent's behavior. This is an endogenous variable that is measured by taking the sum of the inverse Euclidean distances (for simplicity) to the nearest eight service center locations from that cell. Thus, a cell that is surrounded by service centers would receive a score of 8. Because it seems reasonable that the residents of a cell would not receive additional benefit from more than about 2 immediately adjacent service centers, we set the service center score to a maximum of 2. Thus,

$$sd_{xy} = 0.5 * max[2, (\frac{1}{||sc_1||} + \ldots + \frac{1}{||sc_8||})] \quad (1)$$

where $||sc_i||$ is the Euclidean distance to the $i-th$ nearest service center from x, y. Later versions of the model will include options for using manhattan and road network distances

Agents. The basic agent types are residents and service centers (e.g., retail firms), each of which has several heterogeneous attributes and behaviors. Residents and service centers enter the world at each time step and each takes up one cell in the lattice.

Service centers do not have any attributes themselves. At present service centers are merely proto-agents, however their presence greatly affects how residents determine where to live.

Residents have two important attributes: (1) *Beauty Preference* ($\alpha_{nb} \in [0,1]$), the weight that an agent gives to the natural beauty of an area. The beauty value of a cell x, y to an agent i is $nb_{xy} \times \alpha_{nb,i}$; and (2) *Service Center Preference* ($\alpha_{sd} \in [0,1]$), the weight that an agent gives to the nearness of an area to service centers. The service value of a cell x, y to an agent i is $sd_{xy} \times \alpha_{sd,i}$. The distribution of preferences across agents could be normal, uniform, or set to a constant.

Agent Behavior. The agent behavior of interest is the location of new residents and service centers on the lattice. Each turn a number of new residents enter the map. The rate of residents moving into the landscape is determined exogenously (10 per step). Residents choose their location based on the set of defined preferences and landscape attributes. Every time some number of residents is created (arbitrarily set to 100), a service center is created near the last resident to enter the model. There is also an initial service center that is located in the middle of the left side of the map.

To select a cell, a new resident r looks at some number of randomly selected cells (15 for all runs presented here) and moves into the cell that has the highest utility for r, or selects randomly among tied cells. The utility for a given agent with specified α values is determined in the following way:

$$u_{xy} = \quad (2)$$
$$0.5 * (\alpha_{nb} * nb_{xy} * sd_{xy} + \alpha_{sd} * sd_{xy}^2)$$

[1] Available from http://www.swarm.org.

This equation captures the empirical observation that, although beauty is an important determinant of utility, it is not considered independent of distance to services, which provides access to jobs, health care, entertainment, etc. This model allows residents to consider the tradeoffs between beauty and distance, and weights near locations much higher using squared distance.

3 ADDING A GREENBELT TO THE AGENT BASED MODEL

Our goal is to understand the trade-off between the width of a greenbelt, its distance to the left edge, and its effect on keeping development out of the right side of a hypothetical landscape. In the agent-based model, the greenbelt is represented by identifying certain cells as "preserve," which can not be developed. Neither residents nor service centers can locate in these areas.

To construct the greenbelt two parameters are required: (1) Preserve Start (g), the x-location that is the start of the greenbelt, assuming that the far left is 0; and (2) Preserve Width (w), the width of the greenbelt. The greenbelt is assumed to be a continuous rectangle from the top of lattice to the bottom.

3.1 Measures

We collect several measures of clustering and location of development from each run of the model at each time step. The measure that we will be examining within this paper is the number of developments beyond the preserve (*dbp*). This is the number of residents and service centers who have an x value greater than $w + g$. We then calculate $T(dbp = 300)$, the average number of time steps that it takes for 300 cells on the right side of the greenbelt to be developed. The threshold is arbitrary, but selected as a reasonable number to allow comparison among runs. This measure gives an indication of how effective the greenbelt is at controlling development beyond the greenbelt.

The ABM serves as a platform to study the interplay between heterogeneous agents and heterogeneous landscapes, and how two-dimensional patterns of land use change can arise from agent behavior. Given the right assumptions, we can explore some of the underlying processes generating the patterns of interest by analytical means. The next two sections explore the effects that greenbelts have on the patterns of development, taking analytical and agent-based approaches in turn.

4 A ONE DIMENSIONAL MODEL OF GREENBELT WIDTH

To approach the question of greenbelts analytically, we make several simplifications and assumptions that we can relax later using the agent-based model. In this section, we construct a one dimensional model to develop proofs of greenbelt effects.

Agents' preferences are defined over two attributes of the landscape: distance to services and a location's natural beauty. We assume discrete locations that form a one dimensional lattice, and endow each location with natural beauty, or beauty. The number of agents is finite. We say that 'x is to the left of y' if and only if '$x < y$' and 'x is to the right of y' if and only if '$x > y$'. We also make the following five basic assumptions:

A1 *M agents must choose where to locate among $N + 1$ locations on the interval $[0, N]$. Only one agent may locate at any particular location.*

A2 *A greenbelt of width w begins at the point $g \in \{0, 1, 2, 3, \ldots, N\}$. Agents cannot locate in the greenbelt.*

A3 *If the greenbelt begins at g and K agents live to the left of g then $s(K) = \frac{\eta g}{K}$ is the distance to services, where $\frac{1}{\eta}$ is the rate at which services appear. $s(K)$ is constant for all cells left of the greenbelt.*

A4 *If K agents live to the left of the greenbelt, an agent living at a location i to the left of the greenbelt gets utility $u(s) + q_i$, where $u(s)$ is a monotone decreasing function of the distance s to services and q_i is the aesthetic quality of location i.*

A5 *The first agent living to the right of the greenbelt at location $j \geq (g + w)$ has a distance to services equal to $(j - g) + \frac{\eta g}{K}$.*

We assume $g > M$, so it is possible for the greenbelt to prevent sprawl. We do not explicitly model the geographic locations that the agents choose on the left side of the one dimensional lattice. We will explicitly consider locations on the right of the greenbelt. Assume that K agents live to the left of the greenbelt. All agents use the same utility function, which depends on two factors: distance to services $s(K)$ and beauty q_i, where $i \in \{0, 1, 2, \ldots, N\}$ is the agent's location. For tractability, we assume that all locations to the left of the greenbelt have the same density. Services arrive at a rate $\frac{1}{\eta}$, meaning that they are not discrete entities like malls. This differs from our ABM.

4.1 General Results

We will say that a greenbelt of width w beginning at g *prevents sprawl for a population of size M* if none of the first M agents chooses to live on the right hand side of the greenbelt. Further, a greenbelt *efficiently prevents sprawl* if no other greenbelt with a smaller g or a smaller w will also prevent sprawl. This implies that the $M+1$st person would move across the greenbelt. It is straightforward to characterize the set of green belts that efficiently prevent sprawl. Begin with the following assumption:

A6 *The beauty q_i equals q for all i.*

Claim 1 *Given A1-A5 and A6, all agents will choose to live to the left of the greenbelt.*

Proof: The result follows directly from the assumptions: An agent locating to the left of the greenbelt obtains a utility of $u(s(K)) + q$, while an agent to the right of the greenbelt obtains a utility of $u(w + s(K)) + q$.

This is an obvious result, but it is important in that since u decreases in s but s decreases in M (more people implies less distance to services), u is increasing in M. Therefore, all agents will choose to live to the left of the greenbelt. Therefore, we need to replace $A6$ with an assumption that allows for variability in beauty.

A6' *The beauties q_i differ*

Let $\hat{q}(K, g)$ be the Kth highest beauty among those locations to the left of g. The location with the value $\hat{q}(M, g)$ will be the location chosen by the Mth agent. This variable is important in determining whether agents cross the greenbelt.

To align our two models, we assume:

A7: *The utility function is linear in distance to services. This requires that $u(s) = -\beta_s, (\beta > 0)$*

Define $\ell(g, w)$ to be the location $j \geq (g + w)$ that maximizes $q_j - \beta(j - g)$. This will be the best location to the right of the greenbelt. We can now state the following obvious result.

Claim 2 *Given A1-A7, a greenbelt at g of width w prevents sprawl if and only if $\hat{q}(M, g) = -\beta(\ell(g, w) - g) + q_{\ell(g,w)}$*

Proof: Greenbelts that prevent sprawl satisfy

$$-\frac{\beta\eta g}{M} + \hat{q}(M, g) \geq -\beta(j - g + \frac{\eta g}{M}) + q_j \tag{3}$$

for all $j > (g + w)$. This is equivalent to:

$$-\frac{\beta\eta g}{M} + \hat{q}(M, g) \geq \\ -\beta(j - g + \frac{\eta g}{M}) + q_{\ell(g,w)} \tag{4}$$

which can be rewritten

$$\hat{q}(M, w) \geq -\beta(\ell(g, w) - g) + q_{\ell(g,w)} \tag{5}$$

Given these assumptions, the comparative statics results we seek follow immediately. First, $\hat{q}(M, g)$ is increasing in g. Therefore, the larger g the less likely that we see sprawl. Second, for a fixed g, increasing w reduces the set of possible choices for $\ell(g, w)$ so $q_{\ell(g,w)} - \beta(\ell(g, w) - g)$ decreases in w. These two implications suggest a tradeoff between width of the greenbelt and its starting point for sprawl prevention. Formalizing sufficient conditions for this result is beyond the scope of this paper.

4.2 Specific Cases

We now turn to some specific cases that we consider with our ABM. In each of these cases, we vary the spatial distribution of beauty. This spatial distribution will cause the distribution of services to vary. So far, we had assumed that services were uniformly spread over the region to the left of the greenbelt. In all of these cases, the initial service center is located left of the greenbelt.

Case 1: Beauty Decreases From Left Edge

In this scenario, agents will concentrate near the left edge. This implies that if $y > z$ that $q_y < q_z$. Therefore, $\hat{q}(M, g) \geq q_{\ell(g,w)}$, which implies that all M agents will choose to locate in the region bordered by the greenbelt. This occurs regardless of the rate at which qualities decrease.

Case 2: Beauty Increases From Left Edge

In this scenario, if $y > z$ then $q_y > q_z$. The key to determining locational decisions is the rate at which qualities rise. Assume $q_y = \theta_0 + \theta_1 y$. The most attractive locations to the left of the greenbelt will be on the far right edge of that region. Therefore, we can assume that the Mth agent will choose location $g - M$. Assume also that the benefit from being close to services β is larger than θ_1, so that the most attractive location to the right of the greenbelt is on the left edge at location $(g + w)$. The inequality $\hat{q}(M, g) \geq -\beta(\ell(g, w) - g) + q_{\ell(g,w)}$ then can be written as

$$\theta_0 + \theta_1(g - M) \geq -\beta(w) + \theta_0 + \theta_1(g + w) \tag{6}$$

This reduces to

$$\beta w \geq \theta_1(M + w) \tag{7}$$

For large M and θ_1 close to β in value, the greenbelt has to become incredibly wide. This suggests that sprawl will be difficult to prevent. Interestingly, the linearity assumption implies that g does not matter so long as it exceeds M. This typically would not be true if either the quality distribution or the utility function was not linear.

5 AGENT BASED MODEL RESULTS

We now present results for a variety of experiments that we ran using the ABM to test the effectiveness of the greenbelt in keeping the right side of the world undeveloped.

The mathematical model predicts that as the preserve is moved to the right and as its width is increased it takes longer for residents to jump over the greenbelt. Therefore, for each experiment we compare runs with two different values of g (20 and 40) and of w (1 and 15).

5.1 Random Preferences

For our initial experiments the preferences were all set to 0.0, meaning that the agents locate themselves in the world randomly. This serves as a control for the rest of our experiments. Using random placement, a g of 20 and a w of 1, we calculate that it takes 39 time steps to reach $dbp = 300$. Changing g to 40 gives 59 time steps. The first row in Table 1 indicates that the ABM results are within one standard deviation of those expectations, for both $w = 1$ and $w = 15$.

5.2 Modifying Agent Preferences

To add more realistic behavior, and to incorporate the same preferences considered in the mathematical model above, we set non-zero values for the preferences (α_{nb}) and (α_{sd}). First, we set $\alpha_{sd} = 0.5$ and kept $\alpha_{nb} = 0.0$. We expected this to increase the amount of time for development to reach the right side because of the initial service center on the left edge and the feedbacks associated the service center location. This is analogous to the situation in Claim 1 above. Indeed, the results show a significant increase in $T(dbp = 300)$ (Table 1, row 2). The effect is non-linear, with increasing delays accompanying increasing w and g.

Next, we set $\alpha_{sd} = 0.5$ and $\alpha_{nb} = 0.5$. Now the pattern of natural beauty variation has an effect on the process. We start by assuming a uniform random distribution of natural beauty. This has the effect of reducing $T(dbp = 300)$ because some of the most desirable cells are to the right and are selected by residents (Table 1, row 3). For all w and g, random natural beauty patterns reduce $T(dbp = 300)$ by about 75% compared with only service center preference. Further, results from the ABM indicate that increasing the width of the area to the left of the greenbelt allows one to decrease the width of the greenbelt while achieving the same delay of sprawl, in agreement with Claim 2, above. For instance, to achieve $T(dbp = 300) = 180$, increasing g from about 30 to 40 enables a drop of w from 15 to about 1. In fact, if the utility function is changed to be linear in distance to services, and other parameters are modified to make the ABM consistent with the mathematical model, the results are as predicted.

5.3 Patterns of Natural Beauty

To evaluate the effects of landscape heterogeneity on model behavior, we introduce four different patterns of beauty, leaving $\alpha_{sd} = 0.5$ and $\alpha_{nb} = 0.5$. The longest $T(dbp = 300)$ measured across all cases were obtained with a beauty decreasing from the left (Table 1, row 4). This situation and result are similar to Specific Case 1 described above. Agents tend to stay to the left to be near services and to access the more beautiful sites. The increase in $T(dbp = 300)$ is about 1.5 times that for the case of random beauty. For the case of $w = 15$ and $g = 40$, the increase is slightly lower, because we only ran the model to 401 steps and runs that did not reach $dbp = 300$ by then were assigned a value of 401. Reversing the pattern of beauty (i.e., increasing to the right) drops $T(dbp = 300)$ by one-third to one-half compared with random beauty (Table 1, row 5). This is comparable to Specific Case 2 above.

We introduced two alternative beauty patterns that could not be evaluated with the mathematical model. The first, called tent, puts the highest values of beauty along the center two rows of the world, with values decreasing monotonically to the north and south. The second, called valley, is the inverse, with highest values along the top and bottom edges and decreasing towards the center. The results reflect the more complex interactions between the location of the initial service center, the patterns of beauty and the feedback resulting from creation of

Table 1: Average Time to 300 Developments Beyond Preserve, T(dbp=300)
Mean, Standard Deviation of Data (Standard Deviation of Means is roughly $\frac{1}{5}$ this value)

preferences	beauty distribution	$w = 1$		$w = 15$	
		$g = 20$	$g = 40$	$g = 20$	$g = 40$
random preferences	uniform [0,1]	39 (1)	61 (2)	39 (1)	60 (2)
$\alpha_{sd} = 0.5, \alpha_{nb} = 0.0$	uniform [0,1]	113 (22)	275 (46)	150 (25)	337 (18)
$\alpha_{sd} = 0.5, \alpha_{nb} = 0.5$	uniform [0,1]	85 (19)	193 (52)	103 (29)	278 (39)
$\alpha_{sd} = 0.5, \alpha_{nb} = 0.5$	left high	130 (21)	319 (25)	166 (15)	343 (3)
$\alpha_{sd} = 0.5, \alpha_{nb} = 0.5$	right high	43 (6)	70 (29)	46 (13)	98 (62)
$\alpha_{sd} = 0.5, \alpha_{nb} = 0.5$	tent	77 (11)	171 (32)	92 (20)	221 (38)
$\alpha_{sd} = 0.5, \alpha_{nb} = 0.5$	valley	90 (15)	160 (37)	115 (28)	218 (70)

service centers. At $g = 20$ the valley pattern results in consistently higher $T(dbp = 300)$, though not outside the standard deviations of either trial, than does the tent pattern (Table 1, rows 6 and 7). This is because the location of the seed service center in the middle of the left edge coincides with the top of the ridge of the beauty surface. At $g = 40$, however, $T(dbp = 300)$ is not as different. In fact the mean with the tent pattern is slightly higher than that with the valley pattern. This convergence might be explained by the greater amount of time, at $g = 40$, the clusters of development have to align themselves with the ridges of the natural beauty surface and, with the help of the new service centers, develop along the top and bottom edges.

6 Discussion and Conclusions

Many of the results presented here are obvious outcomes of the simple model we have created. The purpose of presenting them is to (a) provide analytical validation of the functioning of our agent based model and (b) form a basis for developing more realistic models using the ABM to test processes that are too complex for analytical solution. Although the problem is overly simplified here, we have focused on the effectiveness of greenbelts to illustrate the value of these modeling frameworks evaluating policies too minimize the ecological impacts of land use change. The ABM gives comparable results about the effectiveness of the greenbelts for preventing sprawl as does the mathematical model, when the conditions are held constant. But the ABM can be extended to include two-dimensions, agents with heterogeneous preferences, and real or designed patterns of landscape properties. Thus the model presented, and others like it, will serve as a foundation for our future work.

Acknowledgements

This work is funded by the US National Science Foundation under the Biocomplexity and the Environment program, grant BCS-0119804.

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