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Evaluating the effects of land-use development policies on ex-urban forest cover: An integrated agent-based GIS approach

D. T. ROBINSON* and D. G. BROWN

School of Natural Resources and Environment, and The Center for the Study of Complex Systems, University of Michigan, 440 Church Street, Ann Arbor, MI 48109 1041, USA

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We use a GIS-based agent-based model (ABM), named dynamic ecological exurban development (DEED), with spatial data in hypothetical scenarios to evaluate the individual and interacting effects of lot-size zoning and municipal land-acquisition strategies on possible forest-cover outcomes in Scio Township, a municipality in Southeastern Michigan. Agent types, characteristics, behavioural methods, and landscape perceptions (i.e. landscape aesthetics) are empirically informed using survey data, spatial analyses, and a USDA methodology for mapping landscape aesthetic quality. Results from our scenario experiments computationally verified literature that show large lot-size zoning policies lead to greater sprawl, and large lot-size zoning policies can lead to increased forest cover, although we found this effect to be small relative to municipal land acquisition. The return on land acquisition for forest conservation was strongly affected by the location strategy used to select parcels for conservation. Furthermore, the location strategy for forest conservation land acquisition was more effective at increasing aggregate forest levels than the independent zoning policies, the quantity of area acquired for forest conservation, and any combination of the two. The results using an integrated GIS and ABM framework for evaluating land-use development policies on forest cover provide additional insight into how these types of policies may act out over time and what aspects of the policies were more influential towards the goal of maximising forest cover.

Keywords: geographical information systems; agent based modelling; land use; land cover; policy

1. Introduction

Land acquisition is probably the most widely implemented ecologically-based land-use policy. Public land acquisition, by a governing agency (e.g. municipality), is used to conserve, preserve, or regenerate an ecosystem(s) and constrain the sale and development of that land. While costly in funds and management resources, conservation areas provide environmental and social benefits to both local and regional residents (e.g. Chiesura 2004). However, little land is actually set aside for public lands in most growing suburban and exurban landscapes. For example, publicly owned lands (which include campgrounds, dedicated open space, golf

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*Corresponding author. Email: dtrobins@umich.edu

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courses, preserves, parks, and federal lands) in seven counties of Southeastern Michigan (St. Clair, Livingston, Oakland, Macomb, Washtenaw, Wayne, and Monroe) accounted for only 64,739.4 ha or 5.4% of the total 1,207,214 ha area (SEMCOG 2005). The low ratio of public to privately owned land suggests that land-use policies that influence private land use may provide a more effective forest-conservation strategy than public-land acquisition.

As a method of influencing private lands and their owners, land-use zoning policies were created in 1926 to extend nuisance laws and have been used to plan for future development to separate land uses and reduce the number of land-use-based nuisances, substitute government-led collective property rights for individual property rights, and to protect and maintain low-density neighbourhoods (Nelson 1989). While debates on the efficiency or effectiveness of zoning have been long lived (Fischel 1980), minimum lot-size or exclusionary zoning has been shown to influence the amount of forest cover and placement of that cover within land parcels (Munroe *et al.* 2005). Furthermore, when minimum lot-size zoning policies are instantiated in combination with other land-use development policies they may have unintended consequences, specifically with regard to forest cover.

The evaluation of these types of land-use policies is difficult and requires consideration of both human and environmental complexity and associated uncertainties. The characteristics of such a complex system, i.e. heterogeneity, interaction, feedback, nonlinearities, and adaptation, all serve to complicate policy evaluations. The goal of this paper is to describe and illustrate the use of a GIS-based agent-based model (ABM), called the dynamic ecological exurban development (DEED) model. We use the model to generate a number of realisations of land-use and land-cover change that are the product of subdivision development and residential-location processes. Then, we evaluate how these processes are altered by minimum lot size zoning and land preservation strategies, both independently and in combination.

Recognising that there are differences in the ecological quality and function provided by privately owned forested areas, secondary succession forest, and conservation areas set aside to protect existing forest or to establish new forest, we used forest cover as the primary measurement to evaluate land-use policies because it has both ecological and social benefits. Ecologically, increased forest cover reduces soil erosion (Dunn *et al.* 1993), reduces surface albedo (Pielke Sr. *et al.* 2002), regulates local temperature through sensible and latent heat flux and evapotranspiration (Betts *et al.* 1996), increases available habitat, and increases carbon storage that, when aggregated over larger areas, can act to mitigate the effects of global warming. Similarly a number of social benefits derived from increased tree cover can be accrued through an increase in: (1) the aesthetic quality of the landscape (Parsons and Daniel 2002), (2) privacy, (3) the filtering of air pollution and improved public health (Brack 2002), and (4) the quality of life for those living in proximity to forests.

In the next section we describe the study area to provide context for understanding how model components are informed by real-world actors and data. Then we introduce DEED and illustrate its use by analysing different land-use development policies. Results of these policy experiments are then presented, followed by a discussion of the modelling process and the implications of our policy evaluations. Lastly we draw conclusions about the use of DEED for policy analysis.

2. Study area

Our study area is the 88.8 km^2 area of Scio Township bounded by 42°15′11.9″N and −83°54′1.8″W, in the southwest, and 42°20′34″N and −83°46′44.6″W, in the northeast. Located in Michigan, USA, the township is encroached on by the city of Ann Arbor on its eastern edge and the Village of Dexter in the northwest. The township population increased by 29% between 1990 and 2000 (US Census 1990, 2001), making it one of only a few areas of Southeastern Michigan experiencing a high rate of growth. Similarly, the City of Ann Arbor experienced a 3.9% growth in population from 1990 to 2000 that made it the only city with positive growth in Southeastern Michigan. The proximity of the township to both urban and rural amenities and within-township access to major transportation routes (e.g. Interstate 94) provide a number of drivers recognised to increase population growth and urban sprawl.

Scio Township has a mixture of land covers and uses that have changed over time (figure 1). Forest, other natural areas, and impervious surfaces have increased at the expense of crop land. Similarly, a decrease in agriculture is marked by an increase in residential land use and abandoned or undeveloped lands. The loss of agricultural land to low density housing, and urban sprawl is common in the Upper Midwest (Brown 2003). Since the township is highly fragmented and lies at Ann Arbor's urban-rural fringe, planning commissions are challenged to accommodate the conflicting needs of multiple actors who exploit public environmental resources.

While land-use changes in the township are the product of forces occurring inside and outside the township, planning in the township might profitably be viewed as a 'closed system' with little cooperation and coordination with other townships. The closed-system perspective is supported by legislation enacted at the state level (Gerber *et al.* 2005), like the Township Zoning Acts (PA 184 of 1943 and PA 168 of 1959), which foster a strong 'home-rule' policy, whereby the majority of power for land-use planning and policy resides at the township level (Wyckoff 2003). For the purposes of this paper, we bound our model to the limits of Scio Township, but incorporate influences from outside the township on the functioning of the model. We do not consider the possibilities of coordination and cooperation with neighbouring municipalities.

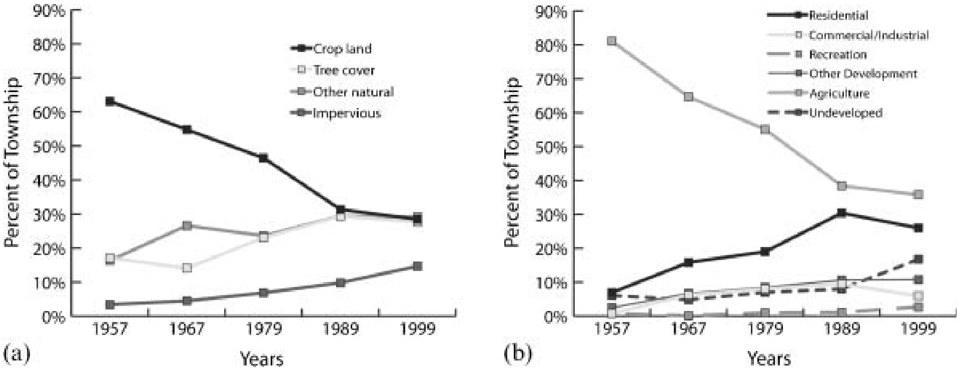
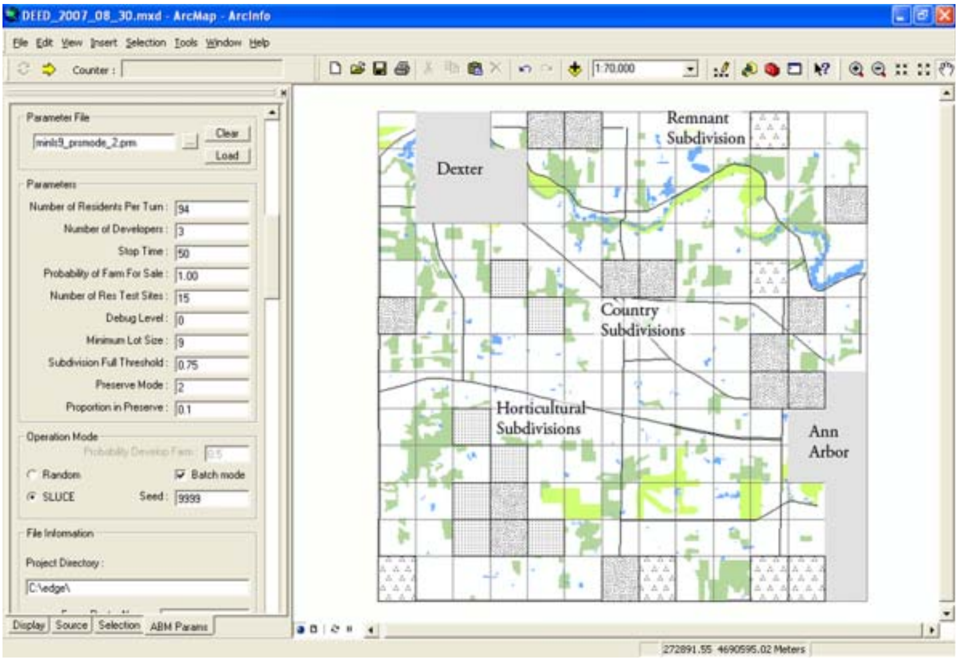


Figure 1. (a) land cover and (b) land use trends in Scio Township from 1957–2000. Values calculated using air photo interpretation.

3. The DEED model

We use an ABM approach to simulate the decision-making behaviours, actions, and interactions of virtual agents that represent real-world actors or decision-making bodies and aggregate to produce landscape-level system outcomes. For a general overview and description of the approach see Parker *et al.* (2003) and Sengupta and Sieber (2007). We have published previous versions of the DEED conceptual model (Brown *et al.* 2008, Zellner *et al.* in press) but altered it substantially by systematically integrating empirical research on agent behaviours and creating a new GIS-based ABM implementation for land-use policy analysis (figure 2). In previous versions residential and developer agents used heuristic decision-making strategies that were based on expert opinion. In the presented version we integrate a residential location model based on survey data (Brown and Robinson 2006) and the results of a survival analysis (An and Brown 2008) to empirically inform the residential and developer agent decision-making strategies. Precursor tests using survival analysis to inform ABMs demonstrated that additional variables of influence were not included in previous versions of DEED (Brown *et al.* 2008) that we do include in the version presented in this paper. Furthermore, in this version of DEED we use a USDA defined method for creating landscape aesthetic maps for agent farm and subdivision-lot evaluation.

A model run begins by converting a grid of cells, representing hypothetical farm parcels, into farm agent polygons. Each farm-agent polygon is approximately 56.25 ha (140 acres). Statistics summarising landscape data by each farm polygon are stored as farm agent properties. Farm centroids are then created and the distance



Parameter File: minls9_prsmode_2.prm

Number of Residents Per Turn: 94
Number of Developers: 3
Stop Time: 50
Probability of Farm For Sale: 1.00
Number of Res Test Sites: 15
Debug Level: 0
Minimum Lot Size: 9
Subdivision Full Threshold: 0.75
Preserve Mode: 2
Proportion in Preserve: 0.1

○ Random
● SLUCE
☑ Batch mode
Seed: 9999

Project Directory: C:\edge\

Figure 2. Screen capture illustrating typical outcome from the unrestricted scenario using the DEED model. A parameter window is integrated into the table of contents and a customised toolbar maintains a count of the simulation steps and allows the user to start and reset the model.

from each centroid to the nearest county road, to Detroit, and the nearest edge of land delineated as a city centre is stored in the farm properties. Next, a selection of farm parcels is acquired and placed in forest conservation by the township agent, which also implements the user defined policy scenarios. Developer agents then evaluate the biophysical and geographical characteristics of farms for subdivision. The subdivision type created by a developer agent has ecological effects on the landscape by altering the forest cover and creating different parcel lot densities. Residential household agents are then created; each one evaluates a bounded set of lots and acquires the deed to the lot that maximises the household's utility. Lastly, the township agent monitors and reports the amount of land use and land cover change that occurred. These and other model components are shown in figure 3. The remainder of this section describes the landscape within which agents act and interact and then the characteristics and behavioural mechanisms for each agent type shown in figure 3.

3.1 *The agent world (landscape)*

The landscape is represented by land cover and soils data acquired from the Michigan Center for Geographic Information[1] (MCGI) and the US Natural Resources Conservation Service (NRCS; SSURGO 2006)[2], respectively. Both datasets were resampled to 15-m resolution, where nine cells approximated the average minimum lot size (~0.5 acres) observed in several Southeastern Michigan townships. Vector soil data were reclassified to prime versus not-prime farmland based on soil types defined as part of the Soil Survey of Washtenaw County conducted by the USDA and NRCS (Engel 1977). All DEED grids were 656 × 660 cells and incorporated *NoData* values to represent the township border. The township was composed of a total of 412,692 cells.

Cell objects are used at each grid location to store multiple values and allow for probing and altering landscape values at a high frequency without impeding model

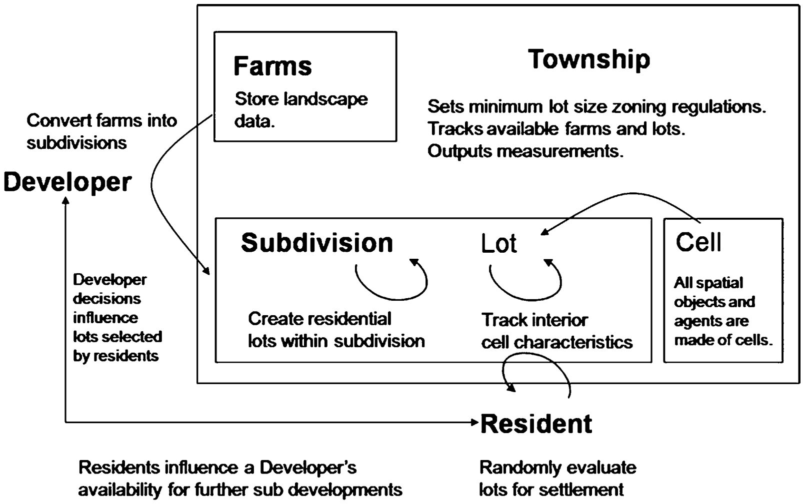


Figure 3. Outline of the interaction among modeled agents and objects as well as the primary behaviour of each. Farms, subdivisions, lots, and cells are all contained within the township agent.

speed by frequent calls to raster grids. These objects also form the basis for land exchange among agents. For example, land holdings of farm agents are represented as a collection of cell objects that can be acquired by a developer agent who subdivides the farm into lots (i.e. smaller collections of cells). Deeds to lots are then transferred to residential household agents. Lastly the cell object framework allows for the extension of cell objects into automaton machines that have behaviours or landscape sub-models of their own (e.g. Box 2002, Deadman *et al.* 2004).

3.1.1 Landscape aesthetic quality. The aesthetic quality of the landscape was created using a methodology developed by the USDA Forest Service (USDA 1974, 1995). The process involved first creating distributions of landscape character (e.g. lake areas and elevation values) and assigning quartiles of the distribution to one of three classes: minimal, common, or distinctive (table 1). We also classified aspect, assuming greater sun exposure was preferred and north facing aspects did not contribute positively (i.e. value of 0), and included all rivers and public lands since few existed in the study area[3]. Next we calculated landscape visibility, as defined by USDA (1974, 1995), by measuring the Euclidean distance from cells to features of interest (i.e. distinctive lakes, rivers, and public lands) and classifying each cell into one of the following four visibility zones: immediate foreground, foreground, middle ground, or background area (USDA 1974, 1995) (table 1).

We then additively overlayed the landscape character and visibility grids and rescaled the resulting values to a range of 0–1 such that values close to one represented locations more aesthetically pleasing than values close to zero. Other methods may be used to derive an aesthetic quality map; however, we found no other useful literature beyond the USDA reports that provide a general evaluation of aesthetic quality that may be used over multiple locations. Furthermore, the incorporation of feature values into the landscape character classes is acceptable because we do not have enough precision in our data on residential preferences to acknowledge the more minor differences that occur in the continuous environmental data. The USDA methodology also incorporates user characteristics and preferences into their aesthetic quality map. Instead of directly including user characteristics and preferences into our map, we extracted them from a household survey and used the results from analysis of the survey to populate the characteristics and preferences of residential agents in the model (see Section

Table 1. Classification of landscape variability and visibility characteristics of Scio Township using the USDA landscape aesthetics and visual management system frameworks.

Aesthetic quality index value	1	2	3	4
Landscape character	Minimal	Common	Common	Distinctive
Elevation (m)	790–877	878–897	898–923	>923
Lake area (m^2)	260–1142	1143–2098	2099–5755	>5755
Landscape visibility (m)	>6437= Background	805–6437= Middleground	92–804= Foreground	0–91= Immediate Foreground
Aspect (°)	Northeast (22.5–67.5)	East (67.6–112.5)	Southeast (112.6–156.5)	South (157.6–202.5)
	Northwest (292.6–337.5)	West (247.6–292.5)	Southwest (202.6–247.5)	

3.2.3). In the next section we describe the agents that act within the landscape we just described.

3.2 *The agents*

3.2.1 Township agent. The role of the township agent is to first implement a policy scenario based on user-specified parameters and then monitor and report on the holdings and transfers of farm, subdivision, and lot deeds at each time-step. The types of scenarios presented in this paper include: (1) unrestricted development, (2) setting the minimum lot size zoning restriction on developers, (3) acquiring a number of farm properties for the creation of forest conservation areas, or (4) both (2) and (3) together. The township agent does not face a budget constraint on acquiring land for conservation. Instead the amount of land acquired is a parameter of the model, which we report values of municipal land acquisition at 0, 5, and 10% of the township area. When the township does acquire land for forest conservation, it pursues one of the following three strategies: locate conservation areas on: (1) the least forested farms, (2) the most forested farms, or (3) randomly. Over time, the conservation area is managed to grow forest and reach a closed-canopy state by 20 years.

As the township agent acquires land for conservation purposes, it may force developers to substitute less preferred farms for subdivision. In addition to this type of substitution interaction between the township and developer agents, the township agent also determines if a developer can operate within the township via minimum lot-size constraints. Lastly, because the township maintains the lists of available farms and residential lots for acquisition it interacts with both developers and residential agents searching to acquire land.

3.2.2 Developer agents. Three developer agents are instantiated in the model, one to build each of three different kinds of subdivision developments. A developer agent begins by querying the township agent to determine if the residential density of the subdivision type it builds satisfies township building constraints (i.e. minimum lot size zoning). If not, then that agent is constrained from further action. If so, then the developer agent evaluates all non-developed farms based on its preferences for biophysical and geographical characteristics (table 2) and subdivides the farm that maximises its utility function. The developer agent may not partake in subsequent developments until the existing subdivision has been filled by residential demand, a threshold we set at 75%. The utility function used by developer agents to evaluate farms for subdivision takes the following form:

$$u_{d(farmx)} = \prod_{i=1}^{m} \left(\gamma_{i(farmx)}\right)^{\alpha_{id}} + \sum_{j=1}^{n} \left(\gamma_{j(farmx)}\right) \alpha_{jd} \tag{1}$$

where $u_{d(farmx)}$ is the utility developer d receives from farm x; α_{id} is the preference weight developer d places on factor i; $\gamma_{i(farmx)}$ is the value of factor i at farm x; m is the number of non-binary factors; n is the number of binary factors evaluated. We separate the presence/absence or binary variables from non-binary variables because a single factor weight of zero would render a multiplicative utility function zero. Similarly, using exponents on values of 1 (presence of binary variable) would result in a 1, which would under-represent the significance of those variables. The above form takes both of these problems into consideration.

Table 2. Hazard and preference weights (alpha values) for location characteristics influencing developer agent site selection decisions for subdivision. Bold numbers are significant at alpha =0.10 level. Minimum lot sizes for country, horticultural, and remnant subdivisions are 0.19, 0.82, and 1.26 ha, respectively. Table adapted from Brown *et al.* (2008).

		Country subdivision		Horticultural subdivision		Remnant subdivision	
Location characteristics	Unit	% Δ in hazard rate per unit Δ	Scaled alpha values	% Δ in hazard rate per unit Δ	Scaled alpha values	% Δ in hazard rate per unit Δ	Scaled alpha values
Soil quality (prime farmland)	0 or 1	48.55	0.175	−3.05	0.103	**69.67**	0.511
Percent slope	1%	**60.65**	0.217	−12.81	0.000	**8.49**	0.082
Percent tree cover	1%	0.93	0.011	−2.06	0.113	**1.26**	0.031
Distance from county roads	1 km	**−0.65**	0.005	−0.21	0.133	**0.13**	0.023
Distance from water	1 km	**164.34**	0.576	24.24	0.390	46.69	0.350
Distance from nearest city	1 km	−2.13	0.000	**4.74**	0.185	**−3.18**	0.000
Distance from detroit	1 km	2.64	0.016	**−5.60**	0.076	**−2.64**	0.004

The preference weights for each developer agent are empirically informed using the relative difference among hazard rate coefficients, calculated by survival analysis (Klein and Moeschberger 1997). A hazard rate, representing the instantaneous risk that a parcel will be developed, is obtained by regression of the logarithm of the hazard against a linear combination of independent variables (those shown as landscape characteristics in table 2, An and Brown 2008). We take the coefficients from the regression and rescale them (range 0–1) to represent the preference weight a developer agent has for each landscape characteristic. A single hazard rate equation is computed for each developer agent based on a sample of subdivisions and their interior lots, interpreted from aerial photographs taken at $\sim$10-year intervals from 1950 to 2000 for eight townships (Flushing, Oregon, Pittsfield, Putnam, Ray, Scio, Washington, and Woodstock) in Southeastern Michigan.

The subdivision typology was designed to represent three subdivision types found in Southeastern Michigan: country, horticultural, and remnant subdivisions (Nassauer personal communication, Brown *et al.* 2008). From the sample of subdivisions described above, the average lot size for each were 0.19 ha (0.48 acres), 0.82 ha (2.02 acres), and 1.26 ha (3.12 acres), respectively. Subdivisions also differ in their respective amounts of forest cover. Specifically, the development of a country subdivision involves clearing all forest and little to no regrowth; horticultural subdivisions maintain pre-developed forest cover levels; remnant subdivisions may increase forest cover up to 4.05 ha (10 acres) after 10 years if less than 4.05 ha exists on the subdivision (Unpublished Data). It is these differences in residential density and the biophysical outcomes of the subdivision process that drive much of our model results, which are shown in figure 4.

The actual subdivision process as implemented in DEED is a rudimentary procedure that starts in the northwest corner of the farm and ends in the southeast

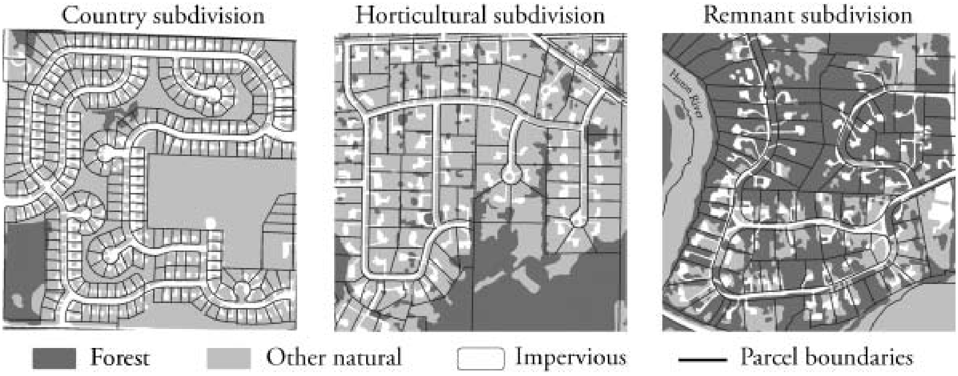


Figure 4. Digitised land-cover data and parcel boundaries for each of the three subdivision types used by the DEED model. Residential density decreases and forest cover increases as we move from the country subdivision (left) to the remnant subdivision (right).

corner. Each cell represents 225 m^2 (0.056 acres) and cells are allocated to lots sequentially until the size of the lot is equal to or greater than the observed average lot size for the subdivision type. The spatial pattern of lots within the subdivision is not an accurate representation of the pattern in the system of study. However, our analysis is at the subdivision level and therefore lot configurations do not influence our results.

3.2.3 Residential household agents. A factor analysis of a household location survey, administered in Southeastern Michigan, identified four factors influencing residential location: distance to schools/work, openness and naturalness, social comfort, and household characteristics (Fernandez *et al.* 2005). The first three factors operate at the scale represented in our model and were mapped into the following residential location drivers in a previously developed residential growth model named SOME: Euclidean distance to service centres (i.e. work, schools, and other urban amenities), aesthetic quality of a location, and neighbourhood similarity (Brown and Robinson 2006). The factor scores and their standard deviations are used to create distributions of values that are rescaled and used to populate residential household agent preference weights in DEED, as conducted by Brown and Robinson (2006).

At each time step of the model the township agent maintains a list of all available residential lots. Each residential household agent randomly chooses a number of those lots and from this subset selects the lot that maximises the following utility function:

$$u_{r(x,y)} = \prod_{i=1}^{m} (1 - |\beta_i - \gamma_i|)^{\alpha_{(i,r)}} \tag{2}$$

where $u_{r(x,y)}$ is the utility of the lot at location (x,y) for resident r; $\alpha_{(i,r)}$ is the preference weight the resident r places on factor i; β_i is the preferred value on factor i and assumed constant for all residents (i.e. all residents desire lower distance to service centres, higher aesthetic quality, and greater neighbourhood similarity); $\gamma_{i(x,y)}$ is the value of factor i from the lot at location (x,y), and m is the number of factors evaluated. Measurement of neighbourhood similarity occurs by randomly selecting eight lots within the same subdivision as the lot being evaluated, based on the similarity of preferences between the searching household agent and those on eight randomly selected lots within the same subdivision those already settled[4]. Since our analysis is at the subdivision level the within-subdivision neighbour selection method does not affect our results.

The number of agents created by the model and populated by those survey data at each time step is based on GIS-derived residential building data. Residential building locations within the study area were digitised using aerial photo data from 1955, 1969, 1978, 1990, and 1998. A linear regression of the building data (excluding areas of Ann Arbor and Dexter) against year yielded the following equation: $y=291.2864+94.1773*(\text{year})$, with an $R^2=0.94$, where y is the number of new households in a given year. Therefore, the model is calibrated to a fixed annual (time-step) increase of 94 residential structures (household agents) each year. Interaction among agents occur by constraining future agent decision-making through the occupation of a lot and influencing future agents' neighbourhood similarity measurements within the subdivision where a potential lot for settlement resides.

4. Computational experiments

We compared and contrasted the effectiveness of land-use policies designed to conserve forest cover by public-land acquisition versus lot-size zoning. To perform this comparison we held the number of new residents constant across all experiments and evaluated each policy independently, and then in combination, with the goal of identifying the most effective policy for forest conservation/restoration. Five scenarios are used to set the context for our policy experiments (i.e. unrestricted development, exclusionary zoning, land acquisition for conservation, conservation location strategy, and integration of lot-size zoning and land acquisition). Each experiment involves running the DEED model 30 times and averaging results to account for stochastic model behaviour.

We initialise the model with a hypothetical distribution of farm parcels that form a grid across the landscape. At each time-step of the model the developer agents evaluate the landscape characteristics of each farm that are initialised using the data described in Section 3.1. Ninety-four new household agents are created by the model at each time-step, based on the regression described in Section 3.2.3, and each household evaluates 15 random available lots for settlement before settling at the lot that maximises the household agent's utility function. The process continues for 50 time-steps where each time-step represents one year, with a time-span chosen for a period that we have decadal land use and land cover data that will be used to validate higher fidelity and non-hypothetical versions of the model in the future.

The unrestricted development experiment indicates how the model performs in the absence of lot-size zoning constraints or land acquisitions by the township. All three types of developers and their subsequent subdivisions exist (i.e. country, horticultural, and remnant) in this experiment, which result in a range of housing densities.

In the exclusionary zoning experiment, the township imposes two minimum lot-size zoning scenarios. The first scenario (EZ1) excludes the development of country subdivisions (i.e. high density developments) by setting the minimum lot-size zoning to parcels of 0.82 ha or greater. The second scenario (EZ2) excludes both country and horticultural subdivisions (i.e. high and medium density developments) by setting the minimum lot-size zoning constraints to parcels greater than or equal to 1.26 ha. In its essence, this experiment evaluates the trade-off between area of development and the type of development.

In the land acquisition for conservation experiment, zoning is removed and the township agent randomly acquires a number of farms for forest conservation. This experiment demonstrates how a fixed proportion of area in forest conservation may affect development and aggregate forest cover in the township. As noted earlier, public land ownership in the greater SEMCOG region, of which Scio Township is a part, approximated 5.4% in 2005. In extreme cases of public land acquisition, such as has been done to conserve panther habitat in Florida (Main *et al.* 1999), 10% of the land has been publicly acquired. Therefore, in this experiment we contrast the acquisition of 5 and 10% of the land area with the unrestricted and exclusionary zoning land use development policy experiments.

Extensive research exists on nature reserve selection and conservation location strategies (e.g. Prendergast *et al.* 1999). We extend the random preserve location strategy used in the land acquisition for conservation experiment with two simple forest conservation location strategies: locate conservation areas on the least forested farms, and locate them on the most forested farms.

To determine if there were significant interaction effects, we evaluated simultaneous changes in minimum lot-size zoning, proportion of the Township placed in conservation, and strategy for locating conservation areas. We interpreted the results of the various policy combinations by calculating the amount of forest cover, the amount of development, and the *added-value* forest from each policy combination, where added value is the difference in forest cover between the unrestricted scenario and that obtained from a given scenario minus the fixed area placed in forest conservation.

5. Results

5.1 *Unrestricted development*

The lack of any policy resulted in the lowest amount of forested land and near lowest amount of developed land. Results from the unrestricted development experiment yielded an average aggregate forest amount of 15.2% of the township or 1332.87 ha in total (table 3). Of the total township area, 17.2% (1523.63 ha) of the area, on average, was developed into some type of subdivision, of which 13 subdivisions were country subdivisions, seven were horticultural subdivisions, and six were remnant subdivisions.

5.2 *Exclusionary zoning*

Since the density of country subdivisions is higher than the other two subdivision types, one less country subdivision would mean four more horticultural subdivisions or six more remnant subdivisions, given a fixed residential demand. Due to these differences in subdivision densities, increasing the minimum lot-size to 0.82 ha (EZ1) tripled the area in residential land use to 52.1% from the unrestricted case of 17.16% (table 3). Despite excluding the subdivision type that removes all forest from its' boundaries (i.e. country subdivisions), gains in aggregate forest cover under the EZ1 scenario were less substantial and led to only a slight increase from 15.2 to 16.7%, a 1.5% gain over the unrestricted case. When we excluded both country and horticultural subdivisions (EZ2 scenario) the area in residential land use exploded to

Table 3. Results from all model runs and reported scenarios. CS= Country Subdivision, HS= Horticultural Subdivision, and RS= Remnant Subdivision. Values presented right of the minimum lot size column represent the average of 30 simulation runs using the same parameter setting. Area values are in hectares and values in parentheses are the average standard deviations for those runs. Cells with x represent an absence of that subdivision type under a given scenario.

Computational experiment	Conservation location strategy	Section	Min. lot size (ha)	Percent in conservation	Forest cover	Developed	Change in forest	Change in developed	Mean total area forested (sd)	Mean number of CS (sd)	Mean number of HS (sd)	Mean Number of RS (sd)
Unrestricted		5.1	0.19	0%	15.20%	17.16%	0.00%	0.00%	1353.72 (1.65)	13.00 (0.00)	7.00 (0.00)	5.96 (0.18)
Exclusionary zoning	EZ1	5.2	0.82	0%	16.70%	52.15%	1.50%	34.99%	1486.50 (2.60)	x x	35.93 (2.17)	44.26 (2.42)
	EZ2	5.2	1.26	0%	17.50%	68.72%	2.30%	51.56%	1552.12 (0.00)	x x	x x	106.00 (0.00)
Land acquisition for conservation	Random	5.3	0.19	5%	19.02%	18.31%	3.82%	1.16%	1689.46 (33.93)	12.80 (0.93)	7.40 (1.40)	7.50 (5.74)
		5.3	0.19	10%	23.30%	18.40%	8.10%	1.24%	2068.96 (34.91)	13.10 (1.11)	7.80 (1.68)	7.00 (4.98)
Conservation location strategy	Most forested	5.4	0.19	5%	16.87%	16.53%	1.67%	−0.63%	1497.81 (2.18)	13.83 (0.37)	5.16 (0.37)	5.96 (0.18)
		5.4	0.19	10%	19.66%	16.73%	4.46%	−0.43%	1745.79 (4.19)	13.96 (0.18)	5.40 (1.02)	5.83 (0.37)
	Least forested	5.4	0.19	5%	21.02%	30.00%	5.82%	12.84%	1865.97 (8.44)	10.00 (0.82)	11.53 (0.81)	24.40 (3.57)
		5.4	0.19	10%	25.98%	30.69%	10.78%	13.53%	2306.85 (5.01)	9.86 (0.34)	11.66 (0.47)	25.46 (1.61)
Combination experiments	Most forested	5.5.1	0.82	5%	18.40%	51.51%	3.20%	34.35%	1633.97 (3.14)	x x	36.03 (2.27)	43.07 (3.16)
		5.5.1	0.82	10%	21.28%	52.17%	6.08%	35.01%	1889.88 (2.81)	x x	35.83 (2.08)	44.17 (2.73)
	Random	5.5.2	0.82	5%	20.43%	51.76%	5.23%	34.61%	1813.66 (29.09)	x x	35.13 (2.01)	44.43 (2.45)
		5.5.2	0.82	10%	24.77%	51.54%	9.57%	34.38%	2199.17 (38.31)	x x	35.30 (1.77)	43.97 (1.92)
	Least forested	5.5.3	0.82	5%	21.92%	51.87%	6.72%	34.71%	1946.25 (2.17)	x x	33.93 (1.69)	46.27 (2.14)
		5.5.3	0.82	10%	26.87%	52.13%	11.67%	34.97%	2386.22 (2.09)	x x	34.00 (1.73)	46.60 (1.98)
	Most forested	5.5.4	1.26	5%	19.25%	69.43%	4.05%	52.27%	1708.99 (0.00)	x x	x x	107.00 (0.00)
		5.5.4	1.26	10%	22.22%	69.43%	7.02%	52.27%	1972.66 (0.00)	x x	x x	107.00 (0.00)
	Random	5.5.5	1.26	5%	21.34%	69.17%	6.14%	52.01%	1894.61 (22.91)	x x	x x	106.53 (0.56)
		5.5.5	1.26	10%	25.66%	68.77%	10.46%	51.61%	2278.42 (29.12)	x x	x x	106.10 (0.65)
	Least forested	5.5.6	1.26	5%	22.50%	69.31%	7.30%	52.15%	1997.53 (0.00)	x x	x x	107.00 (0.00)
		5.5.6	1.26	10%	27.44%	69.31%	12.24%	52.15%	2436.87 (0.00)	x x	x x	107.00 (0.00)

68.7% (6102 ha) or four times the unrestricted case (52.1% or 4630 ha). Similarly, only a modest gain in aggregate forest cover was achieved (EZ2, 17.5%) over the unrestricted case (15.2%). The added value of implementing these two land-use development policies on forest cover above the unrestricted case was 1.5% (133 ha, EZ1) and 2.3% (198 ha, EZ2) (figure 5).

5.3 *Land acquisition for conservation*

The introduction of randomly located conservation areas appeared to have an unbiased substitution effect on developer behaviour. While conservation areas did occupy some lands sought by each developer type, using a random conservation allocation strategy had little effect on the amount of developed land (1626 ha) relative to the unrestricted case (1523 ha). In fact, randomly placing 5 and 10% of the township in conservation only increased developed lands on average by 103 and 111 ha (table 3), respectively, which is less than the size of a single subdivision.

If we look at the changes in forest cover, we see that placing 5% of the township in forest conservation increased forest cover from the unrestricted case of 15.2% (1353 ha) to 19% (1689 ha). While this is a 25% increase in forest cover, perhaps it is more interesting to note that there was less than a 100% return on placing the area in forest conservation. We would expect that if the allocation of conservation areas was unbiased that we could have achieved the 15.2% in the unrestricted outcome + the 5% in conservation to produce 20.2% forest. Therefore while the township allocated a fixed amount of area (5%) in forest, developer behaviour must have been altered to create less aggregate forest cover by the end of the simulation runs. This result is further evidenced when we placed 10% of the township in conservation and obtained only an 8.1% increase in forest cover over the unrestricted case (figure 6).

Clues to why acquiring farms for conservation do not simply add a fixed amount for forest cover to the unrestricted scenario can be found in the high standard deviations associated with the number of country and remnant subdivisions

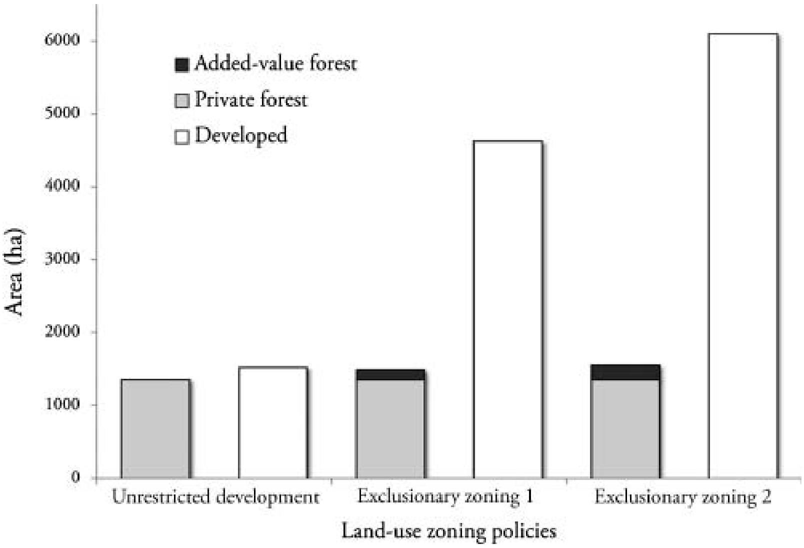


Figure 5. The resulting composition of forest and area developed under the unrestricted and exclusionary zoning land-use policy scenarios.

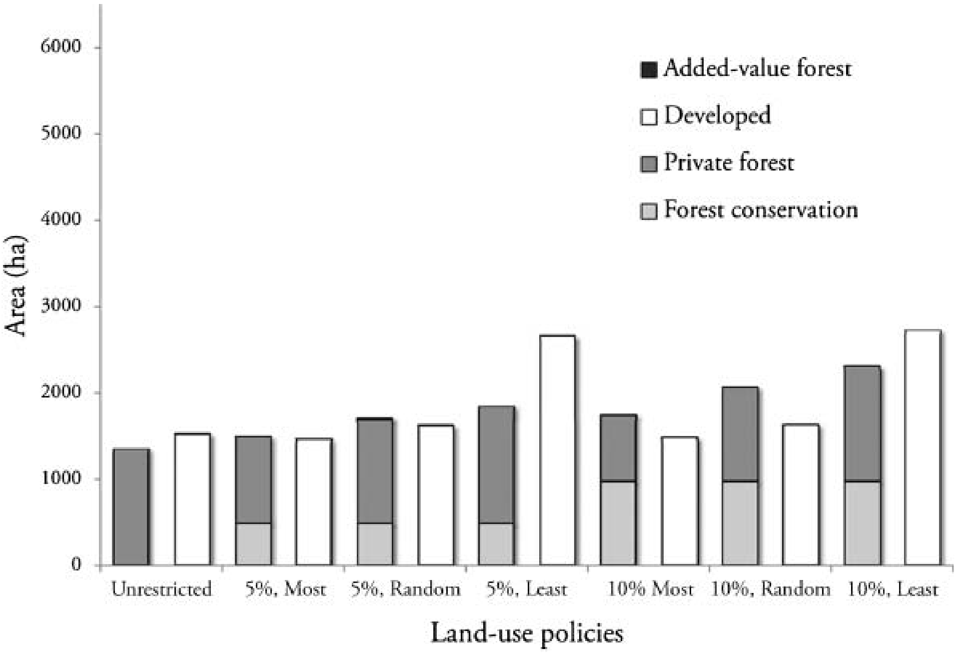


Figure 6. The resulting composition of forest and area developed under various land acquisition for forest conservation policy scenarios. Labels are read as Most = locating conservation areas on the most forested farms, Least = locating conservation areas on the least forested farms, Random = randomly located conservation areas, and 5 and 20% = proportion of the township acquired for forest conservation.

(table 3). By chance some simulations placed conservation areas on farms desired by the remnant subdivision developer. The remnant developer was then forced to substitute other farm locations that produced less desirable lots and because the quality of the environmental amenities were lower, residents moved to the more accessible country and horticultural subdivisions. Since country subdivisions clear forest cover and horticultural ones do not grow new forest cover, the random placement of areas in conservation do increase forest cover overall, but also decrease the amount obtained from larger lot subdivisions in the unrestricted case.

5.4 *Conservation location strategy*

Using a non-random strategy for locating conservation areas affected developer behaviour and, therefore, created different forest outcomes. Specifically, locating conservation areas on the most forested farms created the least effective strategy for maximising forest cover over the entire township (table 3). The benefit of this strategy, however, was that it also led to the least amount of area in residential development. In contrast, locating the preserves on the least forested farms led to the highest forest cover outcomes and some of the highest levels of residential development.

When conservation areas were located on the most forested farms they tended to grow little new forest and forced remnant subdivision developers to substitute preferred farms for those less preferred. The substitution effect was so strong under this conservation location strategy, that the remnant developer experienced its lowest number of subdivision developments on average, relative to all reported scenarios, as well as the lowest level of variation in the number of subdivisions developed. Therefore, locating conservation areas on the most forested lands actually led to the least amount of residential development or exurban sprawl within the scenarios reported (table 3).

The overall forest cover results from this location strategy were 16.87% (1497.8 ha) and 19.66% (1745.8 ha) when 5 and 10% were placed in forest conservation, respectively. These scenario results hardly illustrate the utility of acquiring land for forest conservation on highly forested farms since they only produced a 1.6 and 4.4% increase in forest cover over the unrestricted case. Establishment of an additional 1.5% forest cover can similarly be achieved by increasing the minimum lot-size zoning to exclude country subdivisions (EZ1).

Results from scenarios that allocated conservation areas to the least forested farms are unique in that they created added-value forest, obtained high levels of forest cover within the township relative to other scenarios, and only created medium levels of residential development relative to other scenarios. Specifically, placing 5 and 10% of the landscape in conservation on the least forested farms produced aggregate forest levels of 21.02% (1866 ha) and 25.98% (2307 ha), respectively (table 3). Both quantities of land acquisition resulted in more forest than the fixed amount set aside in conservation, i.e. an additional 567 ha and 1050 ha forested by choosing to locate conservation areas on the least forested farms. These results contrast those from allocating forest conservation areas on the most forested farms, which actually produced less forest cover than the fixed area in conservation plus the unrestricted scenario forest outcome.

Positive forest cover outcomes occurred because conservation areas located on farms with little to no forest were able to grow new closed-canopy forests within the time frame of the model. Also, generally the least forested farms are the most preferred locations for country subdivision development. Therefore, after the country subdivision developer agent achieves a couple of successful subdivisions, it is forced to substitute less preferred locations for those occupied by conservation areas. In doing so, the lots are less appealing and residents move towards the horticultural and remnant subdivisions, which maintain existing forest or may grow new forest. However, it is the success of some country subdivision developments that maintain medium to low levels of residential development or sprawl (approximately 30%) when either 5 or 10% of the township is placed in conservation, relative to other scenarios.

5.5 *Integration of lot-size zoning and land acquisition policies*

5.5.1 Exclusion of country subdivisions, acquisition of the most forested farms. Without country subdivisions the number of horticultural and remnant subdivisions jumped dramatically to ~36 and ~44 over the unrestricted scenario numbers of ~7 and ~6, respectively. Due to the larger minimum lot size and fixed residential demand, the area in residential development tripled that of the unrestricted development case to ~52%, but was not significantly different from the total developed area in the independent minimum-lot size zoning scenario EZ1. Placing a greater area in forest conservation on the most forested farms did not affect the area developed but did affect the total aggregate forest cover in the township. However the effects were little with 5 and 10% in forest conservation leading to only 18.4 and 21.3% or a gain of 3.2 and 6.08% of the township forested over the unrestricted scenario. These results suggest that the combination of excluding high density country subdivisions and locating conservation areas on the most forested lands increased the amount of aggregate forest cover above either land-use policy implemented independently.

5.5.2 Exclusion of country subdivisions, random acquisition of farms. Randomly locating conservation areas in conjunction with a minimum lot-size zoning policy that excludes country subdivisions performed much the same as Section 5.5.1, but resulted in more aggregate forest cover. When 5 and 10% of the township was placed in forest conservation, the result was 20.43% (1814 ha) and 24.77% (2199 ha) forest cover or a 5.23 and 9.57% increase above the unrestricted scenario, respectively. The move to a random land acquisition strategy in conjunction with excluding country subdivisions improved upon the amount of aggregate forest cover obtained in Section 5.5.1 combination policy as well as the independently applied EZ1, EZ2, and random and most forested farm conservation location policies.

5.5.3 Exclusion of country subdivisions, acquisition of the least forested farms. Surprisingly, changing the strategy for locating forest conservation areas again had little effect on the overall amount of residential development (~52%), much like the combinations in Sections 5.5.1 and 5.5.2. Despite the small effect on developed area, the location strategy in combination with EZ1 resulted in 21.92% (1946 ha) and 26.87% (2386 ha) aggregate forest cover or a 6.7 and 11.6% increase in forest cover over the unrestricted scenario, respectively, when 5 and 10% of the township were placed in forest conservation (table 3). Therefore, like our independent comparison of individual land-use acquisition strategies, locating forest conservation areas on the least forested farms in conjunction with excluding country subdivisions outperformed all other combination policies, as well as all isolated policies.

5.5.4 Exclusion of country and horticultural subdivisions, acquisition of the most forested farms. When we implemented a minimum lot-size zoning policy to exclude both country and horticultural subdivision developments in conjunction with acquiring land for forest conservation on the most forested farms we made only modest improvements on the level of forest cover with respect to the combination in Section 5.5.1. Similarly, the outcomes with respect to forest cover 19.25% (1709 ha) and 22.22% (19.73 ha), when 5 and 10% of the township was placed in conservation respectively, were only improvements over the independent land acquisition policy (on most forested farms) and the EZ1 and EZ2 policies. All other policies produced greater amounts of forest cover and less area in residential development (table 3).

5.5.5 Exclusion of country and horticultural subdivisions, random acquisition of farms. Like the previous combination of EZ2 and land acquisition (Section 5.5.4), this strategy combination also had one of the highest levels of residential development at ~69% of the township area. Randomly allocating 5 and 10% of the township in forest conservation areas resulted in 21.34% (1895 ha) and 25.66% (2278 ha) of the township being forested. These results produced added-value forest since they created 6.14 and 10.46% more than the unrestricted case.

5.5.6 Exclusion of country and horticultural subdivisions, acquisition of the least forested farms. Our last policy combination produced the largest amount of forest cover at both 5 and 10% in conservation, 22.5% (1998 ha) and 27.44% (2437 ha) respectively, and the second highest levels of residential development ~69%. The massive increased area in development ~18% over the combinations using EZ1 instead of EZ2 more than offset the minor gains achieved in forest area.

6. Discussion

6.1 *Ex-urban forest cover scenarios*

We began evaluating the effects of minimum lot-size zoning and land acquisition policies by establishing a baseline scenario void of either policy, which we called unrestricted development. In this scenario the model mechanisms were not constrained and produced hypothetical land-use and land-cover change results that were averaged over 30 simulations. Using the DEED model we compared 20 land use policies that each resulted in forest cover levels above that obtained by the unrestricted scenario. From these policies only one, acquiring land for conservation on the most forested locations, was able to increase aggregate forest cover and simultaneously reduce area in residential development.

As expected all policies that acquired land for forest conservation increased overall forest cover in the township. However, what was interesting was that 12 of the 18 policies that involved municipal land acquisition produced less than the expected amount of forest cover, where the expected amount was the unrestricted case plus the fixed area in forest conservation (figure 7). The other six policies produced what we called added-value forest cover, yielding more forest cover than that obtained from the unrestricted scenario plus the fixed area in forest conservation. All scenarios that produced added-value forest were obtained by using a land acquisition strategy that located forest conservation areas on the least forested farms. We attributed the cause of these results to both a substitution effect

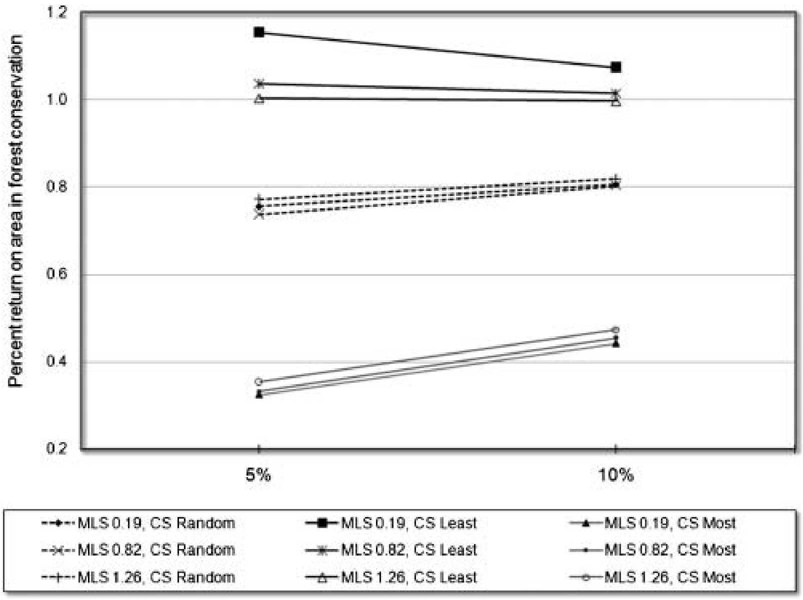


Figure 7. The fraction of return on conservation land from different policy combination experiments. Acronyms are as follows: MLS = minimum lot size, CQ = conservation quantity, CS = conservation location strategy, Least = least forested land, Most = most forested land and Rand = randomly located. For example, CS Most refers to the Conservation location Strategy, whereby conservation areas were located on the lands with the most forest.

and afforestation process. The substitution effect was the primary mechanism influencing model outcomes and occurred when a specific developer agent was forced to substitute less preferred farms for subdivision with those more preferred, but already acquired for conservation by the township. By acquiring land with little to no forest, the township was able to grow substantial forest cover while other forested areas had some probability of remaining depending on development patterns.

Results from our scenario experiments computationally verified literature that show that large lot-size zoning policies lead to greater sprawl (e.g. Esparza and Carruthers 2000), and large lot-size zoning policies can influence the amount of forest cover (e.g. Munroe *et al.* 2005, York *et al.* 2005), although we found this effect to be small relative to municipal land acquisition. We were surprised at the extent to which the location strategy affected the return on land acquisition for forest conservation. The location strategy for forest conservation land acquisition was more effective at increasing aggregate forest levels than the independent zoning policies (EZ1 and EZ2), the quantity of area acquired for forest conservation (5 and 10%), and any combination of the two (figure 7).

6.2 *Integrated approach over independent GIS approach*

Our results from using an integrated GIS and ABM framework for evaluating land-use development policies on forest cover provided us with insights into how those policies would act out over time and what aspects of those policies were more influential towards the goal of maximising forest cover. The ability to play out scenarios or address 'what-if' questions through simulation is one of the key advantages of using agent-based modelling over traditional static accounts of change over time. For example, Taylor *et al.* (2007) evaluate the effectiveness of a local open-space ordinance at preserving natural features and rural character in subdivision developments using basic GIS mapping and spatial functions (e.g. buffering, overlay). While providing an excellent evaluation of an existing policy using historical data, their approach is unable to deal with feedback mechanisms and interaction effects that may influence the location, timing, and heterogeneous aspects of the residential developments affected by the policy. They note that their approach does not capture the dynamic transition between land-covers (e.g. open space to forest cover), which is due to the use of static temporal data (two time-steps in their analysis), and an inability to estimate how those processes will continue into the future.

It is these dynamic elements that we have attempted to bring to GIS by creating an integrated framework for evaluating land-use policy scenarios so that we may better inform decision-makers before they make policy. Furthermore, we may use an ABM approach to develop or generate potentially unknown policies, as was done by Zellner (2007) to generate policies for sustainable water use in Monroe County, Michigan. Lastly, the use of ABM in conjunction with GIS allows us to influence the actors making decisions on the landscape. We could potentially see how incentives (economic, social, or political) could alter land-user behaviours that subsequently alter land cover quantity and placement.

6.3 *Hypothetical world*

Our land-use and land-cover change modeling approach and analysis focused on how developer behaviour, the subdivision process, and residential location are affected by exclusionary zoning and public land acquisition. We used empirical data to populate agent types and characteristics, to calibrate residential agent growth rates, and to provide initial land-cover and landscape aesthetic maps used in DEED. However, the initial conditions of the model (e.g. farm parcel configuration) are hypothetical and are not accurate to a specific time in reality. Furthermore, the missing processes, assumptions, and stochasticity built into the model inhibit our ability to validate aggregate model results. For these reasons our goal has not been a quantitative prediction of forest cover, but rather an assessment of the directional effects of different land use policies (i.e. DEED has been used as an exploratory model to investigate how different land-use development processes and policies act out over time and interact with each other). In its current state, the model can provide insight to land-use policy decision-makers, but it cannot provide predictive prescriptions for specific actions to take place.

To move the DEED model from an exploratory model to a predictive one we would require additional mechanisms and real-world starting conditions. For example, although many of the farms were surveyed to 160 acre parcels (Nelson 1995), the portion of a farm actually found in subdivision is much smaller. The model does not incorporate rural lots, which occupy large portions of land (on average 5 acres with a range up to ~15 acres in the study region) and lead to scattered low density developments that may not be classified within a subdivision typology. Residential agents do not relocate, trade parcels, or directly compete for parcel acquisition. Similarly developer agents do not trade or compete for parcel acquisition. All land is assumed to be available for development and we do not incorporate dynamic on-farm processes such as cropping or abandonment, both of which may affect landscape perceptions.

Despite these constraints to validation, our initial experiments serve to partially verify the implementation of our conceptual model. For example, we anticipated that as smaller lots were excluded the amount of area in residential land use would increase, due to a constant supply of residential household agents at each time step and the lower residential density of the larger lot subdivisions. Similarly, our results would indicate a problem with the implementation if aggregate forest cover did not increase within the township as smaller lot sizes were excluded. This is because, in the conceptual model, forest cover is cleared for country subdivision development, maintained for horticultural subdivision development, and grown to a maximum of 4 ha of the subdivision area for remnant subdivision developments.

7. Conclusions

We illustrated the use of a GIS-based ABM, called DEED, in hypothetical scenarios using real-world data to produce results that describe the individual and interaction effects of minimum lot-size zoning and land-acquisition strategies on forest cover. The results of these scenarios illustrate some fundamental notions that may guide future research and application of land-use development policies. Specifically, we used an empirically-grounded model that incorporates the main actors influencing landscape change and the interactions between them and the environment to computationally verify existing research that suggests that large lots lead to increased residential development or what may be called sprawling development patterns. We found that with larger proportions of a township placed in forest conservation there was a corresponding increase in the amount of forest cover in the township, regardless of lot size zoning or conservation location strategies. Lastly, when minimum lot-size zoning was applied in conjunction with land-acquisition, the rate of return on forest cover for areas placed in forest conservation was dependent on the location strategy used to locate those conservation areas.

The apparent synergies between the process modelling capabilities of ABMs and the data modelling and visualisation capabilities of GIS provide an opportunity for their integration and improved modelling-based research (e.g. Brown *et al.* 2005, Rand *et al.* 2005). The presented application demonstrates how a tight coupling of GIS and ABM can provide additional insight into how a dynamic land-use and land-cover system may be altered by different land-use development policies and how the process of evaluating those policies may be enhanced using this approach. Lastly, it is the authors hope that additional research integrating GIS and ABMs will facilitate ABM development by GIS users and help reduce barriers to entry to agent-based modelling.

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Notes

1. Michigan Center for Geographic Information: Department of Information Technology. Available online at: http://www.mcgi.state.mi.us/mgdl/ (last accessed 16 January 2007).
2. Soil Survey Geographic (SSURGO) Database, Soil Data Mart, Michigan, Washtenaw County. Available online at: http://www.ncgc.nrcs.usda.gov/products/datasets/ssurgo/ (last accessed 16 January 2007).
3. The public lands dataset used was a subset of the conservation and recreation lands (CARL) dataset and was created by the Great Lakes Atlantic Regional Office, Ducks Unlimited, Inc. 1220 Eisenhower Place, Ann Arbor, MI 48108, USA.
4. Empty lots are assigned a neutral similarity value of 0.5, from the range of possible similarity values of 0.0–1.0. A value of 1 corresponds to perfect similarity and 0 corresponds to complete dissimilarity.

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