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Residential location and the biophysical environment: exurban development agents in a heterogeneous landscape

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Abstract. Agent-based models offer a promising framework for analyzing interactions between agents and a heterogeneous landscape. Researchers have identified a complex of factors that influence exurban development, including demographic shifts and location attractiveness of natural amenities as a magnet to amenity-seeking migrants. Attractiveness is often defined in terms of local or on-lot amenities, including scenic views, the availability of natural features, and low levels of noise. However, exurban-growth models have not fully incorporated a fundamental insight of this literature, that the location behavior of exurban residents is sensitive to fine-grained variations in their biophysical environment. In this study we evaluate how agents and households operate in exurban environments and respond to biophysical features. We simulate household decisionmaking in terms of preferences for features such as site accessibility, two-dimensional amenities, and three-dimensional scenic views. Our results show that, as we build two-dimensional and three-dimensional landscape layers, our model captures the characteristics of landscape change with increasing accuracy. This approach has considerable potential to improve our ability to describe development dynamics in heterogeneous land markets.

1 Introduction

A conspicuous feature of Colorado's landscape is dispersed residential development in mountain valleys and foothills at the wildland – urban interface. This settlement pattern, loosely described as 'exurban', is a widespread phenomenon and is becoming an increasingly important issue in many counties across the United States. Researchers have identified a complex of factors that influence exurban development, including appreciation of natural amenities and demographic shifts. These preferences are often defined in terms of local or on-lot amenities, including scenic views, the availability of natural features such as vegetation and trees, and low levels of noise and pollution. However, exurban-growth models have not fully incorporated a fundamental insight of this literature, that the location behavior of exurban residents is sensitive to fine-grained variations in their biophysical environment. An understanding of the role of landscape diversity and heterogeneity in exurban development patterns and households' decisionmaking processes is an important consideration for the design of exurban growth models. Researchers in forest-resource management and environment planning and management have built models to explore the effects of landscape heterogeneity and quality (Meitner, 2004; Plotnick and Gardner, 2002).

This research builds on land-use-change models of the urban – rural fringe (Irwin, 1998), regression-based land-conversion policy models (Muller et al, 2004), and a pilot study on exurban-land development (Yin and Muller, 2002). In this project we evaluate how agents or households operate in an exurban environment and respond to biophysical features, using agent-based models (ABMs). We simulate household decisionmaking in terms of preferences for accessibility and amenities through the implementation of a three-dimensional spatial structure, and we explore the effects of heterogeneity on exurban residential location across a landscape. This approach has considerable potential to improve our ability to describe development dynamics in heterogeneous land markets. Our study area is northwest of Lyons, Boulder County. Lyons is a town of about 1500 people located in a mountain foothills area in the northwestern part of Boulder County. Using data on actual development patterns in Lyons, we compare the actual development to a model in which households respond to two-dimensional accessibility factors, a two-dimensional amenity model, and a full ABM in which agents respond to two-dimensional accessibility as well as two-dimensional and three-dimensional amenities.

2 Modeling exurban residential markets

The agent-based approach is of interest in modeling land-use or land-cover change and residential locations in a wide variety of contexts both in developing and in developed countries (Benenson et al, 2002; Irwin, 1998; Ligtenberg et al, 2001; Portugali, 2000). Amenity migration and exurban residential development are also worldwide phenomena (Price et al, 1997). In this paper we focus on a case study of amenity-based exurbanization in the US West.

A prominent feature of the contemporary US West is its dramatic transition in demography and economy from the 'wild' to the 'new' West (Riebsame et al, 1997) and the associated impact on ecosystems. One of the most noteworthy characteristics of the new West is that rapid population increases are occurring not only in urban areas but also in rural areas. More than 60% of rural counties in the region are gaining population faster than urban areas (Theobald, 2000; US Census Bureau, 2001).

Since the 1960s urban-economic theory has emphasized the journey to work as the primary determinant of location patterns in urban areas. In addition to job accessibility, recent empirical literature suggests that exurban households are attracted to other factors, such as social values, which are closely linked to natural features and systems. Rudzitis (1999) found that only 30% of respondents in two surveys cited job-related reasons for migrating to the rural West. Preferences for a rural lifestyle are often defined in terms of local or on-lot amenities. Researchers have stated that the rural West is attractive because of its scenery, wilderness, wildlife, and outdoor recreation opportunities (Beale and Johnson, 1998; Johnson and Rasker, 1995). Research about amenity-based locations builds in part on the hedonic-price and random-utility literature (McFadden, 1974; Rosen, 1974). In this dimension it focuses on the economic values of scenery and natural amenities, including open space, watersheds, wetlands, lakes, green vegetation, trees, ecological diversity, and scenic views (Acharya and Lewis, 2001; Benson et al, 1998; Chattopadhyay, 2000; Colby and Wishart, 2002; Doss and Taff, 1996; Geoghegan et al, 1997; Mahan et al, 2000; Sengupta and Osgood, 2003; Shultz and King, 2001; Vaughn, 1981). Amenity variables in the literature are summarized in table 1.

Models of amenity preferences and heterogeneous natural landscapes have been developed in two and three dimensions in a variety of contexts. Two-dimensional models rely on distance measures. Darling (1973) and Brown and Pollakowski (1977) found that distance from lakes was a significant determinant of property values. Other empirical studies suggest that distance from the greenbelt or open spaces was found to be negatively correlated with housing prices (Correll et al, 1978; Hammer et al, 1974; Kitchen and Hendon, 1967; Peiser and Schwann, 1993). Three-dimensional models rely on the development of lines of sight and movement over heterogeneous topography. Chattopadhyay (2000) found that trees are important to housing prices. A number of

Table 1. Amenities: literature.

Variables	Literature
Two dimensional	
Distance to water bodies (lakes and reservoirs)	Brown and Pollakowski, 1977; Darling, 1973; Doss and Taff, 1996; Lansford and Jones, 1995; Milon et al, 1984; Sengupta and Osgood, 2003
Distance to greenery (green belt, forest, parks, etc)	Correll et al, 1978; Geoghegan et al, 1997; Hammer et al, 1974; Kitchen and Hendon, 1967; Palmquist 1992; Peiser and Schwann, 1993; Sengupta and Osgood, 2003; Shultz and King, 2001; Vaughn 1981
Three dimensional	
Scenic view (mountain view, lake view, etc)	Benson et al, 1998; 2000; Cassell and Mendelsohn, 1985; Do and Sirmans, 1994; Garrod and Willis, 1992a; 1992b; 1992c; Geoghegan et al, 1997; Gillard, 1981; Do and Grudnitski, 1995; Morton, 1977; Plattner and Campbell, 1978; Rodriguez and Sirmans, 1994

studies have found that scenic views add significantly to the value of residential real estate (Benson et al, 1998; 2000; Cassel and Mendelsohn, 1985; Do and Sirmans, 1994; Gillard, 1981; Rodriguez and Sirmans, 1994). These models permit researchers to capture the effect of views as an influence on exurban location. Aspinall (2004) found that a model with an amenity viewshed variable is useful in explaining land-use change in a county in Montana during the period 1985–2000. People are attracted to exurbia by its aesthetic and scenic beauty, such as mountain and lake views and open-space panoramas. Thus, viewshed analysis provides a window into fundamental social conceptions of space and landscape. Viewshed analysis is used to apply a numerical weight to every point on the landscape describing its degree of visibility from a single location. Undesirable land uses or limited visibility may also affect the desirability of a site as a residential location. In this paper landscape heterogeneity is represented both in two-dimensional and in three-dimensional layers. We explore the role of the local biophysical environment—in particular the effect of access to views—in the attractiveness of alternative residential locations. We have adopted an agent-based approach in order to better understand the interactive effects of different preferences for biophysical neighborhood.

The ABMs have their origins in complexity theory, specifically the complex adaptive system (CAS) framework in which components interact as they adapt to their environment. CAS-related research typically relies on computer simulations as a primary method for analyzing interactions. Cellular automata (CA) and ABMs are two examples of CAS approaches. Building on the groundbreaking work of von Neumann (1966) and Ulam (1962), researchers began in the late 1980s to use CA to explore the dynamics of urban systems (Batty, 1998; Batty and Xie, 1994; 1997; Clarke et al, 1997; Couclelis, 1989; Webster and Wu, 1998; White and Engelen, 1997; Wu, 1998).

Individual human behavior is generally missing in CA models, however. The agent-based approach supports the study of system evolution through accumulation of individual interactions both among humans and between humans and their environment (Franklin and Graesser, 1997). Such models have recently been applied to a variety of problems of land-use and/or land-cover change (Parker et al, 2003), and to the simulation of urban systems (Torrens, 2001). An ABM usually consists of some heterogeneous agents and a framework to simulate their decisions, interactions, and adaptations to their environment.

Therefore, ABMs offer a promising framework for the analysis of interactions between agents or exurban households and the heterogeneous landscape in exurbia. They support the exploration of exurban development patterns at the aggregate level, which emerge from location decisions and behaviors on the part of multiple households. Through the inclusion of interactions across space and time between agents and their environment, the agent-based approach can represent the behavior of homeowners and the characteristics of landscapes at a relatively high level of complexity.

ABMs have the capacity to capture heterogeneity among agents as well as environmental conditions, thereby enabling agents with varied preferences to act according to dynamic rule sets and within a dynamic biophysical environment. In the context of exurban development, households identify accessibility and amenities in their neighbourhood and make land-use decisions on that basis. Individuals in some households prefer to be close to jobs, whereas others have a strong desire for more space, natural amenities, and a sense of isolation (Davis et al, 1994; Nelson, 1992; Riebsame et al, 1996). They respond differently to the land-development activities around them.

3 Research method

In our ABM, households are represented as agents who search for exurban residential locations on the basis of defined rules. We simulate how agents respond to the heterogeneous biophysical features of exurban locations. In this phase of our research we consider only two types of households: commuters, and second-home owners or telecommuters. Commuters' decisions are based on accessibility factors and urban proximity. Second-home owners desire sites that are large, close to public land, water bodies, or streams, or that have scenic views with some consideration of accessibilities. Households from different groups interact with other households and respond to natural amenities and other factors.

The environment is a two-dimensional array of regular spaces (grid cells). It is a virtual space in which agents live and interact on the basis of decision rules. This array combines a developable land layer and cell-characteristics layers. Cell characteristics include (1) two-dimensional accessibility attributes; (2) two-dimensional site amenities; and (3) three-dimensional scenic views. These layers are used to build up heterogeneous landscapes to which households respond. Two-dimensional layers rely on simple distance measures; our three-dimensional layer assumes a topographical spatial structure. Each grid cell has one of the two basic states: developable and not developable. Cells that are not developable include sites on roads, water bodies, and public-owned land, and those occupied by other agents. Agents are allowed to locate only on developable cells in the simulation. We develop models in both the ArcInfo GRID platform and RePast (Recursive Porous Agent Simulation Toolkit).

3.1 Study area

Lyons is a town of about 1500 people (US Census, 2000) located 18 miles northwest of the city of Boulder, Colorado and 20 miles east of Rocky Mountain National Park (figure 1). It sits in a mountain foothills area surrounded by hills of ponderosa pine and red sandstone with a mild climate and lots of sunshine. It is known as the 'double gateway to the Rockies' because it lies at the intersection of two different roads leading to Estes Park. Colorado highway 7 winds up to Estes Park from the south; US highway 36 goes directly north to the park. Lyons is affected by the impacts of growth and changes as development sprawls out from the Denver metropolitan area.

We selected the Lyons area as the geographical focus for our research in part because of its picturesque landscape, including rocky red hills, mountain vistas, the St Vrain River, and agricultural lands. The area has a strong lure to immigrants

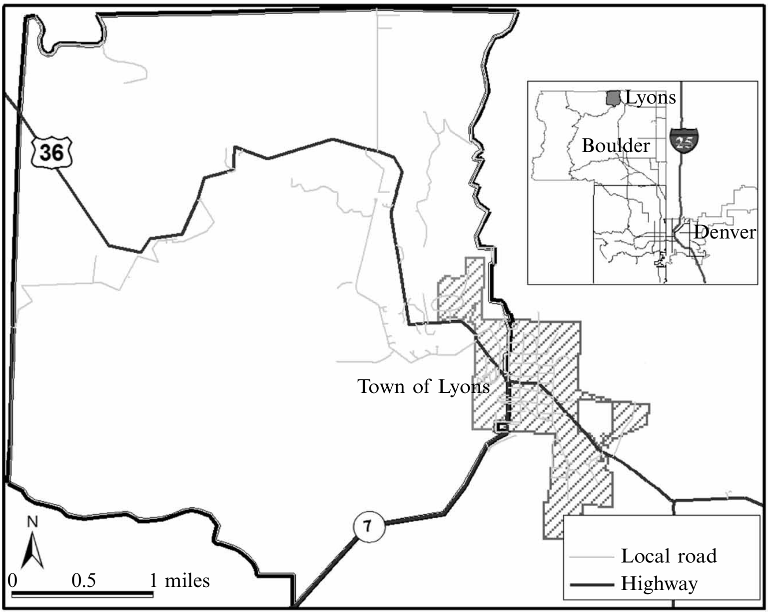

Figure 1. Study area.

looking for locations that are proximate both to employment centers as well as to natural amenities. Most of the residents in and around Lyons commute to work in Boulder, Longmont, and other metropolitan employment centers. Our study area is a zone about 8 miles west of the town of Lyons (figure 1).

3.2 Two-dimensional data collection and processing

We collect data from municipalities, county government, and other sources and produce spatial metrics using geographic information system (GIS) software. Infrastructure data are obtained from the US census [TIGER (topologically integrated geographic encoding and referencing) files], including local streets and highways. Parcel data are obtained from the county assessor's office. These data provide high-resolution information on land use and structure type and offer a historical perspective on exurban land-use changes. Land-ownership maps are obtained from the Bureau of Land Management and digital elevation maps are obtained from the US Geological Survey. These datasets come in different formats, including shapefiles, ArcInfo export files, and coverages. Census 1990 and 2000 data were collected at tract and block level. These datasets contain fine-grained, detailed spatial housing data (table 2).

Data layers are checked, assembled, converted to an appropriate projection and converted to a raster representation with a cell size of 1 hectare or 2.5 acres. We calculate distance from each cell to highways, highway ramps, local roads, and to the nearest developed area. These processing steps are automated using GIS software ArcInfo, Arc Macro Language (AML), and Unix C-shell scripts to produce grid layers describing the biophysical and social characteristics of the environment with which households interact.

3.3 Variables

The dependent variable is measured on land conversion from rural to urban land uses. Conversion is determined on the basis of the 'year built' attribute in the assessor's database. In other words, conversion occurs during the year in which the assessor indicates

Table 2. Data types and sources.

Type	Source
Parcels	County Assessor's offices and county GIS [a] offices
Streets	US Census TIGER [b] data
Highways	US Census TIGER [b] data
Municipalities boundary	US Census TIGER [b] data
Census tract and blocks	US Census TIGER [b] data
Digital elevation model	US Geological Survey
Water bodies	US Geological Survey
Stream	US Census TIGER [b] data and US Geological Survey
Land use/land cover	US Geological Survey
Boulder County open space	Boulder County GIS [a]
Land ownership	Bureau of Land Management

[a] Geographic information system.

[b] Topologically integrated geographic encoding and referencing.

that a structure is built on a parcel. This information is carried into the grid cells as vector data is converted into raster data.

Independent variables were selected with reference to literature review and current growth-modeling practice as represented by projects such as the California Urban Futures Model developed at the University of California at Berkeley (Landis, 1994) and the SLEUTH model developed at the University of California at Santa Barbara (Clarke et al, 1997). Two primary types of independent variables are included in the model.

Accessibility factors—these measure distance from each cell to nearby highways, roads and streets, and urban services. They provide a crude indication of the relative costs of extending roads or streets to service a site, as well as travel times for commuting or shopping trips.

Site amenities—these variables are designed to capture the attractiveness of the site. Variables include location within a 200 m stream buffer, distance to federal and state land, and distance to county open space, and viewshed. All of the variables were found to be significantly related to housing choices by previous studies.

In this project we use the viewshed analysis function of GIS software to generate and define 360° panoramas. The product of viewshed analysis describes the entire area an individual can see from the site of a proposed residential location [figure 2]. We use this method to characterize visibility between locations on the basis of topography and other obstructions. Results are randomly tested by field visits. Calculations are based on the assumption that the camera is one meter high relative to the surface of the earth.

Because of the substantial processing requirements for viewshed analysis, we calculate only the viewshed for each nine-cell area (9×100 m $\times$ 100 m). This process begins with the placing of observers in the center of each nine-cell area. Visual features include lakes, public lands, mountain peaks, streams, and general areas. Each cell is assigned a view score which indicates the scenic quality of that cell. If the lake or peaks of mountains are visible from the site, the view quality of the site is considered better than that of other sites from which fewer natural amenities are viewable. The result is a grid with a view-quality score for each cell (figure 3, over).

All variables are created in ArcInfo using map algebra. We calculate the Euclidean distance to the nearest local road, county open space, and the nearest city, as well as network travel distance to highway. The unit of analysis is a developable cell defined by site characteristics such as rights of way, waterways, and whether the site is

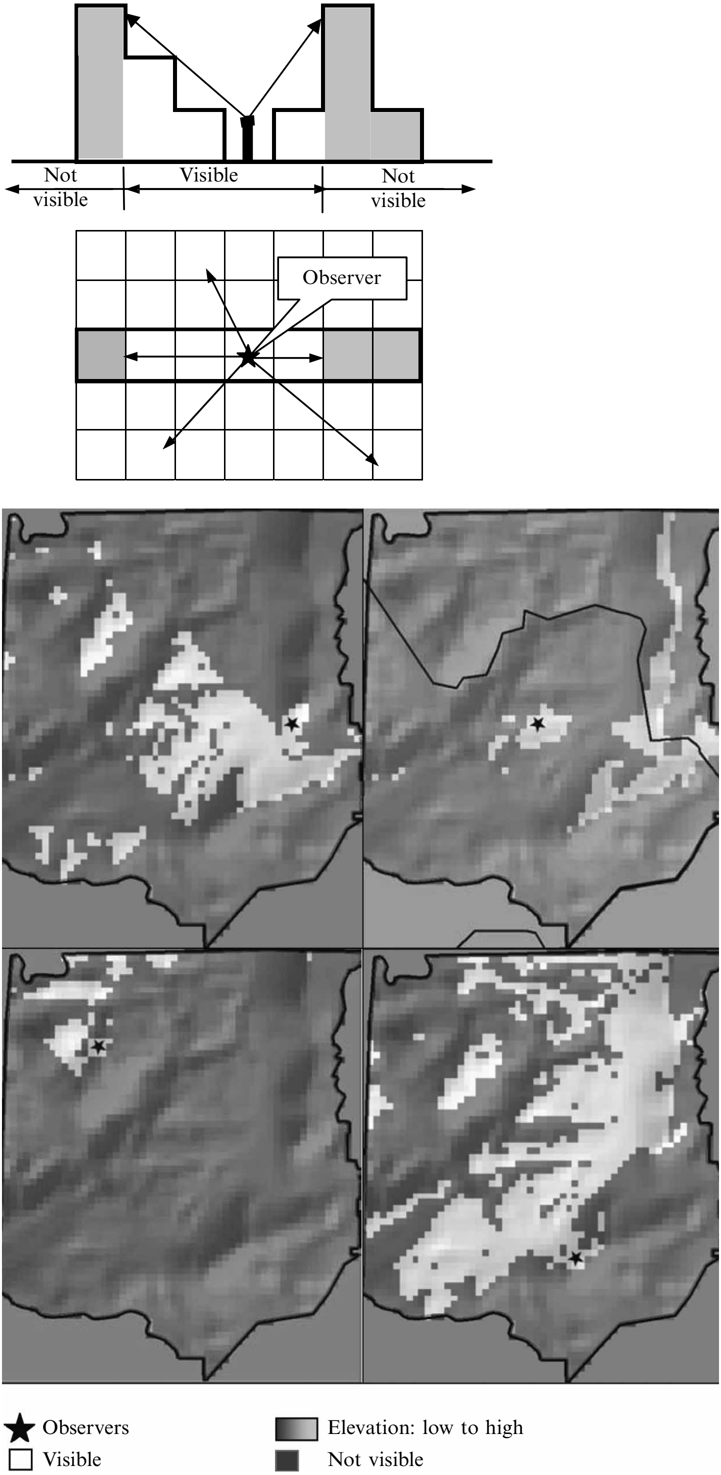

Figure 2. Viewshed illustration and examples.

Figure 3. Scenic view scores.

occupied by other households. The model relates land-use change to site amenities and other attributes of the cell, including proximity to regional freeways, boundaries of developed areas, and location within a 200 m stream or public-land buffer.

3.4 Platform and models

We reviewed a variety of software platforms and scripting approaches including map algebra, ArcInfo AMLs, and specialized agent-based modeling packages, and decided to use RePast, a Java-language-based software framework for creating agent-based simulations. RePast provides a class library to help collect, create, run, and display data for an agent-based simulation. In addition, it includes a mechanism for taking snapshots, running simulations, or creating QuickTime movies of simulations.

We developed three ABMs for this project: a two-dimensional accessibility model in which households respond to site accessibility, as emphasized in conventional urban-growth models; a two-dimensional amenity model including amenity variables derived from theories of development in exurban areas; and a full model including three landscape layers, a two-dimensional site-accessibility layer, a two-dimensional amenity layer, and a three-dimensional viewshed layer (figure 4). In the two-dimensional accessibility model the primary variables relate to travel distance to jobs, and transportation networks. In the two-dimensional amenity model, primary variables include distance measures to natural amenities, and travel distance. The full model integrates the components of the first two models and adds one more layer—three-dimensional scenic views. Both household or agent types appear in the full model. Simulations are run iteratively in order to capture dynamic effects. One second-home-owner cell and one commuter cell are developed at each iteration. The total number of cells developed for the twenty-year period (1980–99) is derived through disaggregation of the existing development from county assessors' data.

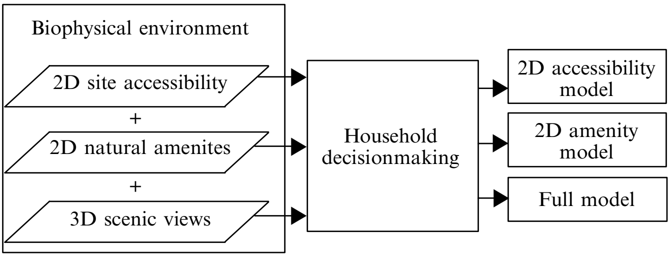

Figure 4. Model design.

3.5 Rule development

There are two main objects coded in the model: cells and agents. Agents or households select exurban sites or cells following a variety of land-conversion rules. The rule structure consists of two main components, the location preferences of different types of households and landscapes (figure 5). We select a simple prioritization approach to explore primary elements of the decision environment and to develop a ranking system for the typologies of actors.

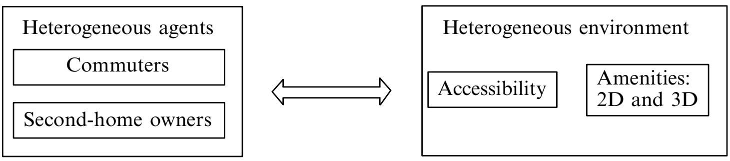

Figure 5. Components of the rule structure.

We design rules according to site characteristics that are likely to attract households, on the basis of literature review and the results of earlier research (Muller et al, 2002; 2004). Rules are coded so that households are able to navigate through heterogeneous environments and make decisions on which piece of land they want to develop. Each cell on the grid is given two summary preference scores, one for each agent type [equation (1)]. The preference score is determined by the level of services and the biophysical characteristics of the environment.

$$S_{hi} = W_{hi}(D_{si}, D_{ai}, V_i) , \quad (1)$$

where S_{hi} is the total score for cell number i and agent of type h, W_{hi} are weights applied to different independent variables, $\boldsymbol{D}$ is a vector of distance variables for amenity a or employment centers and infrastructures s, and V_i is view quality. Note that D_{si}, D_{ai}, and V_i represent three sets of preference functions that are constructed with respect to the independent variables, including preferences for accessibility to employment centers and infrastructure, natural amenities, and three-dimensional scenic views. D_{si} is a collection of all site-accessibility variables ranging from 0 to 4 miles in our study area. D_{ai} is a collection of site-amenity variables. Both D_{si} and D_{ai} are included in the two-dimensional amenity model. Variables from all three collections D_{si}, D_{ai}, and V_i, are in the third model (full model). Note that weights (W) range from 1 to 10 and are different for different types of agents (h) according to their location preferences. The three types of independent variables correspond to different layers of landscapes. Commuters have strong preferences for accessibilities. Therefore they give higher weights to the sites that have easy access to employment centers and transportation networks than sites that are not close to any roads or towns. Second-home owners have strong preferences for natural amenities and scenic views, and are willing to trade off accessibility values. They give higher weights to sites that are adjacent to a lake or that have stunning mountain views, for example, than to sites that are not close to natural amenities and that have lower view scores. These independent variables are introduced into the model to describe the nonhomogeneous nature of the physical space in which agents interact and in which land-use dynamics unfold.

We use various rating, weighting, ranking, and map-overlay techniques to create scores which indicate the probabilities of urban transformation. Agents are programmed to look at each cell, add up the weights, compare scores, randomly select developed cells among top-ranked cells, and record the development for each year. The score is continuously changed by agents' decisions at every time step. We generate our development patterns for 1999 through iterative application of the rules on the households for twenty consecutive years (1980–99).

3.6 Model validation

Model verification and validation are essential parts of the model development process. After the initial model development, we evaluate the accuracy of the models by assessing how they describe historical change in the study area. The literature suggests a mix of some aggregate statistics (Parker et al, 2003; Rand et al, 2003; Sargent, 1988), and visual similarity comparison (Robinson, 1997) with the real-world settlement pattern may be the best way to perform ABM validation. Our approach to testing model accuracy includes two steps: (a) collect performance measures of the system in the study area for 20 years, and (b) compare model outcomes with real-world observations over the given period of time both visually and statistically.

After the initial visual comparison of snapshots from the simulation and the existing development, we export the model results from RePast as an ASCII (American Standard Code for Information Interchange) file and import it to ArcView to create a grid showing predicted development in 1999. We also create a few statistics to validate our model on the basis of this output grid. First, neighborhood density for each cell is created by using ArcInfo GRID and map algebra. Neighborhood density is the total number of newly developed cells between 1980 and 1999 in a half-mile window or neighborhood (9 cells × 9 cells) around each cell. Because the purpose of this study is not to predict precisely in which cell development would occur, neighborhood density is a good indicator to be used for validating how accurate ABMs are for exploring exurban residential-development patterns. We also subtract the model neighborhood-density grid from the neighborhood-density grid for the existing development to see the difference between these two grids. Standard deviation is computed on the basis of the subtraction result, which tells how diverse our model output is from the existing development. A few other important measures of dispersion from the existing development we use include root mean squared error [equation (2)], range, and variance.

$$E_i = \left(\frac{1}{n}\right)^{1/2} \sum_i (P_i - T_i)^2 \ , \qquad (2)$$

where P_i is the predicted neighborhood value for cell number i, T_i is the existing neighborhood density, and n is the number of cells. For a perfect fit P_i is equal to T_i and therefore the root mean squared error $E_i = 0$.

This modeling framework provides a comprehensive portrait of the actual land-use change emerging from the response of households to heterogeneous landscapes present during the study period. This approach relies heavily on the evaluation of biophysical features of the landscape by individual landowners. It can be explained relatively easily to a layperson because it describes land markets in terms of household decisionmaking around preferences for amenities and accessibility.

4 Findings

The modeling results are presented in figure 6. In these maps highway 36 cuts across the study area diagonally and extends northwest from the town of Lyons en route for the Rocky Mountain National Park. Figures 6(a) and 6(b) display the results of the two-dimensional models designed with the intention of looking at dissimilar effects of accessibility and amenities on the landscape. The two-dimensional accessibility model [figure 6(a)] shows the clustering along the transportation network and around the rural places. Most of the sites built in this model cling to either highway 36 or the town of Lyons. On the right side of highway 36 leading out of Lyons, some sites were built not directly adjacent to the highway but very close to it. Moreover, these sites are all adjacent to existing development. This illustrates that, if all the exurban households respond to accessibility factors on the landscape in the same way (in other words, if there is no preference difference among households on the site accessibility), at the aggregate level, exurban development patterns would be similar to a monocentric pattern.

The results of the two-dimensional amenity model are presented in figure 6(b). We see growth not only around the rural places and along transportation networks, but also around amenity-rich areas. About half of the built sites were proximate to Lyons

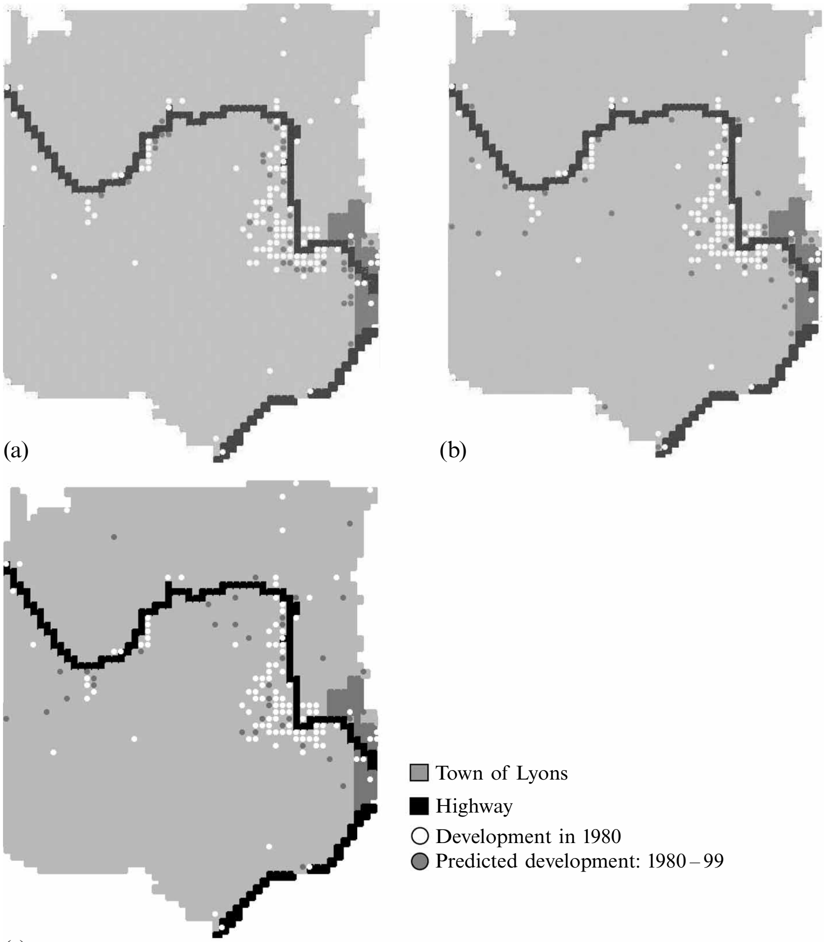

Figure 6. Land-use change 1980 – 99 (a) two-dimensional accessibility model, (b) two-dimensional amenity model, (c) full model.

and accessible to highway 36. One site was built in the northeastern part of the study area north of the highway. Three were built in the southwestern study area south of the highway. These sites are all relatively far from the highway and are not contiguous to current build-out areas. The development of these sites reflects the market attractiveness of factors such as the proximity to public lands, water bodies, or streams. The introduction of the second type of household—second-home owners who respond to natural amenities on the landscape—tends to pull development away from highways and rural places.

In the full model [figure 6(c)] more development was pulled away from the town of Lyons to the central and western part of the study area. One site was built in the northwest. Seven sites were built in the western study area south of the highway, the area rich in amenities. The development pattern reflects the magnetism to households both of two-dimensional and of three-dimensional amenities on the exurban landscape. The map of actual development between 1980 and 1999 is shown in figure 7. The clustering and dispersion pattern in this map more closely resembles the full model than the two-dimensional models.

In this research a three-layered approach is used to build up heterogeneous landscapes. Two layers have two-dimensional distance measures and the third layer has three-dimensional viewsheds as reflected in the three models. The results suggest that the two-dimensional accessibility model tends to cluster development closely around roads and built-up places. As we add additional variables and our models capture additional landscape characteristics, development is progressively dispersed. In the full-model, in which households rely on relatively complex information about landscapes, development tends to scatter most widely. Visually, the full model represents the best approximation of existing development patterns.

Even though visual comparison is a widely used method for comparing spatial patterns, we have also created a few statistics to show the dispersion of our model output from the existing development. The results of our model validation are presented in figure 8 and table 3. Figure 8 illustrates the neighborhood density created both for the model output grid and for the existing development grid. They resemble each other according to visual inspection. Table 3 presents the results of a statistical validation. It lists, for all three models, four very important measures of dispersion

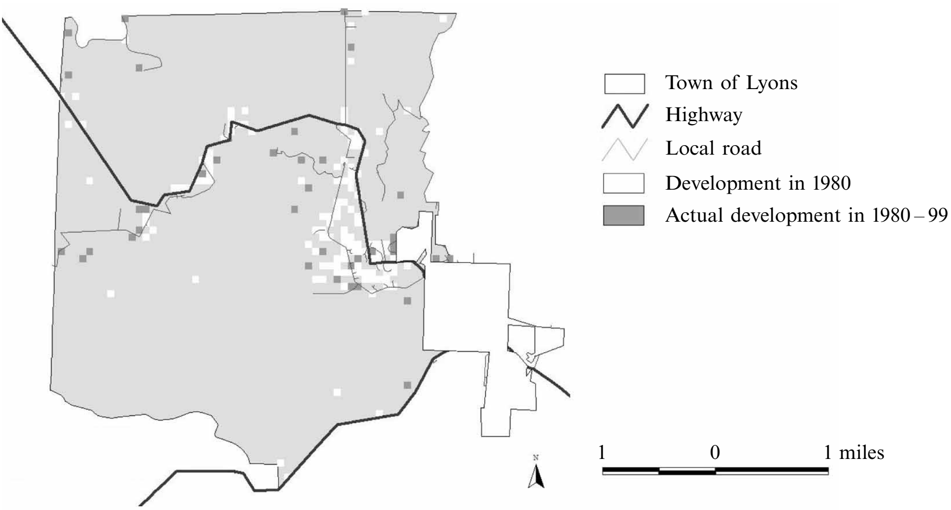

Figure 7. Actual development.

suggested by the literature, including root mean squared error, standard deviation, range, and variance. The smaller these measurements are, the closer the model output is to the existing development. Thus, the full model is shown as the best fit among the three models. These tests suggest that the full model and existing development represent a similar neighborhood density pattern.

Location decisions in amenity-rich, heterogeneous landscapes are associated with a complex process of evaluating different types of landscape features. With increasing heterogeneity the model achieves high levels of predictive power in this high-resolution landscape surrounding Lyons. Modeling land-use development is an inherently spatial task. Many models have been developed after the bid – rent approach by adding a family of variables including accessibility and socioeconomic variables. This research extends bid – rent theory by incorporating interactive effects of the spatial dimensions of the landscapes.

This research also suggests a number of challenges for development of ABMs that accurately predict landscape change. To begin with, data accuracy and resolution are critical to the construction of models that are validated against actual landscape change. In this study the unit of analysis is a 100 m cell (a hectare cell). This resolution may not be high enough to pick up important details related to the correspondence between biophysical environment and the decisionmaking of households. The calculation of viewshed is at a relatively low resolution. We base our viewshed analysis on 9-hectare cells, which are likely to have considerable variability within them. In addition, we are forced, because of data availability, to use datasets that may not meet consistent standards of accuracy. For example, TIGER roads have

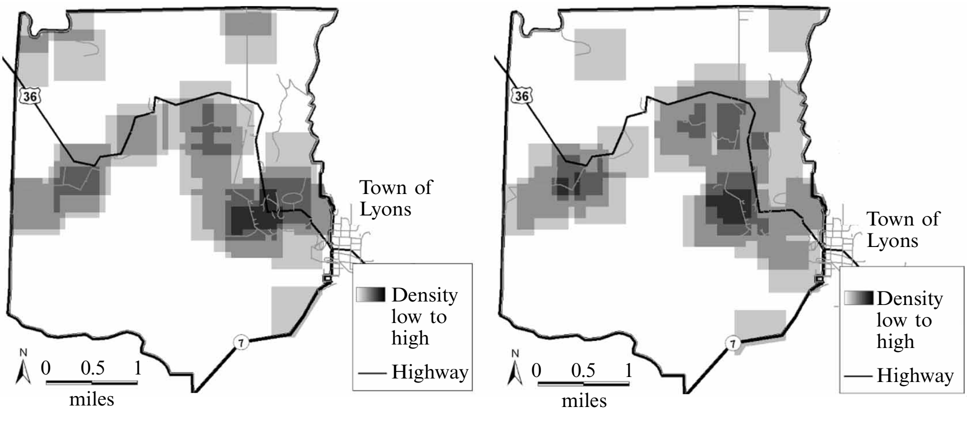

Figure 8. Model validation: comparison of (a) actual development neighborhood density, with (b) predicted development neighborhood density 1980 – 99.

Table 3. Model validation: comparison of neighborhood density.

Measures of dispersion from the existing neighborhood densities	Model		
	accessibility model	amenity model	full model
Root mean squared error	1.6	1.2	1.0
Range	13	12	9
Standard deviation	1.6	1.2	1.0
Variance	2.5	1.3	1.0

been criticized for incomplete coverage of smaller roads and for inaccurate digitization of road locations.

Moreover, more work is necessary in the design of appropriate rules and modes of competition in an amenity-based location. In this research we developed two cells at each time step, one for a second-home owner and one for a commuter—that is, we assumed that the ratio of second-home owners to commuters is 1:1. Even though this could be the future development trend in the Lyons area, it did not hold true for the years between 1980 and 2000 according to US census data. In our next paper we include mechanisms of randomness, and bidding between households in the competition for a lot for development, under the consideration that it is not realistic to assume that people have access to perfect information, and that they make rational decisions.

5 Conclusions

In this study we construct ABMs to help understand exurbanization as a complex and interactive process of household evaluation of the characteristics of exurban landscapes. We evaluate how agents operate in exurban environment and respond to biophysical features—site accessibility, natural amenities, and scenic views—using an ABM. Our comparison of model types suggests that a full agent-based approach, which incorporates households' decisionmaking in terms of preferences for accessibility, amenities, and scenic views, can provide a powerful tool for simulating amenity dynamics in exurban land markets. ABMs with three-dimensional amenity variables may be useful for evaluating land development in many other amenity-rich areas all over the world. ABMs of this type are also important because they enable planners to consider cumulative or emergent effects of market trends. They may have applications to a wide variety of exurban planning problems, including hazard assessment, comprehensive planning, habitat assessment, and even subdivision design. In the long run three-dimensional models may also be appropriate in densifying urban areas, in which views have also become important drivers in land markets and planning disputes.

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