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Agriculture, Ecosystems and Environment 101 (2004) 233–250

Agriculture Ecosystems & Environment

www.elsevier.com/locate/agee

Measuring pattern outcomes in an agent-based model of edge-effect externalities using spatial metrics

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Abstract

This paper presents an agent-based model of land use designed to explore the impacts of edge-effect externalities—distance-dependent spatial externalities—on land-use pattern. While the impacts of externalities on aspatial economics measures such as equilibrium land rents and the distribution of economic activity are well explored, links between externalities and landscape pattern are not well understood. This gap reflects a more general gap between aspatial theoretical land-use models and descriptive, pattern-based empirical analysis. The model presented in this paper, designed to link changes in socioeconomic parameters to changes in macroscale measures of landscape pattern, was developed with the specific goal of formally bridging this gap. The model simulates land-use decisions of parcel managers in an environment where potential conflicts between urban and agricultural land uses affect the payoffs to particular land uses. In the model, spatial and aspatial macroscale outcomes emerge from the independent, but dynamically linked, decisions of individual parcel managers. Land-use composition, land-use pattern, and the location of land uses are jointly determined, and interactions between composition and pattern feedback to microlevel landowner decisions through endogenous land rents. The paper demonstrates a series of results. First, the paper demonstrates the economic inefficiency of landscape fragmentation when edge-effect externalities are present and illustrates a series of landscape metrics appropriate to measure this fragmentation. Second, the agent-based model is used to demonstrate links between externality impacts and landscape pattern: that conflicts between urban and residential land users lead to a more compact urban form, that when the profitability of agricultural production is reduced by proximity to urban land, the urban–rural fringe expands to a socially inefficient degree, and that conflicts between urban land users can lead to fragmented patterns of urban development consistent with existing definitions of urban sprawl. Finally, the paper concludes by proposing a methodology for establishing the robustness of the model's conclusions over a wide range of parameter values.

Keywords: Agent-based models; Land-use pattern; Emergence; Spatial externalities

1. Introduction

Scholars in multiple disciplines are conducting research to explore linkages between social and bio-physical processes and landscape patterns. Substantial descriptive, empirically based analysis has been done to identify associations between particular land uses and patterns. Further, there is a well-developed body of models that formally link socioeconomic factors to land-use allocation in an aspatial context. The large gap between descriptive analysis and aspatial models has been bridged to an extent by spatially explicit simulation models that distribute fixed quantities in

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doi:10.1016/j.agee.2003.09.007

given land-use categories across space, taking allocation of land into particular use classes as given. However, development of spatially explicit simulation models that formally link the socioeconomic determinants of land-use change to resulting spatial patterns is only now beginning. There is a particular need to develop models that can be used to explore hypothetical relationships between changes in socioeconomic parameters and changes in landscape pattern, thereby formalizing process–pattern linkages. Spatially explicit agent-based models (ABMs) offer a promising means to conduct such analysis. This paper presents a simple, stylized ABM model of land-use conversion, focused on interactions between land uses at the urban–rural fringe. The model is used to explore the impacts of urban–rural conflicts on land-use patterns and to specifically demonstrate linkages between socioeconomic factors and landscape pattern.

1.1. The role of ABM in empirical analysis

Agent-based models are simulation models in which decision makers are represented as goal-oriented entities capable of responding to their environment and taking autonomous action. Such models are generally represented via object-oriented computer programs. ABMs often model complex dynamic systems and focus on the macroscale, or "emergent" phenomena that result from the decentralized decisions of and interactions between agents. Emergence can be understood within the geographical context of level or scale, as emergent phenomena at one level may form the units of interaction, or drivers of change, at a higher level (Auyang, 1998). In contrast to many traditional dynamic simulation models, a set of global equilibrium conditions is not imposed in ABMs. Rather, in the cases in which the systems reach a stable solution, the stability stems from the fact that no individual agent has an incentive to change its behavior. Parker et al. (2003) offer an extensive discussion of agent-based models, complexity, and emergence in the context of land-use change modeling.

Spatially explicit ABMs are increasingly being used to model human-environment interactions (see, for example, Gimblett, 2001, Janssen, 2003 and Parker et al., 2002). Agent-based models have also been successfully used to illustrate novel theoretical outcomes in economic systems (see Tesfatsion (2002) for an excellent review). These models have succeeded beyond other modeling techniques in situations where complex mathematical relationships have a critical influence on model outcomes. However, to date, the application of ABMs has been largely theoretical, and the wide gap between the theoretical implications of ABMs and empirical data has not been bridged. While the models are often used to heuristically illustrate observed empirical phenomena, they have rarely been used to derive and empirically test general hypotheses.

There have been substantial discussions of the appropriate role for agent-based models (Casti, 1997; Kohler, 2000; Tesfatsion, 2002; Parker et al., 2003), with some scholars arguing that simple illustration of empirically observed outcomes is a sufficient role for these models (Epstein, 1999). Those who argue against the use of ABMs in a formal scientific context cite two related factors. First, since ABMs are simulation models, they cannot be classified as formally inductive, and as such, researchers cannot be confident of the range over which hypothesized relationships between model parameters and outcomes might hold. Second, ABMs generally incorporate complex dynamic relationships, implying that many possible outcomes are possible, and that small changes in parameter values and initial conditions may result in large changes in model outcomes. These arguments highlight the difficulties in using ABMs to develop empirically testable hypotheses.

As discussed by Lambin et al. (1999), land-use change is influenced by complex interactions between socioeconomic and biophysical drivers. Why then might such models be useful for making linkages between theoretical processes and empirical patterns? Two factors lend support to the use of ABM to develop testable hypotheses. First, although simulation models may not be formally inductive, through sensitivity analysis modelers can come quite close to a complete understanding of the dynamic system under study (Judd, 1997). Second, although it is true that a complex system may have a multitude of possible outcomes at a microscale, outcomes that differ substantially at a microscale may be quite similar in terms of macroscale, or emergent, properties. For example, in the context of land-use modeling, a stochastic simulation model may produce very different locational maps for multiple simulations, but each of these simulations may exhibit similarities in terms of measures of landscape composition and pattern. Thus, the analysis in this paper focuses on macroscale outcomes of interest to land-use modelers, both those aspatial measures that are the traditional focus of socioeconomic models, and measures of landscape pattern that can be linked to both socioeconomic and ecological functions.

1.2. The role of ABM in LUCC modeling

As discussed in detail below, pattern measures are outputs of interest in spatially explicit land-use models, as such pattern measures can reflect both ecological and socioeconomic function. Pontius (2000) and Pontius and Schneider (2001) discuss the importance of modeling both the quantity of land use in a particular class and the particular locations of land uses. Veldkamp and Lambin (2001) stress the need to develop modeling methodologies that model both factors in an integrated way, and note that examples of such models are few. The majority of spatially explicit models of land-use/cover change (LUCC) either take the demand for particular land-use classes as given or separately model land-use composition (using an aspatial model) and the allocation of land use across space (using cellular automata or probabilistic algorithms) (see, for example, Jenerette and Wu (2001),Engelen et al. (2002) and Verburg et al. (2002)). This approach does not capture the dynamic feedbacks between land-use patterns, spatial location, and land-use composition. Agent-based models can potentially capture these feedbacks; as land-use composition, location, and pattern are jointly and endogenously determined in ABMs.

In the model presented here, the structure of demand for competing land uses is taken as given, but the quantity of land in each land use is endogenously determined. An endogenous rent for urban land, dependent on both the amount of land in urban use and on the patterns of urban land use, provides the key feedback mechanism that links quantity and location. In the model, composition and pattern outcomes emerge from the microscale decisions of individual parcel owners. Macroscale composition and pattern then influence the expected returns for converting a parcel to urban land for an individual land owner. Thus, the macroscale outcomes feed back via the price mechanism to influence microscale decision making.

1.3. Objectives

The paper proceeds as follows. First, a brief discussion of literature that links landscape pattern to both ecological and socioeconomic function is provided. Next, the ways in which the set of landscape metrics reported for the model reflects the embedded spatial processes is discussed in some detail. The details of the agent-based model of land use are then presented. Several macroscale outcomes of the model are discussed, and two of these characteristics—landscape composition and landscape pattern—are proposed as promising targets for the development of empirical hypothesis. A series of examples then demonstrates how both composition and pattern change as the parameters of the model related to spatial processes change. Finally, a protocol for using this model to more formally map relationships between process and pattern, leading to the development of a set of model implications that could be subject to empirical testing, is discussed.

2. Methods

2.1. Spatial pattern indicators of ecological and socioeconomic processes

There is a substantial cross-disciplinary history of research that characterizes the spatial patterns of features in the landscape that result from both ecological and anthropogenic phenomena. Although ecological applications are most frequent, social functions can also be associated with the spatial configuration of human-influenced landscapes. In this section, representative literature linking pattern to process using landscape metrics is discussed, placing special emphasis on the use of these metrics in a land use modeling context.

2.1.1. Ecological applications

The association between process and pattern has been most often applied to the study of ecological processes operating in landscapes (Turner et al., 2001). Spatial patterns in land cover arise through environmental variation as well as through anthropogenic (Trani and Giles, 1999) and natural disturbances (Hobbs, 1996; Cooper-Ellis et al., 1999). Not surprisingly, methods to describe spatial pattern have developed more quickly than the understanding of how spatial patterns affect ecological function (Hobbs, 1997). However, land-cover patterns have been shown to affect many ecological processes, including hydrology (Gosselink and Lee, 1989), nutrient cycling (Epstein and Burke, 1998), fire regimes (Nepstad et al., 1996), and plant and animal biodiversity (Corlett and Turner, 1997; Dale et al., 1994).

2.1.2. Urban models

Based on the recognition that urban growth processes can be characterized by particular pattern metrics, many urban growth models have used spatial metrics to analyze the results of spatial simulation models. Much of this work has focused on the structure of urban areas and the fractal nature of landscape components (Batty and Xie, 1994; White and Engelen, 1993). The emergence of spatial segregation has also received attention (Webster and Wu, 1999). Irwin and Bockstael (2002), using a statistically-based simulation model that incorporates estimates of negative spatial externalities, compare predicted and actual landscape patterns via nearest-neighbor distance indices. They find that simulations that include the negative externalities better predict discontinuous patterns of land use than simulations that suppress the externality impacts. Herold et al. (2002) use information on spatial pattern to improve the accuracy of remote-sensing calibrations by linking pattern measures to land-use classes. Jenerette and Wu (2001) use a series of landscape pattern measures to calibrate a cellular automaton model describing the growth of a metropolitan area.

A variety of pattern measures have been used to describe and measure socially undesirable aspects of urban sprawl. Three recent reviews summarize the literature on measurement of sprawl, and each set of authors proposes a comprehensive set of measures. In addition to density surfaces, Torrens and Alberti (2000) propose weighted-distance measures that reflect the "geometry of scatter". They also discuss the use of fractal dimension as a measure of fragmentation and inefficient use of urban space. Finally, they discuss a series of measures of accessibility. Galster et al. (2001) define sprawl in terms of low values in one or more of eight dimensions: density, continuity, concentration, clustering, centrality, nuclearity, mixed uses, and proximity. Each dimension is linked to a formal mathematical measurement. In addition to several qualitative measures, Hasse (2002) identifies several spatial measures of urban sprawl. These include urban density, discontinuous development, segregation of land uses, the efficiency of new road networks, and accessibility to transportation and community nodes.

Review of this literature on urban growth patterns reveals that macroscale urban landscape patterns may have both positive and normative implications. On the positive side, it is clear that particular patterns characterize urban form, and thus, an urban land-use model may be judged on its ability to produce patterns that resemble those found in actual urban areas. On the normative side, it is clear that pattern may be an important measure of the economic efficiency and social desirability of urban land use. Therefore, land-use modelers and policy makers may use pattern metrics outputs in land use models as a way of exploring the impact of different policy scenarios on the desirability of resulting land-use patterns.

2.1.3. Rural models

Balmann (1997) and Berger (2001) use agent-based modeling techniques to examine the impact of agricultural policies on the distribution of farm size. Parker (2000) uses a series of landscape statistics to link impacts of distance-dependent spatial externalities generated by conventional farms on production patterns of certified organic farms in California. Landscape pattern indices also have been used to evaluate the performance of models of rural land-cover change. Manson (2000) uses measures of fractal dimension and contagion to validate an agent-based model of land-cover change in the southern Yucatán peninsula.

2.1.4. Integrated models

Alberti and Waddell (2000) have coupled urban growth models with models of ecosystem processes to evaluate the impact of different demographic and economic scenarios. In an extension of Waddell's UrbanSim model, they suggest the use of spatial metrics for evaluating integrated models of urban ecosystem processes. Torrens and Alberti (2000) also propose a series of spatial metrics designed to measure the ecological impacts of urban sprawl. Spatially explicit decision support systems also have been used to allow planners and policy makers to consider the impact of different policy scenarios on ecosystem functions, using spatial pattern measures to link landscape changes to their ecological impacts. For example, Landis and colleagues extend existing urban growth models (CUF1 and CUF2) to examine conservation scenarios in California. Their California urban and biodiversity analysis model (CURBA) includes a policy simulation component to evaluate the impact of land-cover changes on species habitat (Landis and Zhang, 1998a,b). The CURBA model has been used to look at the connectivity of habitat patches and other spatial habitat indicators to evaluate the impact of different policy scenarios on specific species. The environment explorer model developed by Engelen et al. (2002) reports on a series of spatial measures of the environmental impacts of development, including noise pollution, traffic emissions, availability of open and recreational space, road congestion, and spatial fragmentation. These applications demonstrate that spatial outputs of land-use models may play a dual role by evaluating both socioeconomic and environmental/ecological impacts.

2.1.5. Choosing a set of metrics

As is evident from this discussion, broad and often overlapping sets of metrics are used to describe the social and ecological function of landscapes. Fractal dimension is one commonly used metric to describe the nature of both urban landscapes and less human-influenced landscapes (Batty and Xie, 1994; White and Engelen, 1993; Geoghegan et al., 1997; Alberti and Waddell, 2000; Herold et al., 2002). Additional measures used to evaluate land-use outcomes include landscape composition, diversity, dominance, edge distance, edge density, shape, nearest-neighbor distance, number of patches, patch size standard deviation, patch density, and contagion (Alberti and Waddell, 2000; Jenerette and Wu, 2001; Herold et al., 2002). However, new metrics and new insights into existing metrics continue to develop (McIntyre and Wiens, 2000; Jaeger, 2000).

Metrics vary in the kinds of patterns they are best suited to detect (O'Neill et al., 1988). The choice of metrics can be directed by a structured understanding of the link between socioeconomic process and landscape pattern impacts. Ideally, this investigation should reveal the theoretical relationship between a landscape process and pattern metrics. In the next section, the set of metrics chosen to describe the function of the model's simulated landscape is discussed, and the way in which these measures reflect the economic impacts of the two important spatial processes in the model—spatial externalities and transportation costs—is demonstrated. The examples presented in Section 3 illustrate how changes in these spatial processes lead to changes in these pattern metrics.

2.2. Landscape metrics and edge-effect externalities

The choice of metrics is based on the two spatial processes relevant for the development of cities included in the ABM: transportation costs and negative spatial externalities. In the model, the profitability of land use at each individual parcel is reduced by a per-unit transport cost to the city center, calculated according to Euclidean distance. Profitability of particular land uses at each parcel is also potentially affected by negative, distance-dependent spatial externalities. A negative externality is generally defined as an economic cost incurred by an actor that results from a decision made by a second actor, where the second actor generating the negative impact does not account for the external costs imposed on the first when making the decision. Spatial externalities often have impacts that depend on, and diminish as distance from the generating activity increases. In keeping with parallels with ecological edge effects, these impacts are referred to as "edge-effect externalities" (Parker, 2000).

Examples relevant for urban–rural conflicts include pesticide drift, noise, dust, and odor from agricultural activity, and ecosystem disturbances such as diminished beneficial insect populations. Such conflicts imply that often agricultural and residential land uses are incompatible neighbors (Wacker et al., 2001). Although these conflicts technically reduce the ability of urban residents to enjoy their land, it can be difficult from a policy perspective to identify one party as the generator of the externality and the other as bearing the economic cost. The urban residents are most often the newcomers, and agricultural producers are often forced to change long-standing production practices to accommodate the new residents. A frequently implemented solution to this problem is to institute buffer zone regulations between agricultural and urban residential land uses (Hammond, 2002). This model uses the concept of the buffer zone as a metaphor for the externality impacts and specifically examines the impacts of shifting the buffer zone requirement between the agricultural and urban land users.

Further, a second variant of edge-effect externalities is examined: aversion of urban land users to locating next to other urban land users. Irwin and Bockstael (2002) find empirical evidence for such a NIMBY (not-in-my-backyard) effect. They find that the probability of conversion declines with the share of developed land in a neighborhood surrounding a parcel. In a hedonic analysis of the determinants of housing sales prices, Irwin (2002) finds that permanently preserved open space contributes more to housing values than developable open space, indicating that lack of development is valued. She also finds that property values are decreasing in areas of high residential density.

Below, the metrics used to analyze model outcomes, chosen to concisely measure the important landscape processes operating in the simulations, are discussed. While the discussion focuses primarily on the socioeconomic interpretations of the metrics, many of the same metrics could be used to analyze the ecological function of the landscape. Further, one could easily customize the ABM to report a broader set of pattern measures.

- *Landscape composition*: This measure reports the proportion of land in each economic land use (or class, in landscape ecology terminology). From both economic and environmental policy perspectives, the distribution of economic activity has significant implications, since it influences the availability of land for particular economic uses and for species habitat.
- *Number of patches/mean patch size*: A patch is defined as a group of contiguous cells in the same land use (class). As the number of patches decreases, holding patch shape and class area constant, mean patch size increases. Consequently, the edge/area ratio of the patch will fall, implying a lower proportional loss due to externality damage and therefore a higher average product if the land use in that class is negatively impacted by externalities. Conversely, if the land-use class generates negative externalities, under the same ceteris paribus conditions, as mean patch size increases the total amount of externality damage inflicted will increase. The number of patches may also impact landscape connectivity and the efficiency of transportation networks.

  If patches represent management units, mean patch size may reflect the optimal spatial scale of production for land-use classes in an agricultural setting. Thus, it is important to note that in the examples presented in Section 3, mean patch size is influenced by the model's assumption that each manager controls a single-cell parcel, and that there are no opportunities to increase the number of parcels managed. These assumptions regarding the size of management units in effect define the minimum cell size, or resolution, of the landscape. This resolution will affect all landscape metrics for two reasons. First, the model is a discrete-choice model, since parcels must be assigned to a single use. As the size of management units increases, the number of choices decreases. Second, the shape of patch edges changes with the resolution of the data, with a smaller minimum size implying a less edgy landscape.
- *Area-weighted mean shape index*: This index measures the weighted average deviation of a patch shape from the shape that minimizes edge/area ratio. For cell-based (raster) landscape, the measure is calculated as

$$\text{A-W MSI} = \sum_{i=1}^{n} \left\{ \frac{0.25 p_i}{\sqrt{a_i}} \right\} \left\{ \frac{a_i}{A} \right\}, \tag{1}$$

  where n is the number of patches in that class, p_i and a_i the patch perimeter and area, respectively, and A the total area of the land-use class (McGarigal and Marks, 1994). Holding class area and the number of patches in the class constant, the edge/area ratio will fall as parcel shapes become more compact (more square, in this context). Therefore, a more compact parcel will receive less externality damage and/or inflict less damage on surrounding land uses.
- *Class area concentration*: Holding area, parcel shape, and the number of parcels fixed, the edge/area ratio for a given land-use class will increase as the relative concentration of area within a small number of patches increases. To measure concentration, a normalized concentration index, designed to reflect inequality in area distribution, independent of the number of separate parcels, is used. It is conceptually similar to "evenness" indices found in ecology (McGarigal and Marks, 1994) and is based on the Herfindahl index, often

used to measure inequality in income distribution and concentration of market share. The measure is

$$\mathrm{CI} = \frac{\sum_{i=1}^{n}(1/n)^2}{\sum_{i=1}^{n}(A_i/\mathrm{TA})^2}, \quad (2)$$

where n is the total number of parcels in a particular land-use class, A_i the area of a given parcel, and TA the total land area. The measure has a maximum of one when each parcel has equal area. The numerator is the value for the Herfindahl index if each parcel has equal area; the denominator is the Herfindahl index for the particular parcel configuration, calculated using the share of total land area for each parcel. If not normalized, the Herfindahl index would decrease as the number of parcels increased, regardless of area distribution.

- *Average product/average core area*: Average core area is the proportion of productive land (not in buffers or setbacks) to total land area in each class. Given the assumption of constant marginal productivity of land in the model, it is equivalent to average product. This measure is only relevant when a known process impacts productivity of land within a measurable distance from the borders between land-use classes.
- *Contrasting edge density*: Edge density is simply the ratio of total class edge to total class area. In the examples presented here, a contrasting edge is defined as any border shared between the two land-use classes. These borders represent the economically significant edges in this hypothetical economy, since they will influence the economic decision of individual parcel managers. The assumption of buffer zone requirements implies that additional, potentially ecologically significant, edges will be present in the landscape—shared borders between buffer zones and the two land-use classes. However, the land area in buffer zones is not displayed in the graphics. Contrasting edge density is an aggregate index measure of the total impacts of externalities on landscape productivity. It will be closely correlated with average product/average core area. Edge density is also highly correlated with fractal dimension. Because fractal dimension is an index measure that varies with several factors, we have chosen not to use it in this analysis. Further, fractal dimension is robust only when applied to a landscape with multiple patches (McGarigal and Marks, 1994).

Fig. 1 and Table 1 illustrates the relationships between the above six measures in terms of the economic impacts of edge-effect externalities. In parallel with the non-linear declines in intact habitat that occur with landscape fragmentation when ecological edge effects are present (Kapos et al., 1997), edge-effect externalities have important implications for the efficiency of land-use patterns. Holding land-use composition fixed, the productivity of the landscape will decline as landscape fragmentation increases. Further, parcel shape, the number of parcels, and the distribution of land in a particular class between parcels represent independent dimensions of land-use fragmentation.

In Fig. 1, available land is represented by a square, with no negative production impacts occurring at its edges. For mathematical simplicity, the externality damage is represented by a fixed loss at the recipient's border—no positive production is possible within one unit of the generating border. The production impacts of a marginally declining production loss are similar if the negative impacts are limited to the neighboring cell. The medium gray represents land occupied by an externality generator, the light gray represents the zone of externality damage on the externality recipient's land, and the black area represents externality-free production are for the externality recipient. In each panel, the amount of land area occupied by the externality recipient (the sum of the light gray and black areas) is constant. Average Product is simply the proportion of land held by the externality recipient which goes to productive use, and is thus an indicator of the relative productivity of the landscape.

As illustrated in Table 1, productivity is decreasing with height/width ratio (an indicator of parcel shape, correlated with A-W MSI), decreasing with the number of parcels, and increasing with concentration. There is an inverse relationship between productivity and edge per unit area. The landscape configuration that minimizes conflicting edge per unit area also maximizes production possibilities. The broad implication is that edge per unit area can be used as an empirical proxy for average productivity. However, in order to understand the sources of possible efficiency loss, measures reflecting each potential dimension of fragmentation also must be examined.

- *Total contrasting edge*: In these examples, total contrasting edge reflects the potential externality

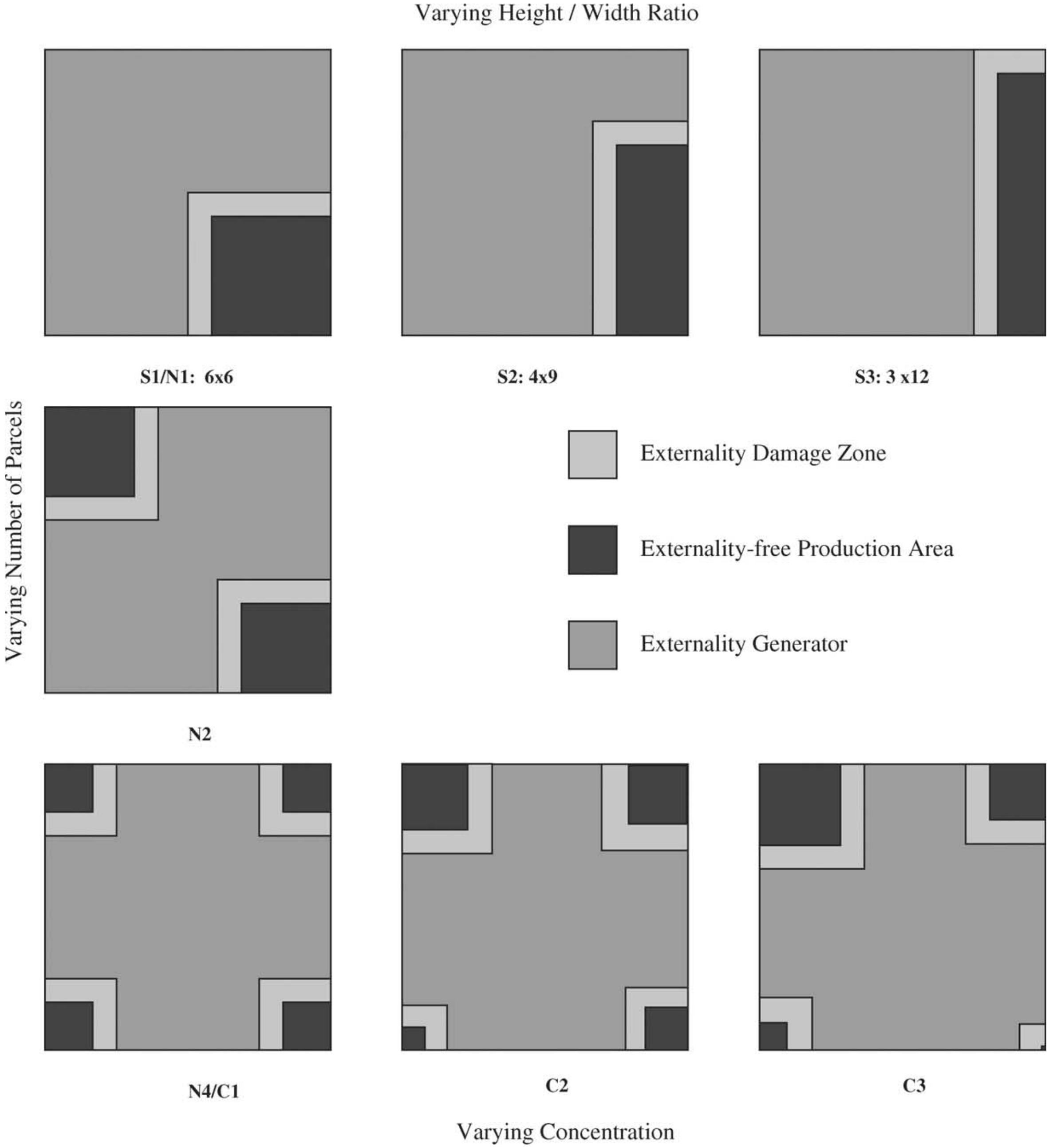

Fig. 1. Varying parcel configurations: medium gray is externality generator; light gray is zone of externality damage; black is externality-free production land; land occupied by the externality recipient (light gray plus black) is constant in each panel.

damage in each economic landscape. Thus, it will be closely correlated with, and may serve as an empirical proxy for, average productivity in a land-use class.

- *Mean nearest-neighbor distance*: Along with the number of patches, mean nearest-neighbor distance can influence the efficiency of transportation networks. This measure is included as a simple

Table 1
Dimensions of fragmentation for Fig. 1[a]

Graph	Average product	Edge density	Height/width	Number of parcels	Adj. Herfindahl
S1/N1	0.7	0.67	1	1	1
S2	0.67	0.72	2.25	1	1
S3	0.61	0.83	4	1	1
N2	0.58	0.94	1	2	1
N4/C1	0.44	1.34	1	4	1
C2	0.46	1.3	1	4	0.83
C3	0.5	1.2	1	4	0.64

[a] Average landscape productivity decreases as parcels become less compact, decreases as the number of parcels increases, and increases as parcel area becomes more concentrated.

measure of accessibility, discussed above as an important indicator of urban sprawl.

2.3. The model

In the model, each agent owns and controls a single cell representing one parcel. Two land uses are possible in each simulation: agricultural and urban. In all simulations, the agricultural (ag) land use can produce up to $\alpha = 1$ unit of output costlessly on each one-cell parcel of land. This output can be sold at a fixed price of $p_a =$ US\$ 1 per unit. The ag use is assumed to sell its product on site and thus is not impacted by transportation costs. If no externalities are present, therefore, a parcel in agriculture always yields a profit of US\$ 1. However, in some of the examples presented, agriculture is impacted by a negative spatial externality generated by the urban land use. This externality results in a fixed loss ω at the border shared with urban land. This assumption is consistent with a setback or buffer zone requirement for the ag use. This loss in production leads to a corresponding loss in profitability, and therefore a reduction in ag rents. Profitability from agriculture is therefore given by

$$\Pi_a = p_a \left[\mathrm{a} - \left(\sum_k U_k \omega \right) \right], \tag{3}$$

where each $U_k = 1$ represents a neighboring urban cell.

The second land use, representing urban activity, faces a downward-sloping, isoelastic demand for its output in all examples. This assumption implies limited demand for urban land, with urban rent falling as the amount of land in urban use increases. The intent of the model is to analyze interactions between an established urban area and its rural surroundings. The isoelastic demand curve implies that as urban land becomes more scarce, the price will rise infinitely. As a result, both land uses—ag and urban—will be represented in the model.

Potential output of $\rho = 1$ is also possible on urban land. While a single urban output is used to represent potentially diverse land uses, it is appropriate to think of this output as the area of a residential parcel at the urban–rural fringe. A fixed transportation cost based on the Euclidean distance from a hypothesized market located at the city center influences urban rent. In Section 3.3, urban production is potentially reduced by a setback requirement of distance ζ at borders shared with ag land. In Sections 3.5 and 3.6, the urban use is potentially impacted by a negative spatial externality with magnitude σ from other urban uses. Similar to the urban–ag externality, the NIMBY externality results in a fixed loss at every border shared with another urban parcel. An interpretation is that urban residents are averse to crowding, and therefore have diminished enjoyment from their land when they share borders with urban neighbors. Potential urban land rent for a parcel located at i, j, therefore, is given by

$$\Pi_u = p_u \left[\rho - \left(\sum_h A_h \zeta \right) - \left(\sum_k U_k \sigma \right) \right] - \mathrm{tc}_u \sqrt{(i - m_x)^2 + (j - m_y)^2}, \tag{4}$$

where each $A_h = 1$ represents a neighboring agricultural cell, each $U_k = 1$ represents a neighboring urban cell, and tc_u represents the urban transport cost to a market located at m_x, m_y.

When each agent has the opportunity to make a decision regarding land use, the agent first forms an expected price for urban output (p_u). This expected price represents the rent that the agent expects to obtain for each unit of usable land on the parcel. For example, an agent may expect to rent out apartments that occupy parts of the parcel not in a mandatory setback. The agent knows the demand curve for urban activity and understands the profit-maximizing incentives of each other agent, given the surrounding of other cells. The agent uses this knowledge to construct a hypothetical supply curve and estimate a market-clearing expected rent for urban parcels. While this price expectation formation mechanism assumes that the agent has substantial information about the marketplace, it still can be characterized as boundedly rational, since the agent does not anticipate the future actions of other agents and their long-run impact on prices. Having formed an expected price, the agent compares the profits from agricultural production to profits from urban land use. If profits from urban use are at least as high as profits from agriculture, the agent chooses the urban use.

In order to avoid oscillation, in each round, every other cell is allowed to choose type according to a checkerboard pattern. For example, in the first round, cells [(2,3), (2,5), (2,7), ... ,(3,2), (3,4), (3,6), ...] move, and in the second round cells [(2,2), (2,4), (2,6), ... ,(3,3), (3,5), (3,7), ...] move. Alternatives would have been to let cells move sequentially according to some random process, or to implement a "Poisson alarm clock" which ensures that each cell moves at a certain rate on average. This sequencing mechanism does induce some degree of path-dependency, as evidenced by the asymmetric outcome in Fig. 5.

After each active agent makes a land-use decision, the market-clearing urban rent is calculated and reported. Since agents do not anticipate that others may also enter the market, over and under supply occur as the market evolves toward equilibrium, and the market-clearing price therefore is correspondingly lower or higher than the expected price. The landscape does, however, converge to a stable market equilibrium. This process mirrors the classic cobweb model of supply of agricultural output. The result is a spatiotemporal equilibrium in which no parcels occupants have an incentive to change their land use. Note that, in contrast to traditional analytical economic models, a set of market-clearing equilibrium conditions is not imposed on the model. Specifically, the calculated market-clearing price does not feed back into the formation of the agents' price expectations for the next round.

3. Model outcomes and discussion

3.1. Macroscale outcomes of interest

A series of aspatial and spatial outcomes for each of the five models presented are analyzed. These outcomes reflect the distribution of economic activity, the relative level of land rents in the economy, the degree to which the simulated economy makes most efficient use of available land resources, and the gains from economic activity that accrue to groups of actors in the economy. Both market-clearing price and the aggregate distribution of economic activity have been identified as macroscale outcomes of interest in ABMs (Epstein and Axtell, 1996). In economic landscapes, the parallels of these measures are land-use composition and land rents at urban–rural fringe. Consumer and producer surplus measures are also commonly used to rank the desirability of economic outcomes. These measures are largely aspatial. In this paper, this traditional set of measures is expanded to include landscape pattern metrics. Kohler (2000) discusses ABMs as a tool for developing links between pattern and process in the social science realm. This paper seeks to meet this challenge in the context of economic geography by formally linking impacts of spatial externalities with measures of spatial pattern. Using the terminology of Axtell and Epstein (1994), the current approach evaluates whether model outcomes exhibit quantitative agreement with empirical macro structures.

Landscape metrics are potentially a key complement to existing aggregate measures. Further, with the wealth of remotely sensed high-resolution data on landscape pattern now available, spatially detailed landscape pattern data may be easier to obtain than disaggregated information on land rents, traditionally a major focus for hypothesis derivation in models of the urban economy. Thus, evaluation of landscape pattern is potentially a practical target for empirical testing of model outcomes.

3.2. The von Thünen outcome

When only transportation costs and the strength of demand for urban land influence landowner decisions, the model produces the classic von Thünen outcome (von Thünen, 1966). This outcome is illustrated in Fig. 2. In this and the following figures, white cells represent parcels in the urban land use, and black cells represent parcels in the ag land use in the "locations" plots. In the "expected profits" plots, the lightest color represents parcels with the highest profits, or rent. The demand and supply diagrams illustrate the exogenously imposed demand curve for urban land and the supply curve based on the expected price formation process described in Section 2.3. The model is implemented using the Mathematica software package. Mathematica is a high-level programming language designed for analytical and numerical mathematics (Wolfram, 1999). Landscape pattern measures were calculated using the raster version of FRAGSTATS (McGarigal and Marks, 1994) and the Mathematica package. The model code is available from the lead author on request.

The spatial scope of urban activity is determined by the urban-agricultural boundary where land rents equate the opportunity cost of agricultural and urban activities. A classic declining rent gradient emerges, illustrating concentric rings of economic activity. Given that complexities are not present in the simple von Thünen economic system, a simple, one-dimensional analytical model would be sufficient to illustrate these outcomes. The von Thünen outcome is illustrated for two reasons: first, to demonstrate that the ABM replicates standard results, and second, to provide a no-externality baseline for comparison purposes. In particular, the economic surplus measures reported for other examples are reported relative to the no-externality von Thünen outcome (Table 2). Landscape metrics for this outcome are also provided in Table 3.

3.3. Urban setback requirement

The macroscale outcomes of the model change when an urban setback requirement is imposed on urban land use. Here, the assumption is that an urban parcel must leave a buffer between development and neighboring ag parcels. This outcome is illustrated in Fig. 3. The setback requirement could be viewed as an external cost of development born by the urban land user. Relative to the von Thünen outcome, changes in market-clearing output price and the aggregate distribution of output are observed which are consistent with well-established theoretical results related to spatial externalities (Baumol and Oates, 1988). In comparison to the no-externality case, a higher proportion of the landscape is in agriculture in equilibrium. The market-clearing rent for urban land is relatively higher than it is without the setback requirement, and the extent of the urban area is smaller. This occurs because market activity balances the private values from development at the urban–rural fringe against the private "opportunity cost" of agricultural activity, without accounting for the social costs of the setback

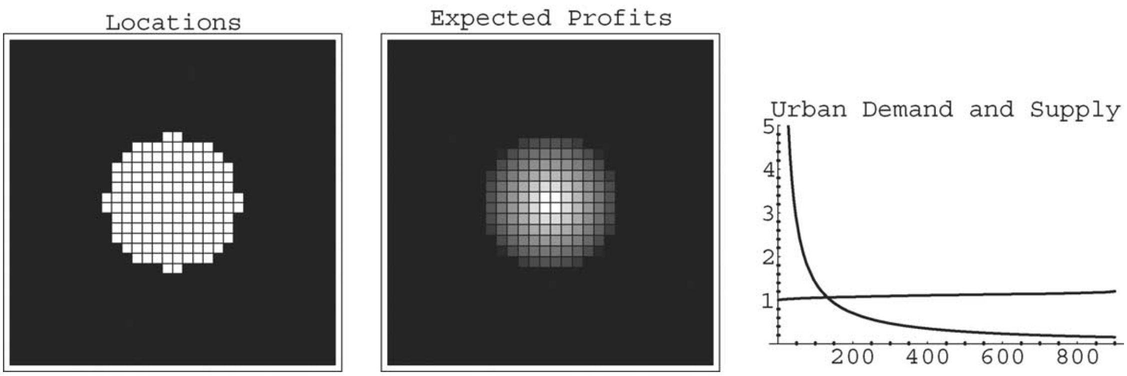

Fig. 2. In the von Thünen outcome, the "expected profits" panel illustrates a declining, concentric rent gradient, and the upward-sloping supply curve depends only on the distance from the central market (white "location" cells are urban; black are ag).

Table 2
Comparing socioeconomic results[a]

Example	Fig. 2	Fig. 3	Fig. 4	Fig. 5	Fig. 6
Transportation costs	0.01	0.01	0.01	0.01	0.06
Externality damage on A by U	0	0	0.125	0.125	0.125
U's setback requirement	0	0.125	0	0	0
U's aversion distance to U	0	0	0	0.125	0.125
Market-clearing rent for U	1.006	1.482	0.819	1.051	1.422
Total urban parcels	140	100	172	170	126
Proportion urban parcels	0.156	0.111	0.191	0.189	0.140
Average urban production	1	0.95	1	0.789	0.786
Average urban transport cost	0.045	0.038	0.049	0.056	0.289
Total agricultural parcels	760	800	728	730	774
Proportion agricultural parcels	0.844	0.889	0.809	0.811	0.860
Average agricultural production	1	1	0.990	0.939	0.953
Change in producer surplus for U	0	−0.084	−0.068	−0.042	−0.218
Change in producer surplus for A	0	0.053	−0.051	−0.104	−0.029
Change in consumer surplus	0	−0.022	0.012	−0.003	−0.020
Change in total surplus	0	−0.008	−0.0058	−0.027	−0.030

[a] Relative to the von Thünen outcome, externality-impacted economic outcomes exhibit lower total surplus measures and less efficient use of land resources.

Table 3
Landscape metric outcomes (urban) relative to the von Thünen outcome, landscapes with setback requirements are more compact and less edgy, while landscapes with "NIMBY" impacts are more fragmented and sprawling

Example	Fig. 2	Fig. 3	Fig. 4	Fig. 5	Fig. 6
Mean patch size	140	100	172	2.10	2.14
Number of patches	1	1	1	81	59
Area-weighted mean shape index	1.183	1.00	1.067	1.27	1.26
Edge density	0.4	0.4	0.326	2.306	2.286
Total edge	56	40	56	392	288
Mean nearest neighbor distance	0	0	0	4.94	6.78
Class area concentration	1	1	1	0.053	0.065

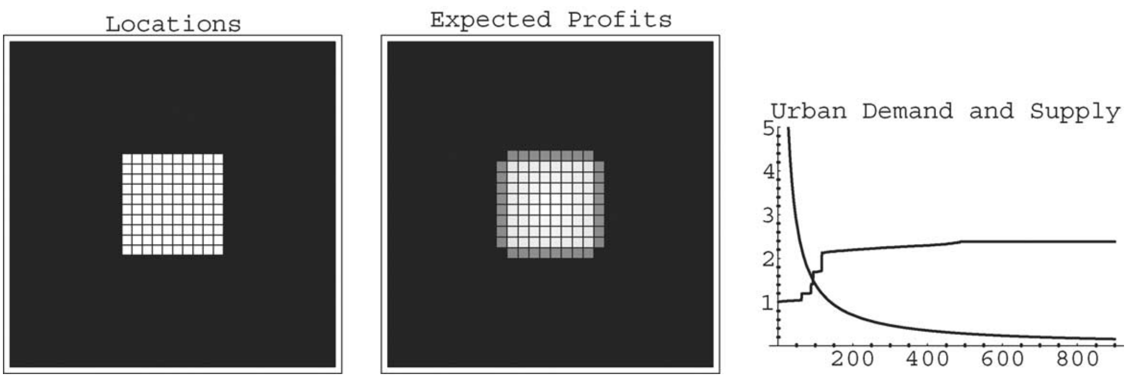

Fig. 3. The urban setback requirement induces a more compact urban form, and the supply price increases with both distance to the central market and the number of ag neighbors (white "location" cells are urban; black are ag).

requirements. The difference in land rents reflects the distortion in relative prices standard in the case of un-internalized externalities. These impacts are reflected in the expected decline in total economic surplus.

In this example, the two spatial processes encourage development of a compact city. Both transportation costs and the urban setback encourage agglomeration of urban land. The use of an ABM to represent this system reveals an additional macroscale property that results from spatial heterogeneity and the interdependencies of agent decisions—development of a more compact, less edgy landscape. Since externality impacts (costs from the setback) are present only at shared borders, urban development will be more profitable on parcels that share fewer borders with ag parcels. Thus, an equilibrium landscape develops that is measurably less edgy than the von Thünen landscape. Compared to the previous outcome, the area-weighted mean shape index is lower, and the edge density is the same, although the total urban area is lower than in the von Thünen outcome.

3.4. Urban–ag externalities

Further changes in macroscale properties are observed when the setback requirement is reversed. An interpretation is that agriculture is negatively impacted by a spatial externality generated by the urban land use. This outcome is illustrated in Fig. 4. In comparison to the no-externality case, a higher proportion of the landscape is urban in equilibrium. The market-clearing rent for urban land (the price for the externality-generating output) is correspondingly lower than it is without externalities. In this case, the market does not account for the social costs imposed on agriculture by urban development and equates the private benefits from urban conversion to the private costs of more limited production on the agricultural parcels.

Patterns of land rents differ substantially between Figs. 2 and 4. Perhaps the most interesting result here is that for most of the landscape, ag rent is higher than urban rent. This result may contradict intuition developed through the von Thünen model. The explanation is that rents at the urban–ag fringe can be sustained at a level lower than the highest potential agricultural rent. In the von Thünen example, an ag producer could earn US$ 1 from ag production at the urban fringe, and therefore, that rent defined the opportunity cost for urban development and thus defined the minimum rent for urban land. Under externalities, that opportunity cost is lower, since the maximum that can be earned from agriculture at the urban–ag fringe is US$ 1 less the cost of externality damage. Therefore, equilibrium rent at the urban–ag fringe is lower. This reduced rent is reflected in an urban–rural border that is farther from the city center than before. Intuitively, the lower rent at the urban–rural fringe balances the increased transportation costs to city center, pushing the urban–rural fringe outward. Further, an equilibrium can exist where urban rents are lower than ag rents, even at city center. (This result depends on the assumption of a fixed price for ag commodities). Note that the lower urban rents and the non-monotonic patterns

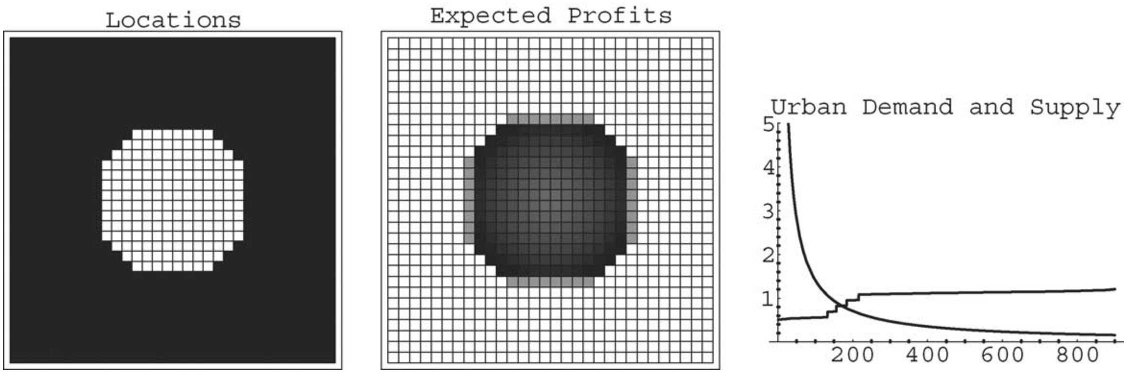

Fig. 4. When the urban use negatively affects ag producers, the urban footprint is larger, and the rent gradient is discontinuous (white “location” cells are urban; black are ag).

of land rent are consistent with general predictions of outcomes under externalities (Kanemoto, 1987).

For this landscape, opposing spatial processes encourage separation of land uses. Transport costs result in an agglomeration incentive for the urban use, while negative spatial externalities create an aversion mechanism for agriculture. Although the urban footprint is larger in this example than in Fig. 2, this landscape is also more compact and less edgy than the von Thünen outcome. This occurs not because urban landowners have an incentive to locate away from ag land users, but because the ag land use is not viable when surrounded by several urban parcels. The area-weighted mean shape index is lower, indicating a more compact shape that implies fewer shared borders for a given area. While the total amount of edge, or shared border, is the same in both cases, edge density for the urban use is lower, since there are more urban parcels in this example.

3.5. Adding NIMBY

Brueckner (2000) discusses three economic externalities that may contribute to socially inefficient urban sprawl. These are based on the failure of individuals to account for the social benefits of open space, to account for the costs of congestion, and to pay for the additional infrastructure costs generated by development. This paper suggests that edge-effect externalities, as presented in this model, should be considered as an additional contributor to urban sprawl. Specifically, the analysis demonstrates that aversion to locating near other urban users can lead to patterns of land use which are consistent with the definitions of urban sprawl discussed above. Land-use patterns are now more fragmented in terms of the number of parcels, the size of parcels, the degree of concentration of land uses, and average transportation costs.

In the example illustrated in Fig. 5, the aversion mechanism is added to the economy represented in Fig. 4. As described in Eq. (4), urban land users are affected by mutual negative externalities. An interpretation is that urban residents prefer a view of the agricultural landscape to a view of their neighbor's back windows. Here, the magnitudes of externality damage from urban to ag parcels and from urban to urban parcels are equal. In this example, spatial processes create counteracting incentives. As in the previous example, transport costs pull urban uses to the center of the landscape, and negative externalities between ag and urban users encourage spatial separation. However, the externalities between urban users encourage dispersal of urban activity. The result is a core of urban activity surrounded by fragmented and leapfrog development patterns. This landscape differs significantly from the previous two in terms of pattern metrics. Relative to the case illustrated in Fig. 4, mean patch size is much smaller and the number of patches is correspondingly higher. Although the smallest patches are constrained to a relatively compact shape by the minimum cell size, the aggregate area-weighted mean shape index is much higher, reflecting the fragmented nature of the urban–ag interface. Edge density is substantially higher, meaning much higher total

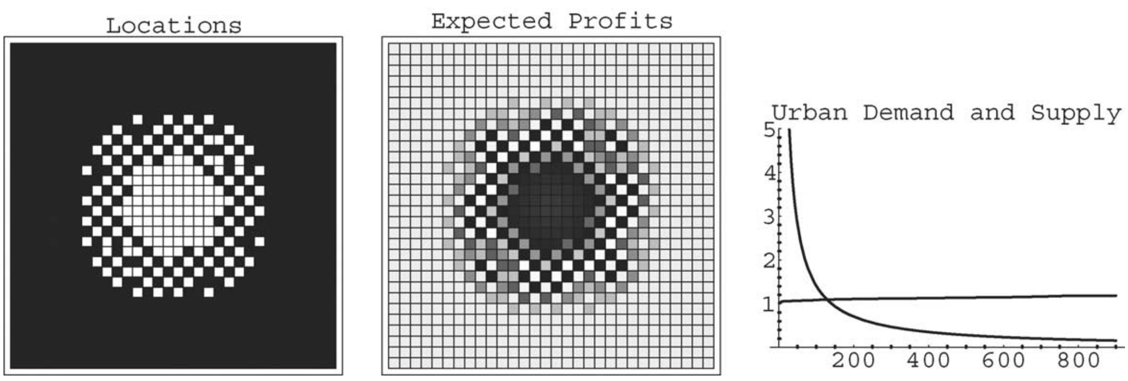

Fig. 5. In comparison to Fig. 4, the urban/urban aversion (NIMBY) effect creates more sprawling and fragmented patterns of development (white "location" cells are urban; black are ag).

externality damage to agriculture since the number of shared borders is also higher. The relative concentration measure is much lower, reflecting the presence of a number of very small patches of urban activity. The mean nearest-neighbor distance is also much higher. Correspondingly, average urban transportation costs are much higher. These patterns match those discussed as indicators of undesirable urban sprawl in Section 2.1. Note also that both average ag production and average urban production are much lower, indicating that available land is not being used efficiently.

3.6. Increasing transportation costs

Fig. 6 is based on the economy illustrated in Fig. 5, but with higher transportation costs. In this example, the higher transportation costs partly counteract the dispersal incentive created by the NIMBY aversion mechanism. The result is a somewhat more compact, less sprawling landscape. The mean patch size is somewhat higher, and the number of patches lower. Patches in the resulting landscape are more compact and more concentrated, and edge density is correspondingly lower. The mean nearest-neighbor distance, however, is higher due to the existence of several isolated patches.

3.7. Next steps: toward general hypotheses

The previous examples suggest a series of hypotheses that could be subjected to empirical testing: Do setback requirements and/or spatial externalities lead to a more compact urban form? Does assignment of the responsibility for the setback to urban developers result in a more compact form than assignment of the setback to agricultural producers? Are aversion mechanisms between residential land users a contributor to urban sprawl? Can increased transportation costs counter this sprawl incentive?

At this point, these hypotheses are only suggested. The discussion in Section 3.6 illustrates the difficulties of drawing generalizations based on representative simulation runs. Changes in the economic parameters induce changes not only in the pattern of land use, but also in the composition and location. Further, due to the raster representation in the simulation and the complex dynamics driving the model, macroscale outcomes do not vary continuously and monotonically with changes in the input parameters. In order to assert that general hypotheses have been developed, an ABM modeler needs to demonstrate that these hypotheses hold true across a wide range of parameter variations.

This general derivation of hypotheses is accomplished in analytical models through “comparative static” and “comparative dynamic” analysis, where differential calculus techniques are used to analyze how equilibrium solution values change as model parameters change. This level of formalism is not possible in an ABM framework. However, the modeler can create a database to map parameter values against simulated outcomes across a wide range of values. Inductive statistical techniques, such as regression analysis, can then be used to analyze this

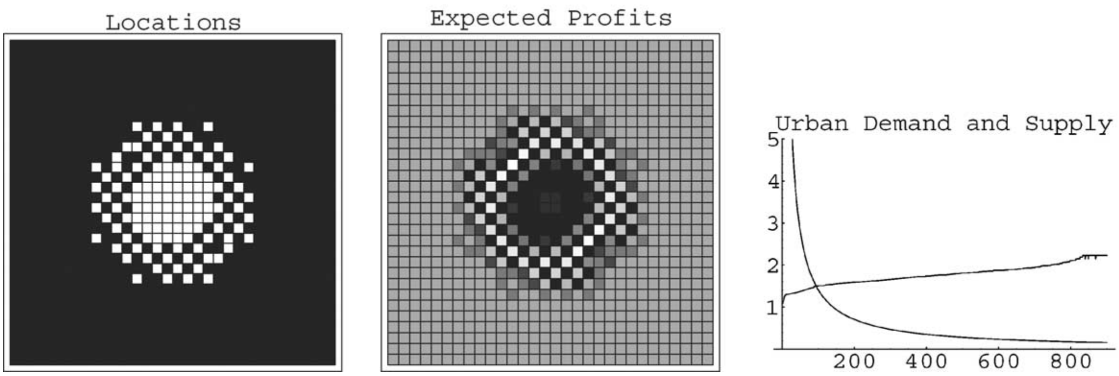

Fig. 6. In comparison to Fig. 5, higher transportation costs decrease fragmentation to an extent (white “location” cells are urban; black are ag).

simulated data, as described by Judd (1997). Generalizable hypotheses can then be gleaned from statistical parameter estimates. For example, in the context of this model, simulated edge density measures could be regressed against model parameters—magnitude of demand, transport costs, and the magnitude of externality impacts—to test the hypothesis that higher "NIMBY" aversion levels led to a higher degree of landscape fragmentation. A positive estimated coefficient for the NIMBY variable, ζ, would support this hypothesis in a theoretical context. This approach, which represents a pseudo-inductive application of ABM modeling as described by Axelrod (1997), is planned by the authors as an extension of current work.

The current model suffers from a number of limitations that may limit the generalizability of the conclusions drawn from this model. This model represents urban land as a single, homogeneous commodity, while cities are characterized by heterogenous land uses that interact positively and negatively with each other. Within this model, there is no storage of wealth from time period to time period, implying that economically inviable land uses may persist in the economy. Most important, agents cannot buy and sell parcels, limiting the ability of agents to capture increasing returns to spatial scale from managing larger parcels. The current model was deliberately constructed to be as simple as possible, in order to isolate complex dynamics related to spatial externalities. However, extension of the current model to include these additional features is planned.

4. Conclusions

This paper has developed a simple, stylized agent-based model of land-use interactions at the urban–rural fringe, and has motivated a set of landscape pattern metrics that measure the impacts of the spatial processes in the ABM model. The model has been used to demonstrate the link between spatial externalities and patterns of land use, and the set of landscape metrics has been used to demonstrate how changes in spatial processes correspond to changes in pattern. These changes in pattern are the result of some of the complex interactions which characterize economic landscapes. Since pattern metrics potentially reflect both the socioeconomic and ecological functioning of the landscape, these linkages provide potentially useful information to both scholars and policy makers. Thus, the pattern/process link illustrates an important advantage of agent-based modeling—the ability to link microscale decisions to macroscale outcomes.

This demonstration suggests an avenue for developing testable hypotheses from spatially explicit, disaggregated agent-based models. Much work remains to complete the goal of hypothesis construction and testing. Simulations to map the relationships between economic parameters and landscape pattern measures are currently being conducted. Exploration of the influence of transportation networks on landscape pattern by introducing more realistic transportation networks and travel-cost overlays is also planned. The development of statistically rigorous tests which compare simulated and actual patterns is an additional challenge. However, the authors hope that the techniques developed will have broad applications for both economic and environmental policy analysis.

Acknowledgements

Financial support from the Center for the Study of Institutions, Population, and Environmental Change through National Science Foundation grants SBR9521918 and SES0083511 is gratefully acknowledged. The work has benefited from helpful discussions with colleagues on the CIPEC biocomplexity project (http://www.cipec.org/research/biocomplexity), input from Tom P. Evans on an earlier draft, and comments by session participants at the 2001 Society for Computational Economics Annual Meetings. All errors and omissions are the authors' responsibility.

References

Alberti, M., Waddell, P., 2000. An integrated urban development and ecological simulation model. Int. Assess. 1 (3), 215–227.

Auyang, S.Y., 1998. Foundations of complex systems theories. In: Economics, Evolutionary Biology, and Statistical Physics. Cambridge University Press, Cambridge, NY.

Axelrod, R.M., 1997. Advancing the art of simulation in the social sciences. In: Conte, R., Hegselmann, R., Terna, P. (Eds.), Simulating Social Phenomena of Lecture Notes in Economics and Mathematical Systems, vol. 456. Springer, Berlin, pp. 21–40.

Axtell, R.L., Epstein, J.M., Winter 1994. Agent-based modeling: understanding our creations. Bull. Santa Fe Inst. 28–32.

Balmann, A., 1997. Farm-based modelling of regional structural change. Eur. Rev. Agric. Econ. 25 (1), 85–108.

Batty, M., Xie, Y., 1994. Modeling inside GIS. Part 1. Model structures, exploratory spatial data analysis and aggregation. Int. J. Geogr. Inform. Syst. 8 (3), 291–307.

Baumol, W.J., Oates, W.E., 1988. In: Externalities: formal analysis. The Theory of Environmental Policy. Cambridge University Press, Cambridge.

Berger, T., 2001. Agent-based spatial models applied to agriculture: a simulation tool for technology diffusion, resource use changes, and policy analysis. Agric. Econ. 25, 2.

Brueckner, J.K., 2000. Urban sprawl: diagnosis and remedies. Int. Region Sci. Rev. 23 (2), 160–171.

Casti, J.L., 1997. Can you trust it? On the reliability of computer simulation models. Complexity 2 (5), 8–11.

Cooper-Ellis, S., Foster, D.R., Carlton, G., Lezberg, A., 1999. Forest response to catastrophic wind: results from an experimental hurricane. Ecology 80 (8), 2683–2696.

Corlett, R., Turner, I., 1997. Long-term survival in tropical forest remnants in Singapore and Hong Kong. In: Laurance, W., Bierregaard, R. (Eds.), Tropical Forest Remnants: Ecology, Management, and Conservation of Fragmented Communities. University of Chicago Press, Chicago, IL, pp. 333–346.

Dale, V.H., Pearson, S.M., Offerman, H.L., O'Neill, R.V., 1994. Relating patterns of land-use change to faunal biodiversity in the central Amazon. Conserv. Biol. 8 (4), 1027–1036.

Engelen, G., White, R., de Nijs, A.C.M., 2002. Environment explorer: a Spatial Policy Support Framework for the Integrated Assessment of Socio-Economic and Environmental Policies in the Netherlands. In: Rizzoli, A.E., Jakeman, A.J. (Eds.), Integrated Assessment and Decision Support, Proceedings of the First Biennial Meeting of the International Environmental Modelling and Software Society, Volume 1, pp. 109–114. IEMSs, June 2002.

Epstein, J.M., 1999. Agent-based models and generative social science. Complexity 4 (5), 41–60.

Epstein, J.M., Axtell, R., 1996. Growing Artificial Societies: Social Science from the Ground Up. Brookings Institution Press, Washington, DC.

Epstein, H.E., Burke, I.C., 1998. Plant effects on spatial and temporal patterns of nitrogen cycling in shortgrass steppe. Ecosystems 1 (4), 374–385.

Galster, G., Hanson, R., Ratcliffe, M.R., Wolman, H., Coleman, S., Freihage, J., 2001. Wrestling sprawl to the ground: defining and measuring an elusive concept. Housing Policy Debate 12 (4), 681–717.

Geoghegan, J., Wainger, L., Bockstael, N., 1997. Spatial landscape indices in a hedonic framework: an ecological economics analysis using GIS. Ecol. Econ. 23, 251–264.

Gimblett, H.R. (Ed.), 2001. Integrating Geographic Information Systems and Agent-Based Modeling Techniques for Understanding Social and Ecological Processes. Oxford University Press, Oxford, UK.

Gosselink, J., Lee, L.C., 1989. Cumulative impact assessment in bottomland hardwood forests. Wetlands 9, 83–174.

Hammond, S.V., March 2002. Can city and farm coexist? The agricultural buffer experience in California. Technical Report. Great Valley Center, Modesto, CA, USA.

Hasse, J., 2002. Geospatial indices of urban sprawl in New Jersey. Ph.D. Thesis, Rutgers.

Herold, M., Clarke, K.C., Scepan, J., 2002. Remote sensing and landscape metrics to describe structures and changes in urban landuse. Environ. Plann. A 34 (8), 1443–1459.

Hobbs, N.T., 1996. Modification of ecosystems by ungulates. J. Wildl. Manage. 60 (4), 695–713.

Hobbs, R., 1997. Future landscapes and the future of landscape ecology. Landsc. Urban Plann. 37 (1–2), 1–9.

Irwin, E., 2002. The effects of open space on residential property values. Land Econ. 78 (4), 465–481.

Irwin, E., Bockstael, N., 2002. Interacting agents, spatial externalities, and the evolution of residential land use patterns. J. Econ. Geogr. 2 (1), 31–54.

Jaeger, J., 2000. Landscape division, splitting index, and effective mesh size: new measures of landscape fragmentation. Landsc. Ecol. 15 (2), 115–130.

Janssen, M. (Ed.), 2003. Complexity and Ecosystem Management: The Theory and Practice of Multi-Agent Approaches. Edward Elgar Publishers, Cheltenham, UK; Northhampton, MA.

Jenerette, D.G., Wu, J., 2001. Analysis and simulation of land-use change in the central Arizona–Phoenix region, USA. Landsc. Ecol. 16, 611–626.

Judd, K.L., 1997. Computational economics and economic theory: substitutes or complements. J. Econ. Dyn. Cont. 21 (6), 907–942.

Kanemoto, Y., 1987. In: Externalities in space. Urban Dynamics and Urban Externalities 11. Fundamentals of Pure and Applied Economics. Harwood Academic Publishers, New York

Kapos, V., Wandelli, E., Camargo, J., Ganade, G., 1997. Edge-related changes in environment and plant responses due to forest fragmentation in central Amazonia. In: Laurance, W.R.O., Bierregaard, J. (Eds.), Tropical Forest Remnants: Ecology, Management, and Conservation of Fragmented Communities. University of Chicago Press, Chicago, pp. 33–44.

Kohler, T.A., 2000.In: Putting social sciences together again: an introduction to the volume. Dynamics in Human and Primate Societies. SFI Studies in the Science of Complexity. Oxford University Press, New York.

Lambin, E.F., Bauleis, X., Bockstael, N., Fischer, G., Krug, T., Leemans, R., Moran, E.F., Rindfuss, R.R., Sato, Y., Skole, II D., Turner, II B.L., Vogel, C., 1999. Land-use and land-cover change (lucc): implementation strategy. Technical Report, IGBP Report No. 48 and IHDP Report No. 10. International Geosphere–Biosphere Programme (IGBP) and International Human Dimensions Programme on Global Environmental Change (IHDP), Stockholm.

Landis, J., Zhang, M., 1998a. The second generation of the California urban futures model. Part 1. Model logic and theory. Environ. Plann. B: Plann. Des. 25 (5), 657–666.

Landis, J., Zhang, M., 1998b. The second generation of the California urban futures model. Part 2. Specification and calibration results of the land-use change submodel. Environ. Plann. B: Plann. Des. 25 (6), 795–824.

Manson, S.M., 2000. Agent-based dynamic spatial simulation of land-use/cover change: methodological aspects. University Consortium for Geographic Information Science.

McGarigal, K., Marks, B.J., 1994. FRAGSTATS: spatial pattern analysis program for quantifying landscape structure. Technical Report, PNW-GTR-351. US Department of Agriculture, Forest Service, Pacific Northwest Research Station, Portland, OR.

McIntyre, N.E., Wiens, J.A., 2000. A novel use of the lacunarity index to discern landscape function. Landsc. Ecol. 15 (4), 313–321.

Nepstad, D., Moutinho, P., Uhl, C., Vieira, I., da Silva, J., 1996. The ecological importance of forest remnants in an eastern Amazonia frontier landscape. In: Schelhas, J., Greenberg, R. (Eds.), Forest Patches in Tropical Landscapes. Island Press, Washington, DC, pp. 133–150.

O'Neill, R., Krummel, J., Gardner, R., Sugihara, G., Jackson, B., DeAngelis, D., Milne, B., Turner, M., Zygmunt, B., Christensen, S., Dale, V., Graham, R., 1988. Indices of landscape pattern. Landsc. Ecol. 11, 153–162.

Parker, D.C., 2000. Edge-effect externalities: theoretical and empirical implications of spatial heterogeneity. Ph.D. Thesis. University of California, Davis.

Parker, D.C., Berger, T., Manson, S.M., 2002. Agent-based models of land-use/land-cover change: report and review of an international workshop. LUCC Report Series 6, LUCC Focus 1, Bloomington, IN.

Parker, D.C., Manson, S.M., Janssen, M.A., Hoffmann, M., Deadman, P., 2003. Multi-Agent Systems for the Simulation of Land-Use and Land-Cover Change: a Review. Ann. Assoc. Am. Geogr. 93 (2).

Pontius, R.G., 2000. Quantification error vs. location error in comparison of categorical maps. Photogram. Eng. Remote Sens. 66 (8), 1011–1016.

Pontius, R.G., Schneider, L., 2001. Land-use change model validation by a ROC method. Agric. Ecosyst. Environ. 85 (1–3), 239–248.

Tesfatsion, L., 2002. Agent-based computational economics: growing economies from the bottom up. Proc. Natl. Acad. Sci. 99 (Suppl. 3), 7191–7192.

Torrens, P., Alberti, M., 2000. Measuring sprawl. Working Paper 27. CASA, University College London, London.

Trani, M., Giles, R., 1999. An analysis of deforestation: metrics used to describe pattern change. For. Ecol. Manage. 114 (2–3), 459–470.

Turner, M.G., Gardner, R.H., O'Neill, R.V., 2001. Landscape Ecology in Theory and Practice: Pattern and Process. Springer, New York.

Veldkamp, A., Lambin, E.F., 2001. Predicting land-use change. Agric. Ecosyst. Environ. 85 (1–3), 1–6.

Verburg, P.H., Soepboer, W., Veldkamp, A., Limpiada, R., Espaldon, V., Mastura, S.S.A., 2002. Modeling the spatial dynamics of regional land use: the CLUE-S model. Environ. Manage. 30 (3), 391–405.

von Thünen, J., 1966. In: Wartenberg, C.M. (Ed.), Isolated State. (an English translation of Der Isolierte Staat). Pergamon Press, Oxford.

Wacker, M., Sokolow, A.D., Elkins, R., 2001. County right-to-farm ordinances in California: an assessment of impacts and effectiveness. AIC Issues Brief 15. Agricultural Issues Center, Davis, CA.

Webster, C.J., Wu, F., 1999. Regulation, land-use mix, and urban performance. Environ. Plann. A 31 (9), 1529–1545.

White, R., Engelen, G., 1993. Cellular automata and fractal urban form: a cellular modeling approach to the evolution of urban land-use patterns. Environ. Plann. A 25 (8), 1175–1199.

Wolfram, S., 1999. The Mathematica Book, 4th ed. Cambridge University Press, Cambridge.