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Spatial simulation of landscape changes in Georgia: A comparison of 3 transition models

Monica Goigel Turner
Institute of Ecology, University of Georgia, Athens, GA 30602, USA

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Abstract

Spatial simulation models were developed to predict temporal changes in land use patterns in a piedmont county in Georgia (USA). Five land use categories were included: urban, cropland, abandoned cropland, pasture, and forest. Land use data were obtained from historical aerial photography and digitized into a matrix based on a 1 ha grid cell format. Three different types of spatial simulation were compared: (1) random simulations based solely on transition probabilities; (2) spatial simulations in which the four nearest neighbors (adjacent cells only) influence transitions; and (3) spatial simulations in which the eight nearest neighbors (adjacent and diagonal cells) influence transitions. Models and data were compared using the mean number and size of patches, fractal dimension of patches, and amount of edge between land uses. The random model simulated a highly fragmented landscape having numerous, small patches with relatively complex shapes. The two versions of the spatial model simulated cropland well, but simulated patches of forest and abandoned cropland were fewer, larger, and more simple than those in the real landscape. Several possible modifications of model structure are proposed. The modeling approach presented here is a potentially general one for simulating human-influenced landscapes.

Introduction

The patterns of landscape development in time and space are the result of complex interactions of physical, biological, and social forces. Most landscapes have been influenced by human land use, and the resulting landscape mosaic is a mixture of natural and human-managed patches that vary in size, shape, and arrangement (e.g., Bowen and Burgess 1981, Burgess and Sharpe 1981, Forman and Godron 1981, 1986, Krummel *et al.* 1987). Land use patterns can influence a variety of ecological phenomena, including animal movements (e.g., Fahrig and Merriam 1985, Henderson *et al.* 1985, Freemark and Merriam 1986), water runoff and erosion (e.g., White *et al.* 1981, Peterjohn and Correll 1984, Kesner 1984) or the spread of disturbance (e.g., Turner in press (a)). Thus, the ability to predict the spatial patterns of land use may be crucial to our understanding of landscape dynamics.

The expansion of ecosystem analyses, such as simulation modeling, to include the spatial heterogeneity of landscapes represents a powerful new approach to ecological research (Risser in press); most ecological modeling has only focused on temporal changes (Costanza and Sklar 1985). Transition models have frequently been used to predict changes in vegetation (e.g., Debussche *et al.* 1977, Van Hulst 1979, Usher 1981, Lippe *et al.* 1985, Hall *et al.* in press) or land use (e.g., Hett 1971, Burnham 1973, Johnson 1977) through time. However, these models have not been spatially explicit, and there is no standard approach to incorporate spatial dynamics into transition models.

In this paper, I compare three types of spatial transition model that simulate changes in land use patterns in Georgia. Spatial influences are modeled in two ways and results are compared to random simulations and to actual landscape data. Simulated and actual land use patterns are compared using statistical descriptors of spatial pattern including: (1) mean number and size of patches; (2) fractal dimension of patches; and (3) amount of edge between land uses.

Methods

Study area and data collection

Georgia (southeastern USA) encompasses three major physiographic regions, each of which has undergone substantial changes in land use during the past two centuries (Nelson 1957, Brender 1974, Healy 1985). These regions include the mountains (1,470,3 10 ha), piedmont (4,606,139 ha) and coastal plain (8,971,206 ha). The piedmont region experienced the most dramatic land use changes during the past 50 years (Turner 1987), and a piedmont county (Oglethorpe) was selected as the initial study area for model development. Data and simulations from Oglethorpe County will be used in the remainder of this paper to demonstrate model behavior.

Net rates of land use transitions in Oglethorpe County were obtained from published statistics including the Census of Agriculture (e.g., USDA 1982) and Forest Service Surveys (e.g., Tansey 1983). Data on the spatial patterns of land use were obtained from historical black and white aerial photography for each of three time periods (1942, 1955, and 1980) beginning with the earliest photography available. Photos from 1942 and 1955 were at the 1:20,000 scale, and photos from 1980 were at the 1:40,000 scale. Six sample areas were studied, each of which was 2,116 ha (4.6 km on a side), the area of an aerial photograph at the 1:20,000 scale. The six samples were contiguous, and the total sample landscape of 12,696 ha represented approximately 12% of the county.

Five land uses were identified on the photographs: (1) urban; (2) cropland; (3) abandoned cropland (transitional land); (4) pasture; and (5) forest. Patches (contiguous areas of the same type) of each land use were delineated, and a square grid representing 1 ha cells was then overlaid on the pattern. Cells were considered to be wholly in one or another of the discrete land uses, and land use patterns were digitized to form a land use matrix. The descriptors of spatial pattern were calculated for each land use matrix, and the 1942 landscape patterns served as initial conditions for simulations.

Model development

There are several challenges in simulating changes in land use patterns. First, land use changes are not strictly Markovian: *i.e.*, the change of state of a cell is not simply a function of its current state but is influenced by surrounding cells. For example, a patch of abandoned land adjacent to an urban area is more likely to become urban than a similar patch that is further away. Thus, there are spatial neighborhood effects. Second, the transition rates are not constant through time. The rate of cropland abandonment in Georgia, e.g., has decreased substantially since the early part of the century (Johnson and Sharpe 1976, Turner 1987). Dynamic transition probabilities are thus required. Third, the causation of land use transition may be largely economic rather than natural (Burnham 1973, Alig 1986), and the use of empirical transition rates masks this causality. Finally, there are practical difficulties with the approach, including defining the states and obtaining the transition probabilities by independent measurement, rather than'inference (Lippe *et al.* 1985).

Given these constraints, I developed a land use transition model using empirically estimated transition probabilities. Simulations were done at random and with spatial influences. In the random simulation, the transition of a cell in the land use matrix was only a function of the transition prob-

Table 1. Transition probabilities[a] used in the simulations of land use changes in Oglethorpe County, Georgia

First time period (1942-1955)

	Urban	Crop	Trans.	Pasture	Forest
Urban	1.00				
Crop		.80	.19	.01	
Trans.	.01		.77		.22
Pasture				1.00	
Forest					1.00

Second time period (1955-1980)

	Urban	Crop	Trans.	Pasture	Forest
Urban	1.00				
Trans.		.430	.570		
Trans.	.008		.212		.780
Pasture				1.00	
Forest					1.00

[a] $p_{i,\,j}$ indicates the probability of making a transition from land use i to land use j.

Note: Trans. refers to transitional land, primarily abandoned cropland.

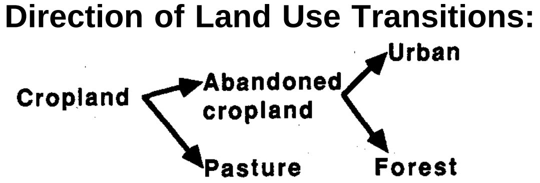

Fig. 1. Direction of net land use changes in Oglethorpe County, Georgia.

ability. Spatial influences were then simulated in two ways, one in which the four adjacent neighbors influenced the transition, and one in which eight neighbors (adjacent and diagonal) influenced the transition. The spatial influence algorithm using eight neighbors has been described in detail elsewhere (Turner in press (b)), and will only be summarized briefly here:

The four or eight neighbors of each cell in the land use matrix are examined, and a transition index is calculated for each cell. The index is a function of the number of neighbors of state j (n_j) and the probability of i going to j ($p_{i\,j}$), and is equal to the maximum value of $n_j * p_{i\,j}$, where j = 1, . . . , number of states. The cell in the land use matrix that has the highest transition index is then changed to the appropriate new state. The transition indices are then recalculated, allowing a ‘domino effect’ to occur where patches can grow or shrink. If there are no neighbors of type j to effect a particular i, j transition, cells of type i are selected at random and changed to j. This may occur, for example, when urban land appears for the first time. During a simulation interval, a cell can be changed only once. When the number of transitions reaches the allowable number, the new land use matrix is output and the spatial pattern analyzed.

Simulations

Simulations of Oglethorpe county were begun with the land use patterns from the 1942 photographs. Land use changes were simulated for two iterations, representing the 1942-1955 period and the 1955–1980 period. Each 2,116 ha sample area was simulated separately (n = 6). Transition probabilities for each interval (Table 1) were derived empirically from net changes in land use for the county from sources other than the aerial photos, such as the Census of Agriculture and Forest Service Surveys. Transition probabilities were established such that urban, pasture and forest lands were sinks (the probability of changing from one of these states to any other was zero), all gains to urban and forest land came from abandoned land, and cropland could be abandoned or converted to pasture; thus, transition probabilities only represented net changes (Fig. 1). The same probabilities were used in each of the simulations.

Analysis of landscape pattern

Descriptive statistics of spatial pattern are necessary to evaluate the behavior of the models and to identify temporal trends in landscape pattern. Although there are a variety of measures that can be used, I will focus on the following descriptors of spatial pattern: (1) the number and mean size of patches of each land use; (2) the fractal dimension of patches of each land use; and (3) the amount of edge between different land uses.

Table 2. Actual and simulated proportions[a] of land area by land use, Oglethorpe County, Georgia

Land use	1942	1955		1980	
	Actual	Actual	Simulated	Actual	Simulated[b]
Urban	.00 (.30)	.00 (.01)	.01 (.00)	.01 (.02)	.01 (.00)
Cropland	.44 (.09)	.35 (.11)	.34 (.07)	.15 (.07)	.15 (.03)
Abandoned cropland	.43 (.06)	.41 (.10)	.42 (.03)	.28 (.07)	.28 (.04)
Pasture	.00 (.00)	.01 (.01)	.01 (.00)	.01 (.01)	.01 (.00)
Forest	.13 (.05)	.22 (.05)	.21 (.05)	.54 (.05)	.55 (.07)

[a] Mean (standard deviation); n = 6 sample areas.

[b] The same proportions of land uses were simulated in the random and spatial models.

A patch was defined as contiguous, adjacent cells of the same land use; diagonal neighbors were not included as part of the same patch. Each patch in the land use matrix was located and its size (S) and perimeter (P) were recorded. Mean numbers of patches and patch sizes were calculated using SAS (SAS Institute 1982). The size and perimeter data were also used to calculate the fractal dimension (Mandelbrot 1977, 1983) of each land use, which was used to measure the complexity of patch perimeters. In this analysis, the fractal dimension can range from 1.0-2.0, with 1.0 representing the perimeter of a perfect square and 2.0 representing a very complex perimeter encompassing the same area. For grid cell data, the fractal is calculated using an edge to area relationship (Burrough 1986, Krummel *et al.* 1987) where (P/4) is the length scale used in measuring P. For each land use in a matrix, linear regression analysis of log (P/4) against log (S) of each patch was done using SAS. The fractal dimension of the patch perimeters is equal to twice the slope of the regression line. It can then be used to compare the geometry of landscape mosaics (Milne in press).

The amount of edge between each land use was determined by summing the number of interfaces between adjacent cells of different land uses, then multiplying by 100 m (the length of a cell). These data were then analyzed with SAS using ANOVA, and means were differentiated using Bonferroni t tests.

Results

The proportion of land in different land uses changed between 1942 and 1980 in the actual and simulated landscapes (Table 2). In the real landscape, forests increase from 13% to 54%, urban and pasture both increased from 0% to 1%, and cropland declined from 44% to 15%. There was close agreement between the simulated and actual landscapes in the proportion of area in each land use. Given that the proportions were adequately simulated, were the spatial patterns similar?

The mean number and size of patches of major land uses are shown in Figs. 2 and 3. For all land uses, the random model simulated two to three times as many patches as occurred in the real landscape (Fig. 2) with the average patch size significantly smaller than in the real landscpe (Fig. 3).

The mean number and size of cropland patches declined during the study period (Figs. 2 and 3, top), and both spatial models appeared to simulate this adequately. For abandoned cropland, however, the spatial simulations predicted fewer, larger patches than were observed in the landscape (Figs. 2 and 3, center). Mean patch size of these transitional lands did not change in the actual landscape, remaining at approximately 10 ha. Both spatial models, however, projected an increase in patch size to approximately 17 ha.

The spatial models yielded different results for forests. Both simulated too few patches of forest, but the 4-neighbor simulation was closer to the actual data than the &neighbor simulation (Fig. 2,

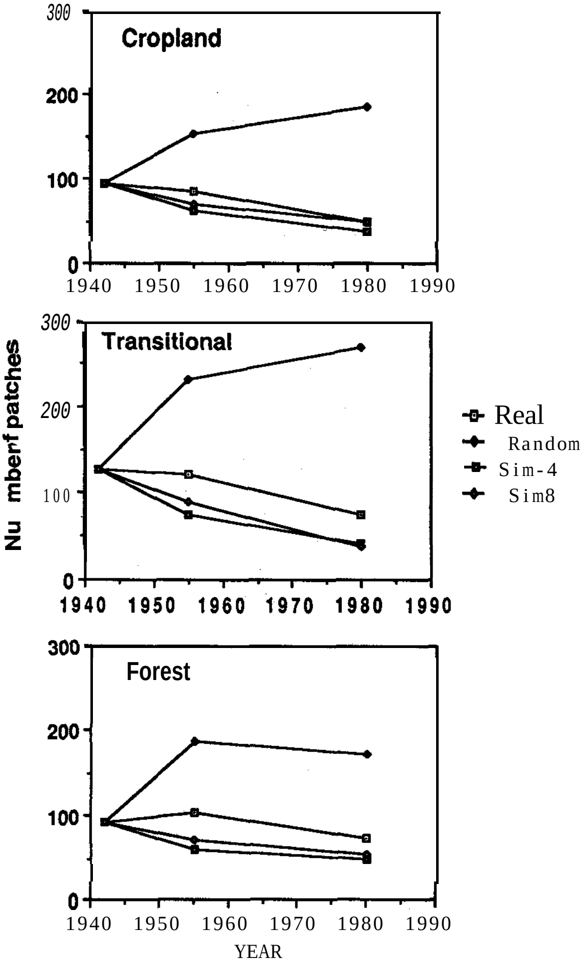

Fig. 2. Simulation results and actual data for mean number of patches of major land uses, Oglethorpe County, Georgia (n = 6). Transitional-land is primarily abandoned cropland.

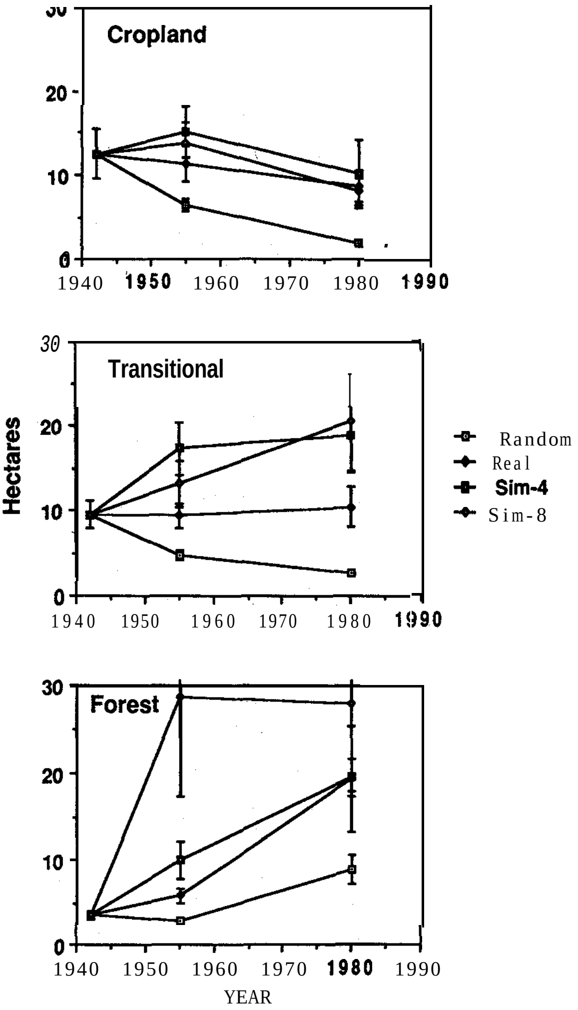

Fig. 3. Simulation results and actual data for mean size of patches of major land uses, Oglethorpe County, Georgia. Error bars are ± two standard errors, n = 6. Transitional land is primarily abandoned cropland.

bottom). Mean forest patch size was also better simulated by the 4-neighbor simulation (Fig. 3, bottom). The S-neighbor model simulated forest patches that were as much as five times larger (1955) than actual.

Determinations of the fractal dimensions were all highly significant ($p < .0001$) with r^2 values ranging between 0.96 and 0.98. Fractal dimensions (D) of patches varied by simulation (Fig. 4). For cropland, D was 1.35 in 1942 and remained fairly constant through 1955 and 1980. In the random simulation, D increased rapidly to 1.45, indicating more complexly shaped boundaries of cropland patches. The 4- and S-neighbor models simulated cropland patches with D approximately 1.35 in 1955, declining to 1.31 (4-neighbor simulation) and 1.29 (S-neighbor simulation) by 1980. This suggests that the perimeters of simulated cropland patches were slightly less complex than in the actual landscape.

The fractal dimension of forests in the real landscape was 1.32 in 1942, declining to 1.28 in 1980. In forest patches that were simulated at random, the fractal dimension increased to 1.44 by 1980, similar to the cropland patches. The spatially influenced models both simulated forest patches with low fractal dimensions, 1.20 (4-neighbors) and 1.22

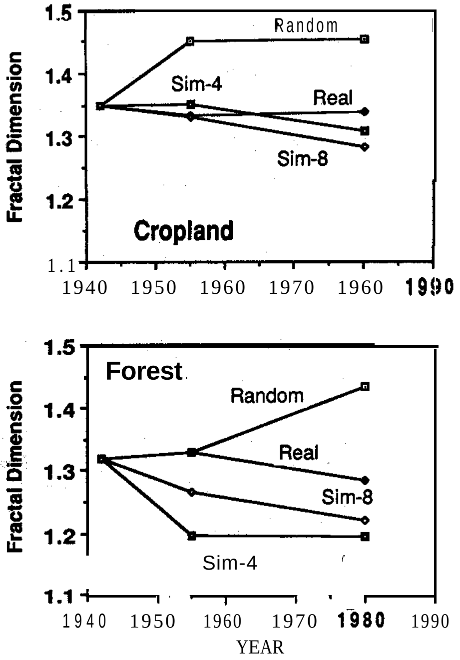

Fig. 4. Simulation results and actual data for fractal dimension of cropland and forest patches, Oglethorpe County, Georgia. The fractal dimension can range from 1.0 to 2.0, with 1.0 representing the perimeter of a perfect square and 2.0 representing a very complex perimeter encompassing the same area.

(S-neighbors) in 1980. This suggests that boundary shapes of the simulated forest patches were much less complex than those of the actual patches. The 8-neighbor simulation represented forest boundary complexity better than the 4-neighbor simulation.

Edges in the landscape were always higher in the random simulations than in the actual landscape or the spatial simulations (Table 3). The spatial models were more successful in simulating edges between some land use combinations than others. The cropland-abandoned cropland edge and the cropland-forest edge showed no significant difference in the spatial simulations and the real landscape (Table 3). Thus, these boundaries were adequately represented in the models. However, the forest-abandoned cropland edge varied by simulation in 1955, and in 1980 there were significant differences between therandom and spatial simulations and the real data. The spatial simulations underrepresented this edge by as much as 50%.

Total edge in the landscape (Table 3) was best represented by the 4-neighbor spatial simulation, which did not differ from the actual landscape. The g-neighbor model simulated approximately 20% less edge than the real landscape, and the random model simulated 100% more edge.

Table 3. Simulated and actual edge (km) between land uses in a 2,116 ha area of Oglethorpe County, Georgia

	Cropland - Abandoned cropland			
1955	Random 92.0	Real 54.1	Sim-4 53.0	Sim-8 46.1
1980	Random 49.3	Sim-4 16.8	Real 13.9	Sim-8 8.9
	Cropland - Forest			
1955	Random 30.1	Real 25.8	Sim-4 21.7	Sim-8 21.0
1980	Random 43.7	Sim-8 29.1	Real 27.6	Sim-4 23.1
	Forest - Abandoned cropland			
1955	Random 14.6	Real 51.5	Sim-4 30.9	Sim-8 28.6
1980	Random 103.1	Real 48.1	Sim-4 30.9	Sim-8 22.9
	Total edge between land uses			
1955	Random 203.6	Real 135.3	Sim-4 111.7	Sim-8 103.4
1980	Random 204.5	Real 96.4	Sim-4 84.5	Sim-8 69.8

Underlined means do not differ ($p < .05$, Bonferoni t tests, n = 6).

Notation

Sim-4 = spatial model with 4-neigbors influencing the transitions; Sim-8 = spatial model with g-neighbors influencing the transitions; Random = random simulation; Real = actual data.

Discussion

The random simulation model produced highly fragmented landscape patterns that were quite different from the actual landscape. This difference supports the non-Markovian nature of land use changes, suggesting there are contagion effects. Differences between random simulations and actual landscapes may be useful in identifying landscape effects (Gardner *et al.* 1987, this journal).

The spatial models simulated the clustering of certain land uses, such as cropland, reasonably well. However, for other land uses, the spatial arrangement of patches was not as complex as in the actual landscape. This variation in simulation adequacy by land use suggests that different factors may influence particular land use transitions. Cropland in the piedmont was generally abandoned from the outside margins inward, and the spatial models adequately captured this shrinking pattern. Abandoned cropland exhibited a geometry similar to that of cropland. However, the boundary between abandoned cropland and forest was not adequately modeled, suggesting that this transition was more complex than the ‘domino effect’. Information about topography or other edaphic conditions is probably necessary to differentially weight the neighborhood effects that influence forest development. Incorporation of edaphic factors should improve the model’s representation of the complex boundary between the forest and transitional lands.

The scale of transitions may also vary by land use. Different scales may affect managed and natural patches (Krummel *et al.* 1987) since a primary influence of humans is to rescale patterns in time and space (Urban *et al.* 1987). It would be useful to incorporate variable scales of land use transitions into the model.

An alternative modeling approach is the development of mechanistic models that run simultaneously in the cells of a landscape matrix (e.g., Sklar *et al.* 1985, Sklar and Costanza 1986). This approach has been successful in a physically driven wetland environment, but it is difficult to translate to land use patterns. To be predictive in a human-dominated landscape, the economic or social mechanisms driving land use transitions should be incorporated into the model. Such dynamically generated transition probabilities would be preferable to empirical ones and might allow for greater cyclic change between land uses.

The modeling approach described here has the potential to adequately represent changing landscapes patterns statistically. To predict the course of an individual parcel of land, much additional information would be necessary. However, this type of spatial transition model can provide the basis for simulating flows across landscape boundaries (Wiens *et al.* 1985), provided the edges are adequately represented. Flows might include the dispersal of organisms, movement of water and dissolved chemicals, or the spread of disturbance. The modeling approach is thus a potentially general one for simulating pattern and function in ‘human-influenced landscapes.

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