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LAND COVER ALONG AN URBAN–RURAL GRADIENT: IMPLICATIONS FOR WATER QUALITY

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Abstract. Development pressures in rural mountainous areas of the United States hold crucial implications for water quality. Especially important are changes in the extent and pattern of various land uses. We examine how position along an urban–rural gradient affects landscape patterns in a southern Appalachian watershed, first by testing for the effect of distance from an urban center on land-cover change probabilities and then simulating the implied development of a landscape at regular distance intervals. By simulating a common hypothetical landscape we control for variable landscape conditions and define how land development might proceed in the future. Results indicate that position along the urban–rural gradient has a significant effect on land-cover changes on private lands but not on public lands. Furthermore, position along the gradient has a compounding effect on land-cover changes through interactions with other variables such as slope. Simulation results indicate that these differences in land-cover changes would give rise to unique "landscape signatures" along the urban–rural gradient. By examining a development sequence, we identify patterns of change that may be most significant for water quality. Two locations along the urban–rural gradient may hold disproportionate influence over water quality in the future: (1) at the most remote portion of the landscape and (2) at the outer envelope of urban expansion. These findings demonstrate how landscape simulation approaches can be used to identify where and how land use decisions may have critical influence over environmental quality, thereby focusing both future research and monitoring efforts and watershed protection measures.

Key words: land-cover dynamics; landscape ecology; simulation modeling; southern Appalachians; water quality.

INTRODUCTION

Water connects and focuses activities throughout a watershed, defining the cumulative impacts of human use of land and resources. The use and condition of land in particular have a profound influence on water quality (Allan and Flecker 1993, Hunsaker and Levine 1995). Integrating social and environmental vitality within properly scaled ecosystems requires a different focus for science, involving both defining mechanisms that organize human behavior and then linking human endeavors and environmental quality. This linkage between people and the environment is bidirectional, involving both the effects of people on ecosystems and the effects of ecosystem structure and environmental quality on people's well-being. Because water quality is so clearly impacted by people's use of resources, and because human well-being is so clearly linked to the availability of clean water, water provides perhaps the strongest demand for social–ecological interdisciplinary research (Naiman et al. 1995).

This article examines factors that organize human behavior in a developing landscape and examines the potential consequences for water quality. The overarching theme is that by understanding patterns of development and linking them to their implications for water quality, planning and regulatory efforts then can be focused on areas critical in determining environmental quality. For example, knowledge of this sort can be used to identify where land use is most likely to be intensified within a watershed and, conversely, where it will likely remain stable or change in only trivial ways. In a world of limited resources, this kind of targeting may be much more effective than broad regulations intended to protect water quality (Wear et al. 1996).

Our specific focus is on understanding patterns of land use change along the urban–rural gradient in the Southern Appalachian Highlands. Portions of this region have experienced nearly exponential population growth with associated development of land since the 1950s. Growth centers have included Hendersonville

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and Boone, North Carolina, USA. In areas where population growth and development are in initial phases, it may be possible to anticipate and thereby redirect some development that would prove detrimental to environmental and aesthetic qualities. We test various hypotheses regarding the way that development, measured as extent and patterns of land-cover change, is organized along the urban–rural gradient and then examine how these changes could be related to planning for the protection of water quality in a developing landscape. In particular, we use statistical models of land-cover change to test whether: (1) land-cover changes are generally determined by topographic and locational features, (2) land-cover regimes are influenced by position along the urban–rural gradient, and (3) land-cover changes differ between public and private lands at various positions along the urban–rural gradient. We use a simulation experiment to test for: (1) differences in the implied equilibrium land cover at different positions along the urban–rural gradient and (2) Implied changes in equilibrium land cover as development proceeds. Findings from these tests are then used to explore the implications that continued development might have for water quality in the southern Appalachians.

Study Area and Data

Our study site was the Little Tennessee River basin in southwestern North Carolina, USA, extending from the North Carolina border north to Fontana Dam and including all of Macon County and parts of Jackson, Swain, and Clay counties. This 104 000-ha area is mountainous with a diverse complement of forests and human residents. The region has grown considerably in the last two decades, with the population in Macon County expanding by ~20% between 1980 and 1990 (SAMAB 1996*b*). Most growth has radiated from Franklin, the Macon County seat, which also serves as the dominant central place for most services and commerce.

Data for the estimation of statistical land-cover change models were compiled as layers in the Geographic Resources Analysis Support System (GRASS) geographic information system (USACERL 1991, see Turner et al. 1996 for complete description). For this analysis we used the following data layers:

1) Land cover interpreted for 1975 and 1980 from Landsat Multi-spectral Scanner (MSS) imagery. Three classes were identified: (1) forest, (2) grassy, and (3) unvegetated.

2) Slope, aspect, and elevation derived from 7.5 foot (2.286 m) digital elevation model (DEM) data obtained from the U.S. Geological Survey.

3) Land ownership digitized from U.S. Forest Service and other maps.

4) Primary and secondary road locations and population density from TIGER/Line Census files in ARC/Info format.

All data were converted to a raster format using an approximate 90-m square grid cell (cell size was limited by the resolution of the MSS imagery).

Methods

We considered urbanization to be a factor or gradient that organizes disturbance regimes and ecosystems in general (see McDonnell and Pickett 1990). The urbanization gradient is best viewed as describing a whole complex of processes that have a bearing on ecosystem structure and function. Two somewhat problematic measures of position along an urban–rural gradient are candidates: human population density and distance to the closest metropolitan area. For this study we chose to measure position along the gradient as the travel distance along roads to the closest city (scaling should not be a problem, because we measure distance with respect to only one city). However, we also include population density as an explanatory variable in the empirical analysis of land-cover changes and account for its covariance with distance. Human population density was not used to measure position along the gradient because, while it is measured by the U.S. Census Bureau for relatively small tracts, the size of the tract increases as population density decreases. Heterogeneity within tracts therefore increases towards the rural end of the gradient.

We applied both empirical and simulation analysis to study the effects of the urban–rural gradient on land-cover patterns. First we extended previous empirical analysis of land-cover change in the southern Appalachians (Turner et al. 1996) to test for effects of position along the gradient on probabilities of land-cover changes. We measured land-cover change from satellite images and related the observed change (or lack of change) to various topographic, social, and locational variables, including position on the urban–rural gradient. We tested for the effect of position on the urban–rural gradient after accounting for the influence of other variables through regression analyses. Comparing different forms of the regression models defines tests for the extent and form of the influence that position on the gradient has had on land-cover changes. Estimated regression models also provide useful insights into the probability that specific changes may occur. However, it is the long-term interaction of these changes that eventually shape a landscape.

To examine the potential cumulative impacts of all land-cover changes taken together, we constructed a simulation model that applies the empirical land-cover change models to a specific landscape for a long period of time. To isolate the effect of position along the urban–rural gradient on landscape development, we constructed a hypothetical landscape with topographic and social conditions in the range of those observed in the study area. We then simulated the development of this hypothetical landscape at different positions along the urban–rural gradient and measured various features of landscape structure at each position.

Statistical models of land-cover change

Observed land-cover changes are the outcomes of decisions by landowners regarding the uses of their lands. Following Turner et al. (1996), we posited that land use choices reflect the highest valued utilization of the site, and changes in land use reflect changes in the ordering of alternative use values. While utility derived from various uses is not observed, the outcomes of, and inputs to, utility comparisons are observed. We assumed that the utility derived from changing land uses is a function of variables that describe the topography and locational characteristics of a site (e.g., slope, distance to road, and distance to a market center), and therefore influence both the benefits and costs associated with each land use. Because we examine land-cover change for a single time period in a relatively small area, we assume that the values of produced goods and services are constant across sites. Accordingly, differences in land use between sites depends on site-specific features that influence the production of goods and services and the costs related to the operability and accessibility of the site. The net benefits of a site dedicated to land use i (NB_i) can be described as:

$$\mathrm{NB}_i = B(\mathrm{pr}, X) - C(X) \qquad (1)$$

where $B(\mathrm{pr}, X)$ defines benefits that depend on prices of produced goods and services, pr, and site characteristics, X, and $C(X)$ defines costs that are dependent only on the structural and locational characteristics of the site. Pr are fixed across the study area, so spatial differences in use-values within the study area are completely described by the attributes of the site (X).

The probability of land-cover change can be estimated using a multinomial Logit model (Turner et al. 1996). The probability of land cover for a grid cell changing from an initial class i to class j (P_{ij}) is defined as:

$$P_{ij} = \frac{e^{(X'\beta_j)}}{\sum_{s=1}^{k} e^{(X'\beta_s)}} \qquad j = 1, \ldots, k \qquad (2)$$

where k is the number of land-cover states. For each initial land-cover class i, k land-cover change equations are defined (including the null case of no change). Among explanatory variables contained in X is the distance from the grid cell along roads to the closest city where products could be marketed or services procured. We use this variable to define the position of the cell along the urban–rural gradient.

Equation 2 defines the simple case where distance has an additive relationship to other variables in the Logit model. To test for more complex interactions between position along the urban–rural gradient and land-cover probabilities, we defined a varying-parameters model that allows the effect (coefficient) of each X variable to vary with position along the gradient through a set of interaction terms. A quadratic varying-parameters model is implemented by introducing the set of interaction terms into the Logit model as follows:

$$P_{ij} = \frac{e^{(X'\alpha_j)}}{\sum_{s=1}^{k} e^{(X'\alpha_j)}} \qquad j = 1, \ldots, k \qquad (3)$$

where $\alpha_i = \alpha_{j0} + D\alpha_{j1} + D^2\alpha_{j2}$, D is the distance variable and X now includes the intercept and all structural and location variables describing the site except distance.

The models (Eq. sets 2 and 3) were estimated using a sample of observations on land-cover change between 1975–1980 and measures of the following variables (elements of X): (1) slope, (2) elevation, (3) population density, (4) distance to the closest road, and (5) distance along road to the city of Franklin, North Carolina. Separate equation sets were estimated for the three initial cover types and for public and private lands. Models were estimated using a maximum likelihood procedure in the software package LIMDEP (Greene 1995).

The significance of models was tested against the null of no explanatory power using log-likelihood ratio tests. In addition, because equation set (2) is a constrained version of (3), we tested the significance of the varying parameters model against the null of the linear model using log-likelihood ratio tests (see Judge et al. 1985). The effect of position along the urban–rural gradient on land-cover changes was similarly tested by estimating constrained models with all coefficients related to the distance variable set to zero and then comparing likelihood values with the appropriate unconstrained model (standard tests on individual coefficients were not applicable because of multiple coefficients related to each variable). Other explanatory variables were tested in the same manner.

Simulation experiment

To examine the effects of position along the urban–rural gradient on landscape structure and water quality, we conducted a landscape simulation experiment. The simulation approach was applied because physically similar areas could not be identified at regular intervals along the gradient. Instead we simulated development of a common hypothetical landscape using the statistical estimates of land-cover change models described in the preceding section. Comparisons were constructed by simulating development at various distances from Franklin. Moving from urban to rural positions along the gradient also defined a development sequence for the landscape. Comparisons between adjacent landscape positions indicate how land would develop as the

TABLE 1. Range of variables in data set used for statistical analyses.

Name	Units	Minimum	Maximum
Slope	degrees	1	36
Distance to road	cells	1	44
Distance to Franklin	cells	8	618
Population	individuals/square mile	15	1415
Elevation	meters	521	1521

edge of the city moved outward, and where changes would be the most severe.

The hypothetical landscape.—A landscape characteristic of the study area in terms of the independent variables (X) was constructed by using observed variable ranges (Table 1) as a general guide. The landscape was defined as a 50 × 50 one-hectare cell matrix for a total size of 2500 ha. Topography was defined as shown in Fig. 1 and slope was calculated using the greatest absolute difference in elevation between adjacent cells. A road was placed along the diagonal of the landscape with the lower left corner being closest to Franklin. Distance to the closest road was calculated in cell lengths. Position along the urban–rural gradient was calculated differently for each scenario.

The density of population varies along the urban–rural gradient, with highest concentration in Franklin and declines with distance. To assign population density to individual cells, we estimated a regression model that defined population density (PD) as a function of distance from town and the slope of the site. We used an inverse logistic functional form,

$$\mathrm{PD} = K\left(1 - \frac{1}{1 + e^{\alpha+\beta_1\mathrm{DTOT}+\beta_2\mathrm{SLOPE}}}\right) \quad (4)$$

and the model was estimated using ordinary least squares applied to a log-odds form:

$$\log\left(\frac{Z}{1 - Z}\right) = \alpha + \beta_1\mathrm{DTOT} + \beta_2\mathrm{SLOPE} \quad (5)$$

where $Z = \mathrm{PD}/K$ and K is the maximum population density for the rural areas of the study site and DTOT is a measure of total distance (distance to Franklin along roads plus two times the distance to the closest road). K was set at 176 individuals/km^2 (only 5% of the area had a density >176 individuals/km^2). Because scenarios varied according to the distance variable, population density was calculated differently for each scenario. For scenarios involving U.S. National Forests, the population density was set at a constant 9.54 individuals/km^2.

Simulation structure.—Each simulation started with a completely forested landscape. Estimated land-cover change equations were then used to estimate the transition probabilities for each of the 2500 cells and land-cover changes were implemented using comparisons with random number draws. This process was completed for 50 five-year time steps (by 50 time steps each simulated landscape had reached a stable structure in terms of amount of cover by type) and a map of the resulting landscape was stored for subsequent analysis

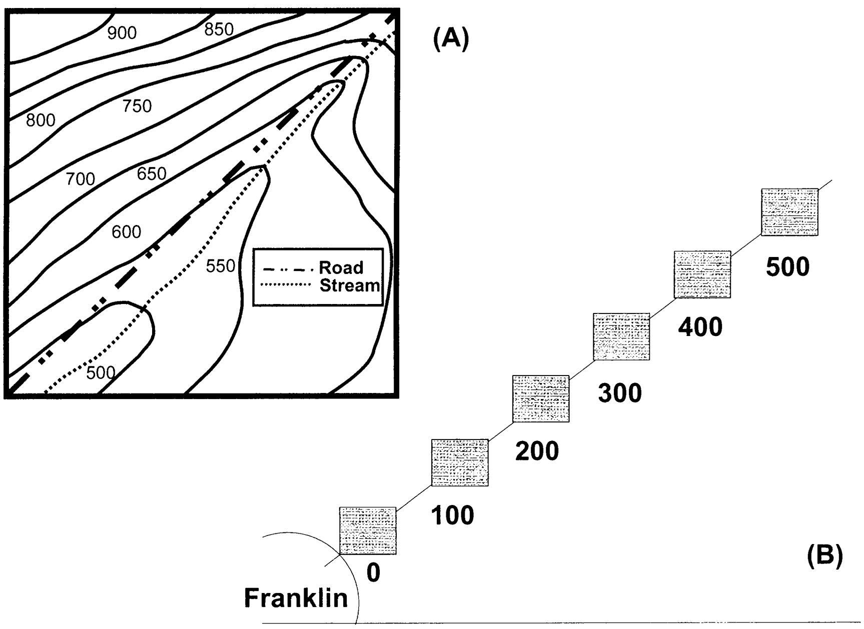

FIG. 1. (A) Elevation profile (meters) and road location for the hypothetical landscape and (B) positioning of the hypothetical landscape for simulation scenarios (scenario labels indicate the distance in cell lengths from Franklin, North Carolina, to the lower left corner of the landscape).

TABLE 2. Significance tests for Multinomial Logit models of land-cover change. Log-likelihood ratios are reported for testing overall significance of the referenced model.

	Ownership			
	National forest		Private	
Initial land cover	Linear	Varying parameter	Linear	Varying parameter
Forest	31.15*	53.65*	205.80*	282.33*
Grassy	NA	NA	36.42*	74.14*
Unvegetated	8.51	19.66	37.13*	58.11*
Degrees of freedom	10	28	10	28

Note: Critical chi-squared values are 41.34 (28 df) and 18.31 (10 df).
* Indicates significance ($P = 0.05$).

(each scenario was replicated five times). To compare land-cover patterns over the urban–rural gradient, this simulation experiment was completed at six different distances from Franklin for both public and private lands. The hypothetical landscape was placed first at the edge of Franklin and then was moved away from the city at 100 cell-length intervals (10 km; Fig. 1) to cover the range of the distance variable in the test data set (see Table 1). We label these scenarios by their distance from Franklin; i.e, "0," "100," and so on.

Analysis of simulated landscapes.—Each simulated landscape was analyzed using a landscape analysis software package (SPAN, Turner 1990). The amount of cover, number of patches, and area-weighted patch size were computed for each of the three cover types. Patches were defined as groups of contiguous adjacent (horizontally or vertically) cells of the same cover type. Total edge between all cover types was calculated along with two overall landscape indices. Dominance, D, measures the deviation from maximum possible landscape diversity and ranges from zero to one, with higher values indicating a landscape dominated by one or few cover types (O'Neil et al. 1988). Contagion, C, measures the aggregation of land-cover types and also ranges from zero to one (Li and Reynolds 1993). High values of C indicate a clumped distribution of land cover, whereas low values indicate a dispersed arrangement.

These landscape metrics can be generally linked to water quality. Research by Swank and Bolstad (1994) in the Coweeta Creek watershed, a part of the Little Tennessee River Basin (Coweeta Creek is 4350 ha or roughly twice the size of our hypothetical watershed), indicates significant correlations between landscape metrics and chemical, physical, and bacterial measures of baseflow water quality. Of the landscape metrics they considered, the percent of non-forest land use and the density of buildings defined significant relationships with the largest number of water quality variables. In addition, findings of a recent assessment of the southern Appalachian region ascribe two-thirds of all water quality impacts with activities associated with either mining or non-forest land uses (SAMAB 1996*a*). Hunsaker and Levine (1995) similarly found that percentage of non-forest cover has a strong influence on water quality in rivers in Illinois and Texas. They also found contagion and dominance of land cover to be related to various measures of water quality.

These findings suggest using the share of non-forest land within the watershed as an indicator of overall landscape effects on water quality. To further capture the effects of spatial pattern on water quality, we constructed another measure that weighted non-forest cover by proximity to the major stream in our hypothetical landscape (Fig. 1). The resulting non-forest index (NFI) is:

$$\mathrm{NFI} = \left|\sum_{i=1}^{n}\sum_{j=1}^{n}\left(\frac{Y_{i,j}}{(d_{i,j}+1)}\right)\right| \Big/ Y_{\max} \qquad (6)$$

where Y_{ij} is a binary variable equal to 1 when cell i,j is in non-forest cover (zero otherwise), d_{ij} is the distance from cell i,j to the stream in number of cells (because a cell containing a stream cell has distance equal to zero, we add one cell length to each distance in the denominator), and $Y_{\max}$ is the maximum possible value of the sum in brackets (i.e., if all cover was non-forest). NFI therefore ranges from 0 for no non-forest cover effects, to 1 for maximum effects, and water quality should be inversely related to the non-forest index.

Post-simulation analysis.—Landscape metrics were compared between simulated landscapes. ANOVA was used to do pairwise comparisons of means of the landscape metrics for adjacent scenarios along the urban–rural gradient (the GLM procedure in SAS was used; SAS Institute 1990). In addition, public and private lands were compared at each location along the gradient.

RESULTS

Land-cover change models

Based on likelihood ratio tests, estimated land-cover change models (Eq. 2 and 3) are different for public and private lands (Table 2). For private land, the simple linear formulation (Eq. 2) proved significant in explaining land-cover transitions for all three initial cover types (forest, grassy, and unvegetated). For public lands, only the model for transitions from forest proved significant using Eq. 2. We could not reject the null hypothesis of no explanatory power for the linear model applied to the unvegetated cover type (there were not enough observations to estimate the models for grassy cover on public lands). This is consistent with the observation that almost all cells with non-forest cover types in 1975 became forest in 1980 on U.S. National Forest land.

For private lands, the varying parameters models

TABLE 3. Tests of significance of varying parameters vs. linear formulation of land-cover change models (null is the linear model). Log-likelihood ratios are reported.

Initial land cover	Ownership	
	National forest	Private
	Log-likelihood ratios	
Forest	22.5	76.52*
Grassy	NA	37.70*
Unvegetated	NA	20.98*

Note: Critical chi-squared value is 28.87 (df = 18).
* Indicates significance ($P = 0.05$).

(Eq. 3) provided a significant improvement over the linear formulation (Eq. 2) in the explanation of land-cover changes for forest and grassy cover types (Table 3). This indicates that position on the urban–rural gradient significantly interacts with the other variables in defining the propensity of landowners to change land cover. The implication for the effect of slope, for example, is that slope is less of a constraint on clearing forests closer to Franklin than farther away. For unvegetated private land the varying-parameters model did not provide significant improvement over the linear formulation. On public lands, we conducted the test for forest transitions only and found that the varying parameters model provided no significant improvement for explaining land-cover change on this ownership, indicating an additive rather than multiplicative effect of position on the urban–rural gradient on land-cover changes.

Tests of the significance of position on the urban–rural gradient and other explanatory variables were applied to the models indicated by the preceding tests. That is, we tested their effects in varying-parameters models for grassy and forested land in private ownership and the linear formulation for unvegetated land on forested land in public ownership (no such tests were constructed for grassy and unvegetated land in public ownership). For all models estimated for private lands, position on the urban–rural gradient had a significant influence on land-cover change regimes (Table 4). Likewise, slope had a significant influence on all change models. Results for the other variables differed between models. Distance to road, elevation, and population density were all significant in explaining changes from unvegetated cover and insignificant in explaining changes from grassy cover. All variables except population density were significant in explaining changes from forest cover on private lands. Looking across all models for private lands, of the 15 tests of explanatory variables (five variables, three models), 11 indicated significant effects.

The results on public lands were much different. Only one model, the one for forest cover, was significant. Of the five variables examined for this model, only distance to road was significant in explaining changes from forest cover. For position on the urban–rural gradient, slope, elevation, and population density we could not reject the null hypothesis of no significant effects.

TABLE 4. Tests for significance of individual variables in specified land-cover change models. Log-likelihood ratios are for reported testing models constrained to exclude the referenced variable (numbers in parentheses are degrees of freedom).

Initial land cover	Variable	Ownership	
		National forest	Private
Forest	Gradient position	0.98 (2)	83.44 (20)*
	Distance to road	6.60 (2)*	14.06 (6)*
	Elevation	4.70 (2)	39.44 (6)*
	Slope	3.92 (2)	18.57 (6)*
	Population	2.70 (2)	5.41 (6)
Grassy	Gradient position		51.32 (20)*
	Distance to road		4.22 (6)
	Elevation		5.94 (6)
	Slope		14.46 (6)*
	Population		10.76 (6)
Unvegetated	Gradient position		12.34 (2)*
	Distance to road		9.32 (2)*
	Elevation		15.98 (2)*
	Slope		10.12 (2)*
	Population		16.42 (2)*

Note: Critical chi-squared values are 5.99 (2 df), 12.59 (6 df), and 31.41 (20 df).
* Indicates significance ($P = 0.05$).

Constructing the simulation model also required fitting the population density model, Eq. 5, using ordinary least squares. The coefficient estimates ($a = -0.8821$, $b_1 = -0.0035$, and $b_2 = -0.0158$) were all significant ($P = 0.01$) and indicated the expected inverse relationships between distance and slope and population density. The overall model was significant ($P = 0.01$) according to the standard F test.

Simulation results

We used the land-cover change models indicated by these tests to construct simulations of the 12 distance scenarios (six positions on the urban–rural gradient for the two ownerships). For private lands we applied the varying-parameters models of cover changes using Eq. 3. For public lands we applied a binary Logit model to explain changes from forest cover to non-forest cover (that is, we combined grassy and unvegetated cover into a non-forest cover class) which we categorize as "unvegetated." All unvegetated cover was then converted back to forest cover in the subsequent period. This is consistent with observed land-cover changes on National Forests in the study area, and warranted by our statistical findings (i.e., insignificant land-cover change models).

The results of one simulation run for each of the 12 scenarios are shown in Fig. 2 and mean values of landscape measures (five replications of each scenario) are shown for each scenario in Table 5. For private land (Table 5), the amount of forest cover increases substantially between the 0 and 100 distance scenarios, remains fairly constant from 100 through 300, and then increases again to distance scenarios 400 and 500. While the amount of non-forest cover decreases with distance from the city (though in an irregular pattern), it becomes less concentrated along this gradient. This is reflected in the patchiness of the landscape (see total patches in Table 5), which increases substantially between 0 and 100, peaks between the 200 and 300 distance scenarios, and then falls off in the 500 distance scenario. Total edge similarly is relatively low (600 cell lengths) close to town and increases to a peak at 300 and then declines to <600 cell lengths at the 500 distance scenario. According to this metric then the landscape is most complex in the middle of the gradient.

The non-forest index also differs substantially by position along the urban–rural gradient. On private land, its highest value is at the urban end of the gradient with a value of 0.74 (recall that the non-forest index is scaled between 0 and 1). It ranges between 0.38 and 0.52 for scenarios 100 through 400, and declines substantially to 0.20 in distance scenario 500. For public land, NFI shows a much smaller range, from 0.04 in distance scenario 0 to 0.12 in scenario 500.

For private lands, a majority of landscape attributes were significantly different between adjacent distance scenarios (e.g., 0 vs. 100, 100 vs. 200, etc. . . . , according to ANOVA tests). Of the 21 attributes evaluated, 10 were statistically different ($P < 0.05$) between every adjacent pair of distance scenarios. In contrast, measures of landscape pattern on public land were not statistically different between any adjacent pairs of scenarios. Differences in attributes were much smaller between scenarios for public land (Table 5). For public land, the share of the landscape that is in forest cover falls from 2446 ha (98%) adjacent to the city to 2331 ha (93%) for distance scenario 500. In addition, the total number of patches and the amount of edge increases from scenario 0 through scenario 500. While the range of effects is narrow, the model suggests that forest management activities increase somewhat towards the rural end of the urban–rural gradient.

At each position along the urban–rural gradient we also compared the two ownerships using ANOVA. For distance scenarios 0 through 400, comparisons of landscape metrics indicated significant differences between the private and U.S. National Forest ownerships for all metrics compared. For distance scenario 500, however,

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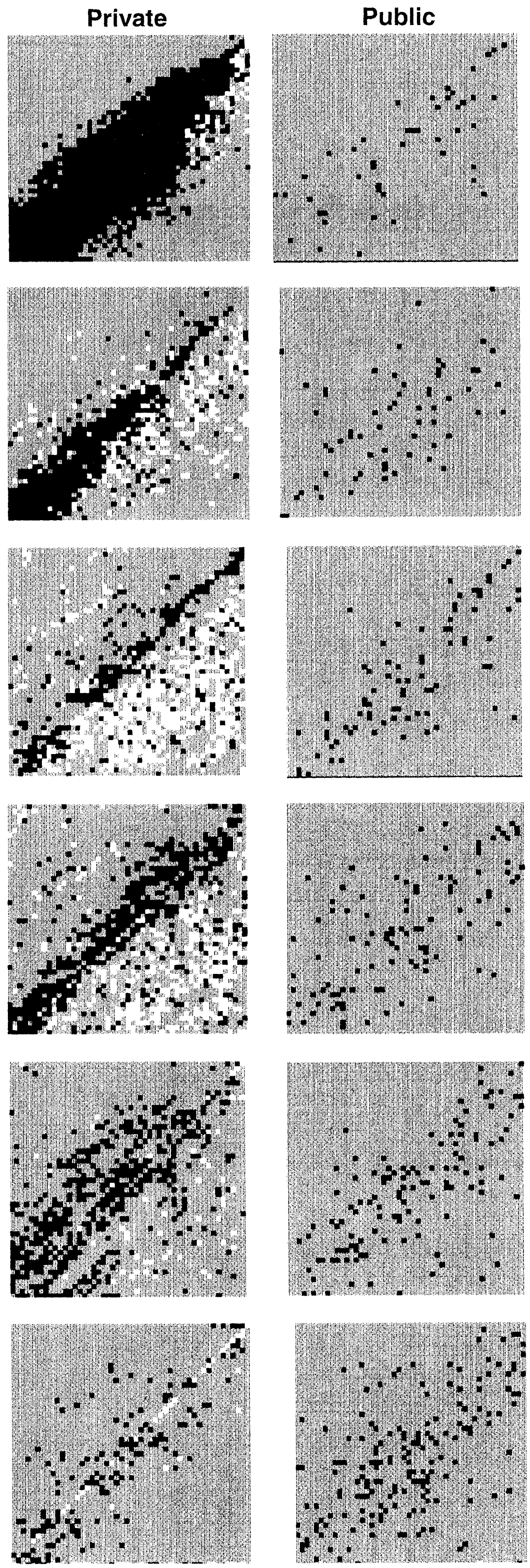

FIG. 2. Landscapes resulting from simulating land-cover change over 50 five-year time steps for each distance scenario applied to private and public land. Scenarios are defined by distance from Franklin, North Carolina (0 cells [top] to 500 cells [bottom] in increments of 100). Gray cells represent forest cover while white and black represent unvegetated and grassy cover, respectively.

TABLE 5. Measures of landscape pattern for six scenarios applied to private land (A), and six scenarios applied to public land (B) (scenario labels refer to distance from the edge of the hypothetical landscape to Franklin, North Carolina, in cell lengths). Values are means for five simulations of the hypothetical landscape.

	Distance constant					
Variable	0	100	200	300	400	500
A) Private land						
Amount of cover (hectares)						
forest	1448.2	1825	1716.2	1691.8	1961	2336.2
grassy	44.2	215.8	482.2	303.6	56.2	31.8
unvegetated	1007.6	459.2	301.6	504.6	482.8	132
Landscape indices						
dominance	0.3138	0.3152	0.2438	0.2322	0.4602	0.7508
contagion	0.728	0.6526	0.5956	0.6112	0.7106	0.7998
Edge (100 m)						
forest : grassy	82.8	486.2	893.6	723.4	174.2	101
forest : unvegetated	467	438.8	540.6	876.2	1109.2	422.8
grassy : unvegetated	56.2	164.6	215.4	156.6	39.8	23
Total	606	1089.6	1649.6	1756.2	1323.2	546.8
Largest patch (hectares)						
forest	936.8	1772	1212.6	930.6	1852.8	2332.6
grassy	8.4	23.2	83.2	18.2	3	1.4
unvegetated	946.2	354.6	62.6	186.8	53.8	6.8
Average patch size (hectares)						
forest	43.94	59.26	21.86	25.2	43.74	739.7
grassy	1.74	1.86	3.54	1.98	1.08	1.02
unvegetated	23.42	5.7	2.4	3.58	3.06	1.36
Weighted average patch size (hectares)						
forest	820.92	1720.84	890.84	706.24	1751.06	2329
grassy	3.82	5.86	28.72	4.86	1.22	1.04
unvegetated	888.88	274.92	23.14	91.46	14.36	1.96
Number of patches						
forest	33.8	31.8	79.4	67.8	45	3.2
grassy	26.2	117.2	137	151.8	51.4	31.2
unvegetated	43.4	81.2	126.0	141.2	157.6	97.0
Total	103.4	230.2	342.4	360.8	254.0	131.4
Non-forest index	0.74	0.52	0.42	0.51	0.38	0.2
B) Public land						
Amount of cover (hectares)						
forest	2445.8	2437	2420.8	2395.6	2356.8	2330.8
unvegetated	54.2	63	79.2	104.4	143.2	169.2
Landscape indices						
dominance	0.905	0.8928	0.872	0.842	0.8002	0.7748
contagion	0.9574	0.9506	0.9424	0.9392	0.9208	0.905
Edge (100 m)						
forest : unvegetated	204.2	236.6	293.4	385.8	514.4	582.4
Total	204.2	236.6	293.4	385.8	514.4	582.4
Largest patch (hectares)						
forest	2445.8	2437	2420.8	2395.4	2356.6	2329.8
unvegetated	2.2	2.6	3	3	4.4	6
Average patch size (hectares)						
forest	2445.8	2437	2420.8	2395.4	2356.6	2329.8
unvegetated	1.12	1.12	1.14	1.16	1.22	1.34
Weighted average patch size (hectares)						
forest	2445.8	2437	2420.8	2395.2	2356.4	2328.8
unvegetated	1.2	1.24	1.32	1.32	1.46	1.84
Number of patches						
forest	1	1	1	1.2	1.2	2
unvegetated	49.2	56.2	69.0	90.8	117.2	126.2
Total	50.2	57.2	70.0	92.0	118.4	126.4
Non-forest index	0.04	0.05	0.06	0.08	0.10	0.12

the pubic and private landscapes did not have significantly different land cover, patchiness, or forest edge. Only at this most remote location did private and public lands have similar attributes.

Evaluated in sequence, these simulations therefore show characteristic landscape patterns at each point along the urban–rural gradient. Distance scenario 0, which is on the urban edge, is dominated by large amounts of unvegetated and forest cover. Both cover types are highly aggregated, leading to low patchiness and high contagion. Distance scenario 0 reflects a mature, urbanized landscape profile, with a large share of unvegetated cover that is essentially stable and highly concentrated. Distance scenario 100 is consistent with the outer envelope of urbanization. Unvegetated cover is agglomerated along the road closer to town (lower left-hand corner), but signs of development taper off with distance (upper right-hand corner). The share of unvegetated cover falls by 54% from distance scenario 0. The contrasts in landscape structure between distance scenarios 0 and 100 are substantial: the weighted average patch size and largest patch for unvegetated cover fall by 69% and 63%, respectively.

Distance scenarios 200 and 300 are consistent with an agricultural, mixed-use landscape with high quantities of grassy and unvegetated cover spread over a much broader range of landscape conditions. While these two scenarios result in an area of forest cover that is similar to distance scenario 100, the cover is much patchier; numbers of patches and the amount of edge is greater for all cover types. Dominance indices indicate that distance scenarios 200 and 300 are the least dominated and the most diverse in terms of extent of cover.

Distance scenario 400 is consistent with transition from the agricultural profile in scenarios 200 and 300 to a remote forest profile in distance scenario 500. Non-forest cover is concentrated in areas close to the road and with gentle slopes. However, non-forest cover is not as agglomerated as in scenarios 200 and 300, consistent with increased forest harvesting activities in the more remote areas. At scenario 500, non-forest cover is highly diffuse and forest covers 93% of the landscape.

By looking at differences between adjacent locations on the urban–rural gradient we can also examine how continued development could affect landscapes. That is, they can be used to show what would happen if development moves the city outward by 10 km. Figure 3 shows the changes in several landscape indices for this type of development on both private and public lands. This figure demonstrates most clearly that there is little difference between scenarios on public lands, especially when compared with private lands. Changes in indices are almost an order of magnitude greater on the private lands.

On private lands, changes in landscape structure would not be constant over the urban–rural gradient. Total change in land cover is greatest at the two ends of the gradient: at the edge of the city and in areas currently dominated by forest cover. Decreases in forest cover and increases in non-forest cover are also concentrated at the two ends of the urban–rural gradient. Change in the non-forest index which weights non-forest cover by its proximity to the major stream in the landscape also has a U-shape, indicating that the largest increases in the non-forest index would also occur at the urban and rural ends of the gradient. The greatest changes in dominance and contagion occur where landscapes shift from scenario 500 to scenario 400 and from 400 to 300. Here the dominance of forest cover decreases substantially and contagion falls as well. Both suggest an increase in the fragmentation of the resulting landscapes. This is borne out in changes in the number of patches as well as the weighted average patch size between these scenarios.

Discussion

Land-cover changes and landscape structure

Estimates of the land-cover change models and related hypothesis tests provide insights into the structure of landscape dynamics. Our findings confirm findings from previous studies in the southern Appalachians (Wear and Flamm 1993, Turner et al. 1996) and indicate that forest disturbance regimes and land-cover changes are significantly related to site quality and location variables, and that structural differences exist between public and private land-cover change regimes. The present analysis shows further that position on the urban–rural gradient has a significant impact on land-cover change regimes and gives rise to substantially different landscape structures. Furthermore, position on the urban–rural gradient was found to have a compounding influence on land-cover change (and therefore pattern) on private lands, by interacting with other site variables in significant ways.

Our findings indicate that position on the urban–rural gradient not only influences land-cover change regimes, but could have a substantial influence on resulting landscape patterns. For nearly every landscape measure we found significant differences between spatially adjacent scenarios on private lands. These findings suggest that institutions and location interact to define unique "landscape signatures."

Water quality implications

Land use is clearly one of the most important factors determining water quality (Allan and Flecker 1993). The phrase "water quality" refers to the biophysical constituents affecting the character of the aquatic environment. Aquatic environments (or streams) in the study area are naturally cool, clear, typically shaded, and of high chemical quality. As such, they are highly sensitive to nutrient enrichment, temperature altera-

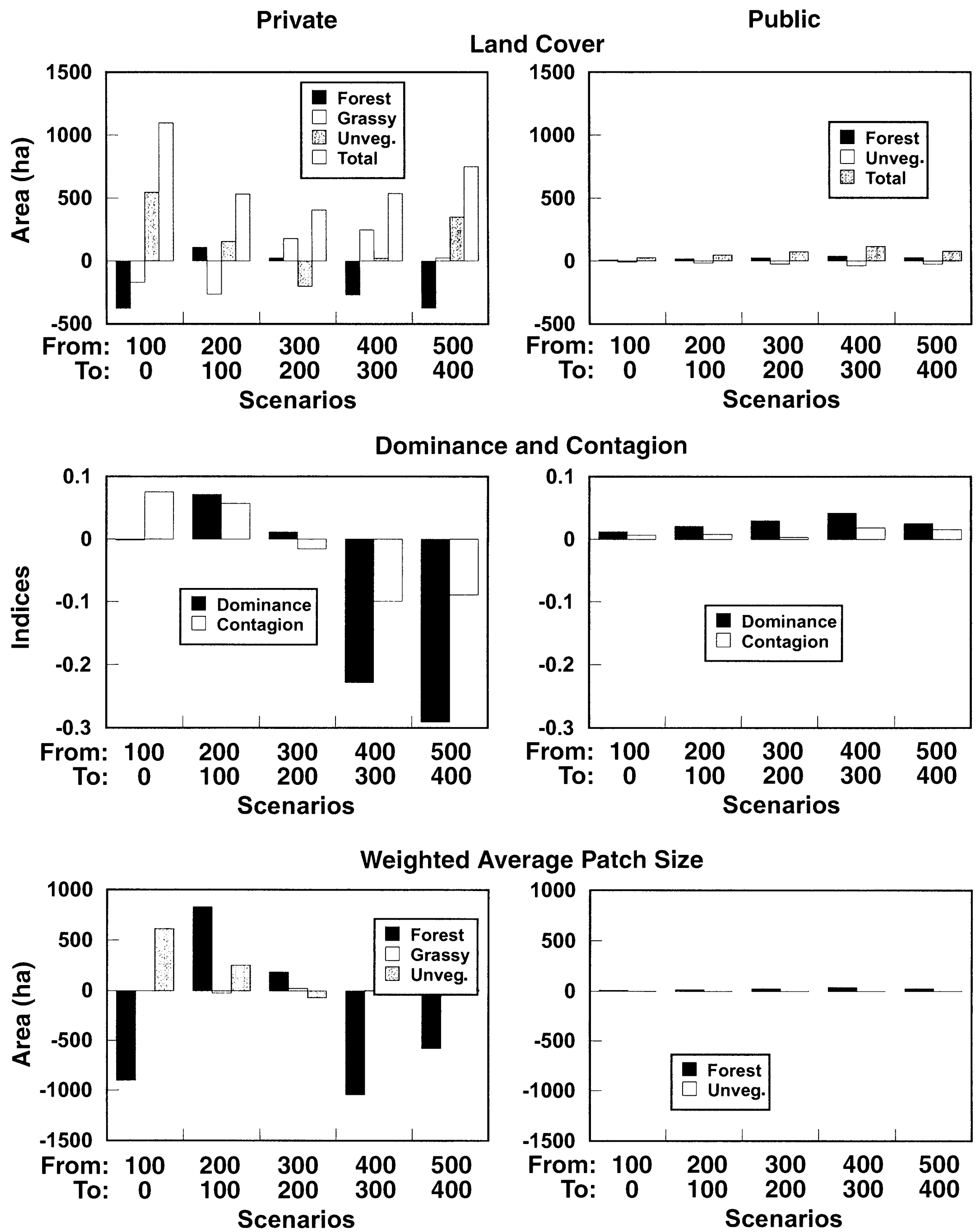

FIG. 3. Changes in landscape measures on private and public lands resulting from shifting the hypothetical landscape 10 000 m (100 cell lengths) closer to Franklin, North Carolina. These show the implied effects of development that would move the city edge outward by 10 km.

tions, introduction of suspended solids, and acid precipitation. Removal of riparian vegetation, as well as alteration of organic inputs and hydrologic regimes by forest and agricultural activities and expanding urbanization, generally results in increased erosion, increased algal production, changes to temperature regimes, and reduced concentrations of dissolved oxygen (Welch et al. 1998). Erosion of fine sediments are generally higher at locations where land use activities, such as road construction, logging, agriculture, or grazing expose soils. Algal communities respond positively to nutrient enrichment causing aesthetic, water quality, and habitat degradation. Changes in water temperature regimes impact all aspects of the physiology, behavior, and life history strategies of aquatic organisms (Naiman and Anderson 1997). The extent of oxygen de-

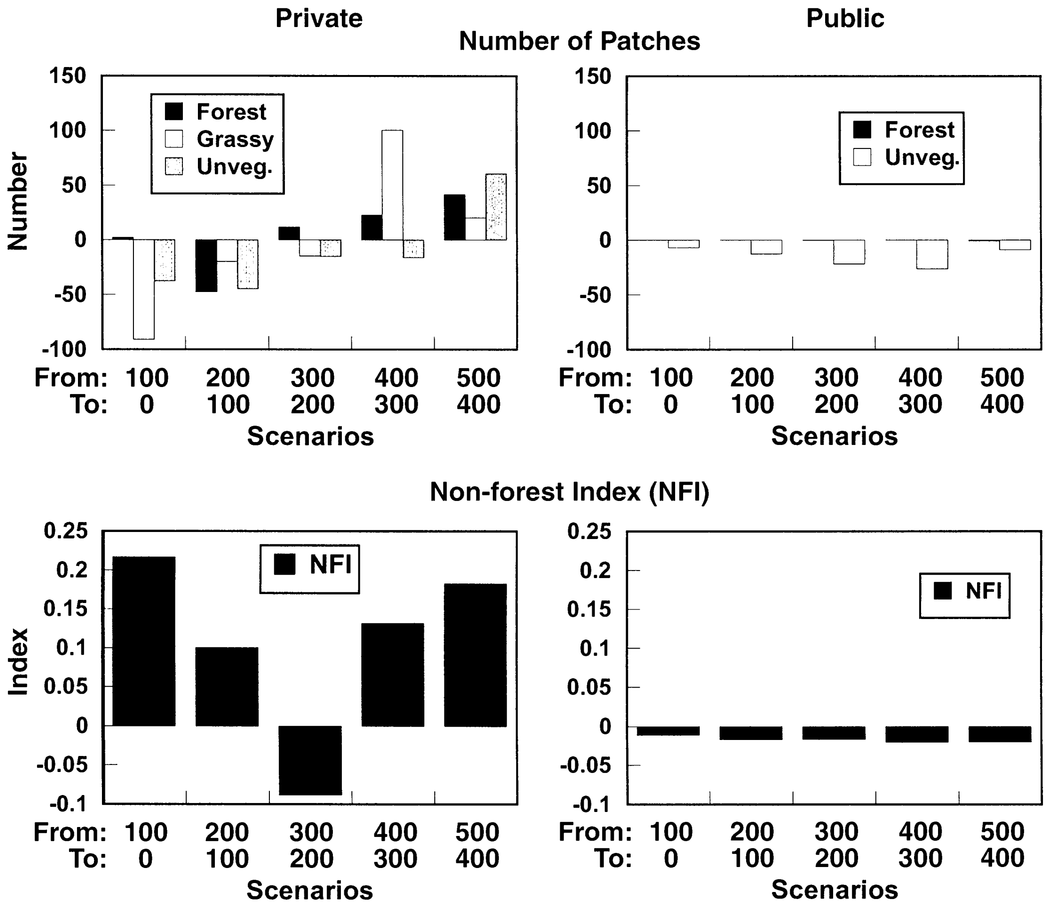

FIG. 3. Continued.

pletion can be severe but ultimately depends on the magnitude of organic matter and nutrient inputs, water temperature, and discharge volume.

Patterns of land use/cover serve as useful indicators of overall water quality. Hunsaker and Levine (1995) found, in river basins in Texas and Illinois, that the percentage of land in forest and other uses were the best predictors of overall water quality. Similarly, Swank and Bolstad (1994), working in the southern Appalachians (in Coweeta Creek, which is contained in our study area), found the percentage of land in non-forest cover and the density of paved roads among the most important variables influencing baseline water quality, and additionally defined a strong link between land cover and water quality changes associated with major storm events. Their findings suggest that even small changes in non-forest land cover have important implications for water quality in their headwater drainage (no site in their study area has >6% non-forest cover). Hunsaker and Levine also found some evidence that the spatial organization of land cover, measured by contagion and dominance, may also have a bearing on water quality. Changes in "landscape signatures" may therefore have important implications for water quality. Understanding that these are only rough indicators of potential effects on water quality, the results of the simulation exercise may provide some insights into where water could be disproportionately impacted by continued development.

The development sequence defined by moving from distance scenario 500 (rural) to distance scenario 0 (urban) shows that the impacts of development on land-cover patterns would vary across the urban–rural gradient (Fig. 3). However, the greatest impacts of development may occur in two positions: (1) where land is moving into an urban use (i.e., moving from distance scenario 100 to distance scenario 0) and (2) where land is moving out of a remote use (i.e, from 500 to 400). In these two locations, total land-cover change, as well as declines in forest cover are at their greatest. To an even greater extent, increases in the non-forest index are concentrated at the two ends of the gradient. Increases in unvegetated cover are likewise concentrated in these areas. To the extent that unvegetated cover is associated with built up areas and impervious surface area, water quality may be heavily influenced by these changes. Impervious cover has especially important impacts on storm surges and stream concentrations of associated pollutants (Swank and Bolstad 1994, Welch et al. 1998). All of these findings suggest that potential water quality impacts are not spread evenly throughout the watershed, nor are they a simple decreasing function of distance from the city. Rather they would be concentrated at the two ends of the urban–rural gradient.

The methodology applied here could be extended. For example, the hypothetical landscape, while constructed to reflect a range of conditions observed in the study area, is essentially arbitrary. Landscape analysis could be constructed for actual places with similar techniques. In addition, these types of models can be applied directly to existing landscapes to define where and how land cover is most likely to change (see Wear et al. 1996). Resulting "hazard maps" could be especially useful for defining short-run implications of development within an area. These models are based on observations of change over relatively short periods. The rate as well as the pattern of change may be variable even within the relatively short period of fifteen years (Turner et al. 1996). Work that extends the analysis to address different epochs of human use could improve our understanding of the full range of effects and of the evolving interactions between people and their environment. A longer time series or more spatial breadth could provide data and insights into the formation of value through land markets and, therefore, more direct information on the economic mechanisms behind land-use and cover changes (see Bockstael 1996).

The methods we describe provide one approach to understanding how human processes act to structure landscapes and ecosystems. Better information on the interactions between human populations and nature, both in terms of how people impact their environment and how environmental quality contributes to human well-being, should improve our ability to structure rational policies and management strategies for protecting environmental quality in developing areas.

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