Simulating Future Forest Fragmentation in Northeastern United States

Jason Parent, Academic Assistant
Daniel Civco, Professor
James Hurd, Research Associate
Center for Land Use Education And Research (CLEAR)
Natural Resources Management and Engineering
University of Connecticut
Storrs, CT 06269-4087
Jason.parent@uconn.edu
Daniel.civco@uconn.edu
James.hurd_jr.@uconn.edu

ABSTRACT

A methodology was developed to simulate future suburban development and analyze the impact of the simulation on forest fragmentation. Maps depicting land suitability for development were created, for each town in the study area, using Multi-Criteria Evaluation (MCE) techniques in ArcGIS. The *Buildout* tool in CommunityViz's Scenario360 extension for ArcGIS was used to populate each town with buildings according to the town's zoning regulations. Scenario 360's *TimeScope* tool was used to assign a build year to each potential future building based on land suitability. Building locations with higher suitability were assigned earlier build years. Square buffers were created at each building location to represent areas in which land cover change would occur. The buffers were used to modify a 2002 Landsat-derived land cover map to depict land cover for several future dates. A forest fragmentation model was applied to the modified land cover maps to quantify the states of forest fragmentation.

INTRODUCTION

Forests provide many important benefits to society in terms of the timber resources and the ecological services they provide. These benefits include maintaining water quality, reducing storm water run-off and erosion, providing habitat for wildlife, and maintaining biodiversity (Barnes *et al*. 1998). The ability of forests to provide timber products and ecological services may be compromised by a loss of forest quality (SAF 1998; Lovejoy 1986; Howarth *et al*. 1996). The fragmentation of the forested landscape is a major contributor to declines in forest quality. Forest fragmentation, in this context, refers to the process of dividing large tracts of forest into smaller isolated tracts surrounded by human-modified environments (SAF 1998). Fragmentation can lead to a reduction in habitat quality and loss of biodiversity for interior forest species (Barnes *et al*. 1998). Forest health may be reduced along the perimeters due to changes in microclimate and increased susceptibility to edge predators, parasites, and invasive species (Barnes *et al*. 1998). According to the Society of American Foresters (1998), there is concern that "…continued declines and fragmentation of the forestland base may lead to the impairment of our forest ecosystems' ability to protect water flow and quality, to provide healthy and diverse forest habitat, and to remain a viable economic resource that provides recreation, timber, and other forest products."

Forest fragmentation does occur naturally in all forest ecosystems. Natural forest fragmentation, however, is typically less extensive and systematic than fragmentation caused by human activities (Barnes *et al*. 1998). In addition, natural forest fragmentation tends to be temporary and contributes to the dynamic heterogeneity in the forested landscape. Concerns about forest fragmentation are associated with fragmentation resulting from human activity.

The purpose of this study is to develop a process for predicting and quantifying changes in the state of forest fragmentation over the next 30 years. The study addresses fragmentation caused by suburban development, which is a major contributor to forest fragmentation in the northeastern United States. Products from this study include ArcGIS models, to facilitate the application of the analysis processes to other study areas, and maps depicting land cover, forest fragmentation type (interior, edge, etc.), and future states of forest fragmentation for the study area. These maps have the potential to aid decision makers in identifying areas in their towns, or regions, that are at risk for significant forest fragmentation and enable them to take appropriate preventative measures.

LITERATURE REVIEW

Land use Change Prediction

GEOMOD

Pontius *et al*. (2001) developed GEOMOD to simulate patterns of land cover change over time. Change can be simulated for two broad land cover categories forward or backward in time. The model generates a suitability map based on digital raster layers depicting relevant physiographic or socioeconomic attributes. The simulation begins with an empirically-derived land cover map that serves as the base map. The user specifies the quantity of change that will occur over a given time period and the model changes grid cells, with the greatest likelihood for change, from the base land cover category to the new land cover category. The likelihood for a given grid cell to change is determined from the suitability maps.

SLEUTH

Clarke (1997) developed a C-based program called SLEUTH[1] to simulate future urban growth based on the following input data layers: slope, land cover, excluded areas, urban areas, transportation networks, and hillshade. The program consists of two models called the Urban Growth Model (UGM) and the Land Cover Deltatron Model (LCDM). The Urban Growth Model creates new urban growth using cellular automata[2] terrain mapping. Selection of urban growth areas is governed by four growth rules: spontaneous growth, new spreading centers, edge growth, and road influenced growth. The growth rules are applied to random grid cells. Five growth parameters control the growth rules – dispersion[3], breed[4], spread[5], slope[6], and road gravity[7]. The UGM is run through a series of Monte Carlo iterations with one iteration equal to a time step *(i.e.*, year) in the simulation. The coefficients for the growth parameters are determined using an intensive calibration process. The calibration process compares the simulated growth, for a given set of parameter coefficients, with the real growth. The coefficients are adjusted until there is an acceptable level of agreement between the simulated growth and the real growth.

The LCDM simulates land cover change resulting from urban expansion. A number of non-urban grid cells are randomly selected and the land cover type of a selected grid cell may be changed depending on the grid cell's probability of a land cover change. The probability for change is based on the slope of the grid cell and on historical land cover conversion data. A changed grid cell becomes a *deltatron*[8] and may initiate a change in the land cover type, of the surrounding grid cells, to the land cover type of the deltatron. A deltatron becomes inactive after it exists for a user-specified number of time steps.

Forest Fragmentation Analyses

Riitters *et al*. (2000) developed a model to quantify forest fragmentation from raster land-cover maps. The model classifies each forest grid cell based on the type of fragmentation that exists in the surrounding area. The surrounding area is defined by a square analysis window that is centered on a forested grid cell. The size of the analysis window affects the results of the analysis and should be adjusted depending on the resolution of the input land cover raster. The analysis' definition of a forest edge can be used to determine the analysis window size. For example, when the input land cover data have a 30 m spatial resolution, a 5 grid cell by 5 grid cell analysis window equates to forest edges that are 2 grid cells wide (60 m). Two metrics are calculated for each grid cell based on the quantity and spatial distribution of forest in the analysis window. The first metric, P_f, is the proportion of forest grid cells in the analysis window. The second metric, P_{ff}, is the apparent connectivity of the forest in the analysis window. P_{ff} is calculated as the number of grid cell pairs where both grid cells are forested divided by the total number of grid cell pairs that have at least one forest grid cell. Values for both metrics range from 0 to 1. Larger P_{ff} values indicate a higher connectivity between forested grid cells. Forest grid cells are categorized into six categories

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[1] **S**lope, **L**and cover, **E**xclusion, **U**rbanization, **T**ransportation, and **H**illshade

[2] In a cellular automota model, grid cells depict a given state - states of land cover in the case of the UGM. In each time step, grid cells can "…change their state according to a rule which determines the new state as a function of the previous states of cells in the neighborhood" (Gutowitz 1995).

[3] The *dispersion* coefficient specifies the number of times to attempt spontaneous urban growth in a time step (year)

[4] The *breed* coefficient is the probability that a spontaneous growth cell will become a spreading center.

[5] The *spread* coefficient is the probability that any cell in a spreading center will have another neighboring cell urbanized.

[6] The *slope* coefficient affects the probability that a cell will become urbanized based on its percent slope.

[7] The *road gravity* coefficient controls the maximum distance from roads that a new cell can be urbanized.

[8] A deltatron is a grid cell that can create land cover changes in neighboring grid cells.

- patch, transitional, perforated, edge, core, and undetermined forest - based on their P_f and P_{ff} values (Figure 1). A core forest grid cell is completely surrounded by forest and thus has no fragmentation. Grid cells that fall into the remaining five categories show some degree of fragmentation. Edge and perforated forest grid cells make up the exterior (forest adjacent to large non-forest features) and interior (forest adjacent to small forest clearings) edges of the forest, respectively. Patch forest grid cells represent isolated forest woodlands surrounded by non-forest land cover and transitional forest grid cells represent an intermediate level of fragmentation. Undetermined grid cells are mostly surrounded by forest but cannot be classified into the edge or perforated categories.

Riitters *et al*. (2002) applied the model to the continental United States using the 30 m spatial resolution National Land Cover Dataset (NLCD). They tested analysis windows of five different sizes. Window sizes included 5 by 5 grid cells (2.25 ha), 9 by 9 grid cells (7.29 ha), 27 by 27 grid cells (65.61 ha), 81 by 81 grid cells (590.49 ha), and 243 by 243 grid cells (5314.41 ha). The proportions of core forest and perforated forest grid cells decreased rapidly with increasing window size. The proportions of edge, patch, and transitional forest increased substantially with larger window sizes. Overall, 43.5% of the forest was within 90 m of a forest edge and 61.8% of the forest was within 150 m of the forest edge. Less than 1% of forest existed more than 1230 m from a forest edge.

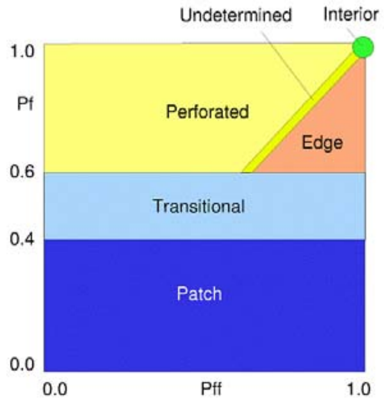

Figure 1: P_f and P_{ff} values for patch, transition, perforated, edge, and core forest.

Hurd *et al*. (2001) analyzed forest fragmentation in the Salmon River watershed in Connecticut following the model developed by Riitters *et al.* (2002). The change in forest fragmentation was analyzed from four dates of land cover data, derived from Landsat imagery, over the period from 1985 to 1999. Analysis windows of the following sizes were examined: 3 by 3 grid cells, 5 by 5 grid cells, 7 by 7 grid cells, and 9 by 9 grid cells. As with Riitters *et al*. (2000), the proportions of interior forest declined with increasing window size while perforated forest increased. Hurd *et al*. (2001) used a 5 by 5 grid cell window for the analysis since they believed it maintained a reasonable representation of the proportion of forested grid cells in the landscape and maintained an appropriate level of interior forest. The study found that interior forest area declined, between 1985 and 1999, while edge, transitional, and perforated forest and urban areas increased.

Hurd *et al*. (2001) also analyzed the patch sizes of land cover types using the Patch Analyst[9] extension for ArcView[10]. The number of forest and urban patches increased, between 1985 and 1999, while mean patch sizes decreased (only slightly for urban patches). The largest urban patch grew substantially over the study period. The results indicated a decentralized pattern of urban growth since the magnitude of the growth of the largest urban patch accounted for much of the significant decline in the mean forest patch area and the increase in the number of forest patches.

DATA AND METHODOLOGY

The Study Area

The study area consists of six adjacent towns located in the Salmon River Watershed just east of central Connecticut. The study area is predominately rural and encompasses an area of 150 square miles. Forestland covered approximately 72% of the study area in 2002. The population of the study area has grown substantially in recent decades with a population increase of 172% between 1960 and 2000. Development has followed a suburban type growth pattern with urban land and associated turf area increases of 16.6% and 18.6%, respectively, between 1985 and 2002. Consequently, the region experienced a 4% decrease in total forest cover between 1985 and 2002. Unfragmented (interior) forest declined by 15.9%, over the same period, while fragmented forest (perforated, edge,

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[9] Centre for Northern Forest Ecosystem Research (OMNR), Lakehead University, Thunder Bay, Ontario, Canada: http://flash.lakeheadu.ca/~rrempel/patch/

[10] ESRI, 380 New York Street, Redlands, CA 92373-810 http://www.esri.com

transition, and patch) increased substantially. The study area was selected since it is heavily forested but is experiencing substantial changes in the fragmentation and quantity of forest as a result of rapid population growth and suburban style development.

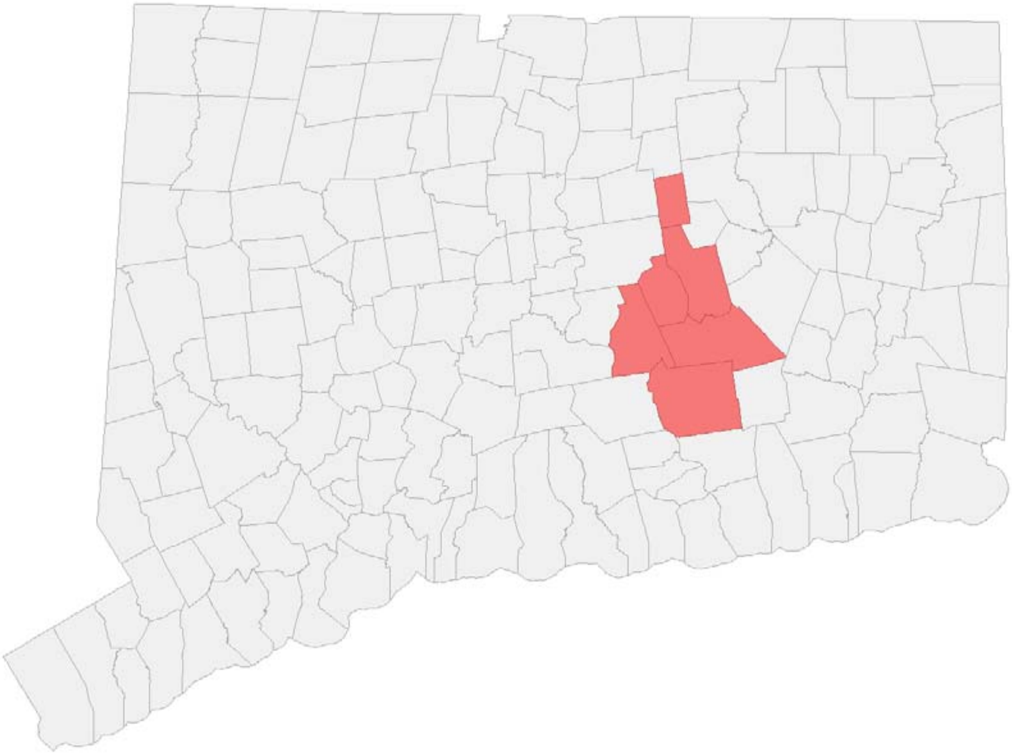

Figure 1: Location of the study area in Connecticut.

Data Acquisition

Connecticut statewide datasets were acquired from the Connecticut Department of Environmental Protection (DEP)[11]. These datasets included the following, in shapefile format: hydrography (polygons and lines), wetlands, FEMA floodzones, DEP land, municipal lands, roads (*circa* 1985), town boundaries, soils, and drainage basins. Digital aerial orthophotographs (Spring 2004) were obtained from the CT DEP and used to digitize the building footprints in the study area. Hypsographic data[12] were obtained from the United States Geological Survey (USGS) and used to interpolate a Digital Elevation Model (DEM). Demographic data were provided by the U.S. Census Bureau[13]. Parcel boundaries and town zoning data were obtained from either the town government or the appropriate regional planning agencies. Soil septic potential ratings were provided by the United States Department of Agriculture Natural Resources Conservation Service. Statewide land cover data for 1985, 1990, 1995, and 2002 were obtained from the Center for Land use Education and Research at the University of Connecticut[14].

Multi-Criteria Evaluation

Suitability maps were created, for each town, to identify the favorability of any given area for development. Multi-Criteria Evaluation (MCE) was used to derive these suitability maps based on multiple *Boolean constraint* and *factor* inputs. Boolean constraints depict areas as either suitable {1} or unsuitable {0}. Factors are continuous

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[11] http://dep.state.ct.us/gis/Data/data.asp

[12] Contour lines digitized from topographic maps

[13] http://www.census.gov/

[14] http://clear.uconn.edu/projects/landscape/statewide_landcover.htm

criteria with varying degrees of suitability reflected by *criterion scores* {0, 100}. These scores are assigned to each factor category with higher scores indicating greater suitability. A weighted linear combination[15] was used on the factors and the constraints were used to mask unsuitable areas from the analysis. This technique requires that all factors and constraints be in raster formats with the same resolution – 20 feet in this case. Factor criterion scores must be scaled to a common range, in this case 0 to 100, when multiple factor layers are used. The MCE in this study included two factors which were assumed to have equal importance in the suitability rating. In the suitability map, generated by the MCE, higher grid cell values indicate greater suitability.

Constraints

The constraints used in the MCE were specific to each town and were determined from town zoning regulations. Figure 2 indicates the constraints used for each town. Constraint data were converted to raster formats with grid cell sizes of 20 feet. Constraint rasters were reclassified into *Boolean constraint* formats where unsuitable areas had values of 0 and suitable areas had values of 1.

	Hydrography	Hydro 50 ' buffer	Wetlands	Wetlands 50' buffer	Floodzones	Floodzone 50' buffer	Slope > 20%	Municipal open space	DEP land
Bolton		●		●		●		●	●
Colchester	●				●			●	●
E. Haddam		●	●				●	●	●
E. Hampton	●							●	●
Hebron	●		●		●		●	●	●
Marlborough	●							●	●

Figure 2: Development constraints by town.

Factors

The MCE in this study included two factors. The first factor was derived from soil maps. Soil types were systematically assigned criterion scores based on the following soil properties: wetlands status, soil rockiness, minimum slope, and soil septicability rating. These properties were selected since they are pertinent to development suitability and the latter three properties have no discernable correlation. Grid cells in the *soils factor* were assigned values based on the criterion scores of the soil types they contain.

The second factor was based on proximities to non-local roads. Preliminary analysis indicated that buildings are constructed within a certain range of distances from existing roads. Grid cells in the *roads factor* were grouped into classes with 20 foot intervals. The percent of developed land in each class was calculated using the building footprint data digitized from the 2004 digital aerial orthophotographs. These percentages were scaled from 0 to 100 and assigned to the *roads factor* grid cells as criterion scores.

Buildout Analysis

CommunityViz's[16] Scenario 360 ArcGIS extension was used to perform a buildout analysis to determine the potential locations where buildings may be constructed in the study area. The buildout analysis positioned points in each parcel in accordance with the town's zoning regulations. Zoning information included minimum lot size, building efficiency[17], dwelling units per structure, minimum building separation distance, and the spatial layout pattern for the buildings[18]. The following areas, considered unsuitable for development, were excluded from the buildout analysis: land identified as unsuitable in the MCE, parcels that are fully developed[19], and land within 50 feet of a structure existing in the 2004 aerial photos.

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[15] In a weighted linear combination, each factor is assigned a weight that determines the factor's contribution toward the final suitability rating. The sum of all weights must equal 1.The suitability rating is equal to the sum of the products of the factors and their weights. (Eastman 2001)

[16] CommunityViz, PO Box 295, Manchester Village, VT 05254 http://www.communityviz.com/

[17] An estimate of the percentage of land in a parcel that is available for building construction. Efficiency is less than 100% due to road construction, open space requirements, etc.

[18] The random spatial layout pattern used in this study. Alternative patterns include *grid* and *follow roads*.

[19] Parcels were considered fully developed if they currently contained a structure and were less than 240,000 ft^2 in area.

TimeScope Analysis

The *TimeScope* tool in Scenario 360 was used to assign a build date to each buildout location in order to simulate the progression of development over time. It was assumed that the more suitable areas would be the preferred locations for development. To reflect this assumption, areas of high suitability were assigned earlier build dates. The annual building growth rate was based on estimates of the town's population growth. The towns in the study area demonstrated linear population growth over the past 40 years. To extrapolate future population growth, a linear regression was used. The estimated annual population growth rate was divided by the average number of people per household, in 2000, to estimate the annual building growth rate.

Building Buffers

Buffers were created around the buildout structures to represent turf and impervious surfaces associated with buildings. The buffers were created as squares to depict the open space around buildings as realistically as possible. Buffers were one of the following four sizes: 3,600 ft^2, 10,000 ft^2, 19,600 ft^2, 32,400 ft^2, or 48,400 ft^2. The size of a buffer created around a buildout building was randomly selected.

Creation of Future Land Cover Images

Future land cover grids were produced by modifying a 2002 land cover grid with the building buffers. The 2002 land cover grid was derived from Landsat imagery and had a resolution of 100 feet. Future land cover grids were created for the years 2010, 2015, 2020, 2025, 2030, and 2036. For each forecast date, the buffers of buildings with the appropriate build dates were selected. The area of the 2002 land cover map contained by the selected buffers was changed from the existing land cover to an urban / turf land cover category.

Forest Fragmentation Analysis

Forest fragmentation, of the predicted forest land covers, was assessed using the forest fragmentation model (Hurd *et al*. 2002; Civco *et al*. 2002). The forest fragmentation model performs the algorithms, derived by Ritters *et al*. (2000), for characterizing forest cover in terms of the types of fragmentation present. The model used a 5 grid cell by 5 grid cell analysis window.

RESULTS

Land Cover Change

Forest cover and agricultural land, in the study area, are predicted to decline by 3.0% and 5.6%, respectively, between 2002 and 2036 (Table 1). Urban and turf areas related to development are predicted to increase by 17.9%. Figure 3 illustrates land cover for Bolton in 2002 and 2036.

Table 1: Predicted land cover change in the study area between 2002 and 2036.

LANDCOVER TYPE	2002 (ha)	2036 (ha)	CHANGE (ha)	CHANGE (%)
forest	442351	428972	-13379	-3.0%
urban / turf	81815	96427	14612	17.9%
agriculture	60758	57332	-3426	-5.6%
non-forested wetland	2711	2702	-9	-0.3%
barren	3888	3770	-118	-3.0%

Forest Fragmentation Type Change

Interior and edge forests are predicted to decline by 27.7% and 15.5%, respectively, between 2002 and 2036 (Table 2). Perforated, transitional, and patch forest will increase by 67%, 10.1%, and 8.3%, respectively. Figure 4 compares forest fragmentation maps, for the study area, from 2002 and 2036.

Table 2: Forest fragmentation type change, in the study area, between 2002 and 2036.

FOREST TYPE	2002 (HA)	2036 (HA)	CHANGE (HA)	CHANGE (%)
interior forest	22617	16359	-6258	-27.7%
perforated forest	8525	14234	5710	67.0%
edge forest	5928	5009	-920	-15.5%
transition forest	2079	2288	209	10.1%
patch forest	663	718	55	8.3%

DISCUSSION

Road Development

Many ecologists consider roads to be fragmenting features in the forested landscape. Forecasting road development, however, was beyond the scope of this study. The predicted decline in edge forest is likely to be an artifact of not accounting for future roads. Intuitively, one would expect edge forest to increase over time in regions undergoing suburban development as a result of the addition of roads to the landscape. Also, while it is not unreasonable for perforated forest to increase as a result of suburban development, it is unlikely to increase at a higher rate than edge forest. Thus, this analysis most likely overestimated the growth of perforated forest while underestimating the increase of edge forest.

Road development reduces total forest cover and increases the ratio of edge forest to other types of forest – especially interior forest. Since this study did not account for future road construction, it is likely that the rate of interior forest loss is somewhat underestimated. Consequently, the predicted loss of interior forest should be considered a conservative estimate.

Building Growth Rates

The rate of building growth in regions undergoing suburban development is an important factor in determining the amount of forest fragmentation that occurs. Realistic building growth rate estimates were important for obtaining useful predictions in this analysis. In this study, building growth rates were assumed to parallel population growth rates. Census data for the study towns over the past 40 years indicated a linear trend in population growth. Thus, future population estimates were extrapolated using linear regression of the past census data. The number of people per household was assumed to remain constant over time in estimating the number of future buildings.

The method for estimating annual building growth is based on data for residential buildings. As a result, the predicted growth rates are probably not applicable to non-residential buildings. Ideally, the residential zones and non-residential zones should be analyzed separately in the *TimeScope* analysis, each with a building growth rate estimate that is specific to the type of zone. Unfortunately, estimating non-residential building growth is problematic since it is not simply a function of population. However, in the rural towns of the study area, which have little area zoned non-residential, the complications arising for non-residential zones are likely to be minor.

Forest Fragmentation Model Limitations

The forest fragmentation model used in this study was designed to work with land cover data derived from Landsat imagery. These land cover data have a spatial resolution of approximately 100 feet. Most of the analysis in this study created rasters with grid cell sizes of 20 feet. The predicted land cover maps, however, had to be created with grid cell sizes of 100 feet to make them compatible with the forest fragmentation model. As a result, some of the finer details of the analysis were not depicted in the future land cover maps. Efforts are underway to make the forest fragmentation map compatible with higher resolution data (J. Hurd personal communication, May 2006).

Future Improvements

The *Road Development* section discussed some of the disadvantages of not accounting for future road development in simulating forest fragmentation. The incorporation of a model for predicting road development, into this study's analysis, would improve estimates of change in edge forest, perforated forest, and interior forest.

At the present time, the area serviced by town sewers in the study area is very limited. However, the expansion of sewers into a given area can have a substantial impact on the development suitability for an area (C. Zimmerman personal communication, May 2006). It may be possible to obtain information on proposals for future sewer expansion from the town governments. The data could be incorporated as a factor in the MCE which may improve the validity of the suitability maps.

This study uses physiographic attributes to determine the land's suitability for development. A more realistic analysis would be based on both socioeconomic and physiographic attributes which would indicate land availability for development as well as land suitability. Land often becomes available for development when it is inherited. High estate taxes may force inheritors to sell some or all of the land to developers (DeCoster 2000). Demographic data, especially population age, would be useful for indicating land that may be inherited in the near future. Such data, included in the MCE as a factor, would yield more realistic assessments of future changes in forest cover and fragmentation.

A useful follow-up for this study would be a comparison of the effects on forest fragmentation of a traditional suburban development scenario, as depicted in this study, and a low impact development scenario. Low impact development strategies, such as cluster developments, would group houses close together while setting aside land for open space. Such strategies are likely to reduce the adverse effect of development on forest fragmentation. An analysis quantifying the potential difference in effects on forest change, between traditional and low-impact development, would help demonstrate the effectiveness of development strategies designed to minimize forest fragmentation.

CONCLUSIONS

This study has developed a method of predicting future states of forest fragmentation for regions in which suburban development is the major fragmenting process. Fragmentation in these regions is due, in large part, to the land cover changes associated with the construction of buildings. The approach used in this study was to simulate future forest fragmentation based on simulations of future building development. Road development was not taken into account in the simulations of future forest fragmentation and consequently the results of the analysis are likely to be conservative. Regardless, the study predicts a substantial increase in the fragmentation of the forests in the study area while the overall amount of forest declines.

Future work could lead to improvements in the methodology of this study. A method that accounts for future road development should be incorporated into the analysis to improve the accuracy of the predictions. In addition, suitability maps could be improved by incorporating socioeconomic data into the multi-criteria evaluation. Socioeconomic data would indicate the availability of parcels for development rather than suitability. A useful application of the analysis would be to analyze the impacts of various zoning scenarios (i.e., smart growth) on the future state of forest fragmentation. The relative impacts of each scenario would help indicate the effectiveness of "smart growth" zoning strategies aimed at minimizing forest fragmentation.

The results of this research will be useful in guiding managers in land use decision making. In addition, the ArcGIS models created in this study can serve as templates for others to use in similar applications across the country.

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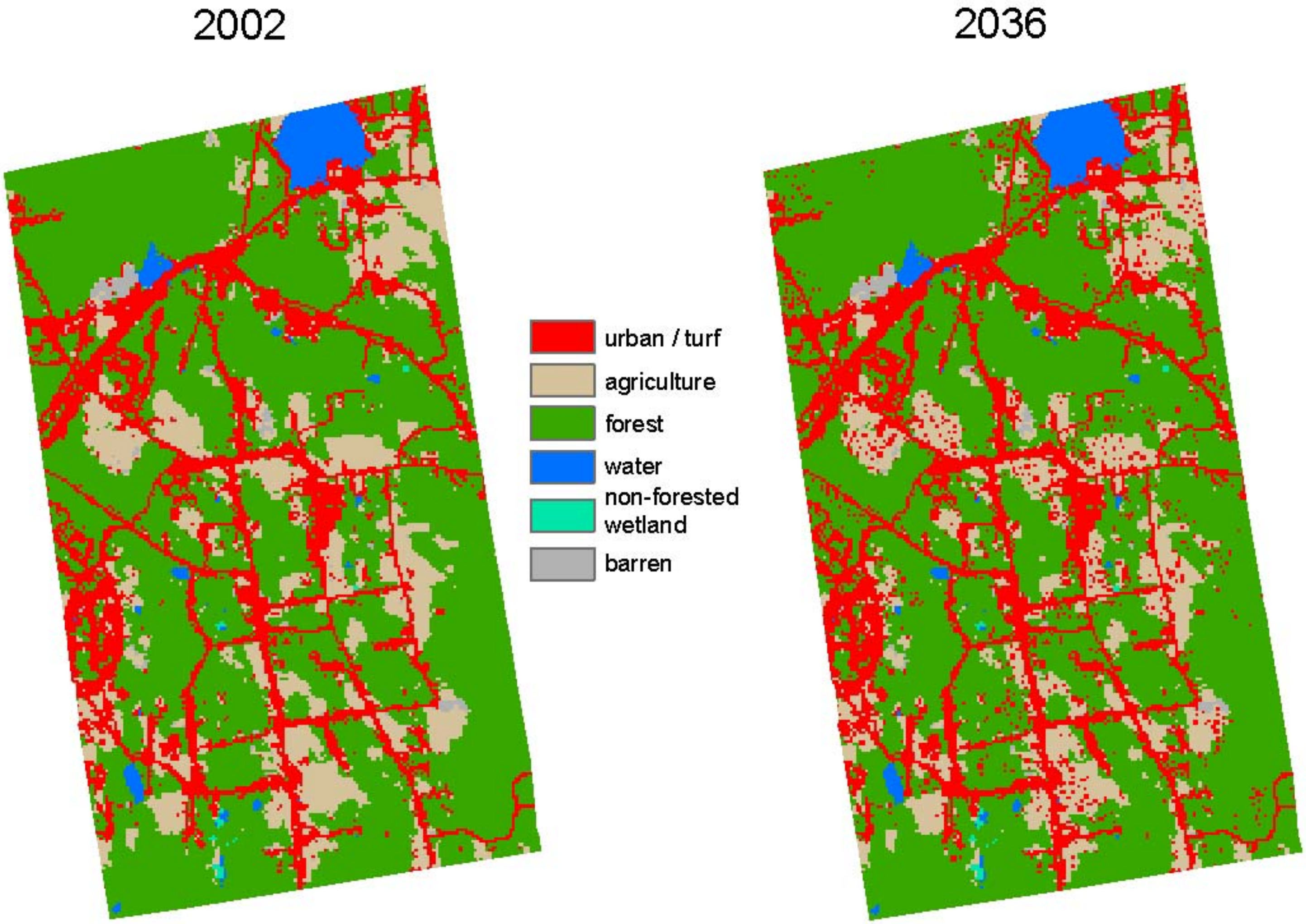

Figure 3: Bolton land cover for 2002 and 2036.

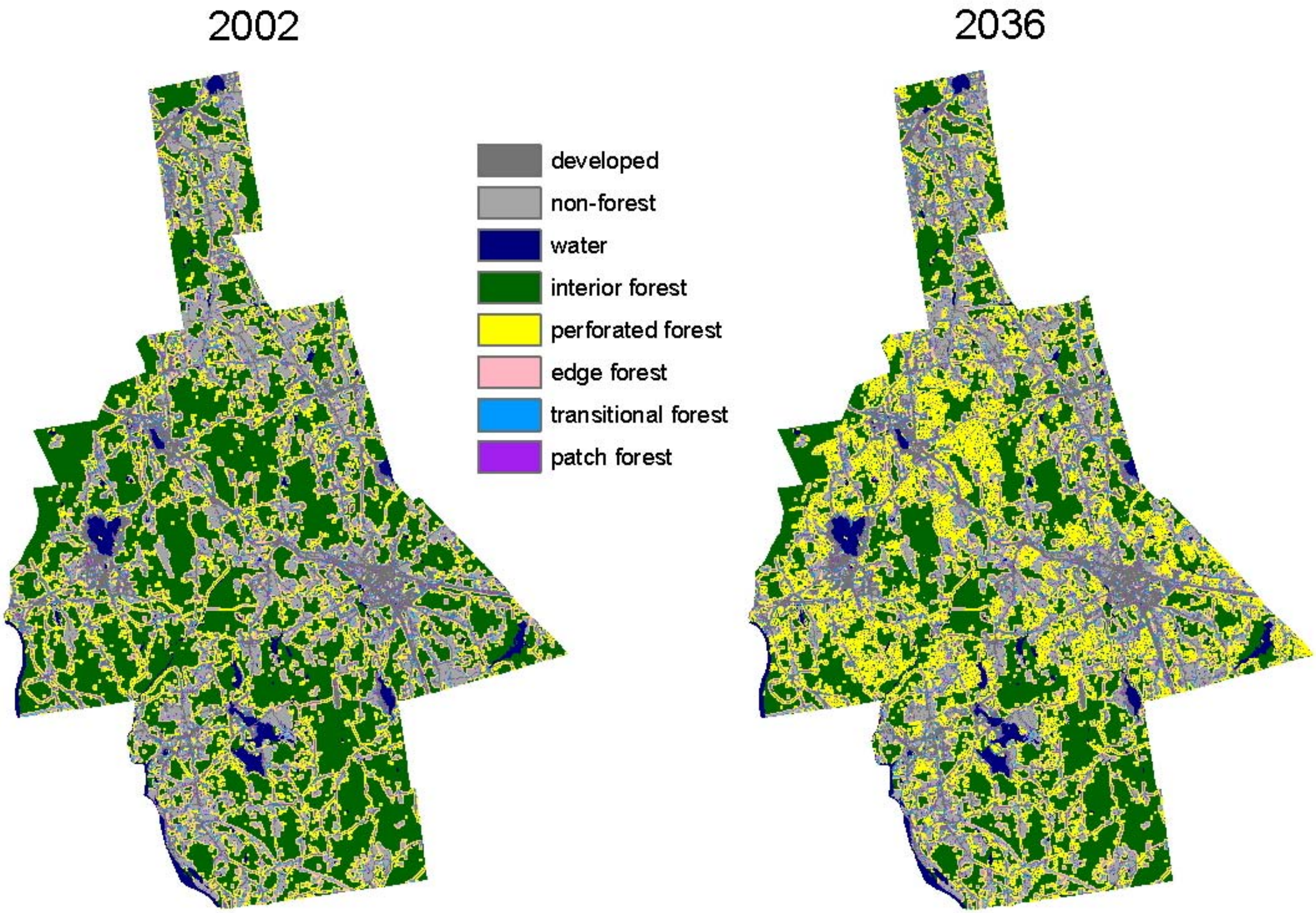

Figure 4: Forest fragmentation maps for 2002 and 2036.