DEVELOPMENT OF A FOREST FRAGMENTATION INDEX TO QUANTIFY THE RATE OF FOREST CHANGE

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ABSTRACT

Forest fragmentation is a growing concern throughout the Northeastern United States where the primary cause of fragmentation is suburban development. However, the extent and rate of change to the forest landscape is not fully understood, particularly by local land use decision makers. As part of the NASA funded Northeast Regional Earth Science Applications Center (RESAC) at the University of Connecticut, research is being conducted to quantify forest fragmentation in four pilot watersheds distributed throughout the Northeast. The forest fragmentation index presented here is based on the results of a forest fragmentation model, developed by researchers from the US EPA and Department of the Interior, in which forest pixels are classified as belonging to one of six types: interior forest, edge forest, perforated forest, undetermined forest, transitional forest, and patch forest. For this research, the forest fragmentation model was modified for use with 30-meter Landsat derived land cover information. The forest fragmentation index calculates a forest continuity value from the results of the forest fragmentation model. This value is used in conjunction with the total proportion of forest for a given area (excluding water) to produce an index of forest fragmentation. Any specified area (watershed or town) can be quantified as having high or low amounts of forest, and the degree to which that forest is fragmented. Using time series land cover information, changes in the forest landscape can be compared over time. This paper presents the details of our model for calculating the forest fragmentation index as well as a case study of its application to a town in one of the study watersheds.

INTRODUCTION

Concern about the economic, environmental and cultural impact of forest fragmentation is a growing concern in the United States, especially in the Northeast where it is having an adverse impact on forest health and forest sustainability. The primary cause of forest fragmentation in the region is suburban development, which causes many of the remaining large parcels of forests to be converted for anthropogenic uses, most notably as residential development. However, the extent and rate of change to the forest landscape is not fully understood, particularly by local officials whose decisions about land use determines the look and feel of the region's landscape (Arnold, 1999). As part of NAUTILUS, the NASA funded Northeast Regional Earth Science Applications Center (RESAC) at the University of Connecticut, one of the major research agendas was to develop a forest fragmentation index to be used in the identification and comparison of the condition of forest fragmentation within a given area. The primary goal was to develop an index that would allow a user to visualize easily the extent of forest fragmentation and track the change in fragmentation over time. The index could be used by local officials to aid in community planning and help local decision makers understand better the effect of land use decisions (Arnold *et al*., 2000). Ultimately, having an understanding of the state and rate of forest fragmentation will allow for inference about potential impacts of forest fragmentation, and the risk of future impacts in similarly forested areas can be inferred (O'Neill *et al*., 1997; Riitters *et al*., 2000).

There are numerous measures of forest fragmentation and forest connectivity currently described in the literature. These include average forest patch size, percent interior forest, mean forest patch density, number of forest patches, interpatch distance, forest patchiness, forest contiguity, forest continuity, and proportion of forest in the largest forest patch (Vogelmann, 1995; Trani and Giles, 1999; Wickham *et al.* 1999). Several of these measures were assessed in a study conducted by Trani and Giles (1999) to determine how change in forest loss influenced their results. In the study, thirty-eight forested maps were selected that represented a wide variety of forested conditions from large contiguous forested landscapes to landscapes with several small patches of forest. Using a 300-meter buffer zone, the inside forest edge was eliminated and the process repeated until no forest remained. Between each buffering operation, the forest fragmentation and forest connectivity measures were applied. The findings show that the behavior of the fragmentation and connectivity measures varied under different deforestation conditions. This highlighted the importance of understanding the sensitivity of a forest fragmentation measure to various deforestation conditions.

While any of the forest fragmentation and connectivity measures could have been applied to the NAUTILUS study areas to assess their condition of forest fragmentation, NAUTILUS researchers wanted to take advantage of a forest fragmentation model developed by Riitters *et al.* (2000). This model, developed to assess forest fragmentation at the global level, generates categories that describe the type of forest fragmentation condition that exists for a given forest pixel. While providing useful information, NAUTILUS researchers wanted to go a step further and use this information to derive a more succinct view of the state of forest fragmentation for a region. The premise was that while the forest fragmentation model produced valuable information, it was difficult to visualize easily the state of forest fragmentation for an area, track trends in forest fragmentation, and also identify areas where forest restoration might prove appropriate to reduce the impact of forest fragmentation. The state of forest fragmentation index was developed to complement the results of the forest fragmentation model

LAND COVER CLASSIFICATION AND CHANGE DETECTION

Since land cover is the input source data for the forest fragmentation model and state of forest fragmentation index, the development of land cover information for this project deserves mention. While the forest fragmentation model and state of forest fragmentation index can be applied to single date land cover images, application to multidate land cover information permits the tracking of forest fragmentation over time. To make the tracking of changes in forest fragmentation most relevant, it is important to have a consistent set of land cover and land cover change information.

A base land cover image was derived using a two-step ISODATA clustering technique from a combined image of two seasons of Landsat TM image data dated April 26, 1985 and August 9, 1985. ISODATA clustering was first applied to the multi-seasonal 14-band image area to produce 75 spectrally separable classes. These classes were identified and labeled into one of eight informational land cover categories: developed land, non-woody vegetated land, deciduous forest, coniferous forest, water, wetland, barren land, and other. The "other" category contained clusters of pixels that were not readily identifiable as belonging to a single informational class. A second ISODATA clustering procedure was performed on these pixels with 50 output classes specified. The classes were identified and labeled into one of the seven land cover categories and added to the first classification to create a single 7-category land cover image. Extensive on-screen digitizing was performed to eliminate apparent gross errors and to add isolated linear roads and utility right-of-ways to the classification. These linear features are important because they are considered fragmenting features of the forest landscape, yet the 30 meter pixel resolution of the Landsat Thematic Mapper image is not always capable of depicting these features using traditional classification techniques.

After examining several techniques for depicting land cover change including post classification change detection, multidate classification change detection, multidate principal components analysis, RGB-NDVI color composite change detection, and cross-correlation analysis (Hurd *et al.,* 1992; Sader and Winne, 1992; Hoffhine, 2000; Koeln and Bissonnette, 2000), cross-correlation analysis (CCA) was identified as the most acceptable method for identifying land cover change for the purposes of this research because it overcomes many of the limitations of other change detection methods. Cross-correlation Analysis was developed by Earthsat, Inc. and measures the differences between an existing land cover image and a recent single date multispectral image (Koeln and Bissonnette, 2000). The benefits of this technique are that it eliminates the problems associated with radiometric and phenological differences that are so often experienced when performing change detection, provides a method for easy identification of changed areas that can be labeled into appropriate changed land cover categories, and provides a consistent set of land cover classifications that can be compared over time.

CCA begins with a base LULC classification. The base classification (here, 1985) is used in conjunction with the next date of Landsat imagery (1990) to extract change in each land cover type of interest. Once a 1990 LULC classification was produced, CCA was used to create 1995 and 1999 LULC maps, respectively.

The final result was a consistent, four date, land cover data set that was used to identify land cover change over the 14-year sampling period. An example of the change pixels for the deciduous and coniferous land cover categories between 1985 and 1990 is shown in Figure 1. Retrospective data on land cover change can be a powerful tool to help community leaders analyze the ultimate landscape results of their past land use decisions, and to begin to grasp what future changes their current land use policies may produce. In addition to the data, the land cover imagery displayed via simple animated sequences, is a striking educational tool that can help underscore more technical points about the impacts of land use regulations.

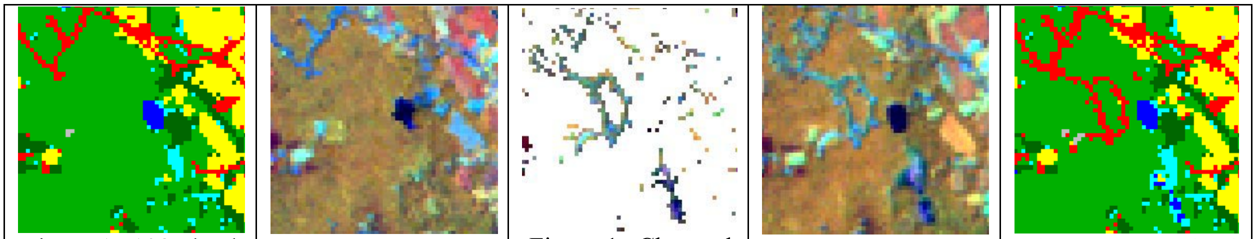

Figure 1a 1985 land cover | Figure 1b Aug. 1985 TM | Figure 1c Changed forest | Figure 1d Aug. 1990 TM | Figure 1e 1990 land cover

Figure 1. Example of the result of cross-correlation analysis on forest pixels between Aug 9, 1985 and Aug 30, 1990. Image (c) represents those pixels having a high likelihood of change from forest.

FOREST FRAGMENTATION MODELING

As mentioned previously, the basis for the forest fragmentation index is a forest fragmentation model developed by Riitters *et al*. (2000). This model was designed to identify patterns of forest fragmentation at a global scale using 1-km resolution land cover information. The model generates two values that characterize a forest pixel located at the center of a sliding window of fixed size, Pf and Pff:

$$\mathrm{Pf} = \frac{\text{\# of forest pixels}}{\text{\# of all non - water pixels}} \qquad \mathrm{Pff} = \frac{\text{\# of pixel pairs with both pixels forest}}{\text{\# of pixels pairs with at least one pixel forest}} \qquad (1)$$

Pff examines pixel pairs only in cardinal directions. Because they are proportions, both Pf and Pff range from 0 to 1. Figure 2 illustrates the procedure for calculating the Pf and Pff values of a forest pixel within a 5x5 window.

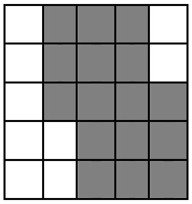

Figure 2. Illustration of the computation of Pf and Pff within a 5x5 grid of pixels. Gray represents forest pixels, white represents non-forest pixels. Of the 25 pixels present, 16 are forest pixels (none are water). Pf therefore equals 16/25 = 0.64. Considering pairs of pixels in cardinal directions, the total number of adjacent pixel pairs is 40. Of these, 32 pixel pairs contain at least 1 forest pixel, and of those, 23 pairs contain 2 forest pixels. Pff therefore equals 23/32 = 0.72. (adapted from Riitters *et al.,* 2000).

From Pf and Pff values, the following six fragmentation categories are derived (Riitters *et al*., 2000). Figure 3 identifies how the Pf and Pff values were used to assign pixels to the six fragmentation categories.

- *Interior forest* - all of the pixels surrounding the center pixel are forest. Pf = 1.0
- *Perforated forest* - most of the pixels in the surrounding area are forested, but the center pixel appears to be part of the inside edge of a forest patch, such as would occur if a small clearing was made within a patch of forest. Pf > 0.6 and Pf - Pff > 0.
- *Edge forest* - most of the pixels in the surrounding area are forested, but the center pixel appears to be part of the outside edge of forest, such as would occur along the boundary of a large urban area, or agricultural field. Pf > 0.6 and Pf - Pff < 0.
- *Transitional forest* - about half of the cells in the surrounding area are forested and the center forest pixel may appear to be part of a patch, edge, or perforation depending on the local forest pattern. 0.4 < Pf < 0.6.
- *Patch forest* - pixel is part of a forest patch on a non-forest background, such as a small wooded lot within an urban region. Pf < 0.4.
- *Undetermined forest* - most of the pixels in the surrounding area are forested, but this center forest pixel could not be classified as being either perforated or edge. Pf > 0.6 and Pf = Pff.

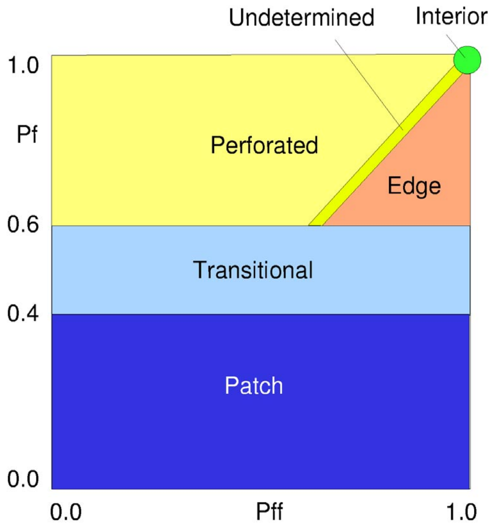

Figure 3. Forest fragmentation categories from local measurements of Pf and Pff. (adapted from Riitters *et al*., 2000).

To implement the process, the size of the analysis window had to be determined. After considering the resolution of the data, the size of the smallest forest feature of interest, and practicality of various window sizes, a 5x5 window was utilized to maintain an adequate representation of the proportion (Pf) of pixels in the window and also maintain interior forest at an appropriate level. The result of applying the forest fragmentation model to 30-meter resolution land cover information is illustrated in Figure 4.

STATE OF FOREST FRAGMENTATION INDEX

Using the results from the forest fragmentation model, further research was conducted to produce maps which identify the state of forest fragmentation of a specified region. The purpose for the forest fragmentation index was to provide a quick means to assess the extent of forest fragmentation within a region, and to track trends in forest fragmentation. and identify areas that would benefit from possible reforestation.

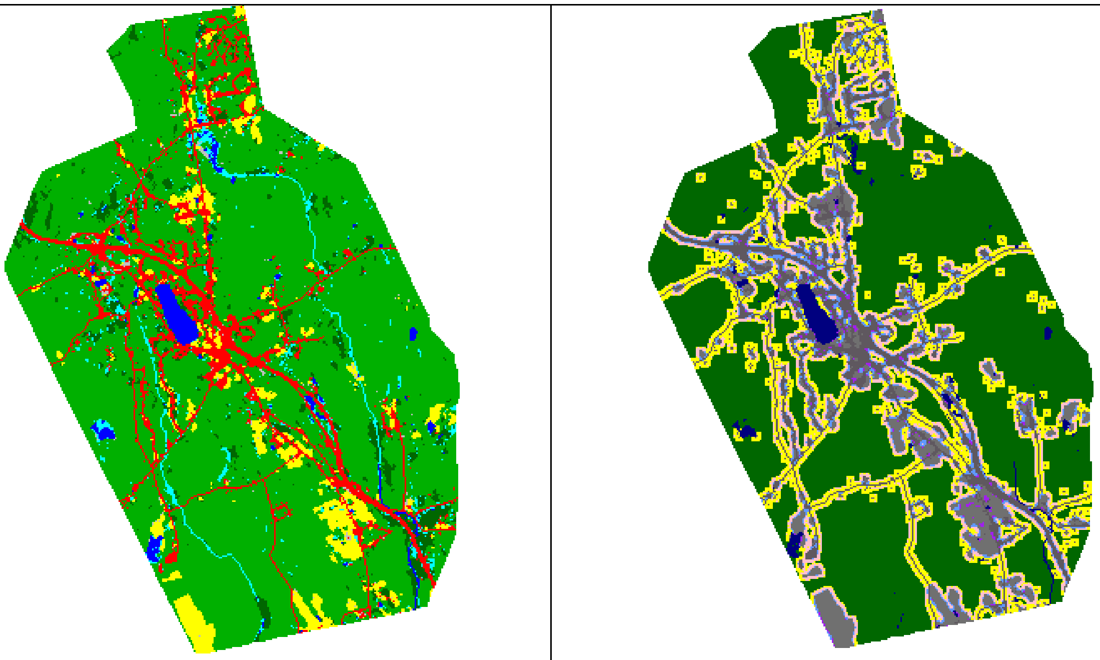

Figure 4a. 1985 land cover map. Red is urban, yellow is non-woody vegetation, green is deciduous forest, dark green is coniferous forest, blue is water, cyan is wetland, and gray is barren.

Figure 4b. 1985 forest fragmentation map. Dark gray is urban, gray is non-woody vegetation, dark green is interior forest, yellow is perforated forest, pink is edge forest, light blue is transition forest, purple is patch forest, and dark blue is water.

Figure 4. Result of applying the forest fragmentation model to a 1985 land cover map of Marlborough, CT.

The state of forest fragmentation index is comprised of two parts. The first is the total forest proportion (TFP):

$$\mathrm{TFP} = \frac{\text{total forest area}}{\text{total non-water area}} \tag{2}$$

The TFP is a general value used by many investigators to provide a basic assessment of forest cover in a region, and many investigations have identified a non-linear relationship between the amount of forest in a region and the level of forest fragmentation (Volgelmann, 1995; Wickham *et al.*, 1999). The TFP ranges from 0 to 1.

The second component of the index is a measure of forest continuity (FC) within the region. The FC value examines only the forested areas within the analysis region:

$$\mathrm{FC} = \frac{\text{weighted forest area}}{\text{total forest area}} * \frac{\text{area of largest interior forest patch}}{\text{total forest area}} \tag{3}$$

The FC measure specifically utilizes the results from the forest fragmentation model. Weighting values for the weighted forest area (WFA) were derived from the median Pf value for each fragmentation class as shown by the equation below. The area of each fragmentation class was then multiplied by the weight.

$$\mathrm{WFA} = (1.0 * \text{interior}) + (0.8 * (\text{perforated} + \text{edge} + \text{undeter.}) + (0.5 + \text{transitional}) + (0.2 * \text{patch}) \tag{4}$$

The rationale is that, given two regions of equal forest cover, the one with more interior forest would have a higher weighted area, and thus be less fragmented. To separate further regions based on the level of fragmentation, the weighted area ratio is multiplied by the ratio of the largest interior forest patch to total forest area for the region. FC ranges from 0 to 1.

The values of TFP and FC calculated for a region are plotted on a graph that specifies six conditions of forest fragmentation as shown in Figure 5. The TFP designations were determined based on the results of both Vogelmann (1995) and Wickham *et al.* (1999). They found that forest fragmentation becomes more severe as forest cover decreases from 100 percent cover towards 80 percent. Between 60 and 80 percent forest cover, the opportunity for re-introduction of forest to connect forest patches is greatest, and below 60 percent, forest patches become small and more fragmented. The FC regions were evenly split and designated high forest continuity (above 0.5) or low forest continuity (below 0.5).

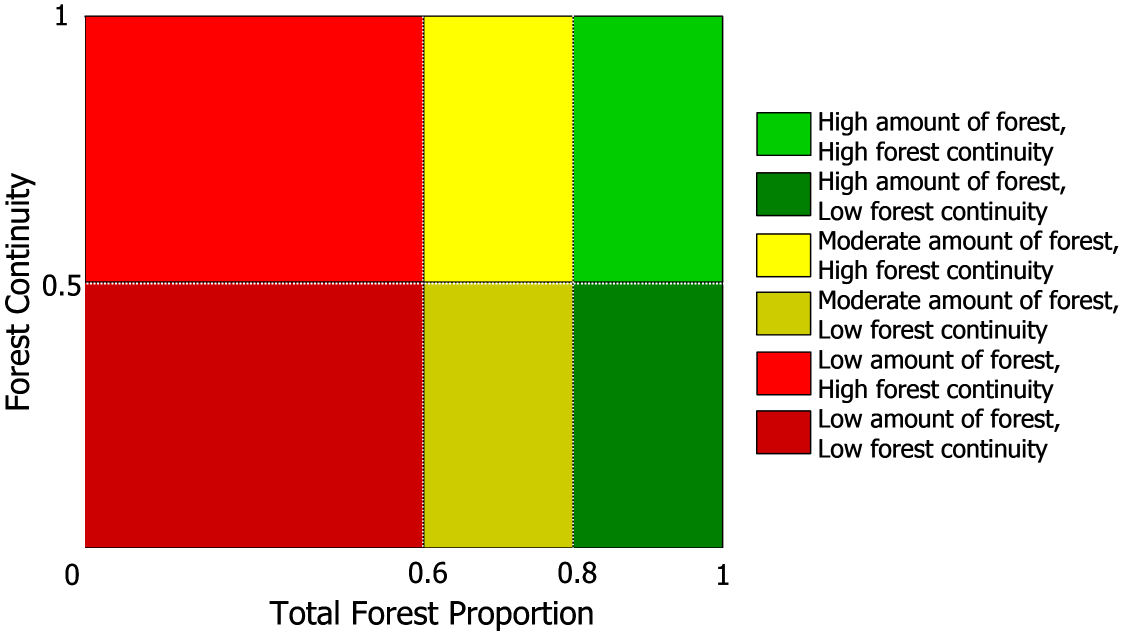

Figure 5. Six forest fragmentation conditions based on the values for Total Forest Proportion and Forest Continuity calculated for a region.

RESULTS AND DISCUSSION

Applying both the forest fragmentation model and state of forest fragmentation index to a time series of land cover data provides a quantitative assessment of the pattern of forest fragmentation at each date and provides a means for tracking trends in forest fragmentation. This is illustrated in Figure 6 for the town of Marlborough, Connecticut. The forest fragmentation images (Figures 6a and 6b) provide a visual representation of the changes occurring in the forested landscape of the town, while Table 1 provides quantitative information concerning these changes. As can be noted, the amount of total forest decreases between 1985 and 1999 with the amount of urban and non-woody vegetation and barren classes increasing. The impact on the forest is that there is less interior forest and more fragmentated forest. Comparing the values of TFP and FC (Figures 6c and 6d) to the graph in Figure 5 identifies the assignment of color to the town wide assessment shown in Figures 6c and 6d. It is easy to identify that the town in 1985 begins with a substantial amount of forest cover, although the forest is significantly fragmented. As more development occurs, the forest landscape continues to lose forest and become increasingly fragmented. While analyzing a single town doesn't necessarily provided a lot of useful information, evaluating several towns can provide a beneficial regional assessment of forest fragmentation and provide a means of comparing the forest fragmentation conditions among towns. Applying the index to discrete areas, such as census block groups or local watersheds as shown in Figures 7a-7d, generates a more detailed analysis of forest fragmentation for a region, and provides a better means to assess where forest fragmentation is most severe. The numbered census block groups and local watersheds in Figures 7a-7d correspond to the values of TFP and FC reported in Tables 2 and 3.

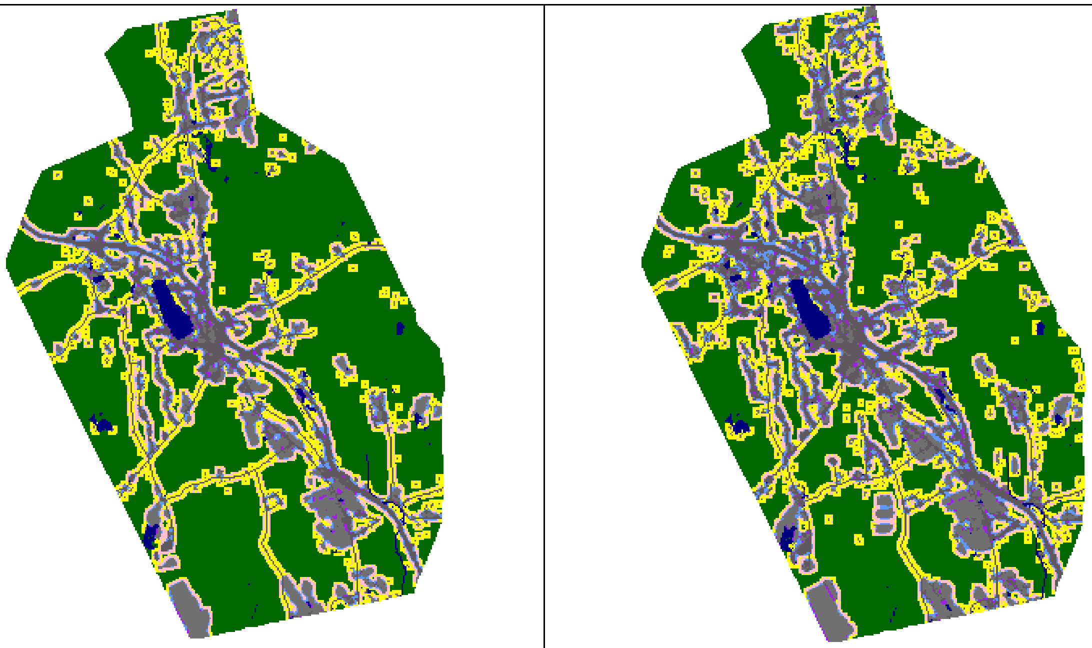

Figure 6a. 1985 Forest Fragmentation map

Figure 6b. 1999 Forest Fragmentation Map

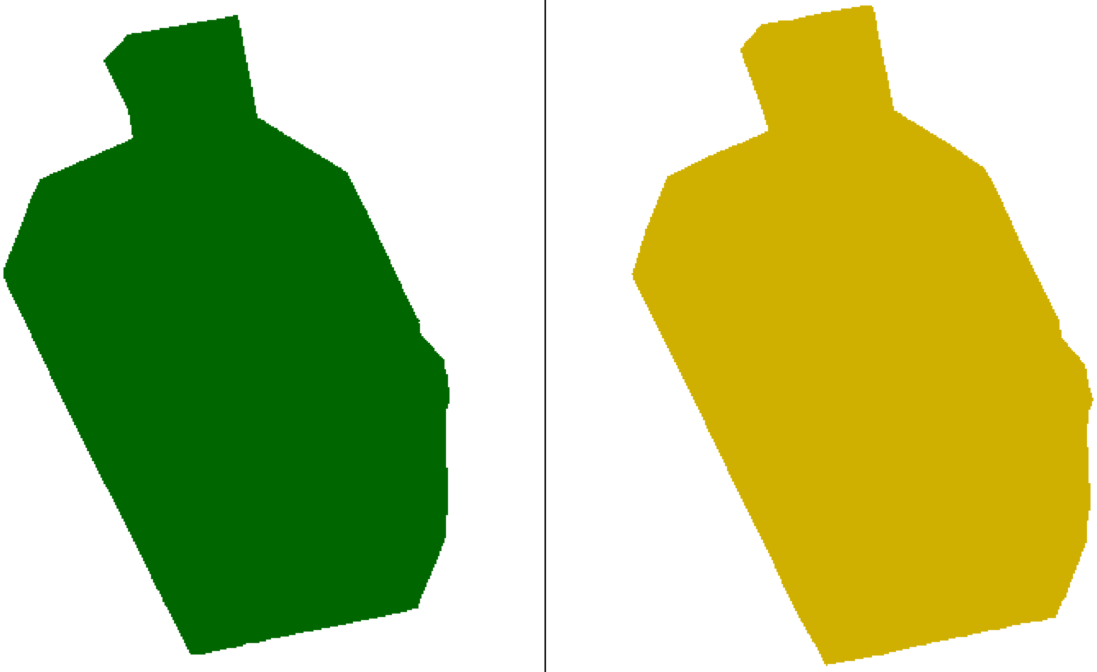

Figure 6c. 1985 State of Forest Fragmentation map
TFP = 0.842, FC = 0.121

Figure 6d. 1999 State of Forest Fragmentation Map
TFP = 0.784, FC = 0.109

Figure 6. Results of applying the forest fragmentation model to two dates of land cover data for the Town of Marlborough, CT (a, b) and results of applying the state of forest fragmentation at the town level. (c, d).

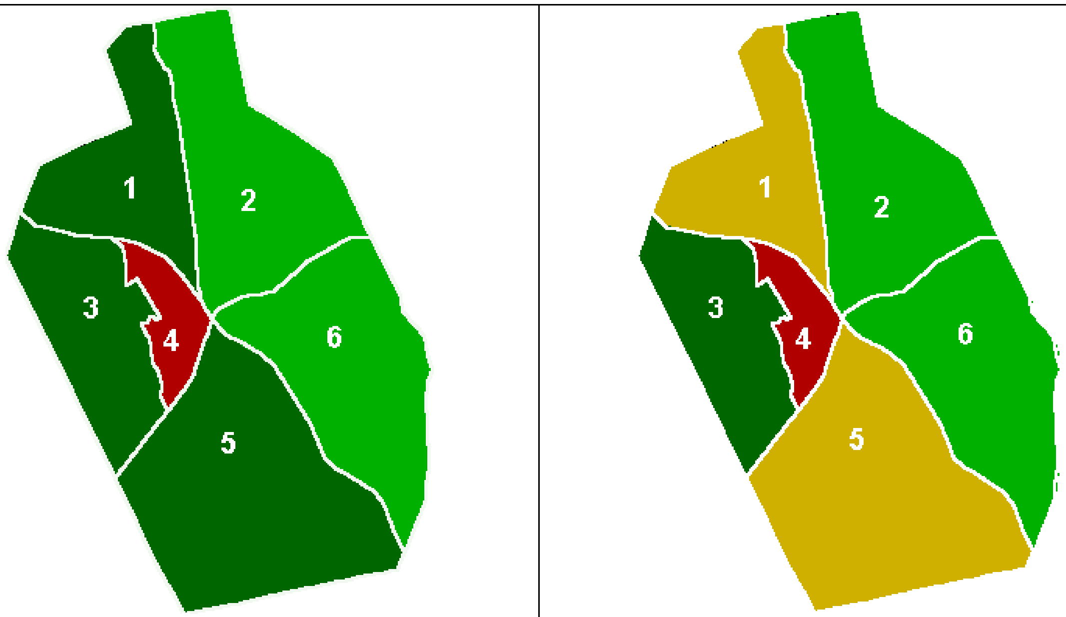

Figure 7a. 1985 State of Forest Fragmentation by Census Block Group

Figure 7b. State of Forest Fragmentation by Census Block Group

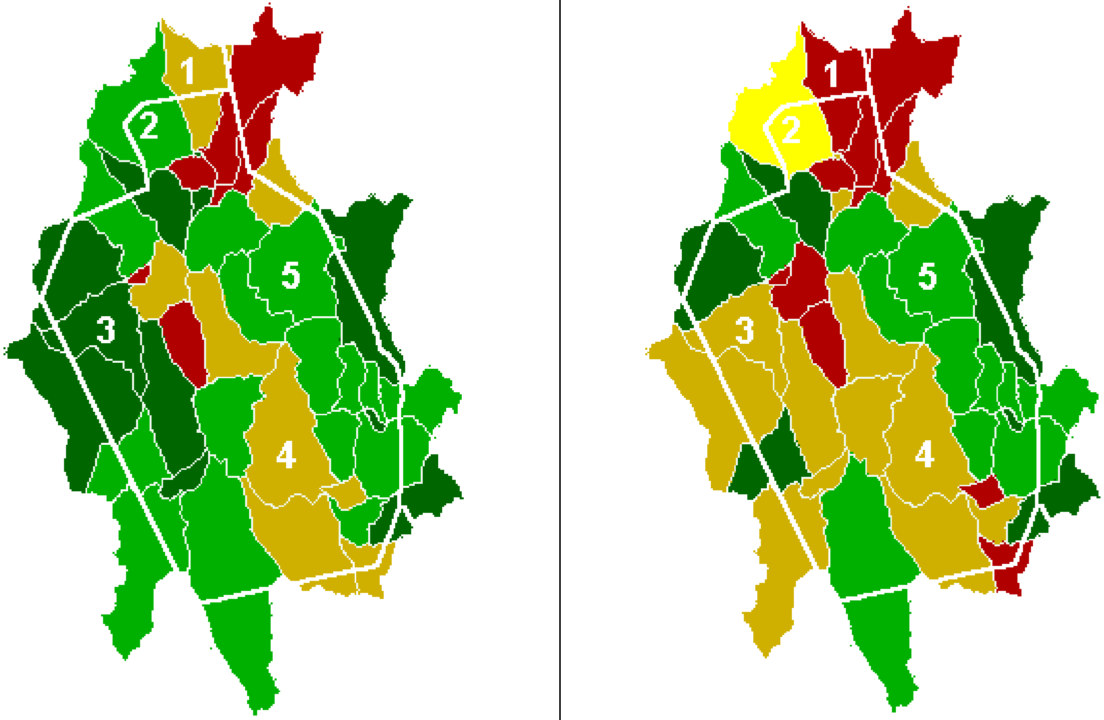

Figure 7c. 1985 State of the Forest Fragmentation by Local Watershed

Figure 7d. 1999 State Forest Fragmentation by Local Watershed

Figure 7. Results of applying the state of forest fragmentation index for two dates to Census block group regions (a, b) and local watersheds (c, d) within the Town of Marlborough, CT (See Figure 5 for color key).

Table 1. The area of land cover and forest fragmentation categories for the 1985 and 1999 Marlborough, CT forest fragmentation images.

	1985 Fragmentation (hectares)	**1999 Fragmentation** (hectares)
Water	103	110
Urban	589	824
Non- woody Veg. & Barren	363	478
Total Forest	5080	4721
Interior Forest	3446	2797
Perforated Forest	878	1001
Edge Forest	482	525
Transitional Forest	238	330
Patch Forest	36	68

Table 2. The TFP and FC values for census block groups from the 1985 and 1999 state of forest fragmentation maps for Marlborough, CT.

	1985 Total Forest Proportion	**1985 Forest Continuity**	**1999 Total Forest Proportion**	**1999 Forest Continuity**
Block Group 1	0.830	0.659	0.800	0.358
Block Group 2	0.862	0.659	0.810	0.589
Block Group 3	0.868	0.334	0.803	0.296
Block Group 4	0.551	0.280	0.465	0.191
Block Group 5	0.811	0.299	0.737	0.286
Block Group 6	0.880	0.738	0.840	0.609

Table 3. The TFP and FC values for select local watersheds from the 1985 and 1999 state of forest fragmentation maps for Marlborough, CT.

	1985 Total Forest Proportion	**1985 Forest Continuity**	**1999 Total Forest Proportion**	**1999 Forest Continuity**
Watershed 1	0.381	0.657	0.324	0.595
Watershed 2	0.661	0.809	0.579	0.754
Watershed 3	0.404	0.849	0.318	0.764
Watershed 4	0.192	0.731	0.187	0.660
Watershed 5	0.740	0.968	0.613	0.926

CONCLUSIONS

While the forest fragmentation index still requires further assessment to determine the validity of its results, it appears to consistently provide the type of information for which it was developed. Future research will assess the results of the forest fragmentation index with other measures of forest fragmentation and to determine other methods to assess regions such as over a constant size grid patchwork as opposed to irregularly shaped, various sized census block groups or watersheds. It is expected that local land use officials will be able to utilize the forest fragmentation model and the forest fragmentation index to assess the impact of forest fragmentation for specific regions and infer future impacts due to continued development and other land use decisions. Currently the forest fragmentation model and forest fragmentation index are being implemented as ERDAS Imagine 8.5 models and scripts to allow for easy analysis of forest fragmentation by other members of the NAUTILUS team.

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