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Transformation of the oak forest spatial structure in the Minneapolis/St. Paul metropolitan area, Minnesota, USA over 7 years

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Abstract

The Twin Cities Metropolitan Area (TCMA) oak (*Quercus* spp.) forest area decreased by 5.6% between 1991 and 1998. Accompanying spatial transformation of the forest can have great impacts on forest health, water flow and quality, wildlife habitat, potential for the spread of invasive species, and the quality of life of urban residents. The types of spatial transformation that occurred along with the loss of oak forest in the TCMA were investigated through the integration of remote sensing, a Geographic Information System (GIS), and landscape and patch metrics in seven ecological subsections between 1991 and 1998. Oak forest patches in the TCMA as a whole decreased in area, number, and complexity. Fragmentation of oak forest took place in all subsections and attrition occurred in three subsections. Knowledge of how the oak forest has changed over time can be integrated with land use change information to help planners make decisions about zoning and development that will minimize the impacts of increasing land conversion pressure on forest areas.

Keywords: *Quercus*; Fragmentation; Attrition; Remote sensing; Landsat

1. Introduction

The Twin Cities Metropolitan area (TCMA) is a rapidly urbanizing region in Minnesota, USA. Northern red oak (*Quercus rubra*), northern pin oak (*Quercus ellipsoidalis*), white oak (*Quercus alba*), and bur oak (*Quercus macrocarpa*) are hardwood tree species that have a widespread distribution in the TCMA and are highly valued for landscape significance, wildlife food and habitat, and aesthetics. The oak species group was a major presettlement forest type in the TCMA area (Marschner, 1974) and is currently the most important aggregation of hardwoods in the United States (Juzwik, 2000). Oak forests are also appealing places to build human dwellings. However, the abrupt environmental transformation accompanying new construction often leads to rapid decline of oak trees (Ware, 1982).

The amount of oak forest in the TCMA decreased by 5.6% (from 33,844 ha to 31,932 ha) between 1991 and 1998 (Ward and Juzwik, 2005). Transformation of the spatial structure (e.g., shrinkage, fragmentation) of the oak forest occurred along with the loss of oak forest area. A common cause of forest transformation is removal of trees for conversion of forest land to urban or suburban use. In the TCMA, 12,000 ha of forest land were converted to urban use between 1991 and 1998 (Yuan et al., 2005). Damage from pathogens or insects can also alter forest structure. For example, oak wilt disease, caused by infection with the fungal pathogen *Ceratocystis fagacearum*, affected over 6000 ha of TCMA oak forests in 1998 (Albers, 2001). The predominant means by which the oak wilt fungus has been introduced to new areas has been through human activities (Wilson, 2001), such as transportation of infected oak firewood, or from wounding of oaks through tree-pruning or construction damage. Since oak wilt infection centers typically result in irregular circular patches of dead and dying trees (Juzwik, 2000), oak wilt has substantially altered the structure of oak forests in the TCMA.

Another cause of transformation associated with development is the construction of roads and powerlines that bisect forest stands. There is a strong relationship between proximity to highways and new development in the TCMA (Yuan et al., 2005). There was an increase in population of 15% between 1990 and 2000 in the TCMA (Land Management Information

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Center, 2003) and the roadway system has expanded similarly to address traffic congestion and mobility.

Five major processes transform the spatial structure of forests: fragmentation, attrition, perforation, shrinkage, and dissection (Forman, 1995). Forest fragmentation is the breaking up of patches (forest stands) into smaller patches, attrition is the disappearance of patches, perforation is the process of making holes in a patch, shrinkage is the decrease in patch size, and dissection is the breaking up of patches by elements such as roads or powerlines. Forest transformation can be quantified over time and space through the use of landscape metrics. The metrics can be used to analyze and monitor the transformation processes and also show how they are inter-related. For example, the numbers of patches increase with fragmentation and dissection and decrease with attrition. In addition, mean patch size decreases with fragmentation, dissection, perforation and shrinkage, and generally increases with attrition because the smallest patches are more likely to disappear.

Civco et al. (2002) used landscape metrics derived from Landsat Thematic Mapper (TM) data to quantify forest fragmentation between 1985 and 1999 in Marlborough, Connecticut. The authors determined that urban growth in the area was associated with a decrease of 7% in total forest, and an increase of 89% in the number of forest patches. The forest landscape structure of private forest holdings in Nurmes, Finland was altered between 1941 and 1997 by intensive forest management with the result of a more fragmented landscape as indicated by changes in several landscape metrics (e.g., mean patch size, largest patch index) (Lofman and Kouki, 2003).

Landscape structure is important because it influences ecological processes and characteristics (McGarigal and Marks, 1995). The smaller or more fragmented the patch the more vulnerable it is to impacts from external factors. The impacts can include loss of biodiversity (Hobbs, 1988a), changes in hydrology and microclimate, reduced water quality (Saunders et al., 1991), and increased potential for spread of invasive species (With, 2004). At the same time, ecological factors may affect not only the quantity of oak transformation, but also the type of transformation process. Ecological factors include physical, geologic, climatic, and floristic characteristics. For example, there are striking differences in topography among the seven ecological subsections in the TCMA (Fig. 1) – from broad, sandy plains to steep, complex slopes, and predominant soil textures range widely from fine sands to clay loams (Keys et al., 1995; Minnesota Department of Natural Resources, 2006). The subsections also differ in rates and types of urbanization due to sociological factors such as the desirability of the land for development. For example, subsections with many lakes may be more attractive for development than subsections with few lakes. Parks and nature preserves are typically protected from development and many of these can be found in some subsections but not in others.

Land use planners, natural resource managers, and planning councils need data on how forest characteristics have changed in order to understand the consequences of past decisions and to consider relationships between development and forest characteristics in future land use decisions. Quantitative spatial inventories of the urban forest over time are essential to the planning process (Pauleit and Duhme, 2000), and remote sensing and Geographic Information Systems (GIS) have become useful tools in addressing the need. The amount of oak forest transformation that occurred in the TCMA has not been documented previously. Given the potential impacts of forest transformation over time, this study was undertaken to integrate remote sensing, GIS, and landscape metrics to quantify the transformation that occurred in the TCMA oak resource between 1991 and 1998. The oak forest in 1991 and 1998 was previously classified from Landsat TM imagery and the change in the extent and distribution between the time periods was quantified (Ward and Juzwik, 2005). The 1991 and 1998 classifications were used in this study as the basis for the derivation of the oak forest landscape metrics, and were also used in a study by Loeffelholz (2003) to identify relationships between the change in oak forest area and condition and TCMA land use classes that varied in degree of urbanization. The oak forest metrics from Ward and Juzwik (2005) and from this study were used subsequently to determine associations between changes in the oak forest and several measures of urbanization, such as changes in area of impervious surface, and population density, and proximity to roads and to lakes or rivers (Kromroy et al., 2007).

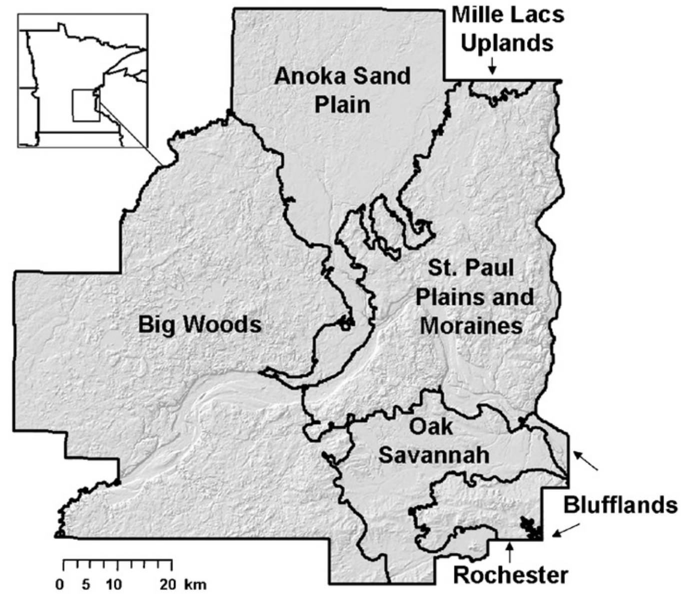

Fig. 1. Location of the study area, and seven ecological subsections in the Minneapolis/St. Paul metropolitan area, Minnesota.

The hypotheses of this study were that (1) changes in the spatial structure of the oak resource were associated with previously determined changes between 1991 and 1998 in the oak forest area, and that (2) there were differences among subsections due to the differences in their ecological and human-associated characteristics. The objectives were to: (1) analyze the oak forest spatial structure in 1991 and 1998 to gain insight on the nature and magnitude of the changes over time, and (2) explore the differences among ecological subsections within the TCMA in the quantities and types of oak forest transformation that occurred. The following landscape metrics were selected for the study based on the hypotheses being tested – patch area, number and size; radius of gyration; perimeter–area ratio; and Euclidean nearest neighbor distance.

2. Methods

2.1. Study area

The 770,000-ha study area encompasses seven counties in east-central Minnesota (Anoka, Carver, Dakota, Hennepin, Ramsey, Scott, and Washington). The area includes all or parts of seven ecological subsections (Table 1, Fig. 1) which are described by Keys et al. (1995) and the Minnesota Department of Natural Resources (2006). The three largest subsections – the Big Woods, St. Paul-Baldwin Plains and Moraines (Plains), and the Anoka Sand Plains (Anoka) – comprise 87% of the total land area and 93% of the oak forest area in the TCMA.

The Anoka subsection is in the north central part of the study area and is a broad, flat, sandy plain with level to gently rolling topography. Soils in the subsection primarily consist of well-drained fine sands and poorly drained prairie soils. Present forest vegetation includes species associated with oak openings and oak barrens. Urban development is rapidly expanding in the Anoka subsection primarily due to the presence of the city of Minneapolis and its suburbs and major transportation corridors in its southern extent.

The Big Woods subsection is in the western part of the TCMA and is characterized by level-topped hills and many lakes and rivers. Soils are predominantly loamy, and present land use is largely agriculture and to a lesser degree includes pasture, wetlands, and widely separated upland forests. Minneapolis city and suburbs are located in the eastern extent of the Big Woods with urban development continuing to expand further into the subsection, resulting in dramatic changes in the landscape.

The Plains subsection comprises the northeast side of the study area, where steep, short slopes and many lakes dominate the landscape. Predominant soils are loams, loam mixtures, and sands. Urban land uses dominate the subsection, which includes the city of St. Paul and its suburbs, though small, forested areas remain.

The four smallest subsections in the TCMA are the Oak Savannah (Savannah), the Rochester Plateau (Rochester), the Blufflands, and the Mille Lacs. The four subsections account for only 13% of the total area and 7% of the TCMA oak forest area. The Savannah subsection is in the southeast part of the TCMA and has gently rolling topography and few lakes. Soils consist of wet prairie soils and well-drained prairie and forest soils. The predominant land use is agriculture, but urban development is accelerating along the northern boundary.

A small portion of the Mille Lacs subsection is contained in the northeast part of the study area, where gently rolling plains with extensive areas of wetlands and lakes are the dominant landforms. Soils in the subsection are loamy, and include dense glacial till that impedes water movement throughout the soil profile. Forestry and recreation are the most prevalent land uses in the central and eastern parts of the subsection, and agriculture is concentrated in the western and southern portions. Due to its proximity to the cities of Minneapolis and St. Paul and its vast network of roads, the Mille Lacs subsection is under increasing pressure from the expansion of motorized recreation and urban development, especially near lakeshores.

A portion of the Rochester subsection is in the southeast part of the study area and it consists of level to gently rolling plains. The subsection contains few lakes, though it has a network of rivers and some coldwater trout streams. The predominant soils are productive forest soils, influenced by siltstones, sandstones, and shales. The majority of the subsection is used for agriculture and pasture, and the remaining small forested areas consist of oak openings and barrens. Areas along the corridor from the major Minnesota cities of Rochester and Minneapolis/St. Paul are projected to grow rapidly over the next decade.

Two portions of the Blufflands subsection are in the southeast part of the study area, where bluff prairies, steep bluffs and deep stream valleys characterize the landscape. The soils are similar to those of the Rochester subsection – productive forest soils and siltstones, sandstones, and shales. The primary land use is woodland, followed by cropland and pasture, and small forested areas of oak openings and barrens. Recreational opportunities are abundant due to significant amounts of public land along the well-developed river network, and numerous coldwater trout streams.

Table 1
Land area, forested area and oak forested area in each of seven ecological subsections in the Minneapolis/St. Paul metropolitan area, Minnesota

Subsection	Total land area (ha)[a]	Total land area (%)	Forested area (ha)	Forested area (%)[b]	Oak area (ha)	Oak area (%)[c]
Anoka	1,47,539	19.2	26,557	3.4	13,533	12.8
Big Woods	3,34,650	43.4	36,812	4.8	6,645	6.3
Blufflands	3,819	0.5	1,375	0.2	265	0.2
Mille Lacs	2,884	0.4	836	0.1	373	0.4
Plains	1,86,199	24.2	35,378	4.6	11,393	10.8
Rochester	24,491	3.2	1,714	0.2	841	0.8
Savannah	70,655	9.2	2,826	0.4	792	0.8
Total	7,70,237	100.0	1,05,498	13.7	33,843	32.1

[a] Derived from Minnesota Department of Natural Resources (2001) data.
[b] Percent of subsection land area that was forested in 1991. Derived from Yuan et al. (2005) data.
[c] Percent of forested area classified as oak in 1991.

2.2. Spatial data and image classification

The subsections were classified separately to minimize classification errors by assuming a greater spectral homogeneity within subsections than between them. Four Landsat TM images were acquired on June 16 and September 4, 1991; and May 18 and September 7, 1998. ERDAS Imagine software (Leica Geosystems, St. Gallen, Switzerland) was used for preparation and manipulation of the imagery. Image rectification was performed with a root mean square error of less than 0.25 pixels using a Minnesota Department of Transportation roads basemap (UTM zone 15, GRS1980, NAD83). A random sample of oak forest stands stratified by subsection was used to select test and training sites ($N = 640$) for data collection in the field. The sites were randomly selected from a previously classified oak cover map (M. Bauer, unpublished data) and were located using a Global Positioning System (GPS) (Trimble Navigation Ltd., Sunnydale, CA). Forest species and condition data were collected at each site. Forest species data from the Minnesota Land Cover Classification System (Minnesota Department of Natural Resources, 2003) and the Gap Analysis Program (Minnesota Department of Natural Resources, 2002) also were used as test and training data.

The two TM images from 1991 were stacked, as were the two images from 1998. A 1993 land cover layer (Minnesota Department of Natural Resources, 2002) was used as a mask to differentiate forested area from other land cover classes in the imagery. Each of the seven ecological subsections was clipped from the masked imagery using boundary layers (Minnesota Department of Natural Resources, 2001). The area covered by each of the dominant forest classes in the TCMA was calculated for each subsection from the 1993 land cover layer. The classes were: ash, aspen, boxelder, bur oak, cottonwood, lowland deciduous, maple-basswood, northern red oak, northern pin oak, red pine, silver maple, tamarack, upland deciduous, white oak, and white pine. The area values were converted to percent cover and were used as expected frequencies. Expected frequencies were entered as prior probabilities (Pedroni, 2004) for each forest class in the spectral Signature Editor within ERDAS Imagine. Supervised classification was performed on bands 3, 4 and 5 in each image stack using the maximum likelihood algorithm, and classified images were produced of the 1991 and 1998 TCMA oak forest (Ward and Juzwik, 2005). Image-differencing (Al-Khudhairy et al., 2005) was used to derive a layer depicting change between the 1991 and 1998 oak classifications. Overall accuracies of the classifications were calculated by ecological subsection (Table 2). The overall accuracy indicates how well the classes were correctly classified.

2.3. Spatial metrics and analyses

The classified images were converted to grids using ArcGIS (ESRI Inc., Redlands, CA). FRAGSTATS software (McGarigal and Marks, 1995) was used to generate the oak forest landscape and patch metrics from the grids. Landscape metrics were calculated for each subsection for the landscape as a whole, and patch metrics were derived for individual forest patches in each subsection. Differences among subsections were analyzed using the individual oak forest patch metrics, the ANOVA procedure with Fisher's LSD, and SAS software (SAS Institute Inc., Cary, NC).

Table 2
Accuracy assessment of classifications of oak forests in 1991 and 1998 from Landsat TM imagery of the Minneapolis/St. Paul metropolitan area, Minnesota

Ecological subsection	Classification (year)	Overall accuracy (%)
Anoka	1991	61
	1998	58
Big Woods	1991	56
	1998	56
Blufflands	1991	75
	1998	71
Mille Lacs	1991	66
	1998	65
Plains	1991	60
	1998	56
Rochester	1991	64
	1998	65
Savannah	1991	52
	1998	58

Change in the number and mean size of patches over time can be used as overall measures of landscape fragmentation and attrition. Radius of gyration is a measure of patch extent and reflects the mean distance between each cell in the patch and the patch centroid. Radius of gyration equals 0 when a patch consists of a single cell and increases as patch length increases. Perimeter–area ratio is a simple measure of shape complexity. Decreases in perimeter–area ratio can indicate forest fragmentation because natural forests tend to have complex shapes with a larger perimeter or edge for a given area. Euclidean nearest neighbor is a simple measure of patch context, reflects patch isolation, and equals the distance to the nearest similar patch.

3. Results

3.1. Classification accuracy

Overall accuracies ranged by subsection from 52% to 75% (Table 2). The classifications of the Blufflands, Mille Lacs and Rochester subsections had the greatest overall accuracies, and the least overall accuracies were of the Savannah and Big Woods classifications (Table 2). Classification accuracies were inversely related to subsection size and forest species heterogeneity. The forest classes most easily discriminated from oak were black ash, upland deciduous and tamarack; the classes most difficult to separate from oak were lowland deciduous, aspen and maple-basswood. Accuracies of the classifications also were affected negatively by the preponderance of small forest patch sizes in the TCMA and small patch numbers in some subsections.

Table 3
Comparisons among seven ecological subsections in mean oak forest patch metrics in 1991, 1998, and the change between the years, in the Minneapolis/St. Paul metropolitan area, Minnesota

Subsection	Patch area (ha)	Patch number	Patch mean size (ha)	Radius of gyration (m)	Perimeter–area ratio	Euclidean nearest neighbor (m)
Oak forest patch metrics, 1991						
Anoka	13,533	14,673	0.92 b[a]	28.31 d	1916.50 d	49.86 a
Big Woods	6,645	19,255	0.34 a	22.76 ab	1908.69 bcd	56.17 b
Blufflands	265	807	0.33 a	20.04 a	1940.69 cd	54.49 ab
Mille Lacs	373	310	1.20 bc	33.70 c	1763.83 a	53.90 abc
Plains	11,393	11,235	1.01 b	30.30 c	1838.43 a	60.65 c
Rochester	841	489	1.72 c	39.58 e	1809.90 abc	86.54 d
Savannah	792	1974	0.40 a	23.66 b	1923.91 cd	69.22 e
1991 Total	33,843	48,743	0.69	26.40	1894.08	56.09
Oak forest patch metrics, 1998						
Anoka	12,304	16,262	0.76 b	27.88 c	1765.25 c	46.49 a
Big Woods	6,416	17,695	0.37 a	22.46 a	1785.45 c	61.13 c
Blufflands	279	969	0.29 a	19.78 d	1596.11 a	49.19 ab
Mille Lacs	362	298	1.22 bcd	34.75 b	1538.96 a	57.11 bc
Plains	11,015	10,946	1.01 c	30.55 b	1672.44 b	61.17 c
Rochester	813	491	1.66 d	41.72 e	1595.65 ab	89.94 d
Savannah	743	1,504	0.49 a	23.83 a	1782.97 c	80.87 e
1998 Total	31,932	48,165	0.66	26.39	1745.60	56.84
Change in metrics between 1991 and 1998 (%)						
Anoka	−9.08	10.83	−17.39	−1.52	−7.89	−6.76
Big Woods	−3.44	−8.10	8.82	−1.32	−6.46	8.83
Blufflands	5.25	20.07	−12.12	−1.30	−17.76	−9.73
Mille Lacs	−3.01	−3.87	1.67	3.12	−12.75	5.96
Plains	−3.32	−2.57	0.00	0.83	−9.03	0.86
Rochester	−3.42	0.41	−3.49	5.41	−11.84	3.93
Savannah	−6.27	−23.81	22.50	0.72	−7.33	16.83
Mean (%)	−5.65	−1.19	0.00	0.85	−10.44	2.85

[a] Measures in the same column followed by the same letter were not significantly different ($P > 0.05$) as determined by ANOVA and Fisher's LSD. Comparisons were made for oak patch mean size, radius of gyration, perimeter–area ratio, and Euclidean nearest neighbor distance metrics.

3.2. Landscape metric changes

Over the total TCMA, patch area, number, mean size, radius of gyration, and perimeter–area ratio decreased, and Euclidean nearest neighbor increased, between 1991 and 1998 (Table 3). Total oak area decreased in all subsections except for the Blufflands, where an increase was observed (Table 3). Within the other six subsections, decreases in total oak area ranged from 3.0% to 9.1% (Table 3). The largest percentage decreases in total oak area and mean patch size were in the subsection that contained the largest amount of oak (Anoka) (Table 3).

Among subsections there were differences in mean patch size, radius of gyration, perimeter–area ratio, and Euclidean nearest neighbor in 1991 ($P < 0.001$) and in 1998 ($P < 0.001$) (Table 3). Between 1991 and 1998, number of patches increased and mean patch size decreased in three of the seven subsections (Anoka, Blufflands, and Rochester) (Table 3). Number of patches decreased and mean patch size increased for three of the seven subsections (Big Woods, Mille Lacs and Savannah) (Table 3). Patch number decreased but mean patch size did not change in the Plains subsection (Table 3). Radius of gyration decreased in three subsections and increased in four subsections (Table 3). Perimeter–area ratio was the only metric for which the direction of change (decrease) was the same for all subsections between 1991 and 1998. The largest decreases in perimeter–area ratio were in three of the smallest subsections – the Blufflands, Mille Lacs, and Rochester (Table 3). Euclidean nearest neighbor decreased in two subsections and increased in five subsections (Table 3).

4. Discussion and conclusions

Overall classification accuracies of the 1991 and 1998 oak resource were less than desirable, though the level is consistent with accuracies published for other forest type classifications derived from moderate spatial resolution imagery. The scale (degree of detail) of satellite imagery is fixed by the spatial resolution of the sensor aboard the satellite because it determines the size of the smallest feature that can be discriminated on the ground (Garcia-Gigorro and Saura, 2005). The spatial resolution of TM imagery is 30 m, and high levels of accuracies have been reported (between 78.5% and 99.8%) for classifications of highly aggregated Level I (Anderson et al., 1976) land cover classes (e.g., agriculture, forest, urban, water) in the TCMA (Yuan et al., 2005). However, as the degree of aggregation decreases to the more detailed Level II forest classes (e.g., deciduous, coniferous, mixed) and further (forest type) land cover classes, classification accuracies likewise decrease. The classifications of Landsat TM imagery used in this study were of Level III land cover classes (oak forest type) and the accuracies were in the range of the Level III land cover accuracies (between 50% and 78%) of a 1990s-era statewide classification of TM images completed by the Minnesota Department of Natural Resources (2002).

A researcher could use high spatial resolution satellite or airborne imagery (e.g., IKONOS, Quickbird) in an attempt to achieve higher accuracies for Level III classifications. However, image acquisition costs are much greater, and the geographic coverage is small compared to that of moderate resolution sensors. For this study, TM imagery was chosen for several reasons: its geographic coverage (one scene covered the seven-county study area), its seasonal and historical scope, the relatively low costs of acquisition and interpretation, the availability of datasets that were previously developed using TM imagery acquired in 1991 and 1998 in the TCMA (e.g., land cover, impervious surface) (Doyle, 2004; Yuan et al., 2005) and that were used in related research (Kromroy et al., 2007).

The oak forest spatial structure of the TCMA was transformed between 1991 and 1998. Across the area as a whole, oak stands diminished in numbers, became more isolated, and became less complex in shape. There were differences among ecological subsections in oak forest spatial patterns in 1991, in 1998, and in how they changed over the time period. The three subsections that comprise most of the oak forest decreased in total oak forest area and perimeter–area ratio, but the direction of change for the other metrics varied among those subsections. Perimeter–area ratio was the only metric that changed in the same direction (decreased) for all subsections.

Decreased perimeter–area ratio of oak patches may increase the potential for spread of invasive species into resultant forest canopy openings. For example, a non-native shrub, common buckthorn (*Rhamnus catharticus*), has aggressively invaded urban forests in the city of St. Paul, and competes successfully with native species in canopy openings (Hobbs, 1988b). Common buckthorn is a frequent invader in TCMA oak stands disturbed by oak wilt (J. Juzwik, personal communication).

Based on decreases over time in mean perimeter–area ratio, all seven subsections underwent fragmentation of the oak forest between 1991 and 1998. Additionally, attrition of the oak forest during the same time interval is indicated in three subsections (Big Woods, Mille Lacs and Savannah) based on decreases in patch numbers and increases in mean patch sizes. The subsections differ in many physical characteristics so it is not surprising that the types of oak forest transformation differ among them. In addition, the subsections may have been in different phases of forest transformation, due in part to varying rates and types of urban development, which, in turn, may be related to proximity to the urban core, or to abundance of lakes or rivers and roadway networks (Kromroy et al., 2007). Phases overlap, but generally fragmentation and shrinkage predominate in the middle phases of forest transformation and attrition peaks in the final phase (Forman, 1995). Oak forests in the Big Woods, Mille Lacs and Savannah subsections may have been in the final phases of transformation due to the attrition of patches. Based on double-digit percentage changes between 1991 and 1998 in oak patch numbers and sizes, the Anoka, Blufflands and Savannah subsections changed at faster rates than the other subsections.

Expansion of housing and road development resulted in forest transformation in urbanizing areas analyzed in other studies. Hobbs (1988a) determined in 1980 that species richness in forest patches in the cities of St. Paul and Minneapolis was positively related to patch size and was reduced by the effects of urbanization. Within the Regional Municipality of York, Canada, density of forest patches increased by 26–189%, and average patch size decreased by 56–87% for several areas between 1975 and 1988 (Puric-Mladenovic et al., 2000). The authors concluded that the forest transformation in the Municipality was due to clearing for timber production, and expansion of agriculture and urban development. Saunders et al. (2002) determined that 1990s-era road development was a primary mechanism of forest fragmentation in northern Wisconsin and parts of Minnesota and Michigan, and that there were more but smaller forest patches in areas with roads compared to roadless areas. Though development of roads in the study area allowed increased access for humans, the authors concluded that the area was negatively impacted through the removal of the original land cover, the creation of edge effects that degraded wildlife habitat, and the alteration of the landscape structure and function.

Along with the changes in oak forest spatial structure and reduction in area of oak forest reported here, the condition of the TCMA oak forest also changed over a similar time period (Loeffelholz, 2003). The author determined that the largest negative impacts on oak forest condition occurred in middle density and low density residential land use classes. Kromroy et al. (2007) found that changes in some of the metrics reported in this study were strongly associated with changes over the same time period in several measures of urbanization in the TCMA. For example, changes in oak patch size and Euclidean nearest neighbor were positively correlated ($r = 0.85$ and 0.79, respectively) with changes in population density between 1990 and 2000. There was a negative correlation ($r = -0.80$) between changes in oak patch perimeter–area ratio and changes in total impervious surface area (e.g., roads, parking lots) between 1991 and 1998. In addition, the authors reported strong relationships between the loss (in all subsections but the Blufflands) of oak forest patches over time and proximity of the patches to roads ($r = 0.88$), and to lakes or rivers ($r = 0.73$).

Landscape metrics offer great promise to land planners and managers because they can be used to measure the arrangement of landscape elements in both time and space (Leitao and Ahern, 2002). The results of this study demonstrate significant spatial changes in the TCMA oak forest between 1991 and 1998. In the next decade, population in the TCMA is projected to increase by 22% and number of households by 31% (Land Management Information Center, 2003). As population increases and road development intensifies, forest transformation and spatial landscape changes are expected to continue. The actual impacts are unknown, but there is great potential for significant damage to ecosystems and the communities they support. The information presented here on how the oak forest structure has changed over time can be integrated with information on changes in land use and other urbanization characteristics to help land planners and natural resource managers make more informed decisions about zoning and development to minimize the impacts of increasing land conversion pressure in forested areas.

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