Distribution of forest ecosystems over two centuries in a highly urbanized landscape

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Abstract

Urban development often results in diminished forest cover and severely fragmented landscapes, but most research on effects of urban development has been focused on densely forested regions and has not distinguished remnant from recently established forest cover. Urban development may have different effects in heterogeneous landscapes with high pre-urban fragmentation. Our study investigated spatial and temporal distribution of remnant forest ecosystems across a large urban landscape to assess effects of landscape structure and development patterns on forest conversion. Forest ecosystem distribution within the greater Chicago region (18,822 km²) was mapped in three time periods using Public Land Survey records (1830's) and aerial imagery (1939 and 2010). Loss of original forest between sampling periods (conversion) was related to landscape features, land use, and sociodemographic factors. In 2010 ~17% of pre-urban forest area remained, which represented ~40% reduction relative to 1939. Conversion did not differ greatly with urbanization, but fragmentation was greater in areas with high population density and rapid population growth. Conversion was lower in areas close to waterways, where there was less impervious surface, and also differed among land uses (highest in agricultural and industrial). Remnant forests had higher canopy cover, basal area, and native species dominance than recently established forests. Urbanization may have lower relative effects on total forest cover in naturally fragmented landscapes, but may result in extreme fragmentation. Remnant forests had characteristics consistent with high functional value, but creating connectivity among ecosystems in highly urbanized areas will require promotion of canopy cover in urban land uses.

Keywords: fragmentation; urban development; remnant forest; aerial image analysis; *Quercus*; Chicago

Introduction

Development in urban regions can have deleterious effects on forest cover and connectivity (Medley et al., 1995; Nowak & Walton, 2005; Riitters et al., 2002), but spatial and temporal patterns of canopy loss within these landscapes can be complex (Sanders, 1984). Intense development in the urban core can lead to extreme loss of canopy cover, although recent urban tree planting may ameliorate this effect to some degree (Zhou et al., 2011). In densely forested regions, this conversion can result in landscapes with strong urban-rural differences in canopy cover and habitat connectivity (Miller, 2012). This is especially true in areas where rural canopy cover has recently increased due to regrowth of forest cover related to agricultural abandonment (Zhou et al., 2011). More recent suburban and exurban development has led to increasing fragmentation of forest cover relative to pre-urban conditions in areas beyond the urban core (Radeloff et al., 2005). Such development may decrease differences in canopy cover between core and rural areas, but these differences likely persist in most densely forested regions (Miller, 2012; Zhou et al., 2011).

Much of the research on the effects of urbanization on forests has been conducted in densely forested regions, but many urban areas are situated in landscapes that were either unforested or had a heterogeneous landscape composed of a variety of ecosystem types prior to urbanization (Nowak et al., 1996; Schleeweis et al., 2013). At the sparsely forested end of this spectrum are biophysical regions such as plains or deserts, where the pattern of tree canopy cover in the urban landscape is essentially the opposite of that in densely forested regions, with greater canopy cover in more urbanized parts of the landscape due to tree planting and water diversion (Nowak et al., 1996). However, intermediate on this spectrum are more heterogeneous, partially-forested landscapes, where the effect of urban development on canopy cover and habitat connectivity

relative to the original landscape condition may be less straightforward and uncertain (Bigsby et al., 2014; Gillespie et al., 2012).

An example of a region where forested ecosystems were patchily distributed and thus relatively fragmented prior to urban development is the central part of North America, which historically consisted of a mixture of prairie and forest ecosystems (Anderson, 1991; Bowles et al., 1994). Modern patterns of forest cover in metropolitan areas in this region have been shaped by this landscape legacy as well as development patterns (Fahey et al., 2012; Iverson & Cook, 2000; Sharpe et al., 1986; Ward et al., 2007). In Midwestern US cities such as Chicago, modern forest cover is strongly concentrated in protected reserves in parks and other natural areas, which are more prevalent in areas closer to the urban core than in the exurban and highly agricultural rural parts of the landscape (Chicago-Wilderness, 2004). In the rural parts of the Midwestern US, intensive agricultural production has persisted into the modern era resulting in relatively little forest regrowth related to agricultural abandonment. Highly urbanized areas in this region could, therefore, have retained equivalent or greater levels of remnant forest (and connectivity between these ecosystems) than surrounding rural landscapes. However, in contrast to urban areas in arid regions, this effect would be more strongly related to development patterns than eco-climatic factors (Nowak et al., 1996).

Absolute canopy cover and the connectivity of this cover is extremely important to many of the ecosystem benefits associated with trees and forests in urban regions (Nowak & Walton, 2005). However, whether or not this cover is constituted by remnant forest patches, spontaneous forests (naturally regenerated following initial clearing for urban or agricultural development), or intentionally planted trees could make a very large difference for some ecological functions and could be very important to the overall functioning of urban region landscapes (Nowak, 1993;

Zipperer, 2002). Remnant forests have been shown to support greater biodiversity, store more carbon, and have fewer invasive species relative to spontaneous forests (Dupouey et al., 2002; Zipperer, 2002). Patterns of development over time are likely to have had a great impact on the balance of remnant versus spontaneous/planted forests and, thus, also on ecosystem functions and services associated with urban regions. It can be difficult to determine whether urban canopy cover is associated with remnant or spontaneous/planted forests, but investigation of a time-series of imagery can aid such assessment (Qian et al., 2015; Ward et al., 2007; Zhou et al., 2011).

Historically, the wooded ecosystems of central North America were highly dominated by oaks (*Quercus* spp.), which functioned as foundational species in these ecosystems by creating structure, providing habitat, and driving disturbance regimes (Abrams, 2003). There has been a significant reduction in the dominance of oaks across this region over the past two centuries, due to a variety of direct and indirect anthropogenic impacts (Abrams, 2003; Lorimer, 1993) as well as climatic shifts (McEwan et al., 2011). For example, in the highly urbanized Chicago metropolitan region, the dominance of oak has been reduced from ~60% of the basal area at the time of Euro-american settlement in the 1830's to ~20% in the modern era (Fahey et al., 2012). Although decreases in oak dominance have resulted from compositional shifts related to successional processes and changes to disturbance regimes (Bowles et al., 2005), a primary factor in the loss and fragmentation of oak ecosystems has been urban and agricultural development (Fahey et al., 2012; Kromroy et al., 2007; Ward et al., 2007). Remnant forests are more likely to have retained oaks (and other associated native species) as a component of the ecosystem and thus provide the benefits associated with these species. Understanding changes in the area dominated by these remnant ecosystems and fragmentation of remnant patches will be

essential to assessing functional changes in the landscape related to urban development (Ward et al., 2007).

The primary goals of this project were to evaluate changes in the extent of forest ecosystems (which were largely oak-dominated) over the past ~180 years (1830's to present) in the greater Chicago metropolitan region, to assess the impact of landscape features and development patterns on the preservation or conversion of these ecosystems, and to compare patterns of forest conversion and fragmentation in this region to other urban areas. Our first specific goal (Objective 1) was to understand how the spatial distribution of forest ecosystems has changed over time across land uses and a gradient in urbanization – including how core habitat and connectivity in this ecosystem type have changed. Our second goal (Objective 2) was to assess what specific landscape features and sociodemographic factors have been associated with conversion of forest ecosystems in this landscape. Finally, we also evaluate how the species composition and structure of remnant forest ecosystems differ from the urban forest of the region as a whole (Objective 3).

Methods

Study area

The study area encompassed the Illinois portion of the Chicago metropolitan region, which covers 18,822 km² and all or part of 18 counties (Fig. 1). The Chicago region is home to ~9 million people and contains a wide variety of land uses, cultural and social milieus, population densities, and around 145,000 ha of natural reserves (Chicago-Wilderness, 2004). The surficial geology of the Chicago region includes glacial material deposited in the last 20,000 years, primarily glacial drift (end moraines, till plains and outwash) and the former bed of glacial Lake

Chicago (Willman, 1971). The area is located within the “Prairie Peninsula” (Transeau, 1935), a region with unpredictable summer drought (Borchert, 1950). The pre-Euroamerican settlement landscape of the Chicago region was about 60-80% grassland, with the remainder comprised of a savanna-woodland-forest gradient corresponding to increasing fire protection (Bowles et al., 1994; McBride & Bowles, 2001). Wooded ecosystems at the time of settlement were largely constrained to fire breaks along the east side of major waterways and other fire-protected landscape positions (Fahey et al., 2014; Fahey et al., 2012).

Forest ecosystem mapping and data sources

Data on the areal extent of forest ecosystems were collected for three time periods – the 1830’s, 1939, and 2010. Data on vegetation for the pre-Euroamerican settlement era (1830’s) were derived from information recorded in the General Land Office Public Land Survey (PLS) notes, which were collected in the region in the period of 1821-1845. The PLS comprised a square-mile landscape grid where the identity, diameter, distance, and direction of one to four bearing trees were recorded at half mile intervals and were accompanied by notation of vegetation intercepted along section lines. Although there may have been some bias in witness tree selection by surveyors in the PLS, these data and derived maps represent a large-scale vegetation survey that can be used to reconstruct landscape-scale vegetation composition and pattern (Schulte & Mladenoff, 2001). PLS-era vegetation maps were developed based on the Chicago region PLS notes, surveyor plat maps, and modern maps relating the distribution of forest-associated soil types (i.e., Alfisols) (full method detailed in Bowles & McBride, 2005; maps available at <http://plantconservation.us/plsmap.phtml>). These maps were used to assess the general pre-settlement distribution of wooded ecosystems (areas identified as “timber”,

“scattering timber”, or “barrens” in the survey notes) across the region. To support specific understanding of trends in oak ecosystems for regional planning purposes, witness tree data were used to determine which of these ecosystems had an oak component in the PLS era (Schulte & Mladenoff, 2001). Bearing and line tree data recorded in the PLS illustrate that the vast majority of forested areas in the region had oak trees present (Fahey et al., 2014; Fahey et al., 2012). In the seven county region (for which witness tree data is available as spatial data), only ~3,600 hectares out of an overall 305,571 ha (~1%) had no evidence for an oak component (i.e., no oak witness trees present in adjacent witness tree records). Thus, forest ecosystems with an oak component represented the vast majority of wooded ecosystems in the region and the patterns illustrated here reflect changes in that resource.

Remnant forest ecosystem extent in 1939 and 2010 was evaluated based on analysis of aerial imagery within the original PLS forest ecosystem areas. Manual aerial image analysis was utilized in this regional analysis (rather than automated methods) to match methods previously applied in county-level analysis in McHenry and Lake counties (McHenry-County-Conservation-District, 2009). Analysis was conducted by a single person with quality control checking and field ground-truthing (on modern imagery) assistance by multiple partners. Areas in the 1939 georectified aerial images (<https://clearinghouse.isgs.illinois.edu/>) identified as having large canopy trees and that fell within or in the vicinity of the PLS forest ecosystem layer were digitized into a 1939 remnant forest ecosystem layer. In this analysis, only forest patches that were located within areas identified as forest/woodland/savanna/barrens in the PLS or near these areas (and with forest soils) were counted as “remnant” forests. Therefore some older forests that arose around the time of settlement (mid to late 1800’s) may not have been included in this analysis and the remnant forest definition likely slightly underestimates the amount of

older forest in the region. Parcels identified in the 1939 images were then compared to 2010 NAIP orthoimagery and reshaped or removed to reflect current remnant forest ecosystem extent. Only parcels greater than 0.4 ha (1 acre – an arbitrary threshold established by McHenry County Conservation District, the originators of the project) that were not divided by roads or other barriers were included in the layers. Sites that retained some canopy but were developed into residential or urban land uses were not counted as remnant forest ecosystems.

Comparing forest ecosystem extent among the three time periods is complicated by the fact that the process of mapping forest ecosystems from the PLS necessarily differed from that used on the aerial imagery from 1939 and 2010. The pre-settlement landscape was almost certainly more of a fine-grained patchwork than is represented by the PLS-derived maps, and the large polygons derived from the PLS likely included open areas mixed within more heavily wooded ecosystems. These would have included areas that were recently or frequently burned, producing open savannas or barrens rather than closed canopy forests. In the modern landscape, areas separating canopy patches are often either developed urban land or agricultural fields, which do not have equivalent value as ecosystems and present more significant barriers for many species. In the modern image analysis, areas that had sparse or discontinuous canopy were included as a single parcel if the area connecting the canopy was not in an urban or agricultural land use or occupied by another vegetation type (e.g., open wetland, conifer plantation). Recreating the PLS method of delineating forest ecosystems in the modern landscape would doubtless have produced much more aggregated parcels, but these would not represent the same functionally connected ecosystems as the patches in the PLS era.

A number of datasets were used to evaluate factors associated with retention of forest ecosystems in the region. These included: land-use data from the Chicago Metropolitan Agency

for Planning (CMAP; <http://www.cmap.illinois.gov/data/land-use/inventory>), sociodemographic data from the US Census Bureau data (US-Census-Bureau, 2010) – specifically median income and household density which are straightforward proxies for urban density and economic status, data on timing of municipal incorporation (Illinois Secretary of State; <http://www.ilsos.gov/>), ownership and protected status data from the Chicago Wilderness Green Infrastructure Vision (Chicago-Wilderness, 2004), and watershed and landform data (<https://clearinghouse.isgs.illinois.edu/>). The CMAP region only covers seven counties (Cook, DuPage, Lake, Kane, Kendall, McHenry, and Will); therefore land use data developed by that agency do not cover the entire study region.

Data analysis

To assess change in forest ecosystem area and landscape structure over time in the Chicago region (Obj. 1) the total area of the PLS, 1939 and 2010 remnant forest ecosystem data layers were calculated as well as the size of each parcel. In addition, parcel sizes were recorded and tabulated by county, watershed, and for land use categories. For each parcel in the 2010 data set the ownership type (private vs. public) and protected status of the parcel were identified and protected land parcels were classified based on type of organization/ownership. Parcel size was assessed for raw parcels in each time period and also with parcels aggregated at distances of 100 and 200m using ArcGIS v. 10.2 (ESRI-Inc., 2015) for the 2010 layer only. Aggregation was performed with the goal of combining parcels in relatively close proximity that might be viewed/utilized as contiguous habitat by certain mobile species.

To assess fragmentation and changes in the structure of the landscape we calculated core area (based on a 100m edge depth definition) and landscape metrics for the PLS, 1939, and 2010

forest ecosystem layers as well as the aggregated 2010 layers using PatchAnalyst in ArcGIS 10.2 (Rempel et al., 2012). Landscape metrics that were calculated included: mean and median patch size, perimeter to area ratio, mean shape index, mean fractal dimension, edge density, and patch size coefficient of variation (McGarigal, 2013). Connectivity was evaluated based on nearest neighbor distances between patches. The ratio of observed to expected nearest neighbor distance (based on number of patches per unit area) was calculated to remove the effect of increasing patch number with increasing fragmentation. As noted above, differences in spatial grain of patches derived from PLS and aerial imagery analysis make direct comparisons between the time periods not quantitatively meaningful. Patches present at the time of the PLS were likely less aggregated than reflected in the data, but were also not separated by non-habitat patches such as the urban land uses prevalent in the modern landscape.

Variation in protected status and measures of fragmentation and connectivity were assessed at the county scale and related to urbanization gradients across the region. We conducted analysis at the broad county scale (rather than census tracts used below) because many decisions related to land use and conservation are made at the county level, analysis of patch characteristics is not meaningful at fine scales, and because counties in the Chicago region align relatively well with an urbanization gradient (Table 2). Comparisons across these counties allow for broad-scale analysis, while capturing an urban to rural gradient with a stable definition of units. We assessed the correlation of these variables and their change from 1939 to 2010 with sociodemographic variables including: 2010 population density, 2010 percent urban population, 2010 median income, and percent change in population from 1940 to 2010. Relationships were evaluated with simple linear regression using Sigmaplot 13.0 (SYSTAT-Software-Inc., 2015).

To evaluate factors associated with preservation/conversion of forest ecosystems (Obj. 2), the 2010 layer was first overlaid on the PLS layer and converted to a raster (1ha pixels). Each pixel in the original PLS forest ecosystem was then classified as either “preserved” or “converted”. Conversion was compared among counties, land uses classes, and watersheds, using 2 x C Contingency Table Analysis on counts of pixels. In addition, percent forest ecosystem retention was calculated for each census tract (small, relatively permanent statistical and geographical subdivisions of a county delineated by the US Census Bureau) as the proportion of pixels that were preserved. For each tract we also determined percent impervious surface cover (based on National Land Cover Dataset; Homer et al., 2015), mean distance to stream, and household density and median income (US-Census-Bureau, 2010). The relationship between tract-level percent retention and these predictors was then assessed using multiple regression in an information theoretic framework using PROC MIXED in SAS v.9.4 (SAS-Institute-Inc., 2015). We also assessed the factors associated with conversion or preservation of individual 1ha pixels using multiple logistic regression with PROC LOGISTIC in SAS. Predictors included were: percent impervious surface, distance to stream, household density and median income (based on census tract values), and land-use class. Finally, to assess whether forest ecosystem retention was related to timing of settlement/development we assessed the relationship between percent retention at the municipal scale and the date of incorporation for each municipality using simple linear regression.

Characteristics of remnant ecosystems relative to the urban forest as a whole (Obj. 3) were evaluated based on analysis of plot data from the Chicago Region Tree Census conducted by The Morton Arboretum and USDA Forest Service in 2007 and 2010 (Nowak et al., 2013). This data set includes 2076 plots located in stratified random fashion across land use types and counties

and covering the seven CMAP counties. In each 0.04 ha plot, all trees >2.5cm in diameter at 1.37m were measured for diameter, height, and canopy dimensions. In order to compare characteristics of spontaneous and planted forests with remnant forests, only plots with current tree cover were analyzed (564 plots). Plot locations were overlaid on the three forest ecosystem layers to group them into the following categories: 1) non-forest in PLS era, 2) converted prior to 1939, 3) converted between 1939 and 2010, and 4) remnant in 2010. The first three categories represent urban land uses with some tree canopy or spontaneous/planted forests of different potential ages. For example, plots in category 2 represent developed areas (either urban or agricultural) converted from their original forested condition (according to the PLS), but that have trees present (e.g., street trees or landscape trees), which could be remnant, spontaneous, or planted in origin. Characteristics of the tree communities recorded in the Tree Census plot data were compared among these categories using analysis of variance (ANOVA) including: canopy cover, total basal area, standing dead basal area, oak dominance, non-native species dominance, maximum diameter, and maximum canopy height. ANOVA tests were conducted using Sigmaplot 13.0 and for each characteristic, individual comparisons were made using the Holm-Sidak multiple comparison test.

Results

By 1939 there was already a strong decrease in the areal extent of forest ecosystems compared to estimates for the pre-Euro-American era. At this point 113,254 hectares of the original forest ecosystem remained intact, which represents ~27% of the original area (Table 1, Fig. 1). In the time interval from the 1830's to 1939 the annual loss of forest ecosystem area was ~3000 hectares per year (based on 1832 as a starting point). Retention rates for this time period

were highest for rural, western counties such as LaSalle (50%), Kendall (43%), and Grundy (42%) where wooded ecosystems were concentrated along large river systems (Table 2, Fig. 1). Lowest retention occurred in the northwestern rural counties of Boone (14%) and McHenry (15%) which had more dispersed original forest ecosystems (Table 2, Fig. 1).

In the period between 1939 and 2010 there were significant additional losses of remnant forest ecosystem area. By 2010 there were 69,958 hectares of remnant forest ecosystem in the region, which represents ~17% of their original area (Table 1, Fig. 1). This also represents ~40% reduction in area relative to the 1939 time period. The annual loss of forest ecosystem area over this time period was ~600 hectares per year. The lowest retention rates during the 1939 to 2010 time period were in suburban counties such as DuPage (46%), Lake (50%) and Kane (55%) counties. Highest retention rates in this time period occurred in rural LaSalle (79%), Grundy (74%), and Ogle (73%) counties.

Although there were strong differences among counties in the degree to which forest ecosystems were retained into the modern era (relative to both the PLS era and 1939; Table 2, Fig. 2), these differences were not strongly correlated with population density, urbanization, population growth, or median income (all $r < 0.3$; Table A1 in Supplementary Material). There was high variability in retention among municipalities, and date of incorporation of the municipality was weakly related to percent forest ecosystem conservation ($r = 0.36$, $p = 0.005$; Fig. C1 in Supplementary Material).

Parcel size and fragmentation

In the period between 1939 and 2010 there were high levels of fragmentation of remnant forest ecosystems. Although there had been high levels of conversion from the original landscape

by 1939, there were nonetheless a significant number of large remnant parcels (e.g., 27 parcels $\geq$ 200 hectares; Table 1). The distribution of parcel sizes shifted strongly toward greater representation of smaller parcels by 2010 (Table 1; see Fig. C2 in Supplementary Material for full frequency distribution). By the modern era most large parcels had been fragmented and only 6 parcels greater than 200 hectares remained intact. Between 1939 and 2010 mean patch size declined greatly and perimeter to area ratio and edge density both greatly increased (Table 3). Core area (area $>100\text{m}$ from patch edge) declined greatly between 1939 and 2010 and at a much higher rate than forest ecosystem area overall (42% retention of core area vs. 61% overall). In addition, only 141 of 322 (44%) core parcels ≥ 10 ha in area remained intact in 2010. Levels of fragmentation were dependent to some extent on the definition of a continuous ecosystem. If parcels within 100m or 200m of each other were aggregated there were many more large semi-contiguous ecosystems, but still far fewer than in the pre-settlement landscape (Table 1).

Parcel sizes and degree of fragmentation or connectivity varied greatly across the landscape (Table 3) and appeared to be strongly related to patterns of population growth and urbanization (Fig. 3). Both percent retention of core area from 1939 to 2010 and change in nearest neighbor ratio (increased isolation of patches) were related to percent change in population at the county scale during that same time period (1940-2010). Edge density tended to increase with increasing urbanization (percent urban population at the county scale; US-Census-Bureau, 2010). The relationship of fragmentation with urbanization and population growth was not consistently strong across all metrics (see Table A1 in Supplementary Material). However, the direction of these relationships tended to be consistent and illustrate positive correlations between urbanization and fragmentation.

Ownership and protected status

Approximately 30% of the remnant forest ecosystem area identified in the 2010 imagery analysis was in some type of protected status, which represents approximately 5% of the original pre-settlement forest ecosystem (Table 1). The majority of these protected parcels (74%) were in local ownership – primarily as county forest preserves (see Table A2 in Supplementary Material for ownership detail). The degree to which remnant forest ecosystems were protected varied greatly across the region (Table 2). There were very strong positive relationships between the degree of protection of remnant forest ecosystems and population density and urbanization (Fig 3a, Table A1 in Supplementary Material). In highly urbanized Cook County 80% of the remnant forest ecosystem was in some form of protected status, whereas the protected proportion was generally much lower in rural counties (<10% in some counties; Table 2). Protected parcels also tended to be small and fragmented; for example in 2010 there was only one protected parcel $\geq$ 200 hectares in area and only 67 protected core parcels $\geq$ 10 ha.

Forest ecosystem retention in relation to landscape characteristics

Retention of forest ecosystems was highly variable among modern land use classes ($X^2 = 107.0$, $df = 8$, $p < 0.001$), with much greater retention in open space (areas reserved for conservation or recreational uses; 37%) and vacant areas (areas with no active land use or management; 28%) than any other land uses (Fig. 2). Retention did not differ among watersheds, as all had between 10 and 32% retention.

The strongest predictors of forest ecosystem retention at the census tract scale were distance to stream and percent impervious surface. The model incorporating these two factors was more strongly supported than any other in the set ($\Delta AIC = 3.3$, Table 4) and was very highly weighted

relative to the model set as a whole ($w_i = 81\%$). Forest ecosystem retention was much more likely in areas in close proximity to streams and where there was lower impervious surface area in the vicinity (Fig. 4).

At the scale of individual 1ha areas of original forest ecosystem, retention was best explained by a combination of impervious surface area, household density, distance to stream, and land use. The model comprised of all four of these factors and that with household density removed were not distinguishable based on AIC and together accounted for 99% of the weighting in the model set (Table 4). Household density and impervious surface were highly correlated ($r = 0.74$), thus the simpler model comprised of impervious surface, distance to stream, and land use was interpreted. Probability of retention was greater with closer proximity to stream and less impervious surface, but the strength and shape of these relationships differed greatly among land uses (Fig. 5). Probability of retention was especially low in areas of agricultural land use.

Characteristics of remnant and non-remnant forest ecosystems

Characteristics of 2010 regional Tree Census plots varied strongly with timing of establishment (Table 5). Locations that were identified as remnant ecosystems in the 2010 landscape had much higher canopy cover, total basal area, snag basal area, oak dominance, maximum diameter, and maximum canopy height and lower non-native dominance than other areas with trees present in the 2010 Tree Census. Areas that were converted from forest to urban or agricultural land use after 1939 (but had some trees present in the 2010 Tree Census) tended to be relatively similar to remnant ecosystems except in terms of snag basal area, maximum canopy height, and non-native dominance. Areas converted from forest to other land uses prior to

1939 tended to be intermediate between areas converted after 1939 and areas that were non-forest in the PLS era in all respects except snag BA (Table 5).

Discussion

Landscape pattern of remnant forest ecosystems in relation to development

Conversion of forest ecosystems in the Chicago region followed a distinctive pattern that was driven by a combination of physical landscape structure, original vegetation conditions, and subsequent urban and agricultural development patterns (Burgess & Sharpe, 1981; McBride & Jacobs, 1986; Sanders, 1984; Sharpe et al., 1986). Remnant forests are limited by definition to the vegetation conditions that existed at the time of settlement, thus in the Chicago region these forests are often constrained to fire-protected areas such as the east sides of major waterways (Fahey et al., 2014). The finding that proximity to waterways also had an important effect on the probability of forest conversion, likely reflects the tendency of the early land preservation movement to focus on densely-canopied forests along major rivers or that these areas were avoided during agricultural development because of frequent flooding (Smith, 2009). There could also be an influence of more recent development patterns; for example, areas in floodplains may have been less likely to be converted into urban land uses. These findings illustrate that the geographic position of forests at the time of settlement has been very important to the modern structure of the landscape, making the “snap-shot” provided by the PLS surveys especially important in this instance (Rhemtulla et al., 2009). On the other hand, the strong relationships of land-use and impervious surface with forest conversion indicate a direct effect of development and urbanization on forest ecosystem retention (Kromroy et al., 2007).

In a landscape such as the Chicago region, which was fragmented by the disturbance regime prior to urban development (Fahey et al. 2014), there may be a lower relative effect of urbanization on connectivity than in more densely forested regions. In this landscape, overall conversion of forest ecosystems was not especially greater in highly urbanized parts of the region. This finding contrasts results from regions with more continuous forest cover where development in the urban core had a disproportionately large effect on forest cover and fragmentation (Civco et al., 2002; Miller, 2012; Radeloff et al., 2005; Riitters et al., 2002; Zhou et al., 2011). This difference was likely associated with both the configuration of the pre-settlement landscape and subsequent (and related) patterns of agricultural development, on which urbanization was superimposed. Also, in this landscape the combination of urbanization and the relatively fragmented starting point have resulted in a landscape with especially low regional connectivity (Chicago-Wilderness, 2004). Although some areas have retained local connectivity, especially some of the river corridors, these areas are isolated from other remnant ecosystems (Fig. 1). Recent suburban and exurban development also appear to have had an especially strong influence on the spatial landscape patch structure of the remnant forest ecosystems of the region over the past ~70 years (Zhou et al., 2011). Areas with rapidly increasing populations in this time period had especially strong decreases in core habitat, especially high levels of fragmentation, and large decreases in connectivity (Civco et al., 2002; Dallimer et al., 2011; Iverson & Cook, 2000). The effect of suburban development on forest fragmentation is widely recognized (Miller, 2012; Radeloff et al., 2005; Zhou et al., 2011), but may have been especially intense in this naturally fragmented landscape.

Pervasive and persistent agricultural development in rural areas may also help explain the limited relative effect of intense urbanization in this landscape. The landscape surrounding

Chicago supports intense agriculture and has undergone extreme levels of conversion of natural ecosystems (Chicago-Wilderness, 1999). The prairies that were the other dominant ecosystem type in the pre-Euroamerican landscape have been almost entirely converted (Samson & Knopf, 1994), but forests have also been subject to conversion and fragmentation due to agricultural development (Fahey et al., 2012). In this analysis, the probability of forest conversion was greatest in agricultural land uses, even relative to commercial and industrial land uses (Fig. 5) and the areas with the highest percent conversion were rural Boone and McHenry counties (Table 2). The intensity of agricultural development has resulted in a landscape that is relatively uniform in terms of conversion and fragmentation, in comparison to other urban regions where the primary development in surrounding rural areas has been more recent exurban development (Kromroy et al., 2007; Miller, 2012; Zhou et al., 2011).

Although highly urbanized areas had the greatest degree of forest conversion and fragmentation, the forests that remained in these areas also had a greater degree of protection, reflecting the importance of natural areas reserve networks (Pickett et al., 2008). There was a very strong positive relationship between the percent of remnant ecosystems in protected land status and the density of population in each county (Fig. 3a). Highly urbanized Cook and DuPage counties (Table 2) had the highest proportion of their remnant forests in protected status. This pattern was not just a function of higher conversion rates, as Cook County had more remnant forest in protected status than all but three other counties had remaining overall (regardless of protected status). In these counties, as well as the other mostly urban/suburban inner counties (Kane, Lake, McHenry, and Will), the majority of the protected remnant forest is in natural areas owned by county forest preserve districts. The creation of this reserve network may have

alleviated the effects of development, resulting in urban core areas that have retained more remnant forest and more connectivity than some parts of the surrounding agricultural landscape.

Characteristics of remnant, non-remnant, and developed forest ecosystems

Even though remnant forests are a relatively minor component of the overall modern Chicago region landscape (~4% of the landscape), they likely provide disproportionate value to the ecology of the region (Fahey et al., 2012; Zipperer, 2002). These remnant ecosystems harbor some of the largest trees in the region and have especially high basal area (and thus carbon storage). These ecosystems are also likely to be important wildlife habitat for some species, as evidenced by high volumes of standing dead wood and an especially tall/deep canopy layer (McShea & Healy, 2002; Rodewald & Matthews, 2005; Wood et al., 2014). These remnant ecosystems also were more “healthy” in other respects, for example they had much lower invasive species dominance than other forested areas (Zipperer, 2002). The preservation of these ecosystems may be essential to the integrity of the regional ecosystem (Ward et al., 2007), but strict focus on preservation is likely to lead to continued degradation of the value of these forests. The high canopy cover of these areas is a positive in some respects (such as providing shade for humans and other animals; Nowak et al., 2013), but is also likely a factor in the consistent lack of oak regeneration evident in the region (Carter et al., 2015; Fahey et al., 2014; Lorimer, 1993). Active restoration (e.g., prescribed fire or canopy thinning) is likely to be necessary in many of these forests, both to maintain the low dominance of invasive species (Knight et al., 2007), and to provide conditions that can promote biodiversity and continued dominance of important native canopy species such as oaks and hickories (Dey et al., 2010).

Although many forested patches within the landscape have been converted to urban land uses, some of these areas have retained some remnant forest canopy (Chicago-Wilderness, 2015). This is reflected in the high basal area and canopy cover of areas converted to urban land uses after 1939 relative to forested areas in the landscape as a whole and areas converted to urban and agricultural land uses prior to 1939 (Table 5). This pattern likely has much to do with the nature of suburban conversion relative to earlier urban and agricultural development (Biggs et al., 2014). More canopy is likely to be retained in the process of suburban residential development than urban or agricultural development. Suburban and exurban areas have therefore retained some of the characteristics of remnant forests and the canopy in these areas is likely still highly valuable both for ecosystem services and to the residents of these areas (Nowak, 1993; Zipperer, 2002). However, additional work is needed to assess the ecosystem service value of these areas and whether they can provide habitat connectivity between remnant patches (Angold et al., 2006; Rudd et al., 2002). Characteristics of the ecosystem beyond the canopy layer (e.g., groundcover, understory structure, woody debris) are likely to have a very strong influence on the suitability of these areas as habitat or movement corridors.

The dominance of oaks varied greatly among the categories of development timing, reflecting the importance of remnant forests for the regional oak resource (Table 5). There are certainly some oak-dominated forests that have established in areas that were not part of the original forest, or were converted from the original ecosystem and then subsequently reverted to oak dominance (Zhou et al., 2011). Although these areas are not likely to have the same structural and functional characteristics as the remnant ecosystems, they nonetheless could also form an important component of the regional oak resource. These forests will become especially important in the future as they become more similar to the remnant ecosystems in age and size

structure (Zipperer, 2002). Further effort is needed to identify these areas to attempt to document the totality of oak ecosystems in the region. Such efforts could rely on remote sensing and image analysis approaches to delineate areas with oak dominance and inform targeted field surveys to assess composition and structure (Gu et al., 2015; Ward et al., 2007).

Implications for urban forest landscape management

In urban and suburban parts of the Chicago region, the existing high levels of protection for remnant forest patches indicates that there may be little opportunity to increase connectivity by adding protection to remnant forests. In some situations, barriers between remnant ecosystems are essentially permanent features of the urban landscape, such as highways or other transportation corridors, where canopy cannot be readily re-introduced (Chicago-Wilderness, 2015). In other cases, though, there may be significant opportunities to utilize components of the urban landscape as connectors between ecosystems. In urbanized landscapes the primary mechanism for connecting remnant forests is likely to be reforestation/reclamation in areas previously in urban land uses or urban canopy enhancement focused on native species (Rudd et al., 2002). Developed areas with some remnant trees could be important connections or buffers for remnant ecosystems, but so could areas that are newly managed for an native species component in the planted tree population (Chicago-Wilderness, 2015). Reforestation or revegetation of vacant land with native species as a component of the planting pool, in both the canopy and groundlayer, could be another avenue for expanding or enhancing the value of existing remnant forest ecosystems (Robinson & Handel, 2000).

In rural and exurban portions of the region there may be more opportunities for putting additional remnant forest patches into some form of protected status as well as connecting

503 remnant patches with either remnant or restored ecosystems. In more rural parts of the region,
504 much of the fragmentation is related to agricultural usage that is unlikely to revert to open space
505 in the foreseeable future, but there are still likely to be many private parcels that may be
506 acquirable or could be targeted for conservation easements (Rissman et al., 2007). Some remnant
507 ecosystems even exist within larger matrices of open space, but may be separated by different
508 ecosystem types (e.g., wetlands) or non-native vegetation (e.g., conifer plantations). Conversion
509 of non-native vegetation to native/oak-dominated vegetation in these locations should be a
510 priority for managers (Chicago-Wilderness, 2015). Further analysis is ongoing to identify and
511 prioritize opportunities for creating connections between remnant ecosystems across the wide
512 variety of milieus present within this large urban landscape.

513

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Tables

Table 1. Characteristics of regional forest ecosystems in the three time periods analyzed and for protected lands and three different levels of parcel aggregation in the modern landscape.

<i>Dataset</i>	<i>Total area (ha)</i>	<i>Percent of PLS Area*</i>	<i>Core Area (ha)^{&}</i>	<i>Parcels >50ha</i>	<i>Parcels >100ha</i>	<i>Parcels >200ha</i>	<i>Parcels >400ha</i>	<i>Core Parcels >10 ha</i>
PLS*	419470	--	185055	89	73	48	145	411
1939	113254	27.0	14096	216	79	27	1	322
2010	69958	16.7	5934	121	46	6	0	141
2010 Protected	21083	5.0	2451	49	17	1	0	67
2010 Agg 100m	78558	18.7	8382	117	59	27	22	175
2010 Agg 200m	97375	23.2	20134	150	91	42	33	408

* PLS and 1939/2010 layers were developed using different data sources (PLS notes vs. aerial imagery) and methodologies and thus comparisons should not be made quantitatively and interpreted with caution

& Area $\geq 100\text{m}$ from patch edge

Table 2. Counties in the Chicago region with characteristics of human population and forest ecosystems.

<i>Counties</i>	<i>Population</i>			<i>Forest ecosystem area (ha)</i>			<i>Percent conserved</i>				
	<i>Density (per km²)</i>	<i>Percent urban population[^]</i>	<i>Percent population change (1940 to current)</i>	<i>PLS</i>	<i>1939</i>	<i>2010</i>	<i>1939</i>	<i>2010</i>	<i>2010 vs 1939</i>	<i>Percent protected</i>	<i>Total area (ha)*</i>
Boone	74.5	80.6	71.9	17904	2522	1586	14.1	8.9	62.9	9.4	57223
Cook	2121.7	99.9	21.8	50396	14092	8963	28.0	17.8	63.6	80.0	244857
DeKalb	64.3	79.7	67.3	14325	3778	2430	26.4	17.0	64.3	11.6	159322
DuPage	1081.0	99.9	88.7	13792	6069	2766	44.0	20.1	45.6	57.6	86116
Grundy	46.3	75.6	63.3	11723	4977	3667	42.5	31.3	73.7	6.4	110220
Iroquois	10.3	28.3	-9.3	16386	4343	3028	26.5	18.5	69.7	8.1	119861
Kane	382.5	96.4	74.7	50390	10445	5758	20.7	11.4	55.1	25.1	134164
Kankakee	64.7	75.5	46.3	22819	8177	4984	35.8	21.8	61.0	19.9	174382
Kendall	138.3	89.6	90.3	9929	4296	2942	43.3	29.6	68.5	13.4	82514
Lake	612.2	98.7	82.8	70648	18803	9442	26.6	13.4	50.2	34.8	120397
LaSalle	38.8	69.8	14.2	18382	9245	7350	50.3	40.0	79.5	8.4	116590
Lee	19.2	46.8	4.0	618	71	29	11.6	4.7	40.7	0	6201
McHenry	197.6	90.1	87.9	70490	10886	7306	15.4	10.4	67.1	15.8	156368
Ogle	27.2	52.9	44.2	1363	419	305	30.7	22.4	72.9	0	28995
Will	312.6	96.1	83.1	39834	12072	7381	30.3	18.5	61.1	38.7	217356
Winnebago	222.1	92.1	59.0	5599	1644	1152	29.4	20.6	70.1	36.3	14831
Total/Avg.	338.3	79.5	55.6	414612	111943	69148	27.0	16.7	61.8	30.1	1882220

*Area of portion of county included within the Chicago Wilderness region.

[^] Based on US Census Bureau definition (US-Census-Bureau, 2010).

Table 3. Counties in the Chicago region with forest ecosystem landscape metrics and changes from 1939 to 2010 in landscape metrics.

<i>Counties</i>	<i>2010 Core area (ha)^{&}</i>	<i>2010 Percent core area</i>	<i>2010 Mean patch size (ha)</i>	<i>2010 Mean PAR*</i>	<i>Relative Change 1939-2010</i>				<i>2010 Nearest neighbor ratio</i>	<i>Change in nearest neighbor ratio 1939- 2010</i>
					<i>2010 ED*</i>	<i>Patch size (ha)</i>	<i>PAR*</i>	<i>ED*</i>		
Boone	35.7	32.4	82.2	63.0	1.02	21.9	10.8	18.0	0.70	0.06
Cook	1510.1	63.9	183.8	61.7	3.75	11.8	15.6	11.6	0.39	0.06
DeKalb	150.1	39.2	125.1	63.0	1.34	19.3	7.3	17.8	0.44	0.07
DuPage	174.5	24.2	100.5	69.6	1.71	36.8	17.4	-3.0	0.57	0.12
Grundy	337.6	54.6	198.8	75.1	2.12	25.6	10.2	28.4	0.59	0.04
Iroquois	165.8	59.4	141.6	76.3	2.14	18.8	19.3	27.4	0.53	0.04
Kane	219.4	23.8	85.7	71.2	3.97	15.6	6.9	13.0	0.76	0.12
Kankakee	392.4	24.9	144.0	69.0	2.85	35.4	17.5	31.1	0.53	0.07
Kendall	170.5	31.9	140.3	74.9	1.82	23.0	8.9	28.8	0.62	0.08
Lake	658.5	28.7	69.0	90.7	7.82	23.5	7.1	4.8	0.85	0.11
LaSalle	961.8	62.2	289.1	67.4	3.48	30.6	10.5	32.9	0.53	0.02
Lee	0.0	0.0	40.8	81.2	0.03	33.9	24.7	-4.4	0.60	0.07
McHenry	313.3	37.7	56.6	94.4	4.81	36.1	16.1	30.8	0.73	0.08
Ogle	13.0	27.9	120.4	70.0	0.18	10.5	5.2	31.8	0.38	0.19
Will	715.2	44.4	121.0	76.0	4.53	28.0	16.0	20.2	0.44	0.04
Winnebago	105.1	46.6	166.2	67.5	0.61	16.9	9.6	24.6	0.64	0.01
Total/Avg.	5923.0	40.1	129.1	73.2	2.60	24.2	12.7	19.6	0.51	0.06

[&] Area $\geq 100\text{m}$ from patch edge

* PAR – perimeter to area ratio, ED – edge density

Table 4. Multiple linear and logistic regression models of forest ecosystem retention at the census tract scale and pixel scale. Only five most highly supported models are included, full model lists included in Table B1 and B2 in Supplementary Material.

<i>Model</i>	<i>Parameters</i>	<i>AIC</i>	<i>ΔAIC</i>	<i>w_i</i>
<u>Linear regression on census tracts</u>				
Impervious_surface Stream_distance*	4	-1124.7	0	0.81
Impervious_surface Stream_distance Median_income	5	-1121.4	3.3	0.16
Impervious_surface Household_density Stream_distance Median_income	6	-1117.2	7.5	0.02
Impervious_surface Household_density Stream_distance	5	-1116	8.7	0.01
Impervious_surface	3	-1079	45.7	0.00
<u>Logistic regression on pixels</u>				
Impervious_surface Household_density Stream_distance Land_use	6	2761.7	0.0	0.63
Impervious_surface Stream_distance Land_use	5	2762.8	1.1	0.36
Impervious_surface Household_density Land_use	5	2773.4	11.8	0.00
Impervious_surface Land_use	4	2774.7	13.0	0.00
Household_density Land_use	4	2949.5	187.9	0.00

* Regression coefficients: Forest Conversion % = 0.4657 + 0.0038*Impervious surface % + 0.039*distance to stream (km)

Table 5. Characteristics of Urban Tree Census plots (Nowak et al., 2013) in relation to pre-settlement land cover and timing of conversion of original forest to urban or agricultural land use.

<i>Category</i>	<i>Count</i>	<i>Canopy cover (%)</i>	<i>Total BA* (m² ha⁻¹)</i>	<i>Snag BA (m² ha⁻¹)</i>	<i>Oak dominance</i>	<i>Non-native dominance</i>	<i>Maximum DBH* (cm)</i>	<i>Maximum height (m)</i>
Non-forest in PLS	342	14.6	8.6	0.21	5.0	53.5	35.9	12.3
Converted pre-1939	158	35.0	16.1	0.03	18.2	41.4	40.2	13.9
Converted post-1939	20	62.7	26.3	0.38	45.7	28.6	59.3	17.6
Remnant 2010	44	73.7	29.5	0.72	51.2	11.9	65.7	23.2
Total/Average	564	22.6	11.5	0.34	10.2	33.9	50.3	16.7
F	--	58.55	42.34	2.78	61.59	2.63	22.02	41.47
p	--	<0.001	<0.001	0.04	<0.001	0.05	<0.001	<0.001

* BA – basal area, DBH – diameter at breast height (1.37m above ground)

List of Appendices

Appendix A

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Table A2. Area (ha) of protected forest ecosystems by county and ownership type

Appendix B

Table B1. Multiple linear regression models of forest ecosystem retention at the census tract scale.

Table B2. Multiple logistic regression models of forest ecosystem retention at the census tract scale.

Appendix C

Figure C1. Retention of forest ecosystem by municipality in relation to municipal incorporation date. Only municipalities with ≥ 1000 ha of original forest ecosystem were included in the analysis.

Figure C2. Frequency distribution of parcel sizes for 1939 and 2010 analysis periods.

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Figure 1. Map of Chicago region illustrating the extent of forest ecosystems in three time periods – 1830's based on Public Land Surveys (PLS), and 1939 and 2010 based on aerial image analysis. Inset illustrates position of Chicago metropolitan region within eastern North America.

Figure 2. Forest ecosystem area in three time periods (PLS Era-1830's, 1939, and 2010) by a) county and b) modern land-use type. Numbers indicate percent of original PLS forest ecosystem that remained in 2010 in each category and * indicates that standardized residual from contingency table analysis was significant (≥ 2 or ≤ -2).

Figure 3. Relationships between county-level population characteristics, measures of protected status, and fragmentation.

Figure 4. Multiple linear regression model of forest ecosystem retention at the census tract level as a function of distance to stream (note logarithmic scale) and percent impervious surface.

Figure 5. Probability of forest ecosystem retention as a function of distance to stream and percent impervious surface by modern land use category based on multiple logistic regression analysis of individual 1ha pixels in original PLS forest ecosystem layer. For Agricultural land use (top left panel) probability was <0.2 for all values of stream distance and impervious surface.