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Green infrastructure and bird diversity across an urban socioeconomic gradient

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Abstract. As the world continues to urbanize, ensuring that urban residents have access to green infrastructure and the ecosystem services it provides will be critical. Furthermore, the distribution of green infrastructure within cities should be equitable so that no socioeconomic group is underserved in terms of the benefits derived from ecosystem services. Our goal was to test whether there were any differences among socioeconomic groups in terms of (1) proximity to open space, (2) proximity to Lake Michigan, (3) tree canopy cover, or (4) bird biodiversity in census tracts across Chicago, IL (USA). These four variables were used as proxies for a number of different ecosystem services. We characterized the first three variables with GIS operations using classified Quickbird imagery and other datasets that describe the urban and natural environment. We used MaxEnt to model suitable bird habitat for 52 species that are regularly observed in the area and combined the habitat maps to estimate bird biodiversity in a spatially explicit manner. Our results suggest that census tracts with more low- to mid-income Hispanic residents were farther away from both open space and Lake Michigan, and had less tree canopy cover and bird biodiversity than other census tracts. Tracts characterized mostly by low-income African Americans were not statistically different in terms of proximity to open space, nor in terms of tree canopy cover or bird biodiversity, than those characterized by higher income residents. Those tracts were, however, significantly farther from Lake Michigan compared to the higher income census tracts. This research suggests the potential for environmental injustice in Chicago and we discuss some possible causes and implications of our findings.

Key words: biodiversity; ecosystem services; environmental justice; species distribution modeling; urban ecology.

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Introduction

Half of our planet's 7 billion people now live in urbanized areas (UNPFA 2011). Because of the environmental degradation that often accompanies urban development, urban residents are sometimes thought to live in "biological poverty" (Turner et al. 2004). However, cities are not

devoid of nature (Pickett et al. 2008). Urban areas often include a mix of street trees, parks, cultivated land, wetlands, lakes, and streams (Bolund and Hunhammar 1999), which are collectively referred to as "green infrastructure" (Benedict and McMahon 2006). This green infrastructure provides a multitude of ecosystem services to urban residents (Bolund and Hunhammar 1999), including air pollution removal (Nowak et al. 2006), microclimate regulation (Hough 1989), stormwater mitigation (McPherson et al. 2011), noise reduction, water purification, aesthetic experiences, and educational and recreational opportunities (MEA 2005). Green infrastructure is also linked with increased social interactions among neighbors (Kuo et al. 1998) and decreased crime rates (Kuo and Sullivan 2001). Because many of the benefits provided by trees and open spaces diminish with increasing distance, evaluating the distribution of green infrastructure across a city would be a first step toward ensuring equitable and just access to ecosystem services for all residents.

In addition to containing green infrastructure, cities often support many different species of wildlife. Birds in particular provide a number of different ecosystem services (Table 1). They regulate pest populations, disperse seeds, provide aesthetic and recreational value (Sekercioglu et al. 2004, Whelan et al. 2008), and enhance visitors' experiences in urban parks and open spaces (Fuller et al. 2007, Dallimer et al. 2012). For urban birds, proximity to small patches of green space can be just as important as proximity to large, "natural" preserves (Loss et al. 2009*b*, Evans et al. 2009). Environmental factors like canopy cover (MacGregor-Fors and Schondube 2011, Alberti and Marzluff 2004), building density (Germaine et al. 1998), and presence of water bodies (Melles et al. 2003) have all been related to the abundance and diversity of urban birds. These kinds of environmental characteristics can vary substantially within a single city, leading to different bird communities in different neighborhoods.

Recent research in urban areas indicates that green infrastructure and biodiversity are not always distributed evenly among socioeconomic groups. Several studies indicate that economically privileged groups inhabit more ecologically productive and diverse environments. For example, in Baltimore, Maryland (USA), neighborhoods characterized by residents with high incomes, advanced degrees, and sophisticated tastes (based on Claritas PRIZM data) had more tree canopy cover than other neighborhoods (Troy et al. 2007). Similarly, in the greater Chicago area, wealthier neighborhoods had more tree cover than poorer neighborhoods (Iverson and Cook 2000). A study in Phoenix, Arizona (USA), found that family income and housing age best explained the variation in plant diversity across the city, which the researchers termed the "luxury effect" (Hope et al. 2003). Phoenix residents also experienced varying levels of bird biodiversity across neighborhoods, with lower avian diversity found in parks in lower-income areas (Kinzig et al. 2005). The patterns in distribution of green space are somewhat different. For example, two studies in England found that traditionally disadvantaged socioeconomic groups had better access to green space than groups with higher socioeconomic status (Barbosa et al. 2007, Kessel et al. 2009). While one cannot infer causation, socioeconomic characteristics clearly vary across cities, as does access to green infrastructure, biodiversity, and their associated ecosystem services. Trees, open spaces, lakes, and birds provide many different ecosystem services to urban residents (Table 1), but few (if any) studies have simultaneously examined the distribution of all of these factors across an urban environment. If local ecosystem services have a great impact on the quality of life in cities, as asserted by Bolund and Hunhammar (1999), then socioeconomic groups who receive fewer ecosystem services might experience a diminished quality of life, which could constitute an environmental justice issue.

Traditionally, environmental justice refers to increased concentration of pollutants and toxins or unwanted land uses in poorer or minority neighborhoods (Bullard 2000), but recent studies have made the case that lack of or reduced access to green spaces and other natural resources for low-income or minority communities constitutes an environmental justice issue as well (Taylor et al. 2002, Boone et al. 2009, Landry and Chakraborty 2009, Jennings et al. 2012). Uneven access to urban green spaces has human health consequences (see Jennings et al. 2012 for a review) but can also help perpetuate injustices. Research has

Table 1. Summary of direct ecosystem services potentially provided by the environmental variables used in this study.

Proxy variable	Ecosystem service	Sample references and quotes
Lake Michigan	Microclimate regulation; Aesthetic value; Sense of place; Educational opportunities; Recreation	see Table 1 of Wilson and Carpenter (1999)
Open space	Air quality regulation; Microclimate regulation; Stormwater regulation; Water purification and treatment; Noise regulation; Aesthetic value; Sense of place; Educational opportunities; Recreation	"These parks are viewed as spaces where a spectrum of recreational and leisure activities can be pursued, from active endeavors such as baseball and soccer to passive activities such as walking, picnicking, and relaxing. But they are also seen as [. . .] landscapes that [. . .] provide people with unique experiences as a result of the natural and cultural features present and the social communities that gravitate to them" (Gobster 2001). "The impervious surfaces and high extraction of water cause the groundwater level of many cities to decrease. Vegetated areas contribute to solving this problem in several ways. The soft ground of vegetated areas allows water to seep through and the vegetation takes up water and releases it into the air through evapotranspiration.)" (Bolund and Hunhammar 1999).
Tree canopy	Air quality regulation; Microclimate regulation; Stormwater regulation; Water purification and treatment; Noise regulation; Aesthetic value; Educational opportunities	"During 1991, [Chicago's] trees removed an estimated 5575 metric tons of air pollutants, providing air cleansing worth $9.2 million" (McPherson et al. 1997). In LA "Average annual benefits were $38 and $56 per tree planted. Eighty-one percent of total benefits were aesthetic/other, 8% were stormwater runoff reduction, 6% energy savings, 4% air quality improvement, and less than 1% atmospheric carbon reduction." (McPherson et al. 2011).
Bird biodiversity	Pest regulation; Aesthetic value; Sense of place; Educational opportunities; Recreation	"Most of the important ecological roles that birds fill, however, involve supporting and regulating services, such as insect pest control and seed dispersal" (Wenny et al. 2011). In 1996 "an estimated 17.7 million birdwatchers travelled more than a mile from their homes in order to observe birds" in the United States (Sekercioglu 2002). "Biodiversity, and its endemic features, contribute to a person's attachment to a particular place and become part of a person's identity" (Horwitz et al. 2001).

shown that when school girls in Chicago's inner city had a view of green space from their home, they performed better on tests of concentration, impulse inhibition, and delay of gratification—skills that could help them avoid the ills typically found in inner city neighborhoods (Taylor et al. 2002).

We examined whether green infrastructure and bird biodiversity were distributed evenly across a socioeconomic gradient in Chicago, IL (USA). We considered four environmental factors expected to be among the most important providers of ecosystem services to Chicago residents: tree canopy cover, bird species richness, the presence of large open spaces such as parks and forest preserves, and proximity to Lake Michigan (Table 1). We found evidence of differences in these environmental factors between some but not all socioeconomic groups and discuss the implications of these patterns and how they relate to environmental justice and urban ecology.

Methods

Study site

Chicago, Illinois is the third largest city in the United States, with approximately 2.5 million

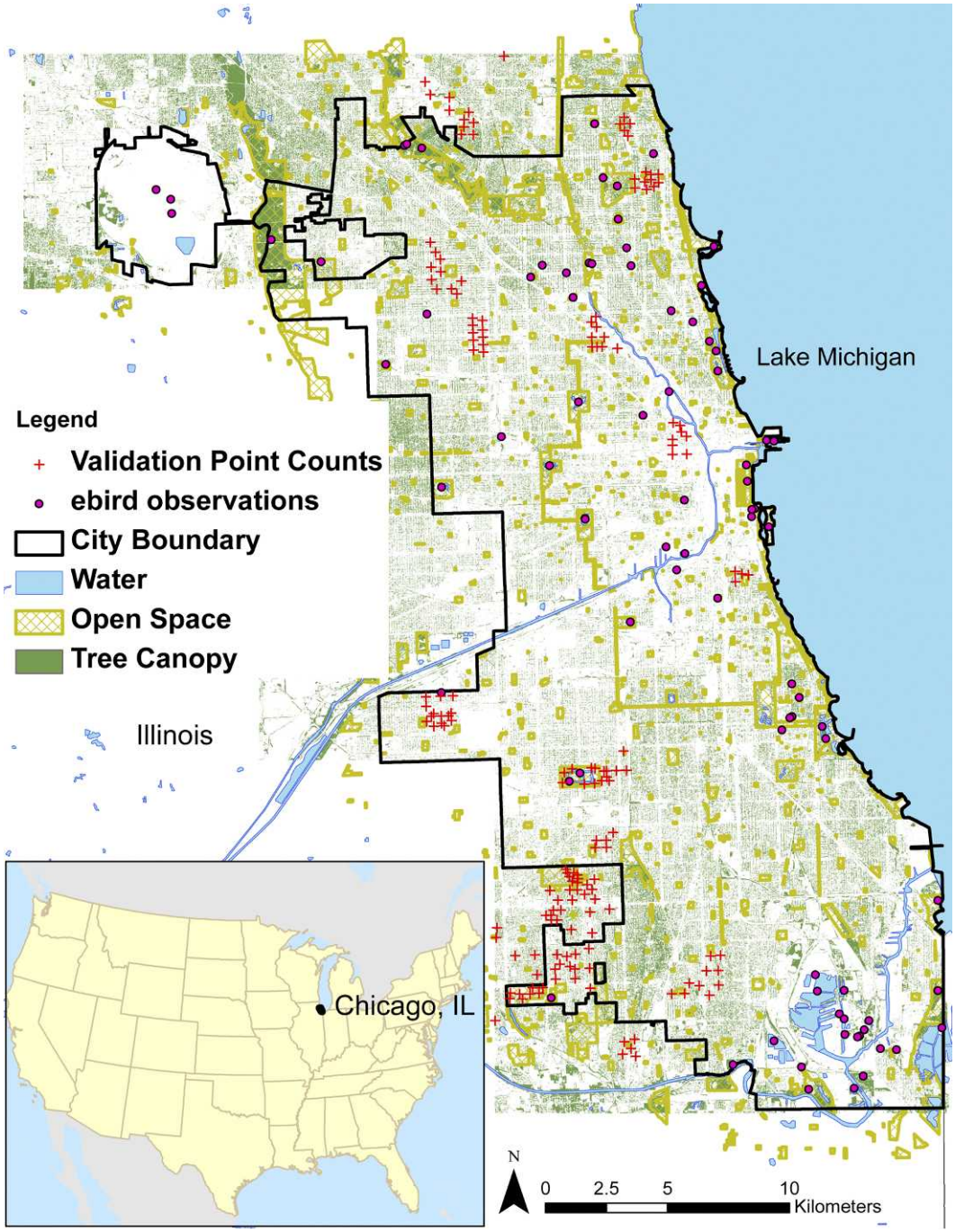

Fig. 1. The study area. The black line delineates the Chicago city boundary. The purple points represent locations of casual bird observations reported to the e-bird dataset, which were used in the MaxEnt models. The red crosses are where point counts were performed (see Loss et al. 2009*a*, *b*); point counts were used to validate the MaxEnt model results. The map also depicts tree canopy and location of open space. Note that the land cover data did not cover the entire city. The inset map locates Chicago, IL within the United States.

residents (2010 U.S. Census). The city covers almost 600 km^2, is situated in Cook County, Illinois, and borders Lake Michigan, one of the largest fresh water bodies in the world. Chicago's climate is classified as humid continental, with four distinct seasons throughout the year. Although the city is home to numerous racial and ethnic groups, and almost 60% of the population self-reported as a race other than "white" in the 2005–2009 American Community Survey (2010 U.S. Census), Chicago is considered one of the most racially-separated cities in the United States (Glaeser and Vigdor 2012). Publically-accessible open space, including city parks, forest preserves, and cemeteries, comprises approximately 10% (8,171 ha) of the city's area, while tree canopy covers approximately 17% (108,200 ha) (Fig. 1). Lake Michigan provides a host of recreational, aesthetic, and economic benefits to Chicago and is the dominant natural feature of the city.

Socioeconomic data

United States census tracts within city limits ($n = 1007$) were the geographical and statistical unit of analysis. A census tract is a spatial unit defined by the U.S. Census Bureau that usually contains between 2,500 and 8,000 people and is designed to be homogeneous with respect to socioeconomic characteristics. Socioeconomic data for each census tract within Chicago were obtained from the 2005–2009 5-year American Community Survey (ACS). The ACS is a sample survey conducted by the U.S. Census Bureau to provide statistically reliable estimates of demographics for years between decennial censuses (U.S. Census Bureau 2009). We extracted the following variables from the ACS dataset for each census tract: proportion of population that self-reports as African American (non-Hispanic), proportion of population that reports as Hispanic, and median household income.

Because ACS variables exhibited non-normality and were moderately to strongly correlated with each other (Table 2), we used a hierarchical agglomerative clustering technique to identify groups of tracts with similar socioeconomic characteristics. Clustering is based on a dissimilarity matrix and the objective is to group together samples that are most similar. We used Euclidean distance as the measure of dissimilarity between census tracts and Ward's linkage method to determine placement of tracts into groups. Each socioeconomic variable was relativized by its maximum value before undertaking the clustering procedure. We used multiresponse permutation procedures (MRPP; Mielke 1991) to statistically test group differences. The MRPP test provides an "A" statistic, which signifies the chance-corrected within-group agreement. $A = 1$ means that all the socioeconomic variables within groups had the same values, and $A > 0.3$ is considered high agreement (McCune and Grace 2002). The above exercise was computed with PC-ORD 6.0 (McCune and Mefford 2011).

Distribution of parks and other green infrastructure

We used ArcGIS 10.0 (ESRI, Redlands, CA, USA) to measure tree canopy cover and the distance to Lake Michigan and to the nearest large open space (>20 ha) for each census tract. We extracted canopy cover data from a 0.6m resolution land cover dataset derived from Quickbird satellite imagery and calculated the percent of each census tract classified as tree canopy. We defined open space as publically accessible outdoor space, including cemeteries, city parks, forest preserves, and public beaches. We excluded private golf courses, because they are not publically accessible, but included municipal golf courses, which are open to the public and often used by residents for activities like cross-country skiing or jogging. Open spaces were identified from several different spatial datasets: (1) a land-use dataset created by the Chicago Metropolitan Agency for Planning, (2) a map of Cook County forest preserves created by the Cook County Forest Preserve District, and (3) a map of city parks provided by the City of Chicago. Distance to open space was measured from the centroid of each census block, rather than each census tract, and mean distance to open space was then calculated over all blocks in each census tract. We used the ArcGIS Network Analyst extension to measure distance along roads from each block to the nearest open space. We calculated distance to Lake Michigan by averaging the distance to Lake Michigan for each 30m cell in a census tract.

Table 2. Correlations (Spearman rho) between variables of interest (*** $P < 0.001$, * $P < 0.05$, $n = 822$).

Variable	% African American	% Hispanic	Median income	Distance to open space	Distance to lake	Bird species richness	% Canopy cover
% African American	1						
% Hispanic	−0.70***	1					
Median income	−0.56***	0.20***	1				
Distance to open space	−0.17***	0.15***	0.15***	1			
Distance to lake	0.00	0.19***	−0.12***	0.27***	1		
Bird species richness	0.12***	−0.07*	−0.09*	−0.47***	−0.15***	1	
% Canopy cover	0.14***	−0.19***	0.06	−0.25***	0.00	0.27***	1

Modeling bird biodiversity

We downloaded bird sightings submitted by citizen scientists to the eBird online database (http://ebird.org/). The sightings used in our models are referred to as "incidental" or "casual" observations in both the database and this study. We limited these casual observations to the breeding season in Chicago (June 1–July 15) between the years 2000–2010. We excluded species with less than 10 observations over the 10-year study period. Lastly, we removed all bird observations within 200m of other conspecific observations to increase spatial independence of the observations. The remaining observations represented "presence" locations for each species of interest (total n = 1,091 for 52 species, see the Appendix) and were used as input for the habitat suitability models described below.

The eBird database has some limitations, including bias in spatial and temporal coverage of an area, and also errors based on detection abilities of observers (Dickinson et al. 2010). However, the eBird data are filtered for errors (both geographic and numeric) and birders that submit potentially faulty sightings are asked to validate their reports before the dataset is published online (Dickinson et al. 2010). Furthermore, we account for spatial bias in our modeling approach (described below) and believe that detection errors should not contribute systematically to bias in our analysis.

To estimate bird species richness, we used MaxEnt v3.3 (Phillips et al. 2006, Phillips and Dudík 2008) to model habitat suitability for each bird species. We chose MaxEnt because it consistently builds accurate models with presence-only data (e.g., Elith et al. 2011) and has been shown to be accurate even with very small sample sizes (e.g., Hernandez et al. 2006). Most importantly, it can provide maps of predicted suitability for multiple species, which can then be combined to estimate species richness (e.g., Graham and Hijmans 2006, Pineda and Lobo 2009). MaxEnt requires spatially-explicit presence data for each species of interest as well as information about the environmental variables which are thought to explain species distributions. The environmental conditions at presence locations are compared to the environmental conditions at a set of background points (Elith et al. 2011). The background points represent "a sample of the set of conditions available" to the species in the area (Phillips et al. 2009). MaxEnt compares probability densities of the environmental variables between presence locations and the background points and then rates the habitat suitability of each pixel for the species in question.

We created raster layers at a spatial resolution of 30 m for a set of environmental variables expected to influence bird distribution (Table 3). First, we extracted cells classified as "tree" and "grass" from the land cover data described above. We used focal statistics in ArcGIS to calculate the amount of grass and trees at two spatial scales (25 m and 100 m circular buffers) around each 30 m pixel. We also calculated building density following the same procedure. Finally, we created four additional layers to represent landscape-scale variables that may be important to birds: distance to forest preserves, distance to Lake Michigan, distance to swamps and marshes, and distance to ponds, rivers, streams, and lakes (excluding Lake Michigan).

The casual observations submitted to the eBird site were not randomly distributed across the study area (observations were concentrated in large parks). To mitigate this sampling bias, we used a customized set of background points rather than randomly selected points to build the

Table 3. Spatial data layers used as input for habitat suitability models.

Derived data layer	Data source	Mean (SD)	Range	Unit
Distance to				
Lake Michigan	National Hydrography Dataset	8.5 (6.6)	0–26.8	km
Rivers, streams, ponds, and lakes (excluding Lake Michigan)	National Hydrography Dataset	1.7 (1.3)	0–7.4	km
Swamps/marshes	National Hydrography Dataset	8.0 (5.2)	0–21.1	km
Forest preserves	City of Chicago†	5.2 (3.9)	0–17.6	km
Total area of				
Buildings within 25 m radius‡	City of Chicago†	158.1 (248.5)	0–1,300.0	m^2
Buildings within 100 m radius‡	City of Chicago†	3,800.9 (4,610.0)	0–31,600.0	m^2
Grass within 25 m radius§	Quickbird 2007–2008 data	182.8 (324.1)	0–1,894.0	m^2
Grass within 100 m radius§	Quickbird 2007–2008 data	3,005.9 (4,596.1)	0–31,149.6	m^2
Trees within 25 m radius§	Quickbird 2007–2008 data	304.4 (386.5)	0–1,894.0	m^2
Trees within 100 m radius§	Quickbird 2007–2008 data	4,936.4 (5,102.3)	0–31,149.6	m^2

† http://data.cityofchicago.org/
‡ Sums calculated for 10 m pixels before averaging and aggregating to 30 m.
§ Sums calculated for 0.6 m pixels before averaging and aggregating to 30 m.

models. We selected points from locations where any bird had been reported, irrespective of species or season (i.e., all sightings reported to the eBird site from January 2000 through December 2010). These points provided an indication of where volunteers preferred to go birding and therefore represented the inherent spatial bias in the presence points. This approach, outlined in Mateo et al. (2010) and Elith et al. (2011), ensures that the environmental data used for the background points contain the same bias as the environmental data associated with the presence points.

We ran MaxEnt 25 times to obtain replicate maps for each species, and averaged the replicates to create a single map of probability of presence for each species. For each model run, 20% of observations were withheld for testing. The Area Under the Curve (AUC) for the receiver operating characteristic (ROC) plots were calculated as a measure of the model's performance (Hernandez et al. 2006). MaxEnt produces probability distribution maps for each species, which we converted to binary, habitat/non-habitat maps. We used the lowest probability at which a species was observed (Pearson et al. 2007) as the threshold value for creating the binary habitat map. We then added the binary habitat maps of all 52 species together to create a habitat suitability map for birds in Chicago—each pixel's value indicated the total number of bird species for which MaxEnt predicted the habitat was suitable. We used this summary map as our proxy for bird species richness, representing predicted number of bird species at any 30m pixel across the city.

To validate our model of species richness, we compared the MaxEnt-derived species richness map, at the scale of a single 30m pixel, to empirical bird data from the same geographic area. The empirical data were systematically collected for previous studies of West Nile virus ecology (Loss et al. 2009*a*) and environmental and socioeconomic factors related to bird diversity and abundance (Loss et al. 2009*b*). The data, described in Loss et al. (2009a and b), came from 5-min unlimited radius point counts ($n = 171$) performed during the 2005 and 2006 breeding seasons. Waterfowl, raptors, and overhead sightings were removed from the empirical point count data but were included in our model.

Finally, we laid our map of predicted species richness over census tracts in the city. We calculated an index of neighborhood diversity following Strohbach et al. (2009). Neighborhood diversity is the maximum number of species predicted within a 400 m radius around each pixel. A quarter mile (~400 m) is generally the distance most people are willing to walk for social, recreational and public transit-access trips in the United States (Ewing 1999). Thus, we approximated the number of species a Chicago resident living in any particular pixel could theoretically encounter on a daily basis. We then calculated the average neighborhood diversity over all pixels in each census tract. We refer to this mean neighborhood diversity for each tract as "bird biodiversity" in subsequent discussions.

Table 4. Summary statistics for census tracts used in analysis ($n = 822$).

Description	Mean (SD)	Range
Median household income (U.S. $)	47,480 (25,195)	6,923–158,375
Population in tract self-reporting as African American (non-Hispanic) (%)	41.47 (42.34)	0.00–100.00
Population in tract self-reporting as Hispanic (%)	23.12 (29.04)	0.00–100.00
Proportion of census tract covered in canopy (%)	15.98 (8.10)	0.41–64.44
Distance to nearest large open space from each block (m), averaged at tract level	1,729 (1,040)	91–5,261
Neighborhood bird species richness (number of bird species)	28 (12)	3–52
Distance to Lake Michigan (m)	5,459 (3,605)	0–16,496

Statistical analyses

Our final goal was to test whether there were any differences among socioeconomic groups in terms of (1) proximity to open space, (2) proximity to Lake Michigan, (3) tree canopy cover, or (4) bird biodiversity in each census tract. These four variables represent proxies for ecosystem services. Because each variable exhibited non-normal distributions that could not be corrected using standard transformations, we used a Kruskal-Wallis analysis of variance on ranks to test for differences among the socioeconomic groups extracted from the cluster analysis. The Kruskal-Wallis analysis was conducted with Sigma Plot 11.0 (Systat Software, San Jose, CA, USA).

We conducted a nonmetric, multidimensional scaling (NMDS) ordination on the census tracts to further explore our data and also validate our socioeconomic groupings. NMDS iteratively searches for the best smaller dimensional solution that is the least different from the original multi-dimensional data space and seeks to minimize this difference or "stress". A step-down procedure can first be performed to determine the best number of axes (i.e., dimensionality) for the dataset. Tracts were sorted according to the three socioeconomic variables (% African American, % Hispanic, and median household income) and each tract was subsequently identified according to the group it was assigned in the clustering analysis described above. We used the metaMDS function with Euclidian distance measure in the vegan package (Oksanen et al. 2011) in R to perform the ordination. This function automatically selects different random starts for the ordination to ensure that a global minimum is found. Those dimensions are then used to determine a final ordination of the data. Fitted surfaces of our environmental variables (i.e., contour plots) were added to the ordination model using the ordisurf function in the R vegan package, which uses thinplate splines in a generalized additive model (Oksanen et al. 2011) to fit values of environmental variables in the ordination space. This allowed us to examine the distribution of the environmental variables (used as surrogates for ecosystem services) relative to the socioeconomic characteristics of each census tract.

Results

Socioeconomic data

We removed 185 census tracts from the analysis (out of the 1007 tracts that are within the Chicago city limits) because they had no recorded population ($n = 15$), no reported income ($n = 4$), incomplete coverage of environmental data ($n = 165$), or there was an error in the ACS data ($n = 1$). Eight hundred and twenty-two tracts remained for data analysis. The remaining tracts had a mean household income of $47,480 (ranging from $7,000 to $158,000; Table 4). On average, 41% of the population self-reports as African American (non-Hispanic) while 23% self-reports as Hispanic (Table 4).

Clustering revealed three distinct sets of tracts with similar socioeconomic characteristics. The three clusters or groups retained 81.3% of the information contained in the original dataset. The MRPP analysis indicated that the difference between the three socioeconomic clusters was statistically significant ($P < 0.001$) and large ($A = 0.59$), indicating relatively homogeneous groups of tracts. Cluster 1 ($n = 288$) was primarily characterized by residents self-reporting as African-American with low-to-medium household income (Figs. 2 and 3). Cluster 2 ($n = 191$) was composed of residents in the low-to mid-income range, with the majority self-reporting as Hispanic. Cluster 3 ($n = 343$) was racially diverse and

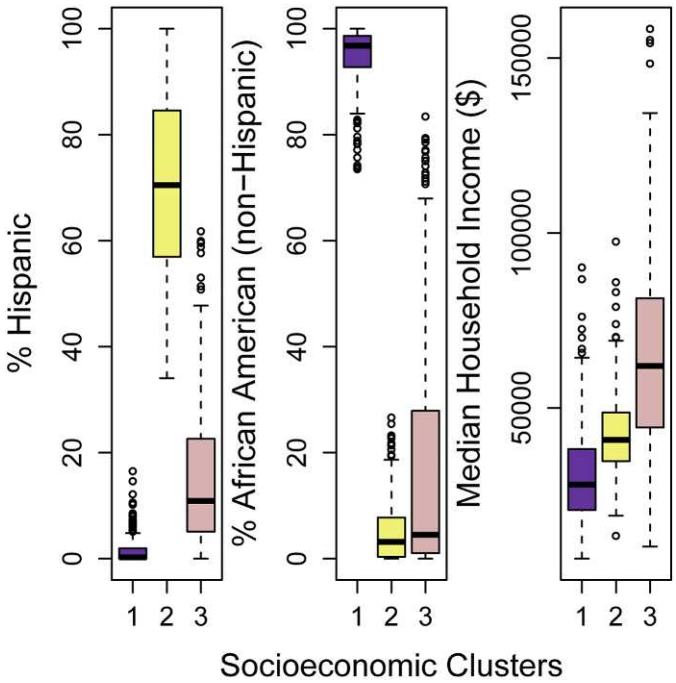

Fig. 2. Box plots of socioeconomic data for each socioeconomic group or cluster. The plots show the percentage of individuals who self-report as Hispanic (left), the percentage of individuals who self-report as African-American (middle), and the the median household income in U.S. dollars (right), in each socioeconomic cluster. Clusters 1, 2, and 3 consist of 288, 191 and 343 tracts, respectively.

dominated by citizens with relatively higher income than those in clusters 1 and 2.

Green infrastructure

Tracts in our study area had an average tree canopy cover of 15.98%, ranging from 0.41% to 64.64% (Fig. 4). The average distance to open space was 1.7 km (ranging from 0.09 to 5.3 km (Fig. 5), while the average distance to Lake Michigan was 5.5 km, ranging from 1.4 to 16.5 km (Fig. 6, Table 4).

Bird biodiversity

In total, we obtained 1091 presence points for 52 species (Appendix) from the eBird database to be used as inputs to habitat suitability models. On average, each species was reported in 23 unique locations. The most common species were the American Crow (*Corvus brachyrhynchos*, 50 locations), European Starling (*Sturnus vulgaris*, 45 locations), Common Grackle (*Quiscalus quiscula*, 41 locations), and Ring-billed Gull (*Larus delawarensis*, 42 locations). For MaxEnt models, AUC values less than 0.7 are generally considered to be an indicator of a poor model (Elith and Leathwick 2007). In our case, all but two species had testing AUC values > 0.71 (Appendix). All 52 species were retained to create the bird biodiversity layer.

Compared to the empirical data from Loss et al. (2009*a*, *b*), our model overestimated species richness; the mean and maximum number of bird species at a sample location in the systematically collected dataset was 7 and 23, respectively, while our model predicted a mean species richness of 28 and a maximum of 52. We expected our model to overestimate species richness for a number of reasons: (1) it was based on predicted habitat suitability, not actual presence of each species, (2) it integrated data over a 10-year period, rather than the 2-year period of the point counts, and (3) as described previously, our model included waterfowl, raptors, and overhead sightings. However, modeled species richness was positively and significantly associated with the empirical data from Loss et al. ($\rho =$

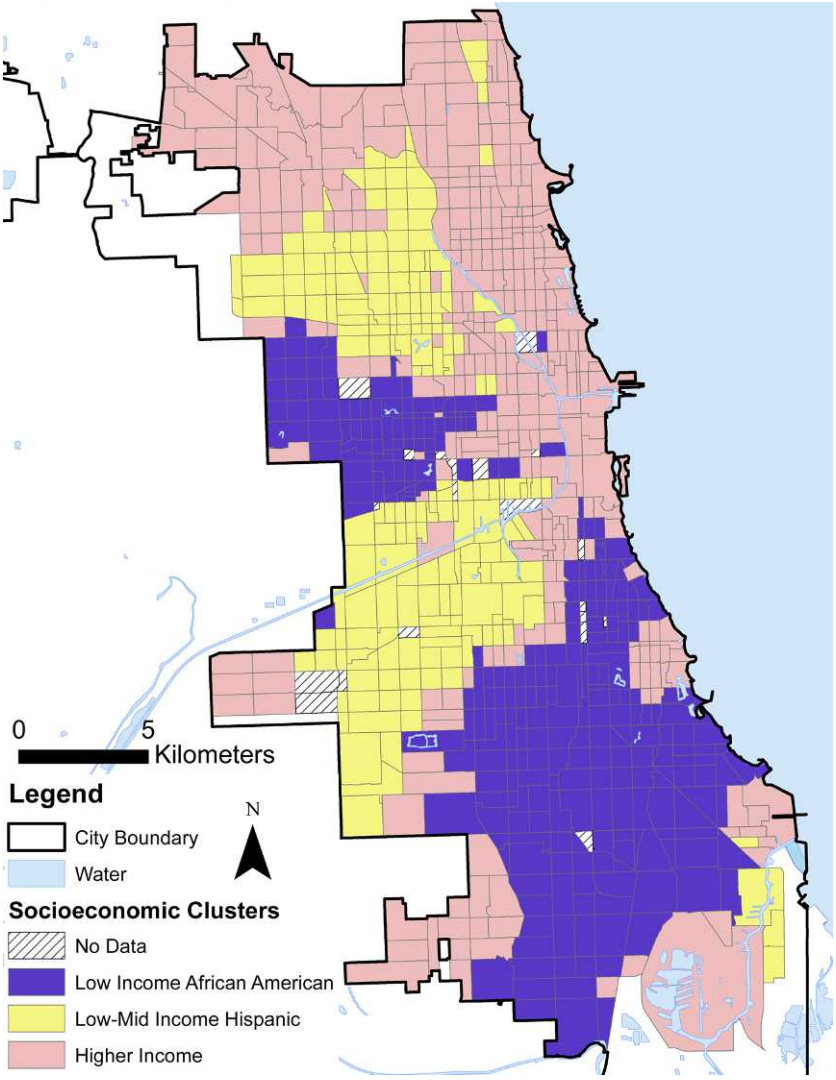

Fig. 3. Geographic distribution of the cluster assignment for our study area. Census tracts depicted in purple were assigned to cluster 1, which is mostly composed of low-income African Americans. Yellow clusters represent cluster 2, which is mostly composed of low- to mid-income Hispanic individuals. Cluster 3 is shown in pink and is mostly composed of higher income residents with a smaller proportion of minorities.

0.55, $n = 171$, $P < 0.001$), and thus appears to serve as a suitable index of bird species richness (Fig. 7).

Statistical analyses

We tested for differences between the three clusters of census tracts in terms of (1) proximity to open space, (2) proximity to Lake Michigan, (3) tree canopy cover, and (4) bird biodiversity. The differences in the mean ranks among the clusters were greater than would be expected by chance across all four environmental variables ($P < 0.001$ for all variables). To isolate the groups that differed from the others, we used Dunn's method for pairwise comparisons (Table 5). Tracts within cluster 2 (low to mid-income Hispanic) were significantly farther away from open space ($H = 16.62$, df $= 2$, $n = 822$, $P < 0.001$) and had significantly less canopy cover ($H = 56.06$, df $= 2$, $n = 822$, $P < 0.001$) and bird biodiversity ($H = 15.267$, df $= 2$, $n = 822$, $P < 0.001$) compared to the other two clusters ($P <$

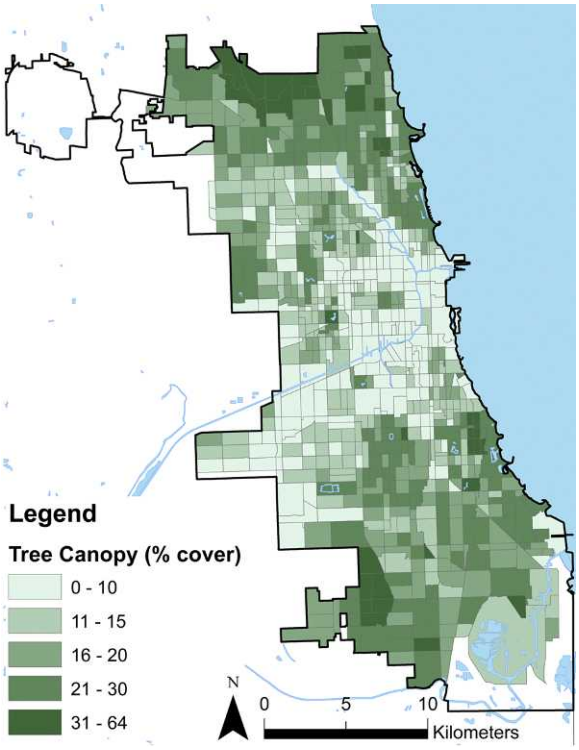

Fig. 4. Percent of U.S. Census tract covered in tree canopy.

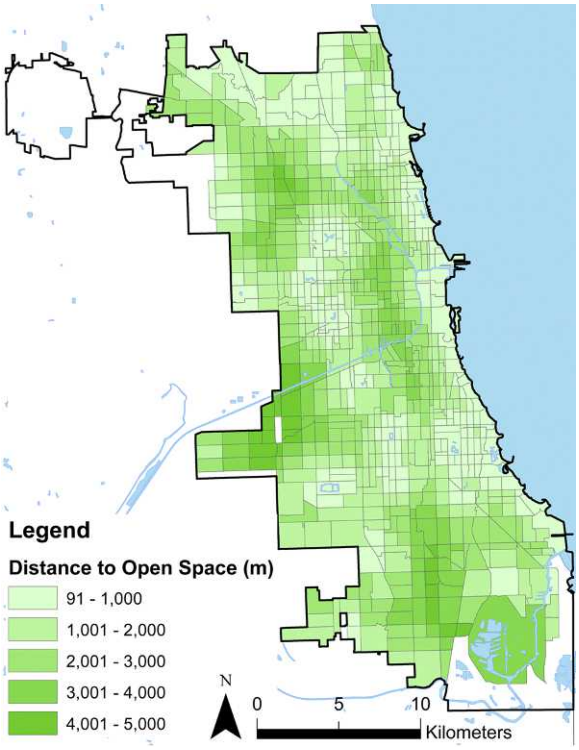

Fig. 5. Average distance to large open spaces (>20 ha) per U.S. Census tract, in meters.

0.05). No significant difference in these environmental factors was detected between cluster 1 (low-income African Americans) and cluster 3 (high income) tracts but the median value for each variable was consistently lower for cluster 1 than cluster 3. All three clusters are significantly different from each other in terms of proximity to Lake Michigan, with cluster 3 living much closer to the lake (median distance = 2.9 km), followed by cluster 1 (median distance = 6.2 km) and cluster 2 (median distance = 6.8 km) ($H = 115.92$, df = 2, $n = 822$, $P < 0.001$).

The results of the NMDS step-down procedure suggest a 2-dimentional solution with a stress of 5.3%, indicating that the ordination is a good representation of the data (Kruskal 1964). A regression of the ordination scores against the original distance matrix showed that the ordination scores had a cumulative r^2 of 0.99. The ordination was rotated so that median household income was represented on the x-axis in Fig. 8. This axis accounted for the greatest proportion of the variation ($r^2 = 0.87$) in the ordination. In Fig. 8, the tracts with the highest median household income are on the far right side of the plot. The contour lines reveal that higher income tracts have high canopy cover and are close to Lake Michigan and open spaces, although these tracts do not appear to have more bird biodiversity than lower income tracts. The ordination confirms the results seen with the clustering and Kruskal-Wallis tests.

Discussion

Our findings reveal differences in the distribution of the environmental variables we used as ecosystem service proxies among socioeconomic groups in Chicago. First, tracts with more low- to mid-income Hispanic residents (cluster 2) appeared to live farther away from Lake Michigan and open space and the amenities they provide. Residents of these tracts also experience lower bird biodiversity and have less tree canopy cover. Second, while we did not find that clusters 1 and 3 differed statistically in terms of distance to

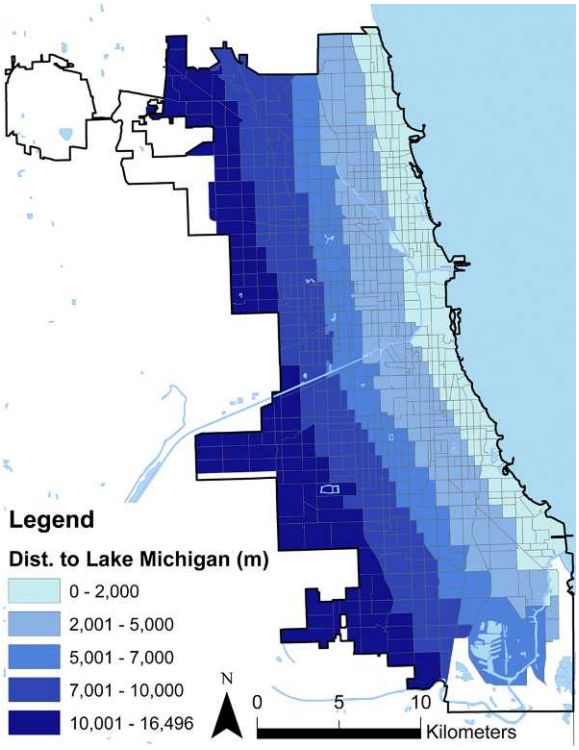

Fig. 6. Average distance to Lake Michigan per U.S. Census tract, in meters.

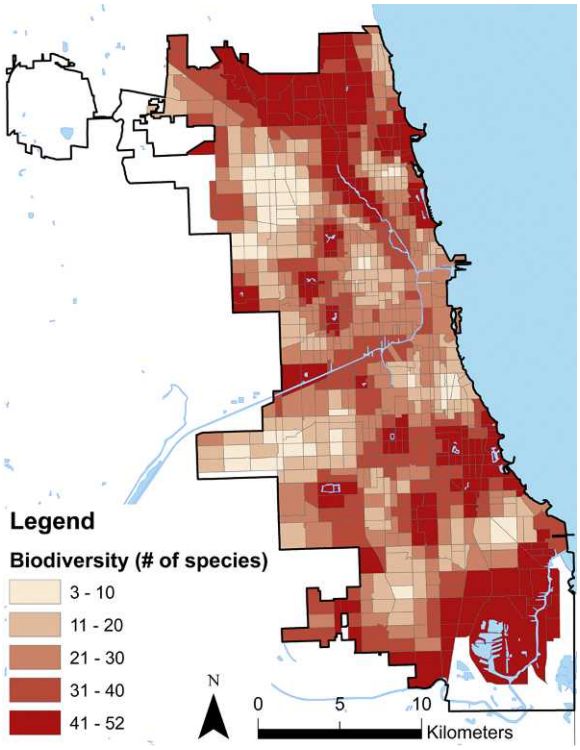

Fig. 7. Neighborhood bird biodiversity averaged per U.S. Census tract. Bird biodiversity was modelled using MaxEnt. A neighborhood is considered as a 400 m radius around each pixel so that the neighborhood bird biodiversity is representative of the the number of birds residents might encounter in their area.

open space, tree canopy cover or bird biodiversity, tracts dominated by low-income African Americans had consistently (but not statistically significant) less desirable levels of the environmental variables we measured compared to the higher income group. Individuals with greater financial means are thus occupying parts of the city with greater bird biodiversity, more canopy cover, and greater proximity to Lake Michigan and other large open spaces in the city (Fig. 8). Assuming these factors are both desirable and provide ecosystem services to urban residents, then we find evidence of disparate distribution of ecosystem services among socio-economic groups in Chicago, especially for low-to mid-income Hispanic residents.

We can only speculate as to the possible mechanisms that lead to the patterns described above, but they may include differences in cultural preferences for certain amenities. These patterns could also stem from a conscious choice of people with financial means to live near Lake Michigan and other open spaces and in neighborhoods with greater canopy cover. Wealthier residents might move into more expensive neighborhoods with greater tree canopy or might have greater means to plant their own trees, make landscaping choices that attract birds, and know the proper institutional channels as well as have the connections to rally for new street trees and attractive open spaces in their neighborhood.

From an urban ecology standpoint, the indication that one socioeconomic group may have reduced provision of ecosystem services is worrisome for several reasons. Some biologists fear that global urbanization causes an "extinction of experience" in which, as the biodiversity in cities diminishes, so too does our appreciation for and connection with nature (Pyle 1978, Turner et al. 2004). This can have far-reaching negative consequences for both biodiversity conservation and human quality of life. From a

Table 5. Distribution measures for the four environmental variables (ecosystem service proxies) according to the three socioeconomic groups assigned by clustering census tracts. Data are medians and 25–75% ranges.

Group	*N*	Distance to open space (km)	Canopy cover (%)	Bird biodiversity (no. species)	Distance to Lake Michigan (km)
Cluster 1	288	1.46^{A} (0.78–2.30)	16.40^{A} (12.42–21.19)	28^{A} (18–36)	6.19^{A} (3.00–8.19)
Cluster 2	191	1.93^{B} (1.11–2.80)	11.97^{B} (8.38–15.70)	23^{B} (14–33)	6.81^{B} (5.31–8.85)
Cluster 3	343	1.49^{A} (0.85–2.34)	17.08^{A} (10.42–22.87)	28^{A} (19–41)	2.87^{C} (1.26–5.74)

Note: Cluster 1: low income, high proportion of African Americans; cluster 2: medium income, high proportion of Hispanics; cluster 3: high income, low proportion of minorities. Medians that do not share superscripts differ at $P < 0.05$ (Dunn's method for comparison of pairs).

conservation perspective, people who experience less biodiversity may have lowered expectations about environmental quality and be apathetic about the natural world, which can in turn lead to even more environmental degradation (Miller 2005). On the other hand, local biodiversity has the potential to foster conservation-mindedness in urban residents (Miller and Hobbs 2002). From a human quality of life perspective, people often experience physical and mental benefits from natural environments (e.g., Ulrich 1984, Kuo 2001) and diversity of wildlife (Fuller et al.

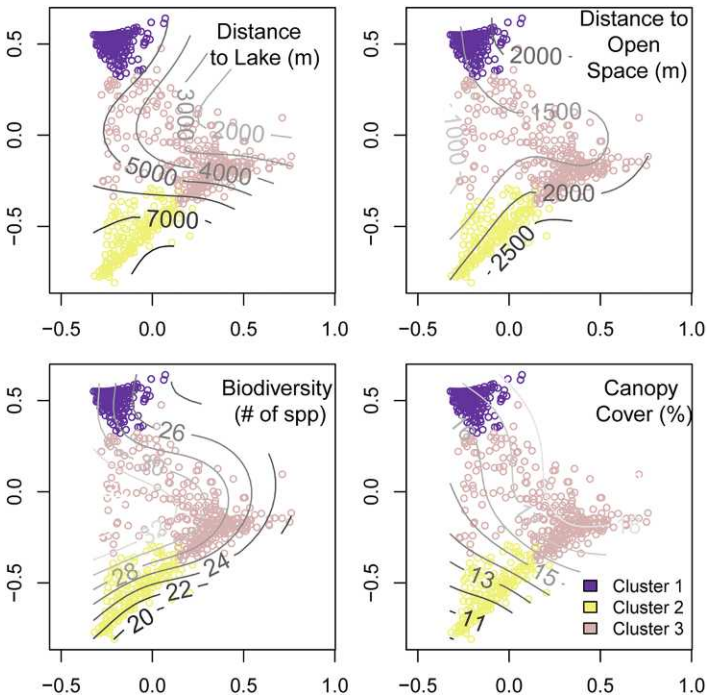

Fig. 8. NMS ordination plots of census tracts according to socioeconomic variables, overlaid with a smooth fitted surface of estimated values for the various ecosytem service proxies. Axes were rotated so that median income is on the x-axis. Tracts that are most similar in their socioeconomic characteristics are closer in space in the plot. Tracts are colored according to the clustering procedure, which was undertaken separately of the ordination. Census tracts depicted in purple represent cluster 1, which is mostly composed of low-income African Americans. Yellow circles represent cluster 2, which is mostly composed of low- to mid-income Hispanic individuals. Cluster 3 (in pink) is mostly composed of tracts with higher income residents and a smaller proportion of minorities. Greyscale contour lines represent a smooth fitted surface of the distance to Lake Michigan (meters), distance to large open space (meters), bird biodiversity (in number of species) and tree canopy cover (%). The darker contour lines indicate the lowest levels of ecosystem services.

2007). Therefore, if certain socioeconomic groups are less exposed to biodiversity, then a self-reinforcing feedback loop might occur wherein individuals from a group become more and more detached from nature and are thus benefit less from its services.

That the environmental variables we used as proxies for ecosystem services are not evenly distributed between different socioeconomic groups in Chicago can be considered an environmental justice issue. In this study, we found indications of environmental injustice in terms of potential ecosystem service provision for tracts dominated by low to mid-income Hispanic residents. However, our research focused on the equal distribution of the ecosystem service proxies, which differs from an equitable distribution. Equitable, or fair, distribution "incorporates needs, choices and merits" (Boone et al. 2009). For example, it has been documented that different racial and ethnic groups have different park use patterns and preferences (Gobster 1998, Gobster 2002). If low income individuals need the services provided by local green infrastructure and biodiversity more than higher income individuals in order to have the same quality of life, then an equal distribution of those services cannot be considered equitable.

To determine whether the patterns we see here are equitable, inquiries about procedural justice, or the drivers of the observed patterns, are needed since the location of parks, street trees and open space, as well as affordable housing, is a result of social and institutional forces that go beyond our investigation (Boone et al. 2009). Future research could involve surveying Chicago residents to examine drivers of settlement patterns as well as cultural preferences for green infrastructure or knowledge of the benefits afforded by green infrastructure and bird diversity. Historical records of settlement in Chicago neighborhoods would be another accessible source of information about possible legacy effects influencing current residential patterns. We hypothesize that an individual's preference to live in a certain neighborhood is influenced by proximity to individuals of similar economic and sociocultural background (Clark 1991). However, it is important to note that existing patterns of settlement in other cities (e.g., Baltimore and Phoenix) reflect the "long history of de jure and de facto segregation" (Boone et al. 2009), such as through the use of restrictive covenants and deeds (Bolin et al. 2005). If that is true in Chicago, the patterns we report here for low-income African American neighborhoods could also be considered environmental injustice if they are the result of social or political injustices committed in the past.

Lastly, to definitively claim that environmental justice is at play, it would be necessary to investigate whether the patterns we observed differ in the *quality* of the ecosystem services provided. All open spaces are not equal, nor are all trees, birds, or sections of the lakefront (e.g., Tyrväinen et al. 2007). For example, a study in Phoenix, AZ found that while neighborhood parks were more accessible in neighborhoods with large minority populations, those parks also experienced the highest crime rates (Cutts et al. 2009).

A major assumption underlying the interpretation of this research is that the presence of nature, in a variety of forms, is unequivocally beneficial for Chicagoans. While much of the literature supports this perspective, some research does provide evidence to the contrary. For example, the value of a park relates significantly to the acceptable crime threshold of residents and potential residents. Areas in Baltimore near parks with high crime indices showed a trend toward having lower housing prices (Troy and Grove 2008). Other researchers have reported that trees may be perceived negatively because of the property damage they can cause after wind storms (Jim and Liu 1997) or hurricanes (Duryea et al. 1996). Additionally, leaves can cause problems for the draining of storm-water off roofs and gutters of residences, making trees a nuisance for homeowners (Westphal 1993). Lastly, some birds can be considered nuisances. In Chicago, there has been concern over the role gulls have played in *E. coli* outbreaks in beaches along Lake Michigan (Whitman et al. 2004). In such high profile instances, it is possible that the benefits of birds could be overshadowed by the negative perception of birds being unclean (Jerolmack 2008). However, many urban residents still report that birds are a source of pleasure rather than a source of disturbance or annoyance (Clergeau et al. 2001, Bjerke and Ostdahl 2004). It is clear that people perceive trees, birds, and other urban

environmental characteristics differently but overall the association seems to be a positive one.

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Supplemental Material

Appendix

Table A1. Table of common name, scientific name, number of unique presence locations included in modeling (20% of which were used for training), training and testing AUC for each bird species modeled in this study. Common names in boldface are species with a test AUC that is below 0.7.

Common name	Scientific name	No. observations	Training AUC	Test AUC
American Crow	*Corvus brachyrhynchos*	25	0.91	0.75
American Goldfinch	*Spinus tristis*	31	0.90	0.80
American Robin	*Turdus migratorius*	40	0.87	0.72
Baltimore Oriole	*Icterus galbula*	19	0.93	0.78
Bank Swallow	*Riparia riparia*	10	0.95	0.91
Barn Swallow	*Hirundo rustica*	32	0.90	0.76
Black-crowned Night-Heron	*Nycticorax nycticorax*	23	0.94	0.82
Black-capped Chickadee	*Peocile atricapillus*	16	0.89	0.85
Blue Jay	*Cyanocitta cristata*	14	0.84	0.79
Brown-headed Cowbird	*Molothrus ater*	17	0.86	0.79
Canada Goose	*Branta canadensis*	29	0.91	0.80
Caspian Tern	*Hydroprogne caspia*	19	0.95	0.89
Cedar Waxwing	*Bombycilla cedrorum*	23	0.93	0.74
Chimney Swift	*Chaetura pelagica*	30	0.89	0.75
Common Grackle	*Quiscalus quiscula*	38	0.88	0.73
Common Yellowthroat	*Geothlypis trichas*	17	0.86	0.78
Dickcissel	*Spiza americana*	9	0.97	0.96
Double-crested Cormorant	*Phalacrocorax auritus*	10	0.88	0.80
Downy Woodpecker	*Picoides pubescens*	22	0.93	0.77
Eastern Kingbird	*Tyrannus tyrannus*	25	0.92	0.82
Eastern Wood-Pewee	*Contopus virens*	12	0.88	0.81
European Starling	*Sturnus vulgaris*	42	0.86	0.71
Great Blue Heron	*Ardea herodias*	15	0.92	0.87
Great Crested Flycatcher	*Myiarchus crinitus*	10	0.85	0.78
Great Egret	*Ardea alba*	11	0.97	0.94
Green Heron	*Butorides virescens*	16	0.91	0.86
Gray Catbird	*Dumetella carolinensis*	23	0.94	0.80
Herring Gull	*Larus smithsonianus*	12	0.85	0.72
House Finch	*Carpodacus mexicanus*	19	0.93	0.74
House Sparrow	*Passer domesticus*	36	0.87	0.69
House Wren	*Troglodytes aedon*	13	0.91	0.88
Indigo Bunting	*Passerina cyanea*	19	0.94	0.85
Killdeer	*Charadrius vociferus*	17	0.86	0.82
Mallard	*Anas platyrhynchos*	32	0.91	0.77
Monk Parakeet	*Myiopsitta monachus*	12	0.83	0.78
Mourning Dove	*Zenaida macroura*	37	0.88	0.80
Northern Cardinal	*Cardinalis cardinalis*	26	0.91	0.80
Northern Flicker	*Colaptes auratus*	14	0.92	0.90
Northern Rough-winged Swallow	*Stelgidopteryx serripennis*	16	0.85	0.78
Peregrine Falcon	*Falco peregrinus*	12	0.83	0.74
Red-eyed Vireo	*Vireo olivaceus*	14	0.86	0.80
Red-tailed Hawk	*Buteo jamaicensis*	12	0.89	0.81
Red-winged Blackbird	*Agelaius phoeniceus*	35	0.90	0.78
Ring-billed Gull	*Larus delawarensis*	39	0.88	0.73
Rock Pigeon	*Columba livia*	38	0.86	0.69
Song Sparrow	*Melospiza melodia*	20	0.93	0.82
Spotted Sandpiper	*Actitis macularius*	12	0.89	0.80
Tree Swallow	*Tachycineta bicolor*	16	0.91	0.85
Warbling Vireo	*Vireo gilvus*	19	0.94	0.81
Willow Flycatcher	*Empidonax traillii*	10	0.89	0.80
Wood Duck	*Aix sponsa*	15	0.89	0.83
Yellow Warbler	*Setophaga petechia*	18	0.93	0.86