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Cover Phograph: A Great Egret (*Ardea alba*) is one of many avian species that utilizes the Bronx River as a source of food, water, and habitat. Camera Trap Photograph © Bobby Habig.

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Avian Diversity and Land Use Along the Bronx River

Amanda J. Goldstein[1], David C. Lahti[1,2], and Bobby Habig[1,3,4*]

Abstract – Urbanization can negatively affect avian diversity. However, certain areas within cities, including rivers and parks, may create refuges for birds. Here, we compare avian species richness, Shannon diversity, and abundance with urban land use features across 18 sites along the Bronx River in New York City by using multiple linear regression. We found 4 key results: (1) artificial green space was negatively associated with avian diversity; (2) natural green space was positively associated with Neotropical migrant diversity; (3) development was positively associated with avian abundance; and (4) avian diversity was higher at sites closer to the Bronx River Parkway. Our results indicate that artificial green spaces, such as golf courses, country clubs, and lawns, might not be the best habitats to support avian diversity, and natural green spaces in New York City are important habitats for Neotropical migrant diversity.

Introduction

Over the past century, increased urbanization has become a global trend, with more people emigrating from suburban and rural areas to city centers, leading to higher levels of development (Elmqvist et al. 2013). The effects of urbanization on avian diversity are well-documented. The most common trends are either that diversity decreases as developed land increases (Chace and Walsh 2006, Clergeau et al. 1998, Marzluff 2001, Pennington et al. 2008) or that diversity is lower in the least- and most-developed habitats, with the highest diversity in moderately developed areas (Batáry et al. 2018, Blair 1996, Marzluff 2017). These patterns can be influenced by spatial scale. For example, development within ~100 m of a river is negatively correlated with avian diversity (Hennings and Edge 2003, McClure et al. 2015, Pennington et al. 2008). On the other hand, tree cover on an intermediate spatial scale (up to 500 m) has been found to be positively correlated with avian diversity (Pennington and Blair 2011, Pennington et al. 2008, Petersen and Westmark 2013). Despite the many studies indicating that urbanization at various spatial scales negatively affects avian diversity, certain habitats within the urban matrix (e.g., rivers and parks) might serve as refuges that harbor high diversity.

Riparian zones are important features of urban ecosystems, containing high biodiversity and abundant resources (Gregory et al. 1991, Naiman et al. 2005). They are also sources of habitat connectivity, acting as corridors for migration and dispersal of taxa, including birds (Décamps et al. 1987, Naiman and Décamps 1997). Additionally, riparian zones are constantly in flux because of changing water flows above- and below-ground, leading to small-scale habitat heterogeneity (Naiman et al. 2005). As a result, avian abundance and richness can be greater in urban wetlands compared to urban uplands (McKinney et al. 2011). Because urban riparian zones are composed of heterogeneous habitat and a variety of resources, these habitats may serve as refuges for birds within cities.

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Urban parks are likewise valuable habitats in the urban landscape, providing resources that are lacking in the surrounding developed matrix. A growing body of literature supports the importance of urban parks for avian diversity (Callaghan et al. 2019, Ikin et al. 2013, Kang et al. 2015, Nielsen et al. 2014). Throughout the contiguous United States, there is significantly higher avian richness and Shannon diversity in urban green areas compared to natural green areas, likely due to heightened habitat heterogeneity within these urban green spaces (Callaghan et al. 2019). Additionally, forested riparian areas serve as critical habitat for Neotropical migratory birds, resulting in higher migrant diversity in these habitats (Pennington and Blair 2011, Pennington et al. 2008). Hence, urban parks, especially those including riparian habitat, may serve as refuges for birds in cities.

The Bronx River is a major waterway of the New York metropolitan area. From its source in central Westchester, it flows 37 km south, cutting through the Bronx to become New York City's only freshwater river. Along the Bronx River, variation in avian diversity may be influenced by land cover, including developed land, artificial green spaces, and natural green spaces, and by proximity to 2 heavily used commuter arteries that track the river over most of its length: the Bronx River Parkway and the Harlem Line of the Metro-North Railroad. First, land cover type often predicts trends in avian diversity; generally, developed land is negatively correlated with avian diversity, while both suburban development (i.e., artificial green spaces) and natural green space are positively correlated with avian diversity (Blair 1996, Marzluff 2001, McClure et al. 2015, Pennington and Blair 2011, Pennington et al. 2008). In addition, non-native bird species abundance is higher in habitats surrounded by more buildings and roads (Blair 1996, Hennings and Edge 2003, Marzluff 2001, Pennington et al. 2008). Neotropical migrant diversity also tends to be positively associated with a higher percentage of forest cover, especially along riparian zones (Pennington and Blair 2011, Pennington et al. 2008). Second, proximity to major roads is associated with reductions in avian abundance (Hennings and Edge 2003, Trammell and Bassett 2012) due to the negative effects of habitat fragmentation, vehicle collisions, pollution, physical barriers, traffic noise, and artificial lighting (Kociolek et al. 2011). Major roads may also create edge habitat, which tends to have higher levels of biodiversity because multiple species are able to exploit and utilize diverse roadside habitats (McCollin 1998). Railroads may also establish edge habitat, although birds tend to avoid railroads because of the risk of collision with either the train itself or the electrical equipment associated with the train (Malo et al. 2017) or because of noise intensity from trains (Dorsey et al. 2015).

The aim of this study was to investigate the association between avian diversity and land use along the Bronx River. We conducted line transect counts at different sites along the reaches of the Bronx River and measured land use variables surrounding these sites. Our objectives were to determine (1) how land cover at 2 spatial scales (100 m and 500 m buffers surrounding each study site) correlates with avian richness, diversity, and abundance and (2) whether land use factors contribute to non-native avian abundance and to Neotropical migrant diversity and species richness. We included Neotropical migrants separately because of the ~58% decline in migratory bird species since 1970 (Rosenberg et al. 2019) and because New York City is on the Atlantic Flyway. We predicted that overall avian diversity along the Bronx River would be higher at sites surrounded by less development across multiple spatial scales and that were farther from the Bronx River Parkway and the Metro-North Railroad. Additionally, we predicted that overall and non-native species abundance would be higher at sites surrounded by more development and that Neotropical migrant diversity would be higher at sites surrounded by more natural green space.

Methods

Field-Site Description

This study took place at 18 sites along the Bronx River in New York, which flows for ~37 km from its source in Valhalla, NY, to its mouth on the East River between Clason Point and Hunts Point (Fig. 1). The upper 24 km of the river pass through the suburban and lightly developed landscape of Westchester County. The lower reaches of the river traverse

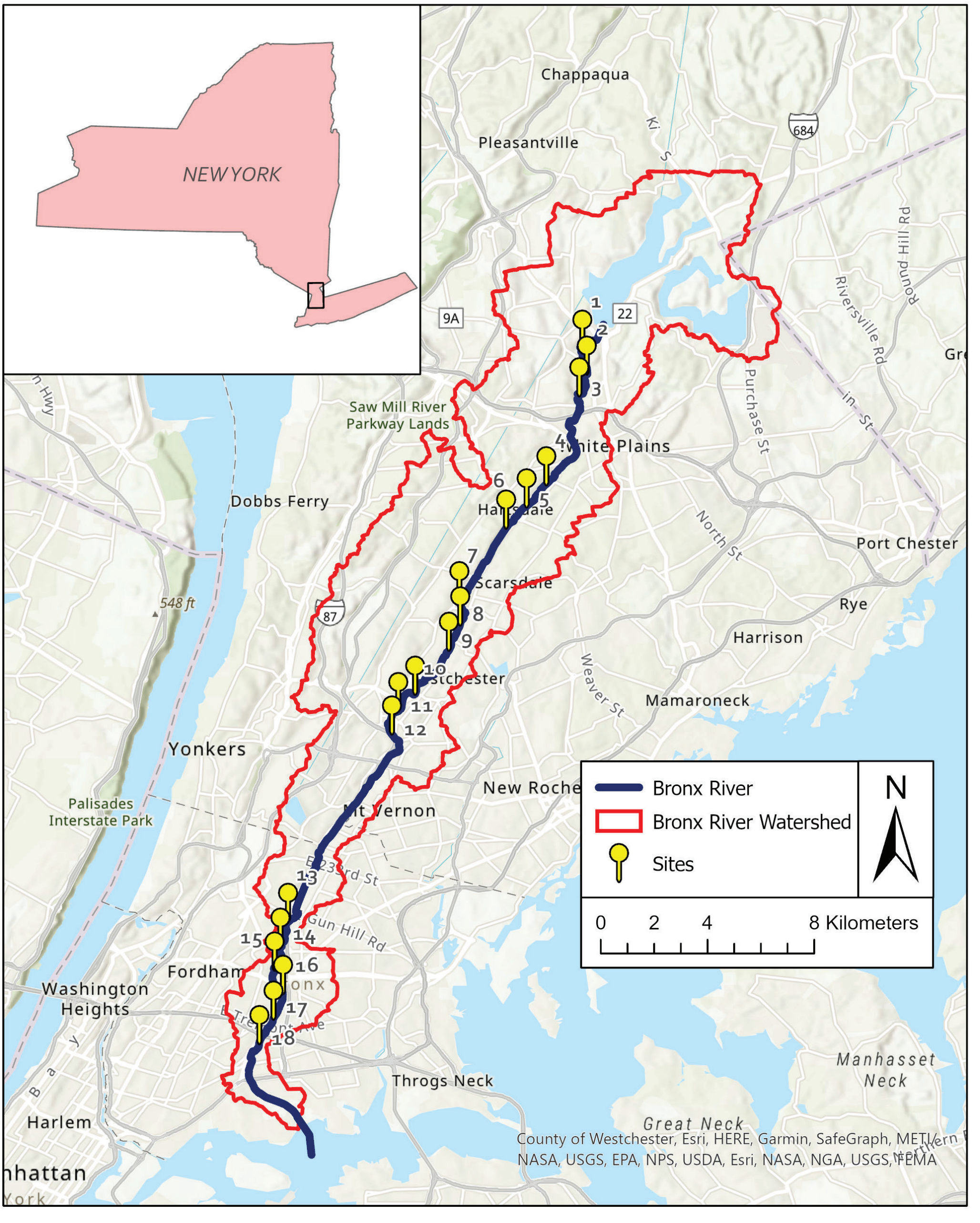

Figure 1. Map of the 18 bird survey locations along the Bronx River in New York City, USA.

the heavily urbanized landscape of Bronx County. During the nineteenth and twentieth centuries, the Bronx River underwent serious environmental degradation stemming from intensifying urbanization and industrialization (de Kadt 2011). Today, the Bronx River remains degraded because of disturbed hydrology, poor water quality, combined sewage overflows, invasive plant species, and dams (Baladrón and Yozzo 2020, Center for Watershed Protection 2010). However, several local agencies have implemented restoration projects along the river (Center for Watershed Protection 2010). Perhaps in light of these efforts, Bronx Park, a 718-acre urban park that encompasses ~4.5 km of the river, is a key stopover site for Neotropical migrants (Bricklin et al. 2016; Seewagen et al. 2011, 2013; Seewagen and Slayton 2008). The Bronx River is a unique habitat in which to study the avian diversity of New York City, the largest city in the United States (US Census Bureau 2019).

Survey Methods

During the spring 2019 migration season, we surveyed avian diversity at 18 sites spaced at least 1 km apart along the Bronx River. We divided the river into 3 reaches and randomly selected 3 consecutive sites within a reach to ensure minimal travel time between sites, selecting groups twice for each reach. The 18 survey locations along the Bronx River included parkland, greenways, backyards, and small green spaces next to roads (see Fig. 1 for a map of the study sites and Table 1 for a description and location of each site).

We surveyed avian diversity and abundance by conducting line transect sampling 3 times at each site beginning at dawn, alternating the order of sites sampled daily to limit time-of-day bias (Bibby et al. 1992, Hennings and Edge 2003). For each sampling session, 1 of us (AJG) recorded all individuals seen or heard within 50 m of the Bronx River while walking parallel to 1 side of the river for 10 min, then immediately crossing the river and completing the survey while walking parallel to the other side of the river for 10 min. For locations where access to the river was limited to 1 side because of dense vegetation, we walked on that side of the river twice, focusing on each side separately and recording all individuals seen or heard within 50 m of both sides for 10 min each. For sampling locations where walking alongside the river was impossible, we conducted the surveys while walking in the river. We included flyover birds and waterfowl in our data, despite many papers excluding these groups of birds (Hennings and Edge 2003, McClure et al. 2015), because certain species (e.g., swifts and swallows) glean insects off the surface of the river while flying and therefore have a clear relationship with the river (Billerman et al. 2020).

Measuring Land Use

We used ArcGIS Pro 2.6 (Esri, Redlands, CA) and the National Land Cover Database (2016) to calculate percentage land cover within 100 m and 500 m of the 18 sites. We simplified the land cover classes by combining the percentage land cover of similar groups into 4 categories: "artificial green space", "natural green space", "developed", and "other" (e.g., Callaghan et al. 2019; Stark et al. 2020). Artificial green spaces consisted of homogeneous vegetation in the form of lawn grasses, including homeowners' yards, parks, golf courses, and country clubs. Natural green spaces consisted of areas covered by over 20% vegetation, including forests and woody or herbaceous wetlands. Developed land, which included areas ranging from low to high development, consisted of a mixture of built materials and vegetation and had impervious surface cover ranging from 20–49% (low) to 80–100% (high). We also used ArcGIS Pro 2.6 to calculate the distance from each of the 18 sites to the Bronx River Parkway and the tracks of the Harlem Line of the Metro-North Railroad.

Statistical Analyses

We performed all statistical analyses using RStudio version 1.3 (RStudio, Boston, MA) with R version 4.0 (R Project for Statistical Computing, Vienna, Austria). To calcu-

Table 1. Locations, coordinates, and descriptions of the bird survey locations along the Bronx River.

Site	Site location	Coordinates	Site description and features
1	Valhalla	(41.0662462, -73.773939)	Located behind a baseball field and parking lot, next to an emergent wetland.
2	N. White Plains I	(41.0576192, -73.772465)	Along a greenway next to the Metro-North railroad hub.
3	N. White Plains II	(41.0504071, -73.774942)	In a forest behind single-family houses, right off of the Bronx River Parkway.
4	Hartsdale	(41.020832, -73.785904)	Along a greenway in a small stretch of green space between the parkway and the railroad.
5	Scarsdale I	(41.0134625, -73.792457)	Along a greenway in a small stretch of green space between the parkway and the railroad.
6	Scarsdale II	(41.0063952, -73.799277)	In a small stretch of green space between the parkway and the railroad; a greenway is currently being built; however, when avian surveys were occurring, there was no construction occurring.
7	Beech Hill	(40.9825942, -73.814828)	In a small park sandwiched between the parkway and the railroad.
8	Eastchester I	(40.9742089, -73.814543)	In a small park sandwiched between the parkway and the railroad; there is a lot of foot and bicycle traffic at this site.
9	Eastchester II	(40.9657551, -73.818318)	In a small park sandwiched between the parkway and the railroad.
10	Tuckahoe	(40.9511473, -73.829524)	Located in a very small area of green space surrounded by small local businesses and streets.
11	Yonkers	(40.9457037, -73.83514)	In a park; the river widens briefly and becomes Bronxville Lake.
12	Bronxville	(40.9379084, -73.837252)	By a small open green space right off the parkway.
13	Bronx Park I	(40.8755822, -73.871796)	Bronx Park; in the Bronx River Forest section.
14	Bronx Park II	(40.8673237, -73.874325)	Bronx Park; in the Bronx River Forest section.
15	New York Botanical Garden	(40.8593842, -73.876259)	In the New York Botanical Garden, behind the Goldman Stone Mill. The river is very deep and wide here.
16	Bronx Zoo	(40.8516295, -73.873465)	On the Bronx Zoo Riverwalk, between 2 dams. The river is very deep and wide here.
17	River Park	(40.8430418, -73.876625)	In River Park, which features a playground, barbecues, and a dam with a fish passage.
18	Starlight Park	(40.8349188, -73.881317)	In Starlight Park, which features a playground, a soccer field, and the offices of the Bronx River Alliance. This location was an amusement park in the early 20th century.

late abundance, we totaled the maximum number of individuals per species at each site. To calculate species richness and Shannon–Wiener diversity (hereafter Shannon diversity), we used the "diversity" and "specnumber" functions within the "vegan" package (Oksanen et al. 2020). In addition to total diversity, we calculated diversity indices separately for non-native species and Neotropical migrant species because these groups may respond to the predictor variables differently (Hennings and Edge 2003, Pennington et al. 2008). Neotropical migrants were defined as birds that live in Central and South America during the winter before migrating long distances in the spring to breed in North America in the summer (Pennington et al. 2008). We classified species into these categories based on data from Birds of the World (Billerman et al. 2020).

Species inventory completeness. Observed species richness is sensitive to sample size (Chao et al. 2014); therefore, we evaluated avian inventory completeness using the 'iNEXT' package in R (Hsieh et al. 2020; Table 2). Three sites had species completeness values of less than 80%, indicating an incomplete inventory (Barragán et al. 2011). As a result, we standardized species richness and Shannon diversity of overall species and Neotropical migrants using the 'ChaoRichness' and 'ChaoShannon' functions in 'iNEXT' (Chao et al. 2014, Hsieh et al. 2016; Table 2). We included estimated species richness and

Table 2. Observed and estimated overall and Neotropical migrant avian species richness and Shannon diversity as well as overall abundance, non-native abundance, and species inventory completeness.

Site	S_{obs}	S_{est}	H_{obs}	H_{est}	MH_{obs}	MH_{est}	MS_{obs}	MS_{est}	OA	NNA	SC (%)
1	17	57	2.7	3.8	1.8	3.3	6	19	24	0	44
2	11	13	1.9	2.1	1.3	2.1	4	8	40	15	90
3	17	46	2.6	3.3	1.4	2.5	4	9	33	0	64
4	16	26	2.5	2.9	1.6	2.5	5	12	45	0	79
5	16	18	2.6	2.9	1.3	1.7	4	5	45	0	87
6	10	13	1.8	2.0	1.1	1.2	3	3	40	0	88
7	16	24	2.4	2.7	1.3	1.7	4	5	52	0	81
8	16	18	2.4	2.5	1.5	1.8	5	5	68	0	93
9	16	32	2.4	2.7	1.2	1.5	4	5	63	0	84
10	19	29	2.7	3.1	2.2	2.7	10	16	55	7	75
11	22	34	2.7	2.9	2.3	2.9	11	19	87	11	86
12	23	38	2.6	2.9	2.1	2.4	11	15	95	8	86
13	25	29	3.0	3.2	2.1	2.4	9	10	95	13	86
14	22	27	2.6	2.8	2.1	2.4	9	10	100	1	89
15	16	28	2.5	3.1	1.9	3.2	7	23	56	1	64
16	23	35	2.5	2.7	1.7	2.2	7	11	133	4	90
17	13	28	2.1	2.3	1.2	1.8	4	7	87	22	90
18	14	18	1.9	2.0	0.8	1.0	3	3	147	82	96

S_{obs} = species richness observed; S_{est} = species richness estimated; H_{obs} = Shannon diversity observed; H_{est} = Shannon diversity estimated; MH_{obs} = Neotropical migrant Shannon diversity observed; MH_{obs} = Neotropical migrant Shannon diversity estimated; MS_{obs} = Neotropical migrant species richness observed; MS_{est} = Neotropical migrant species richness estimated; OA = overall abundance; NNA = non-native abundance; SC (%) = percentage species inventory completeness.

Shannon diversity values as response variables in the multiple linear regression models.

Modeling avian diversity. We used a mixed modeling approach to test predictors of avian diversity. Our models included 3 response variables: (1) species abundance, the total number of individuals present at a site; (2) species richness, the number of species present at a single location (Magurran 1988); and (3) Shannon diversity, the proportional abundance of species within a community (Magurran 1988). We also included 8 predictor variables in the models: (1) percentage artificial green space within 100 m and (2) 500 m of the Bronx River; (3) percentage developed land within 100 m and (4) 500 m of the Bronx River; (5) percentage natural green space within 100 m and (6) 500 m of the Bronx River; (7) distance to the Bronx River Parkway (hereafter "parkway"); and (8) distance to the nearest Metro-North Railroad (hereafter "railroad"). Finally, river depth, river width, temperature, and wind speed were included in the models to control for variations across sites.

We tested all predictor variables for multicollinearity (Fox and Weisberg 2019). Percentage developed land and percentage artificial green space were moderately correlated (correlation coefficient = -0.61); therefore, we restricted all models to include no more than 1 of these variables by using the 'subset' function. None of the other variables exhibited problematic multicollinearity. We modeled Shannon diversity by using the 'lm' function in the 'stats' package (R Core Team 2020), and we tested these models with the package 'gvlma' (Peña and Slate 2019) to ensure that they did not violate any assumptions of linear models. Because abundance and species richness incorporated count data, we used the 'glm' function to model these variables with a Poisson error distribution and a log link function in the 'stats' package (R Core Team 2020). We modeled abundance, estimated species richness, and estimated Shannon diversity for the overall dataset twice, once considering land cover within a 100-m radius and then considering land cover within a 500-m radius. We created similar models for the Neotropical migrant and non-native datasets. However, for non-native species, we only modeled abundance because we only observed 3 non-native species, and many studies report that non-native species abundance is higher in more urbanized locations (Mao et al. 2019, Miller et al. 2003, Pennington et al. 2008). We performed comparison tests of all possible parameter combinations with the 'MuMIn' package (Bartoń 2020). We used Akaike's information criterion corrected for small sample size (AICc) to select the best model (ΔAICc = 0) and reported all models with ΔAICc < 2 because these models are considered equally parsimonious (Burnham and Anderson 2002). We considered model results significant for variables where $P < 0.05$. Finally, we estimated R^2 values for abundance and richness because these are count variables and generalized linear models do not automatically generate R^2 values when using Poisson error distributions. To estimate these R^2 values, we used the 'rsquared' function in the 'piecewiseSEM' package using the Nagelkerke method (Lefcheck 2016).

Results

Avian Community Composition

We recorded 1,613 detections of 59 species at the 18 sites along the Bronx River. Of these species, 56 (95%) were native, 3 (5%) were non-native, and 27 (46%) were Neotropical migrants (Supplemental File 1, available online at https://eaglehill.us/URNAonline2/suppl-files/urna-190-Habig-s1.pdf). Five species accounted for 49.5% of all detections; in descending order of prevalence, these were *Turdus migratorius* L. (American Robin), *Branta canadensis* L. (Canada Goose), *Quiscalus quiscula* L. (Common Grackle), *Agelaius phoeniceus* L. (Red-winged Blackbird), and *Passer domesticus* L. (House Sparrow). Of these 5 most abundant species, only the House Sparrow is non-native.

Estimated overall species richness ranged from 13 to 57 species, and estimated migratory species richness ranged from 3 to 23 species (Table 2). Estimated overall Shannon diversity ranged from 2.0 to 3.8, and estimated migratory Shannon diversity ranged from 1.0 to 3.3 (Table 2). Percentage land cover varied across sites and at different spatial scales (Table 3), with artificial green space ranging from 0% to 100%, natural green space ranging from 0% to 79%, and developed land ranging from 0% to 96% (Table 3). Distance to the Bronx River Parkway ranged from 8 m to 610 m, and distance to the railroad ranged from 17 m to 1311 m (Table 3).

Avian Diversity at Multiple Land Cover Scales

Whether we included either land cover within 100 m of the survey sites or land cover within 500 m of the survey sites in our regression models, the best supported models were the same for avian species richness, Shannon diversity, and overall avian abundance but not for non-native abundance (Table 4; Table 5). Therefore, we report and discuss the model results for avian species richness, Shannon diversity, and overall avian abundance based on land cover within 500 m (Pennington and Blair 2011, Pennington et al. 2008, Petersen and Westmark 2013), but for non-native abundance, we report results at scales of both 100 m and 500 m.

Table 3. Land cover and land use variables for each bird survey site along the Bronx River.

Site	% AGS (100 m)	% AGS (500 m)	% NGS (100 m)	% NGS (500 m)	% D (100 m)	% D (500 m)	Distance to BRP (m)	Distance to RR (m)
1	32	41	32	21	36	38	47	164
2	35	39	30	4	35	56	111	60
3	38	40	42	15	21	45	8	173
4	52	60	36	7	12	32	31	30
5	59	57	0	8	41	36	29	60
6	65	69	30	8	4	23	55	17
7	100	49	0	0	0	50	27	339
8	75	67	0	0	25	33	80	36
9	75	49	0	0	25	51	58	51
10	0	28	4	2	96	71	272	96
11	52	41	5	2	33	56	47	80
12	57	30	0	2	44	69	37	152
13	39	13	0	5	61	82	55	33
14	36	24	52	35	12	40	173	361
15	29	20	50	38	21	42	305	981
16	21	25	79	37	0	37	168	1311
17	9	8	36	25	50	66	378	583
18	4	4	0	1	96	95	610	101

% AGS = artificial green space; % NGS = natural green space; % D = developed; BRP = Bronx River Parkway; RR = Metro-North Railroad.

Predictors Of Overall And Neotropical Migrant Species Richness

Overall species richness was negatively correlated with percentage artificial green space (estimate: -0.014, $P < 0.001$; Fig. 2A, Table 5A) and with distance to the parkway (estimate: -0.0019, $P < 0.001$; Fig. 2B, Table 5A). Neotropical migrant species richness was also negatively correlated with percentage artificial green space (estimate: -0.017, $P < 0.01$; Fig. 3A, Table 5B) and with distance to the parkway (estimate: -0.0016 $P < 0.05$; Fig. 3B, Table 5B).

Predictors of Overall and Neotropical Migrant Shannon Diversity

Overall Shannon diversity was negatively associated with percentage artificial green space and distance to the parkway. Shannon diversity was lower at sites that had a greater percentage cover of artificial green space (estimate: -0.0015, $P < 0.05$; Fig. 4A, Table 5C). Additionally, Shannon diversity was lower at sites that were farther from the parkway (estimate: -0.0025, P < 0.01; Fig. 4B, Table 5C). Shannon diversity of Neotropical migrants was positively correlated with natural green space (estimate: 0.032, P < 0.01; Fig. 5, Table 5D). For every 10% increase in natural green space within 500 m, Neotropical migrant Shannon diversity increased by 32%.

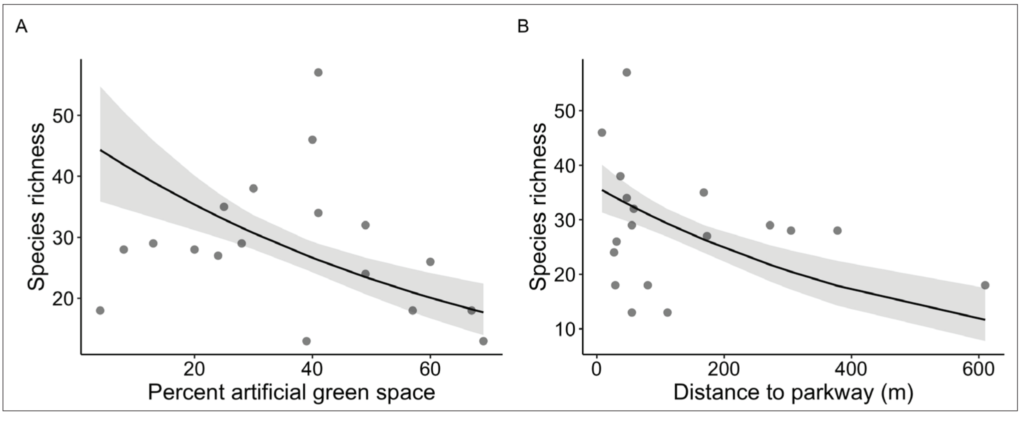

Figure 2. Associations of avian species richness at 18 survey sites with (A) percentage artificial green space within 500 m ($P < 0.001$) and (B) distance to the Bronx River Parkway ($P < 0.001$). Black line indicates model regression line; shaded gray area is the 95% confidence interval.

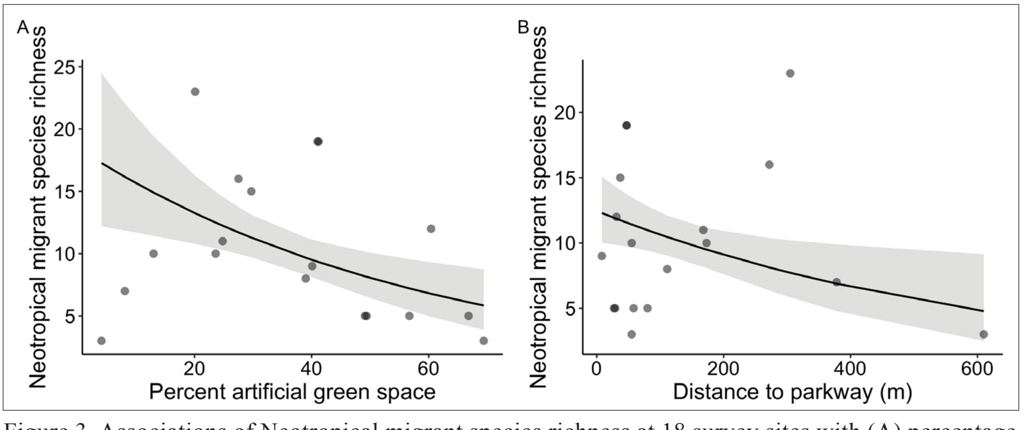

Figure 3. Associations of Neotropical migrant species richness at 18 survey sites with (A) percentage artificial green space within 500 m ($P < 0.01$) and (B) distance to the Bronx River Parkway ($P < 0.05$). Black line indicates model regression line; shaded gray area is the 95% confidence interval.

Table 4. Best supported models (based on change in Akaike's information criterion corrected for small sample size [ΔAICc] < 2) for the overall dataset of avian diversity along the Bronx River. Models in bold are those with ΔAICc = 0; these results are reported in the Results section and Table 5.

Model parameters	ΔAICc	Weight	Log likelihood
Overall species richness (within 100 m of the river)			
Distance to parkway + % artificial green space	**0.0**	**0.36**	**-66**
Distance to parkway	1.8	0.14	-68
% natural green space	1.9	0.14	-68
Overall species richness (within 500 m of the river)			
Distance to parkway + % artificial green space	**0.0**	**0.47**	**-65**
Distance to parkway	0.57	0.35	-69
% natural green space	1.8	0.19	-68
Overall Shannon diversity (within 100 m of the river)			
Distance to parkway + % artificial green space	**0.0**	**0.40**	**-7.2**
Distance to parkway + distance to railroad + % developed	1.0	0.25	-5.7
Distance to parkway + distance to railroad + % developed + river width	1.6	0.18	-3.7
Distance to parkway + % artificial green space + river depth	1.7	0.17	-6.1
Overall Shannon diversity (within 500 m of the river)			
Distance to parkway + % artificial green space	**0.0**	**0.55**	**-7.3**
Distance to parkway	1.7	0.23	-9.9
Distance to parkway + % artificial green space + river width	1.8	0.22	-6.3
Overall abundance (within 100 m of the river)			
% developed + river depth + river width + air temperature	**0.0**	**1.0**	**-88**
Overall abundance (within 500 m of the river)			
% developed + river depth + river width + air temperature	**0.0**	**0.50**	**-88**
% artificial green space + river depth + river width + air temperature	1.3	0.27	-88
Distance to railroad + % artificial green space + river depth + river width + air temperature	1.6	0.23	-86
Non-native abundance (within 100 m of the river)			
Distance to railroad + % artificial green space + river depth + river width + air temperature	**0.0**	**0.42**	**-51**
Distance to railroad + wind speed + % artificial green space + river depth + river width	0.19	0.38	-51
Distance to railroad + wind speed + % natural green space + % artificial green space + river depth + river width	1.6	0.20	-49
Non-native abundance (within 500 m of the river)			
Distance to parkway + % developed + river width	**0.0**	**0.17**	**-50**
Distance to parkway + % developed + river depth	0.15	0.16	-50
Wind speed + % developed + air temperature	0.50	0.13	-50

Table 4. Continued.

Model parameters	ΔAICc	Weight	Log likelihood
Distance to parkway + % natural green space + % artificial green space + river depth	0.87	0.11	-48
Distance to parkway + % developed + river depth + river width	1.2	0.095	-48
Distance to parkway + % natural green space + % artificial green space + river width	1.2	0.094	-48
Distance to parkway + % natural green space + % artificial green space	1.2	0.092	-50
Wind speed + % artificial green space + % natural green space + air temperature	1.4	0.086	-48
Wind speed + % artificial green space + % natural green space + river depth + air temperature	2.0	0.063	-46
Neotropical migrant Shannon diversity (within 100 m of the river)			
% natural green space + air temperature	**0.0**	**0.27**	**-12**
Distance to parkway + % artificial green space	0.5	0.22	-12
Distance to parkway + % artificial green space + wind speed	1.2	0.15	-10
Distance to parkway + % artificial green space + river depth	1.4	0.14	-11
% artificial green space + % natural green space + air temperature	1.7	0.12	-11
% developed + % natural green space + air temperature	1.9	0.10	-11
Neotropical migrant Shannon diversity (within 500 m of the river)			
% natural green space + air temperature	**0.0**	**1.0**	**-10**
Neotropical migrant species richness (within 100 m of the river)			
Distance to parkway + % artificial green space	**0.0**	**0.36**	**-66**
Distance to parkway	1.8	0.14	-68
% natural green space	1.9	0.14	-68
Neotropical migrant species richness (within 500 m of the river)			
Distance to parkway + % artificial green space	**0.0**	**0.47**	**-65**
% natural green space	1.8	0.19	-68
Neotropical migrant abundance (within 100 m of the river)			
River depth + river width + air temperature	**0.0**	**1.0**	**-45**
Neotropical migrant abundance (within 500 m of the river)			
River depth + river width + air temperature	**0.0**	**0.36**	**-45**
% artificial green space + river width + air temperature	0.26	0.31	-45
% artificial green space + river depth + river width + air temperature	1.3	0.19	-43
% developed + river width + air temperature	1.9	0.14	-45

Predictors of Overall, Non-Native, and Neotropical Migrant Abundance

Overall avian abundance along the Bronx River was higher at sites that had a greater percentage cover of developed land (estimate: 0.0052, $P < 0.001$; Fig. 6, Table 5E). Non-native species abundance was negatively correlated with percentage cover of artificial green space within 100 m (estimate: -0.042, $P < 0.001$; Fig. 7A, Table 5F) and distance to the railroad (estimate: -0.0032, $P < 0.001$; Fig. 7B, Table 5F), but in a separate model, it was positively correlated with percentage developed land within 500 m (estimate: 0.055, $P < 0.001$; Fig. 7C, Table 5G) and distance to the parkway (estimate: 0.0021, $P < 0.001$; Fig. 7D, Table 5G). Neither land cover type nor distance to the railroad nor distance to the parkway was a significant predictor of Neotropical abundance (Table 5H).

Discussion

Patterns of avian diversity and abundance along the Bronx River were associated with human use of the surrounding landscape. In support of our predictions, avian abundance was positively associated with developed land, and Neotropical migrant Shannon diversity was positively associated with percentage natural green space. Contrary to our predictions, avian diversity and abundance were negatively associated with percentage artificial green space. Diversity was also higher closer to the Bronx River Parkway. These results suggest that artificial green spaces might not be suitable habitats for sustaining avian diversity in New York City and that natural green spaces along the Bronx River are important habitats for supporting Neotropical migrant diversity.

The Association Between Avian Diversity and Land Cover Along the Bronx River

Sites with higher percentages of artificial green space had lower overall Shannon diversity, overall species richness, and Neotropical migrant species richness. Artificial green spaces include yards, parks, golf courses, and country clubs, and maintenance of these areas often involves mowing grasses, removing leaf litter, and applying pesticides and herbicides, all of which

Table 5. Best supported multiple linear regression model for each response variable: (A) overall avian species richness, (B) Neotropical migrant species richness, (C) overall Shannon diversity, (D) Neotropical migrant Shannon diversity, (E) overall abundance, (F) non-native abundance within 100 m of the river, (G) non-native abundance within 500 m of the river, and (H) Neotropical migrant abundance.

Predictor	Estimate	SE	z value	P	Interpretation	R^2
A. Overall species richness ~ distance to parkway + % artificial green space within 500 m						
Distance to parkway	-0.0019	4.1 E-04	-4.5	6.1 E-06	Distance to parkway ↑; species richness ↓	0.73
% AGS (500 m)	-0.014	0.0032	-4.4	1.1 E-05	% AGS (500 m) ↑; species richness ↓	
B. Neotropical migrant species richness ~ distance to parkway + % artificial green space within 500 m						
Distance to parkway	-0.0016	6.6 E-04	-2.4	0.017	Distance to parkway ↑; Neotropical migrant species richness ↓	0.41
% AGS (500 m)	-0.017	0.0054	-3.1	0.0022	% AGS (500m) ↑; Neotropical migrant species richness ↓	
C. Overall Shannon diversity ~ distance to parkway + % artificial green space within 500 m						
Distance to parkway	-0.0025	8.6 E-04	-3.0	0.0095	Distance to parkway ↑ Shannon diversity ↓	0.28
% AGS (500 m)	-0.0015	0.0069	-2.2	0.042	% AGS (500 m) ↑ Shannon diversity ↓	

Table 5. Continued.

Predictor	Estimate	SE	z value	P	Interpretation	R^2
D. Neotropical Migrant Shannon diversity ~ % natural green space within 500 m + air temperature						
% NGS (500 m)	0.032	0.0093	3.4	0.0037	% NGS (500 m) ↑; Neotropical migrant Shannon diversity ↑	0.45
Air temperature	-0.14	0.041	-3.3	0.0045	Air temperature included in model as control	
E. Overall abundance ~ % developed land within 500 m + river depth + river width + air temperature						
% D (500 m)	0.0052	9.1 E-04	5.7	1.5 E-08	% D (500 m) ↑; abundance ↑	1.0
River depth	3.3 E-04	3.5 E-05	9.3	<2.0 E-16	River depth included in model as control	
River width	0.042	0.0085	5.0	6.8 E-07	River width included in model as control	
Air temperature	0.0052	0.0017	3.0	0.0026	Air temperature included in model as control	
F. Non-native abundance ~ distance to railroad + % artificial green space within 100 m + river depth + river width + air temperature						
% AGS (100 m)	-0.042	0.0050	-8.5	<2E -16	% AGS (100 m) ↑; abundance ↓	1.0
Distance to railroad	-0.0032	6.1E-04	-5.2	1.6E-07	Distance ↑; abundance ↓	
River depth	0.0093	0.0023	4.0	5.1E-05	River depth included in model as control	
River width	0.011	1.9 E-04	5.9	4.2E-09	River width included in model as control	
Air temperature	0.14	0.027	5.2	2.6E-07	Air temperature included in model as control	
G. Non-native abundance ~ distance to parkway + % developed land within 500 m + river width						
% D (500 m)	0.055	0.0069	7.9	1.9 E-15	% D (500 m) ↑; abundance ↑	1.0
Distance to parkway	0.0021	5.2 E-04	3.9	8.6 E-05	Distance ↑; abundance ↑	
River width	4.0 E-04	1.4 E-04	2.6	0.0089	River width included in model as control	
H. Neotropical migrant abundance ~ river depth + river width + air temperature						
River width	0.035	0.0093	3.8	1.6 E-04	River width included in model as control	0.79
River depth	0.058	0.023	2.5	0.012	River depth included in model as control	
Air temperature	-0.074	0.023	-3.3	0.0010	Air temperature included in model as control	

% AGS = artificial green space; % NGS = natural green space; % D = developed.

reduce overall biodiversity and therefore may impact avian diversity (Aronson et al. 2017, Marzluff and Ewing 2001). Reductions in mowing frequency may increase plant diversity (Chollet et al. 2018), which likely translates into higher insect diversity (Smith et al. 2015). In addition, native and mixed native/non-native grass-free plots have higher insect abundance compared to turf grass and non-native grass-free plots (Smith et al. 2015). Twenty-seven of the 59 avian species (46%) observed at sites along the Bronx River were insectivores. Therefore, the lower avian diversity and species richness in artificial green spaces surrounding the Bronx River may be a result of reduced food availability in these human-maintained areas.

Sites along the Bronx River surrounded by more natural green space had higher Neotropical migrant Shannon diversity. The Atlantic Coast Migration Route, on which New York City is a key stop, consists of highly developed cities with minimal habitat for migrants, so migratory birds are drawn to large urban green spaces (Seewagen et al. 2011). Bronx Park is a contiguous patch of green space within the densely developed city, containing both the Bronx Zoo and the New York Botanical Garden, the latter of which is home to the Thain Family Forest, a 50-acre old-growth forest that has apparently never been cut (Loeb 2011, Schuler and Forrest 2016). Several studies indicate that Bronx Park is a key stopover site for migrating birds (Bricklin et al. 2016; Seewagen et al. 2011, 2013; Seewagen and Slayton 2008). Our results add to a small body of literature showing that Bronx Park is likely valuable habitat for Neotropical migrants.

Finally, urbanization in the form of heightened levels of developed land surrounding survey locations along the Bronx River did not appear to affect avian diversity, either positively or negatively. The lack of a negative correlation between diversity and developed land may be because birds in New York City have become habituated to development. Perhaps an effect may be present at a larger spatial scale, such as 1 km around the study sites; in our study, where sites were only 1 km apart from each other, measuring land cover on a larger scale was impractical. Developed land was associated with higher overall abundance, as has been shown in other studies (reviewed in Chace and Walsh 2006). This positive relationship between avian abundance and urbanization is likely due to a few species groups, specifically non-native species, building-nesters, and omnivores, exploiting the resources available in the urban environment (Batáry et al. 2018, Blair 1996, Chace and Walsh 2006, Clergeau et al. 1998, Marzluff 2001). The 17 omnivorous species (Supplemental File 1, available online at:

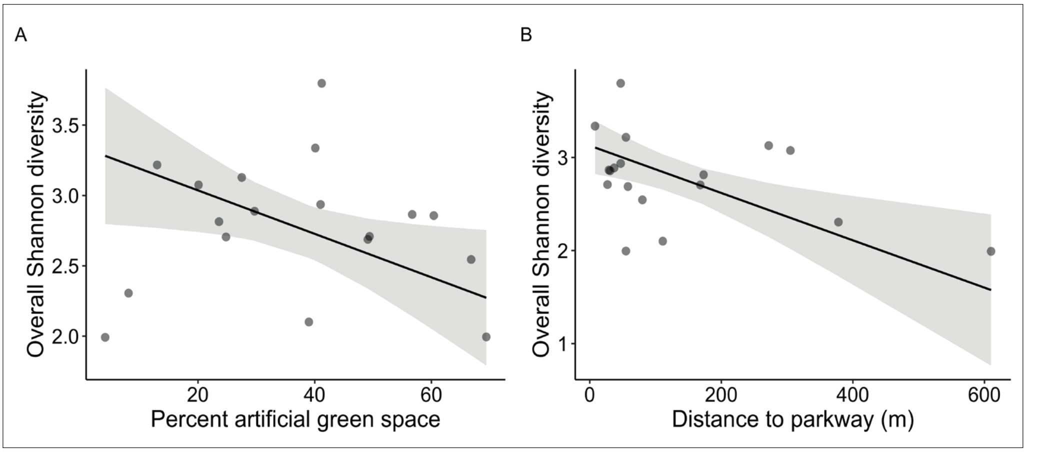

Figure 4. Associations of avian Shannon diversity at 18 survey sites with (A) percentage artificial green space within 500 m ($P < 0.05$) and (B) distance to the Bronx River Parkway ($P < 0.01$). Black line indicates model regression line; shaded gray area is the 95% confidence interval.

https://eaglehill.us/URNAonline2/suppl-files/urna-190-Habig-s1.pdf) accounted for 58% of all detections of birds along the Bronx River, and the 3 non-native species accounted for 16% of all detections of birds along the Bronx River. Our findings suggest that low to moderate levels of development might be more advantageous than artificial green space for some species because these anthropogenic habitats provide new resources, such as structural diversity for more nesting spaces and novel sources of food (Blair 1996). Therefore, it is plausible that the increased abundance in more developed areas is due to omnivores and non-native species taking advantage of the unique resources in the urban environment.

The Association Between Avian Diversity and Distance to the Bronx River Parkway

Sites closer to the Bronx River Parkway had higher overall species richness, Neotropical migrant species richness, and overall Shannon diversity. This pattern diverges from the literature describing the negative effects of major roads on avian abundance and diversity (Kociolek et al. 2011). However, roads have certain positive effects on birds, including creating places for foraging, reducing predation pressures, and providing a warm surface that helps birds conserve energy (Morelli et al. 2014), which may be the case along the Bronx River Parkway. Additionally, the parkway is unusual in that it is forested along nearly its entire length. Roads neighboring forests create edge habitat,

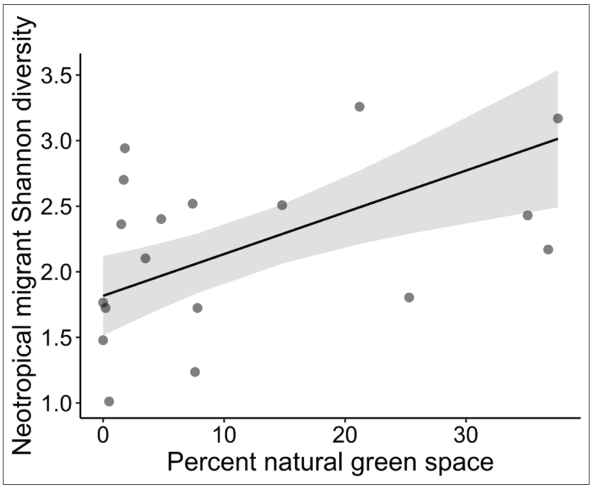

Figure 5. Association between Neotropical migrant Shannon diversity at 18 survey sites and percentage natural green space within 500 m ($P < 0.01$). Black line indicates model regression line; shaded gray area is the 95% confidence interval.

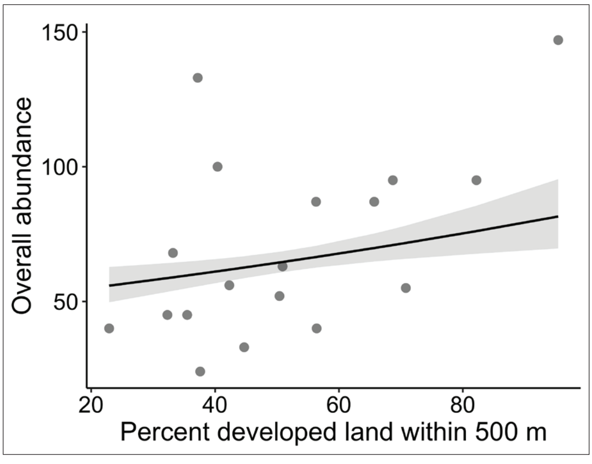

Figure 6. Association between overall avian abundance at 18 survey sites and percentage developed land within 500 m ($P < 0.001$). Black line indicates model regression line; shaded gray area is the 95% confidence interval.

which some specialist species prefer, possibly because of increased resource accessibility from small-scale changes in vegetation structure in these areas (Terraube et al. 2016). In support of this hypothesis, our results show that non-native species abundance was lower at sites closer to the parkway, possibly because such generalists do not need edge habitat for food sources. Furthermore, the Bronx River Parkway's formation of edge habitat may also result in higher levels of biodiversity (McCollin 1998). The Bronx River Parkway possibly creates quality edge habitat that attracts native species and Neotropical migrants, resulting in higher avian diversity at sites that are closer to this major road.

The Association Between Avian Diversity and Abundance and Distance to the Metro-North Railroad

Contrary to our prediction, distance to the railroad was not positively or negatively associated with avian diversity, although non-native species abundance was higher at sites closer to the railroad. Despite the general trend of birds avoiding railroads because of noise pollution (Dorsey et al. 2015) or risk of collision (Malo et al. 2017), the non-native bird species (specifically *Columba livia* Gmelin [Rock Dove] and the House Sparrow) may be drawn to the habitat surrounding the railroad, which includes rocky land cover. Based on our results, the Metro-North Railroad is an urban feature that appears to be conducive to non-native bird abundance.

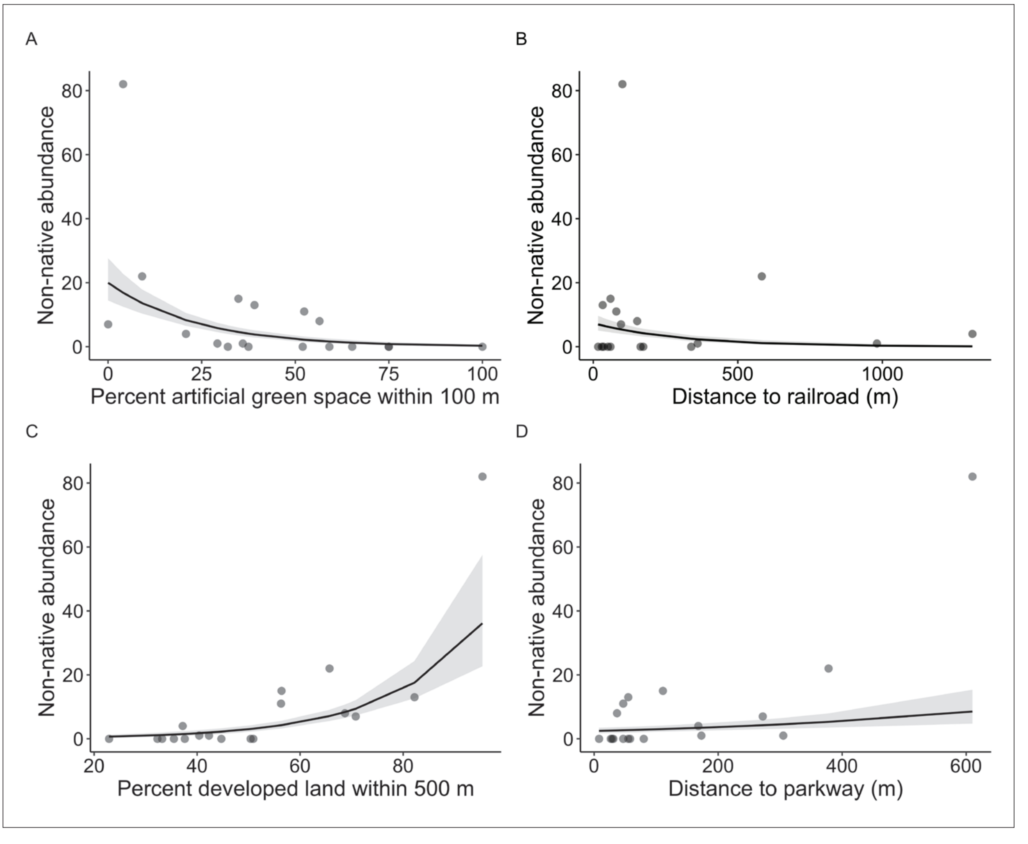

Figure 7. Associations of non-native avian abundance at 18 survey sites with (A) percentage artificial green space within 100 m ($P < 0.001$); (B) distance to railroad ($P < 0.001$); (C) percentage developed land within 500 m ($P < 0.001$); and (D) distance to parkway ($P < 0.001$). Black line indicates model regression line; shaded gray area is the 95% confidence interval.

Study Limitations

We recognize some limitations associated with the present study. First, we only sampled the river across 1 season; future studies should survey the river throughout all seasons and across several years. Second, we were unable to sample consistently at each site because of the inaccessibility of certain sections of the river due to dense invasive vegetation on the riverbank. However, excluding sites where we had to modify our sampling methods because portions of the riverbank were inaccessible did not significantly alter our results.

Conclusions and Future Directions

Our study provides insight into the land use factors associated with avian diversity along the Bronx River. One key result of our study is that Neotropical migrant diversity was positively associated with natural green space. To ensure that areas surrounding the Bronx River provide quality habitat and continue to attract migratory birds, we recommend that land managers preserve forested areas and create additional green spaces consisting of diverse vegetation. A second key finding was that artificial green space surrounding the Bronx River was negatively associated with overall and Neotropical migrant species richness and overall Shannon diversity. Based on these results, we suggest that homeowners and managers of country clubs and golf courses reduce mowing frequency, plant more native species, and decrease pesticide usage (Marzluff and Ewing 2001). We also found that avian abundance along the Bronx River was positively correlated with developed land. This relationship is likely due to the increased structural diversity and provisioned food sources in developed areas. Finally, avian diversity was higher at sites that were closer to the Bronx River Parkway, possibly because of the creation of unique types of habitats on either side of the parkway, creating more niches for birds. To test this hypothesis, we suggest a more comprehensive study classifying the habitat around the Bronx River Parkway to determine if the parkway borders distinct habitat types that support higher avian diversity along the Bronx River.

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