# PREDICTORS OF AVIAN DIVERSITY ALONG THE BRONX RIVER


**by**

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## *Abstract*

Urbanization is predicted to increase significantly across the United States within the next forty years, resulting in decreased biodiversity due to habitat loss. Studies show that as developed land increases, avian diversity decreases, as species that exploit urban resources replace species that require more natural habitats. However, certain areas within cities, including rivers and parks, may provide a refuge for avian diversity. The Bronx River in New York is a critical source of fresh water that is surrounded by urban parks throughout its course. The objectives of my study were to: (1) determine what factors contribute to avian diversity; (2) explore how land cover at three spatial scales (100 m, 500 m, and 1 km) affects avian diversity and abundance; (3) compare native and nonnative avian abundance; and (4) determine if there are specific variables that impact Neotropical migrant diversity along the Bronx River. I conducted line transect counts to calculate avian abundance, species richness, Shannon diversity, and evenness at different sites along the Bronx River. I compared each of these predictor variables with land use and river morphology response variables: percent developed land, percent artificial green space, percent natural green space, distance to the Bronx River Parkway, distance to the Metro-North train, river depth, and river width. After conducting multiple linear regressions and general linear models, I found three main results. First, patterns in avian diversity changed with land cover on multiple spatial scales. Higher levels of developed land within 100 m of the Bronx River were positively correlated with avian diversity, whereas higher percent artificial green space within 500 m of the Bronx River was negatively correlated with avian diversity. In addition, diversity of Neotropical migrants was higher at sites that had more percent natural green space within 500 m. Land cover within 1 km of the Bronx River did

not predict avian diversity. The variable that best predicted avian abundance, Shannon diversity, and species evenness was percent developed land within 100 meters. Meanwhile, the variable that best predicted species richness was percent artificial green space within 500 meters, and natural green space within 500 meters best predicted Neotropical migrant Shannon diversity and evenness. The higher diversity at sites surrounded by intense development was likely because the Bronx River is surrounded by a buffer of parkland throughout its course, which provides a refuge for birds within the dense urban matrix. Meanwhile, artificial green spaces were negatively correlated with avian diversity because of the intense mowing and maintenance involved with these habitats; natural green spaces were positively correlated with Neotropical migrant diversity because they provide places to nest and forage. Second, the effects of the Bronx River Parkway and the Metro-North Railroad on avian diversity opposed each other: sites that were closer to the parkway had higher diversity, whereas sites closer to the railroad had lower diversity. The Bronx River Parkway is surrounded by vegetation, creating edge habitat where birds may forage with lowered risk of predation; the railroad creates less useful habitat due to the gravel and rocks surrounding the tracks. Finally, morphological features of the Bronx River were positively correlated with avian abundance: deeper and wider reaches of the river were associated with higher bird abundance, possibly because deeper and wider sections of the river can support more food resources for birds. This research contributes to a growing body of literature on the importance of urban green spaces within a densely developed urban matrix, in addition to the influence of edge effects on patterns of avian diversity.

## *Introduction*

The future of the world is in cities. Over the past century, the world has witnessed a global trend of increased urbanization as more people emigrate from suburban and rural areas to city centers. Urbanization, which is defined as the process by which human settlement grows in the intensity of land use within an area and in population density (Marzluff 2001), can have profound consequences on biodiversity (McKinney 2002). Scientists project that urban land in the contiguous United States will increase from 3.0% of the land cover in 2010 (275,000 square kilometers) to 8.6% in 2060, a total of 660,000 square kilometers of urban land (Nowak & Greenfield 2018); additionally, wetlands may be most affected by these changes in land use (Theobald 2010). This increase in developed land is anticipated to lead to further losses of biodiversity (McKinney and Lockwood 1999).

Urbanization is frequently cited as a major threat to biodiversity; it replaces natural habitats with anthropogenic features including buildings, roads, and other impervious surfaces, resulting in native habitat loss while creating new artificial habitat spaces (McKinney and Lockwood 1999; McKinney 2002; McKinney 2008; Grimm et al. 2008). As natural habitats become transformed into cities, the species that can adapt to urban areas replace species that are unable to adapt, leading to decreased biodiversity in cities (McKinney 2002; Olden et al. 2006; McKinney 2006; Grimm et al. 2008). The effects of urbanization on avian diversity are well documented in the literature; general trends show that either overall diversity decreases as developed land increases (Clergeau et al. 1998; Marzluff 2001; Chace & Walsh 2006; Pennington et al. 2008), or overall diversity is lower in the least- and most-developed habitats, with highest diversity in moderately disturbed areas (Blair 1996; Batáry et al. 2018; Marzluff 2017). In addition, the abundance of certain species groups, specifically non-native species, building-nesters, and omnivores, tends to increase as urbanization increases (Blair 1996; Clergeau et al. 1998; Marzluff 2001; Chace & Walsh 2006; Batáry et al. 2018). These trends are also evident along riparian urbanization gradients, with overall bird diversity higher in more natural habitats, and non-native species and building-nester abundance higher in more urbanized habitats (Rottenborn 1999; Miller et al. 2003; Smith and Wachob 2006; Pennington et al. 2008; Mao et al. 2019). Studies also show that the impacts of developed land along an urbanized riparian gradient occur at several spatial scales: Hennings and Edge (2003), Pennington et al. (2008), and McClure et al. (2015) all found that development on a small spatial scale (within ~100 m of the river) had a negative impact on avian diversity. Additionally, land cover on an intermediate spatial scale (up to 500 m) may also have important effects on avian diversity (Hennings and Edge 2003; Pennington et al. 2008; Pennington and Blair 2011; Petersen and Westmark 2013), and research indicates that large spatial scales (1 km) are also significant for certain bird species (Pennington and Blair 2011; McKinney et al. 2011). Despite many studies indicating that urbanization within various spatial scales reduces bird diversity, there may be certain habitats within the urban matrix serving as biodiversity refuges that harbor high bird diversity: urban rivers and parks. In these unique ecosystems, avian diversity may be greater than anticipated within a heavily developed matrix.

Riparian zones are important features of urban ecosystems. They contain critical water resources, diverse wildlife, and plant communities (Gregory et al. 1991); are hotspots of ecological interactions between vegetation, soil, water, microbes, and humans

(Groffman et al. 2003); and have high levels of floral and faunal diversity (Naiman et al. 2005). Riparian zones are also sources of habitat connectivity, acting as corridors for migration and dispersal of several taxa, including birds (Decamps et al. 1987; Naiman & Decamps 1997). Finally, riparian zones are sources of small-scale habitat heterogeneity due to abiotic and biotic responses to changes in water flow (Naiman et al. 2005). As a result, avian abundance and richness have been found to be greater in urban wetlands compared to urban uplands (McKinney et al. 2011). In certain ecosystems, due to their sources of biodiversity and heterogeneous habitat, urban riparian areas may serve as refuges for wildlife within cities.

Urban parks are also critical habitats of the urban ecosystem, providing resources that are not found in the surrounding developed matrix. They are defined as open areas set aside within an urban setting that are usually for public use, dominated by plants and water sources, and consisting of highly diverse and heterogeneous habitats (Nielsen et al. 2014). Urban green spaces harboring water bodies and high plant richness tend to have increased faunal biodiversity (Nielsen et al. 2014). There is a growing body of literature that supports the importance of urban parks for avian diversity (Ikin et al. 2013; Nielsen et al. 2014; Kang et al. 2015; Shih 2018; Callaghan et al. 2019; Zorzal et al. 2020). Throughout the contiguous United States, there is significantly higher bird 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). In addition, larger urban parks harbor greater bird diversity (Nielsen et al. 2014; Kang et al. 2015; Yang et al. 2020). Finally, urban parks are often oases for avian diversity within highly developed areas, providing heterogeneous habitats and resources unavailable in surrounding cities (Nielsen et al. 2014; Callaghan et al. 2019; Zorzal et al. 2020).

The Bronx River is home to a riparian habitat comprised of several parks along an urbanization gradient. As New York City's only freshwater river (de Kadt 2011; Russ et al. 2015), the Bronx River has not only been an important source of drinking water, but it is also likely a wellspring of food and habitat resources for many bird species. Strikingly, during the nineteenth and twentieth centuries, the Bronx River underwent serious environmental degradation stemming from intensifying urbanization and industrialization. The construction of mills and railroads along the river resulted in increased runoff and the release of pollutants (de Kadt 2011). Additionally, the construction of the Bronx River Parkway between 1916 and 1925 prompted the rechanneling and straightening of the Bronx River (Rachlin et al. 2007), which might have resulted in negative impacts on local biodiversity including possible declines in avian communities (Brooker 1985). Moreover, several forms of anthropogenic degradation have made the Bronx River less habitable for avian communities: (1) disturbed hydrology, which results in reduced infiltration to groundwater, sedimentation, greater erosion, and habitat disturbance; (2) poor water quality due to sewage and untreated stormwater, which limits aquatic life; (3) aging infrastructure resulting in combined sewage overflows (CSOs); (4) invasive plants, limiting the ecological functionality of the river and resulting in bank instability; (5) degraded habitat due to aforementioned channel alterations, disturbance, and poor water quality, which reduces biodiversity; and (6) dams, which limit the connectivity of the river (Center for Watershed Protection 2010). Considering the ramifications of urban development on the Bronx River, the Bronx River Alliance, the New York City Department of Parks and Recreation, and the Westchester County Parks Department have separately implemented restoration projects along the river, including planting native species and removing invasive species, removing garbage, restoring the floodplain, restocking the river with native fish, and managing stormwater runoff to collect pollution before it enters the river (Center for Watershed Protection 2010). Perhaps in light of these restoration efforts, Bronx Park, a 718-acre urban park that encompasses approximately 4.5 kilometers of the river and is almost directly in the center of the Bronx, is a key stopover site for Neotropical migrants (Seewagen et al. 2011; Seewagen et al. 2013; Bricklin et al. 2016). The Bronx River is a unique habitat in which to study the biodiversity of New York City, the largest city in the United States (U.S. Census Bureau 2019).

Several land use features along the Bronx River are thought to contribute to patterns of avian diversity. These include (1) land cover, including developed land, artificial green spaces, and natural green spaces; (2) proximity to major roads, specifically the Bronx River Parkway; and (3) proximity to train tracks, specifically the Metro-North Railroad. First, land cover often predicts trends in avian diversity; generally, developed land is negatively correlated with avian diversity, while both suburban development (i.e., artificial green spaces, including lawns) and natural green space are positively correlated with avian diversity (Blair 1996; Marzluff 2001; Smith and Wachob 2006; Pennington et al. 2008; Pennington and Blair 2011; McClure et al. 2015). In addition, non-native species abundance is higher in habitats surrounded by more buildings and/or roads (Blair 1996; Marzluff 2001; Hennings and Edge 2003; Pennington et al. 2008). Second, proximity to major roads is associated with reductions in bird 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). In the literature, negative effects of roads on wildlife abundance exceed positive effects by a factor of five, and birds tend to show either a negative or lack of response due to roads (Fahrig and Rytwinski 2009). However, birds may benefit from roads, because they provide edge habitat for foraging, limit predation pressure, and serve as a warm surface that helps birds conserve energy; furthermore, roadside vegetation forms an ecological corridor (Morelli et al. 2014). Species that tend to use resources associated with roads include raptors, passerines, and woodland species that may prefer proximity to roads due to edge effects (Palomino and Carrascal 2007; Morelli et al. 2014). Finally, birds tend to avoid railroads due to 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). However, similar to the effects of roads, birds may benefit from the edge habitat created by railroads (Morelli et al. 2014; Wiącek et al. 2015). Altogether, anthropogenic features surrounding the Bronx River, including percent land cover, the Bronx River Parkway, and the Metro-North Railroad, likely impact patterns of avian diversity and abundance.

Morphological features (e.g., river depth and width) at locations along the Bronx River might also contribute to variation in avian diversity and abundance. Generally, bird abundance is higher on rivers that are wider and deeper (Lock and Naiman 1998; Mason and Macdonald 2000; Mason et al. 2006; O'Neal Campbell 2008). This may be due to a positive correlation between vegetation and stream size (Lock and Naiman 1998), or because biodiversity of aquatic organisms within the river, which are sources of food for birds, may be higher in larger rivers (Ivicheva et al. 2019). Both waterbirds and terrestrial birds benefit from riparian nutritional pathways (Jackson et al. 2020), and therefore, larger rivers presumably have more diverse food sources for birds, translating to higher avian diversity. However, it is also possible that shallower sections of rivers have higher macroinvertebrate diversity and density (Nakano and Nakamura, 1998). Collectively, research indicates that river structure might influence avian abundance and diversity along the Bronx River.

The aim of this study was to investigate what drives patterns of avian diversity along a critical and understudied water body, the Bronx River. To accomplish this goal, I conducted line transect counts at different sites along the reaches of the Bronx River. I also measured and calculated abiotic and anthropogenic variables that might influence the biodiversity of the Bronx River. I used these data to complete the following research objectives: (1) Determine what factors contribute to avian diversity; (2) Explore how land cover at three spatial scales (100 m, 500 m, and 1 km) affects avian diversity and abundance; (3) Compare native and nonnative avian abundance; and (4) Determine if there are specific variables that impact Neotropical migrant diversity along the Bronx River.

I predicted that avian diversity would be higher at sites with more natural green space surrounding the Bronx River than at sites with more developed land surrounding the Bronx River because greenspaces are sources of nesting and food resources (Pennington et al. 2008; Ikin et al. 2014). In support of this prediction, many studies that investigated predictors of avian diversity along urbanized riparian gradients found that diversity was higher in more natural areas (Rottenborn 1999; Miller et al. 2003; Smith and Wachob 2006; Pennington et al. 2008; Mao et al. 2019). In addition, I predicted that avian diversity would be higher at sites with more artificial green space surrounding the Bronx River than at sites with more developed land because intermediate levels of development tend to promote bird diversity (Blair 1996; Marzluff 2017; Batáry et al. 2018). I expected that non-native birds would be more abundant at sites that have a higher percent developed land cover because they can exploit the resources of developed habitats (Blair 1996; Marzluff 2001; McKinney 2002). In support of this prediction, many studies report higher abundance of non-native species in more urbanized locations (Rottenborn 1999; Miller et al. 2003; Smith and Wachob 2006; Pennington et al. 2008; Mao et al. 2019). Furthermore, I predicted that Neotropical migrants should have higher diversity at sites in Bronx Park compared to other locations because this location is an important Neotropical migrant stopover site (Seewagen et al. 2013; Seewagen et al. 2011; Bricklin et al. 2016). I also predicted that sites closer to the Bronx River Parkway and the Metro-North Railroad would have lower avian diversity because increased density of roads (Hennings and Edge 2003; Kociolek et al. 2011; Trammell and Bassett 2012) and proximity to railroads (Dorsey et al. 2015; Malo et al. 2017) tend to reduce bird diversity. Finally, I predicted that avian abundance would be higher where the Bronx River is wider and deeper because there might be more food sources in larger rivers (Ivicheva et al. 2019). Understanding which variables influence variation in bird diversity along an urbanized riparian gradient is becoming increasingly necessary as more people move to cities and development increases. My goal is that the results of this study will help to inform the organizations that manage green spaces within the New York metropolitan area how to improve greenspace habitat for avian diversity.

## *Methods*

### *Study site*

The Bronx River is the only freshwater river in New York City (de Kadt 2011; Russ et al. 2015). The river flows for 37 kilometers from its source at the Kensico Dam in Westchester County, south through the heart of the Bronx, to its mouth between Clason Point Park and Hunts Point on the East River (Rachlin et al. 2007; Center for Watershed Protection 2010; A.J. Smith et al. 2015). The freshwater portion of the river extends 33.3 kilometers while the tidally influenced estuary portion flows for approximately the last 4 km until reaching the mouth of the river (Center for Watershed Protection 2010). For its initial 22.3 kilometers, the river passes through the suburban and lightly urbanized landscape of Westchester County. For the latter part of the river, it begins its passage through the heavily urbanized landscape of Bronx County, featuring increased developed land. The Bronx River passes through a variety of land cover types including public parks, residences ranging from single-family home units to large apartment buildings, and industrial and commercial land uses. In Westchester County, the land is dominated by single-family homes, small businesses, country clubs, and small parks, and as the river nears the county boundary, development increases. In addition, the area directly surrounding the river in Westchester is designated as the Bronx River Parkway Reservation, with a greenway that is almost completed. For the portion of the Bronx River in Bronx County, the landscape is dominated by medium to high levels of development, including apartment complexes and industrial/commercial businesses, with pockets of green spaces in the form of several large New York City parks including Bronx Park, home of the New York Botanical Garden and the Bronx Zoo. Along most of the river, the Bronx

River Parkway and the Metro-North train line borders and crisscrosses its banks. There are seven dams along the Bronx river: in Westchester, there is the Kensico Dam at the source of the river, the Hartsdale Dam, the Scarsdale Dam, and the Tuckahoe Dam; and in the Bronx, there is the Snuff Mill Dam, the Twin Dam Complex, and the 182nd Street Dam. In addition, there are five combined sewage overflows on the river in Bronx County.

*Survey methods*

**Site selection**

To determine which sites to sample, I divided the Bronx River into three equal reaches: upper, middle, and lower. The upper and middle reaches are part of Westchester County, while the lower reach is the section of the river in Bronx County. Each reach was further divided into 11 possible sampling locations, stationed 1 kilometer apart from each other, with there being 33 total potential sites along the Bronx River. I used a random number generator to pick a site number for each reach and conducted avian surveys at that location in addition to the two sites downstream of it. I selected sites in groups of three because it was essential that there was minimal time between surveys at each site due to time-of-day bias (Bibby et al. 1992; Hennings and Edge 2003). I generated these numbers twice, resulting in 18 survey sites (six in the upper reach, six in the middle reach, and six in the lower reach). I selected sites in this way to minimize survey effort while ensuring that the selected sites were random. The 18 survey locations along the Bronx River include 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 for each site).

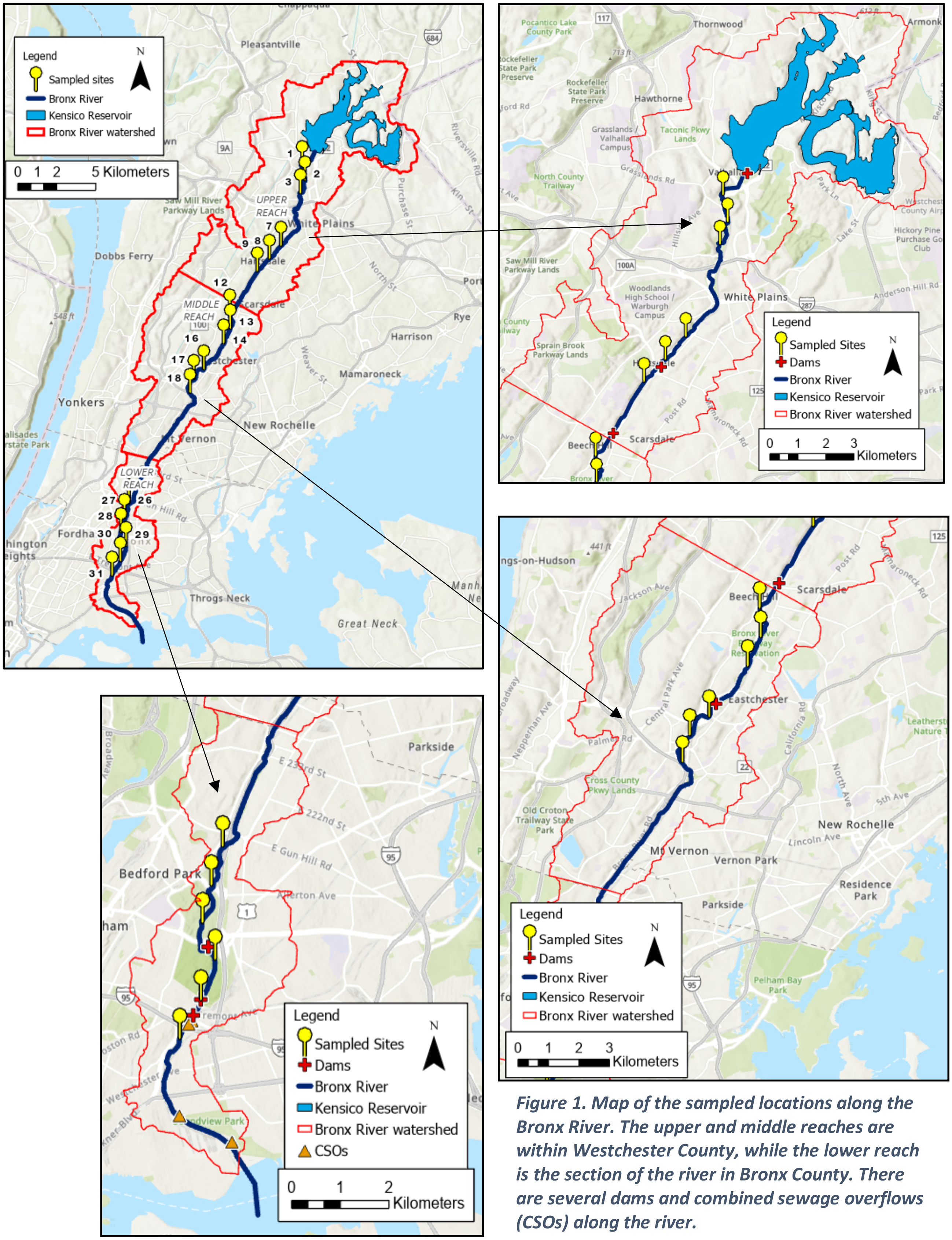


*Figure 1. Map of the sampled locations along the Bronx River. The upper and middle reaches are within Westchester County, while the lower reach is the section of the river in Bronx County. There are several dams and combined sewage overflows (CSOs) along the river.*

| Site | Site location | Reach | Coordinates | Site description and features |
|---|---|---|---|---|
| **1** | Valhalla | Upper | (41.0662462, -73.773939) | Located behind a baseball field and parking lot, with overgrown rose bushes, next to an emergent wetland. |
| **2** | N. White Plains I | Upper | (41.0576192, -73.772465) | Along a greenway next to a Metro-North hub. |
| **3** | N. White Plains II | Upper | (41.0504071, -73.774942) | In a forest behind single-family houses, right off the Bronx River Parkway. |
| **7** | Hartsdale | Upper | (41.020832, -73.785904) | Along a greenway in a small stretch of green space between the parkway and the train. |
| **8** | Scarsdale I | Upper | (41.0134625, -73.792457) | Along a greenway in a small stretch of green space between the parkway and the train. |
| **9** | Scarsdale II | Upper | (41.0063952, -73.799277) | In a small stretch of green space between the parkway and the train; currently, a greenway is being built, however when avian surveys were occurring there was no construction occurring. |
| **12** | Beech Hill | Middle | (40.9825942, -73.814828) | In a small park sandwiched between the parkway and the train. |
| **13** | Eastchester I | Middle | (40.9742089, -73.814543) | In a small park sandwiched between the parkway and the train; there is a lot of foot and bicycle traffic at this site. |
| **14** | Eastchester II | Middle | (40.9657551, -73.818318) | In a small park sandwiched between the parkway and the train. |
| **16** | Tuckahoe | Middle | (40.9511473, -73.829524) | Located in a very small area of green space surrounded by small local businesses and streets. |
| **17** | Yonkers | Middle | (40.9457037, -73.83514) | In a park, where the river opens up briefly and becomes Bronxville Lake. |
| **18** | Bronxville | Middle | (40.9379084, -73.837252) | By a small open green space right off the Bronx River Parkway. |
| **26** | Bronx Park I | Lower | (40.8755822, -73.871796) | In Bronx Park; in the Bronx River Forest section. |
| **27** | Bronx Park II | Lower | (40.8673237, -73.874325) | In Bronx Park; in the Bronx River Forest section. |
| **28** | New York Botanical Garden | Lower | (40.8593842, -73.876259) | In the New York Botanical Garden; behind the Goldman Stone Mill. The river is quite deep and wide here. |
| **29** | Bronx Zoo | Lower | (40.8516295, -73.873465) | Along the Bronx Zoo Riverwalk, between two dams. The river is quite deep and wide here. |
| **30** | River Park | Lower | (40.8430418, -73.876625) | In the small River Park, which features a playground, barbecues that are extensively used in the warmer months, and a large dam with a fish passage. |
| **31** | Starlight Park | Lower | (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 $20^{th}$ century. |

***Table 1. Location, coordinates, and description of the bird survey locations along the Bronx River.***

**Bird surveys**

I surveyed 18 sites along the Bronx River during the 2019 spring migration season from May 10th to June 29th. I counted birds at each site three times, once at dawn, a second time one hour after dawn, and a third time two hours after dawn, alternating the order of sites sampled daily to limit time-of-day bias (Bibby et al. 1992; Hennings and Edge 2003). To sample avian diversity and abundance, I conducted line transect sampling, which is appropriate for sampling along the river because rivers are somewhat linear (Hennings and Edge 2003) and because this method has been shown to be more useful in detecting more species and individuals in structurally complex forests similar to those found on the banks of the Bronx River (Wilson et al. 2000). I included birds that I identified by sound (Hennings and Edge 2003; Pennington et al. 2008; Yang et al. 2020); prior to the fieldwork season, I practiced gauging bird distances with a graduate student playing birdsong recordings at varying distances in different levels of vegetation cover and density. I recorded all individuals seen or heard within 50 meters of the Bronx River while walking parallel to one side of the river for ten minutes, and I immediately crossed the river and completed the line transect survey while walking parallel to the other side of the river for ten minutes, for a total survey time of twenty minutes per study site (see Fig. 2 for survey and environmental variable collection methods). For sampling locations where access to the river was limited to one side due to dense vegetation, I walked on that side of

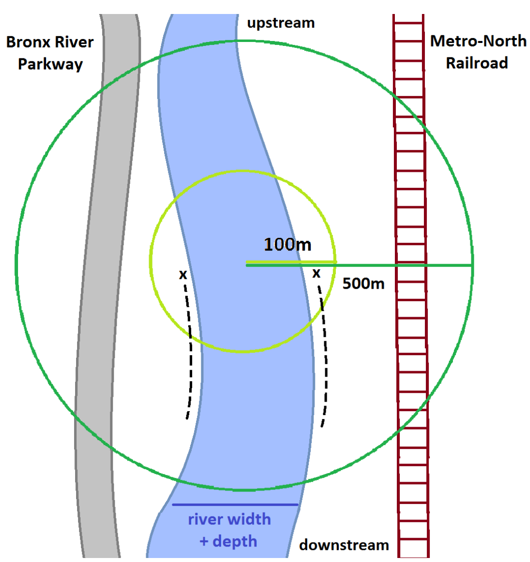


*Figure 2. Diagram showing line transect counts and the methods of collecting predictor variables.*

the river twice, focusing on the side I was walking on first, and focusing on the opposite side second, recording all individuals seen or heard within 50 meters of both sides for ten minutes each. For sampling locations where walking alongside the river was impossible, I waded in the river and recorded all bird species seen or heard within 50 meters while looking at one side for ten minutes, and then I returned to the starting location in the river and recorded birds seen or heard within 50 meters of the other side for ten minutes. I included flyover birds and waterfowl in my data, despite many papers excluding these groups of birds (Hennings & Edge 2003; Trammell & Bassett 2012; McClure et al. 2015), because certain species including chimney swifts or swallows glean insects off the surface of the river while flying, and therefore had a clear relationship with the river (Billerman et al. 2020).

*Measuring land use factors*

**Percent land cover**

I used ArcGIS Pro 2.6 (Esri Inc. 2020) and the National Land Cover Database 2016 (NLCD) to calculate the percent land cover surrounding each of the 18 sites. The NLCD provides national data on land cover at a 30-meter resolution, classifying each 30-m square into sixteen different categories, of which fourteen were found in my study area; see Supplementary Table 1 for these categories and their descriptions (Yang et al. 2018).

I inputted the sampling location coordinates into ArcGIS Pro 2.6 (Esri Inc. 2020) and used the Buffer tool to create circular buffers around each site with 100 m and 500 m radii. An issue arose where the 500 m buffers overlapped in some places due to the curvature of the river, and to remedy this, I created separate shapefiles that included every other sampling site and created the 500 m buffer layer for the separate shapefiles. The

| NLCD Land Cover Classification | | Land Cover Classification Simplification |
|---|---|---|
| Developed – open space | ⟶ | Artificial green space |
| Developed – low intensity | ⟶ | Developed |
| Developed – medium intensity | | |
| Developed – high intensity | | |
| Deciduous forest | ⟶ | Natural green space |
| Evergreen forest | | |
| Mixed forest | | |
| Shrub/scrub | | |
| Grassland/herbaceous | | |
| Woody wetlands | | |
| Emergent herbaceous wetlands | | |
| Open water | ⟶ | Other |
| Barren land | | |
| Pasture/hay | | |

*Table 3. Simplification of NLCD land cover classes.*

buffers were converted to raster layers using the Polygon to Raster tool (ensuring that each layer maintained the same grid size as the NLCD layer), and then I used the Zonal Histogram tool, which created a table that shows the frequency distribution of values in each buffer layer within the NLCD land cover classes. I calculated the percent land cover for each class by dividing the number of cells per land cover class by the total number of cells within the raster. Because sites were only 1 km apart, to calculate percent land cover within 1 kilometer of each site, I combined each group of 3 sites that I surveyed on the same days into one large site. I then created a 1 km-radius buffer surrounding the center point of the large site using the Buffer tool and followed the same methods to calculate percent land cover. Finally, I simplified the land cover classes by combining the percent land cover of similar groups into four categories: "artificial green space," "developed," "natural green space," and "other" (e.g., Callaghan et al. 2019; Stark et al. 2020) (Table 2).

### Distance to the Bronx River Parkway and Metro-North train lines

To calculate the distance of each of the 18 sites to the Bronx River Parkway and the Metro-North train lines, I used the Generate Near Table tool in ArcGIS Pro 2.6 (Esri Inc. 2020), with the input feature a shapefile containing the point locations for the sites and the near feature being a shapefile containing the line features of either the Bronx River Parkway or the Metro-North train lines. This tool generated a table containing the distance in meters from the starting point of each survey location to the nearest point on the parkway or the railroad line.

*Measuring river morphology and weather patterns*

**River width and depth**

A graduate student collaborator measured river width in centimeters by extending a closed reel tape measure from one side of the riverbank directly across to the other side. The graduate student collaborator also measured river depth by placing a Secchi disk in the middle of the river and lowering it until it touched the riverbed. The student placed a finger on the point of the cord where it stopped lowering down into the river and then pulled the disk up and measured the length of the cord from where the finger was placed to the disk at the bottom with a tape measure. I converted both river width and depth to meters.

**Temperature and wind speed**

A graduate student collaborator measured and recorded temperature at each site using a handheld digital thermometer and a field notebook. I determined wind speed (in KPH) at each site by inputting the GPS coordinates into Weather Underground (www.wunderground.com), which keeps a log of past weather patterns for local weather stations. I averaged the temperature and wind speed over the three days spent at each study site.

*Statistical analyses*

**Measuring avian diversity**

The aim of this research was to determine predictors of avian diversity and abundance at multiple locations along the Bronx River. To accomplish this aim, I included four response variables in my models: (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); (3) Shannon-Wiener diversity (hereafter Shannon diversity), the proportional abundance of species within a community (Magurran 1988); and (4) species evenness, the relative abundance of species within a community (Magurran 1988). I also modelled 13 predictor variables: (1) percent artificial green space within 100 meters, (2) 500 meters, and (3) 1 kilometer of the Bronx River; (4) percent developed land within 100 meters, (5) 500 meters, and (6) 1 kilometer of the Bronx River; (7) percent natural green space within 100 meters, (8) 500 meters, and (9) 1 kilometer of the Bronx River; (10) distance to the Bronx River Parkway; (11) distance to the nearest Metro-North train tracks; (12) river width; and (13) river depth. Finally, temperature and wind speed were included in the model to control for temporal variations in weather patterns.

I performed all statistical analyses using RStudio version 1.3 (RStudio Team 2020). To calculate abundance, I totaled the maximum number of individuals per species at each site. To calculate species richness, Shannon diversity, and species evenness, I used the diversity and specnumber functions within the *vegan* package (Oksanen et al. 2019). I calculated diversity indices separately for native species, non-native species, Neotropical migrant species, and year-round resident species, because each of 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). Year-round residents were defined as birds that remain in the study area throughout the year (Pennington et al. 2008). I classified species into guilds based on data from the Handbook of the Birds of the World (Billerman et al. 2020).

**Modeling predictor and response variables**

Using the package *car* (Fox and Weisberg 2019), I tested all predictor variables for multicollinearity; percent developed land and percent artificial green space were highly correlated (correlation coefficient = -0.61), therefore these variables were excluded from the same models using the subset function. All other variables were not significantly correlated, and therefore they were included in the same models. I modeled Shannon diversity and species evenness using the lm function in the *stats* package (R Core Team 2020); I tested these models with the package *gvlma* to ensure that they did not violate the assumptions of linear models: linearity, homoscedasticity, normality, and independence of observations (Pena and Slate 2019). Because abundance and species richness incorporated count data, I modeled these variables using the glm function using a Poisson error distribution with a log link function in the *stats* package (R Core Team 2020). I modeled all anthropogenic and abiotic variables against abundance, species richness, Shannon diversity, and species evenness for the overall dataset three times, once considering land cover within a 100 m radius, then considering land cover within a 500 m radius, and finally considering land cover within a 1 km radius. I conducted similar models for the Neotropical migrant, year-round resident, native, and non-native datasets, although for native and non-native species I only modeled abundance, because many studies report that non-native species abundance is higher in more urbanized locations (Rottenborn 1999; Miller et al.

2003; Smith and Wachob 2006; Pennington et al. 2008; Mao et al. 2019). I performed comparison tests of all possible parameter combinations with the *MuMIn* package (Bartoń 2020). I used Akaike's information criterion (AICc) to select the best model ($\Delta$AICc = 0) and reported all models with $\Delta$AICc of less than 2 because these are considered equally parsimonious (Burnham and Anderson 2002; see Table 3 for the overall model selection table and Tables S2A-D for the Neotropical migrant, year-round resident, native, and non-native species model selection tables). I considered model results significant for variables where $P < 0.05$.

**Avian community similarities**

Finally, to test if avian communities were similar based on their location along the river, I used the metaMDS and adonis functions in the vegan package to conduct a nonmetric multidimensional scaling (NMDS) ordination using the Bray-Curtis index and to test if the associations between the reaches and the dissimilarity of sites were significant.

| Model Parameters | ΔAICc | Weight | Log likelihood | Adjusted $R^2$ * |
|---|---|---|---|---|
| **Species richness (100 m)** | | | | |
| wind speed | 0 | 0.166 | -48.997 | — |
| river width | 0.27 | 0.145 | -49.133 | — |
| river width + temperature | 0.98 | 0.101 | -48.03 | — |
| distance to parkway + wind speed | 1.18 | 0.092 | -48.129 | — |
| river depth + river width | 1.72 | 0.07 | -48.4 | — |
| river depth | 1.74 | 0.07 | -49.866 | — |
| wind speed + river width | 1.75 | 0.069 | -48.412 | — |
| distance to parkway + river width | 1.75 | 0.069 | -48.415 | — |
| distance to parkway + % artificial green space + river depth | 1.91 | 0.064 | -46.812 | — |
| temperature | 1.93 | 0.063 | -49.961 | — |
| **Species richness (500 m)** | | | | |
| distance to parkway + % artificial green space | 0 | 0.43 | -46.31 | — |
| distance to parkway + wind speed + % artificial green space | 1.26 | 0.23 | -45.26 | — |
| distance to parkway + % artificial green space + river depth | 1.66 | 0.19 | -45.46 | — |
| distance to parkway + % artificial green space + temp | 1.96 | 0.16 | -45.61 | — |
| **Shannon diversity (100 m)** | | | | |
| distance to parkway + distance to train + % developed | 0 | 0.661 | 3.076 | 0.49 |
| distance to parkway + distance to train + % developed + river depth | 1.34 | 0.339 | 4.725 | 0.55 |
| **Shannon diversity (500 m)** | | | | |
| distance to parkway + % artificial green space | 0 | 0.411 | 1.102 | 0.41 |
| distance to parkway + % artificial green space + temp | 0.06 | 0.398 | 3.031 | 0.49 |
| distance to parkway + % artificial green space + wind speed | 1.54 | 0.191 | 2.295 | 0.45 |
| **Species evenness (100 m)** | | | | |
| distance to parkway + distance to train + % developed + river width | 0 | 1 | 35.625 | 0.63 |
| **Species evenness (500 m)** | | | | |
| distance to parkway | 0 | 0.281 | 26.837 | 0.20 |
| distance to parkway + % artificial green space + river width | 0.9 | 0.18 | 30.032 | 0.37 |
| temperature | 1.13 | 0.16 | 26.272 | 0.14 |
| distance to parkway + river width | 1.44 | 0.137 | 27.801 | 0.23 |
| % natural green space + river width + temperature | 1.48 | 0.134 | 29.74 | 0.33 |
| distance to parkway + % artificial green space | 1.90 | 0.109 | 27.569 | 0.21 |
| **Abundance (100 m)** | | | | — |
| % developed + river depth + river width + temperature | 0 | 1 | -87.943 | — |
| **Abundance (500 m)** | | | | |
| % developed + river depth + river width + temperature | 0.00 | 0.50 | -87.57 | — |
| % artificial green space + river depth + river width + temperature | 1.26 | 0.27 | -88.20 | — |
| distance to train + % artificial green space + river depth + river + width + temperature | 1.57 | 0.23 | -86.04 | — |

***Table 3. Best supported models (AICc < 2) for the overall dataset of bird diversity along the Bronx River. * Adjusted $R^2$ values not applicable for species richness and abundance due to the nature of generalized linear models.***

## *Results*

### *Bird community composition*

I recorded 1613 detections of 57 species at the 18 sites along the Bronx River (Fig. 3). Of these species, 95% were native, and 47% were Neotropical migrants. Five species accounted for 49.5% of all detections; in descending order, these include the American robin (*Turdus migratorius*), Canada goose (*Branta canadensis*), common grackle (*Quiscalus quiscula*), red-winged blackbird (*Agelaius phoeniceus*), and house sparrow (*Passer domesticus*). The most abundant species, the American robin, was found at every site except for the first two (88% of sites; see Fig. 1 and Table 1), while the second most abundant species, the Canada goose, was only found at 8 of the sites (44%; see Fig. 1 and Table 1). Of the five most abundant species, only the house sparrow was non-native, and it only occurred downstream of site 16 (44% of sites; see Fig. 1 and Table 1). Abiotic and anthropogenic variables including percent land cover, distance to the Bronx River Parkway, distance to the Metro-North Railroad, temperature, wind speed, river depth, and river width were different between sites and did not appear to vary on a suburban-urban gradient (Table 4). Abundance, richness, Shannon diversity, and evenness varied across sites (Table 5). The NMDS analysis indicated that sites were significantly different depending on which reach they were located within (Stress=0.2, $P < 0.05$).

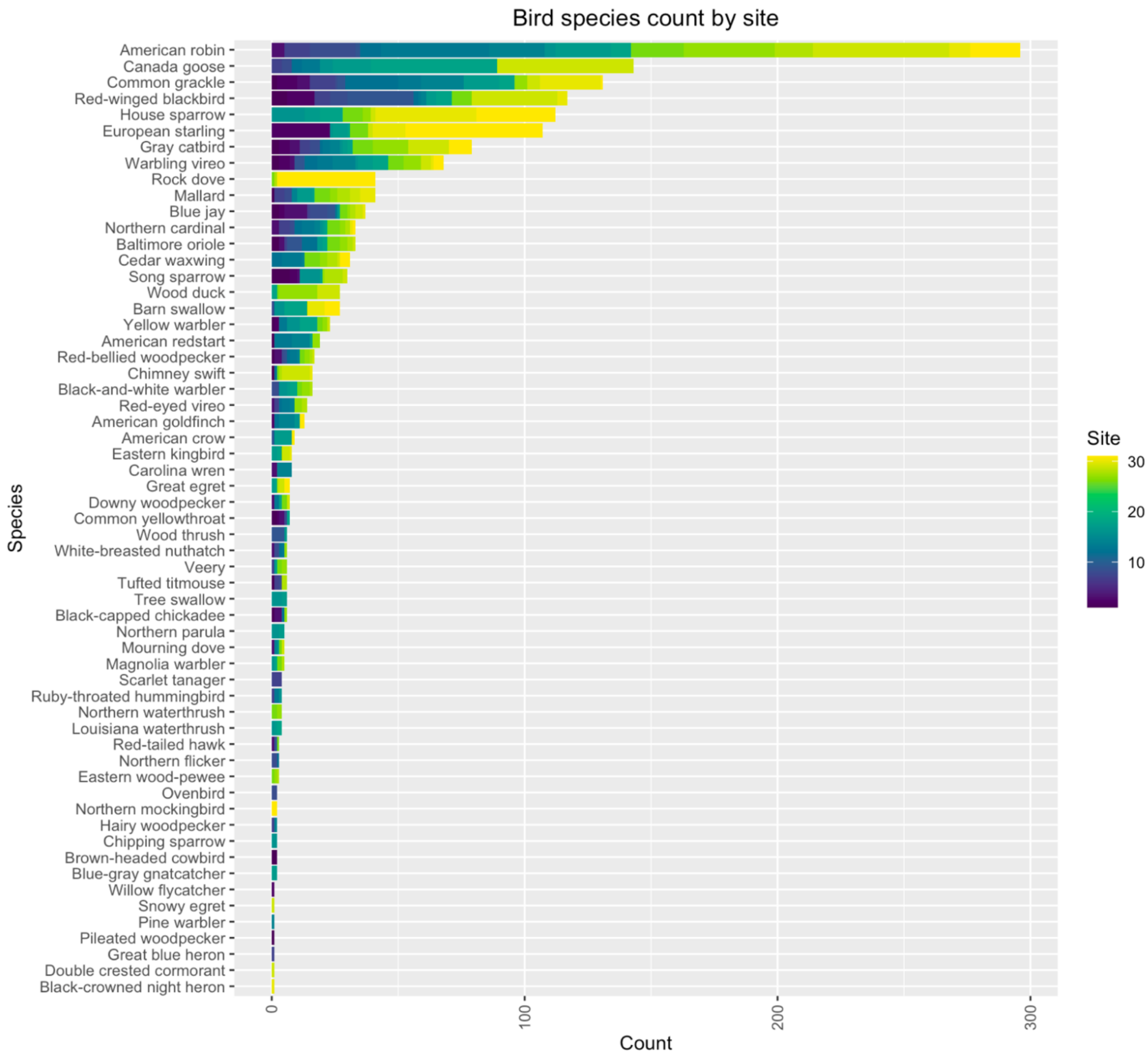


***Figure 3. Species count by site. 57 species were observed along the Bronx River at varying abundances per site.***

| Predictor variable | Mean | Min | Max | SE |
|---|---|---|---|---|
| Temperature (°C) | 18 | 13 | 23 | 0.73 |
| Wind speed (KPH) | 18 | 12 | 26 | 0.96 |
| Distance to parkway (m) | 138 | 8 | 610 | 38 |
| Distance to train (m) | 257 | 17 | 1311 | 85 |
| River width (m) | 13 | 3.7 | 30 | 1.9 |
| River depth (m) | 0.72 | 0.35 | 1.2 | 0.084 |
| % Artificial green space within 100 m | 43% | 0% | 100% | 6.2% |
| % Developed within 100 m | 34% | 0% | 96% | 6.6% |
| % Natural green space within 100 m | 22% | 0% | 79% | 5.7% |
| % Artificial green space within 500 m | 37% | 4.1% | 69% | 4.6% |
| % Developed within 500 m | 51% | 23% | 95% | 4.5% |
| % Natural green space within 500 m | 12% | 0% | 38% | 3.2% |

*Table 4. Mean, minimum, maximum, and standard error (SE) of predictor variables.*

| Response variable | Mean | Min | Max | SE |
|---|---|---|---|---|
| Abundance | 70 | 24 | 147 | 8.1 |
| Richness | 17 | 10 | 25 | 1.0 |
| Shannon diversity | 2.4 | 1.8 | 3.0 | 0.077 |
| Evenness | 0.86 | 0.72 | 0.96 | 0.015 |

*Table 5. Mean, minimum, maximum, and standard error (SE) of response variables.*

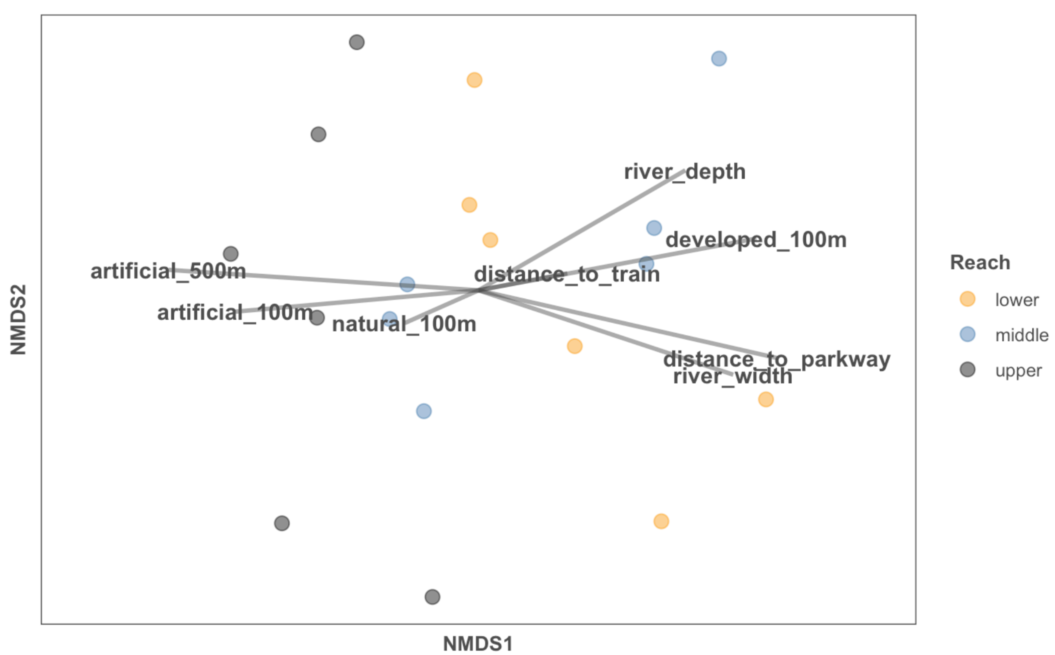


*Figure 4. NMDS plot of similarities between sites. Closer points indicate more similar communities. Color-coding is based on location along the Bronx River: upper, middle, or lower reach. Labels indicate environmental variables, and line length is proportional to the degree of correlation between the environmental variable and the ordination. River depth, river width, percent developed within 100 m, and distance to parkway align predominantly with the second dimension (NMDS2); distance to train, artificial green space within 100 m and 500 m, and natural green space within 100 m align with the first dimension (NMDS1).*

*Predictors of overall abundance*

Avian abundance along the Bronx River was best predicted by five variables: (1) percent developed land within 100 m, (2) percent developed land within 500 m, (3) river depth, and (4) river width (Tables 6A-B). Abundance was higher at sites that had a higher percent cover of developed land within 100 meters (estimate: 3.2 E-03, *P*=3.6 E-04; Fig. 5A) and within 500 meters (estimate: 5.2 E-03, *P*=2.6 E-03; Fig. 5B); for every 1% increase in developed land within 100 m, abundance increased by 0.0032 individuals, and for every 1% increase in developed land within 500 meters, abundance increased by 0.0052. Additionally, sites where the Bronx River was deeper (estimate: 5.6 E-03; *P*= 2.0 E-11; Fig. 5C) and wider (estimate: 3.5 E-04; *P* < 2 E-16; Fig. 5D) had higher avian abundance.

| Predictor | Estimate | SE | z value | *P* | Interpretation |
|---|---|---|---|---|---|
| % Developed land within 100 m | 3.2 E-03 | 1.1 E-03 | 2.9 | 3.6 E-03 | % Developed land within 100 m ↑ Abundance ↑ |
| River depth (m) | 5.6 E-03 | 8.3 E-04 | 6.7 | 2.0 E-11 | River depth ↑ Abundance ↑ |
| River width (m) | 3.6 E-04 | 3.6 E-05 | 9.9 | < 2E-16 | River width ↑ Abundance ↑ |
| Temperature ($^{\circ}$C) | 4.5 E-02 | 8.3 E-03 | 5.4 | 5.9 E-08 | Temperature included in model as control |

***Table 6A. Best supported model for avian abundance considering land cover within a 100 m radius. Percent developed land within 100 m, river depth, and river width are positively associated with avian abundance.***

| Predictor | Estimate | SE | z value | *P* | Interpretation |
|---|---|---|---|---|---|
| % Developed land within 500 m | 5.2 E-03 | 9.1 E-04 | 5.7 | 1.5 E-08 | % Developed land within 500 m ↑ Abundance ↑ |
| River depth (m) | 3.3 E-04 | 3.5 E-05 | 9.3 | < 2e-16 | River depth ↑ Abundance ↑ |
| River width (m) | 4.2 E-02 | 8.5 E-03 | 5.0 | 6.8 E-07 | River width ↑ Abundance ↑ |
| Temperature ($^{\circ}$C) | 5.2 E-03 | 1.7 E-03 | 3.0 | 2.6 E-03 | Temperature included in model as control |

***Table 6B. Best supported model for avian abundance considering land cover within a 500 m radius. Percent developed land within 500 m, river depth, and river width are positively associated with avian abundance.***

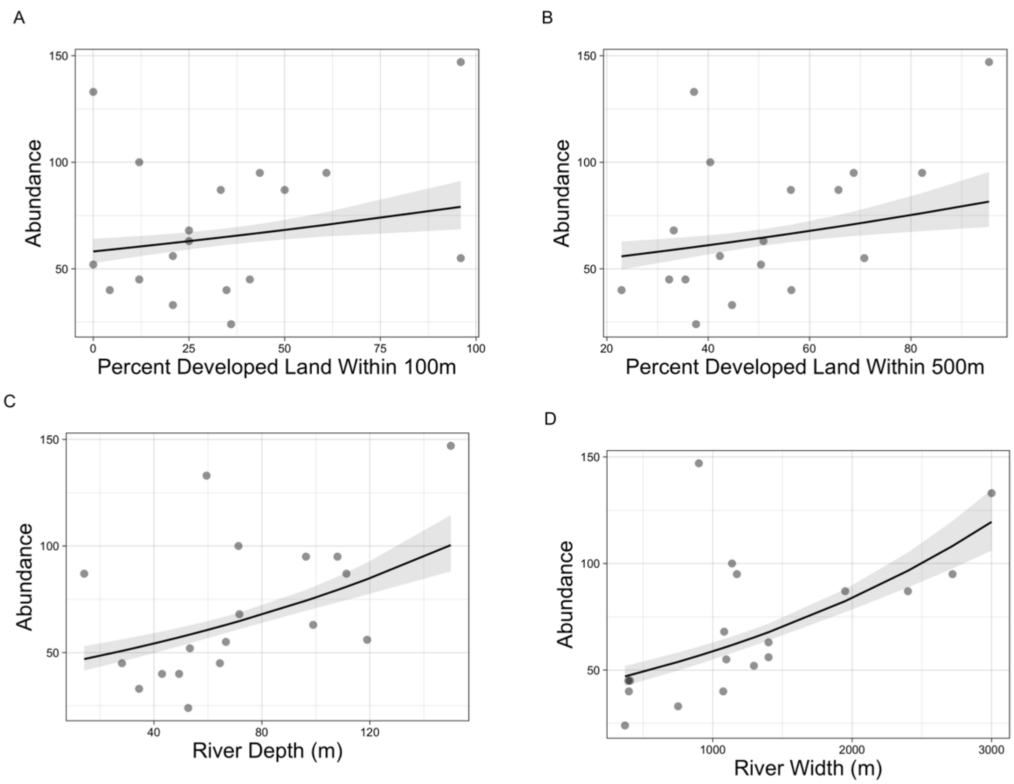


***Figure 5. Association between avian abundance and (a) percent developed land within 100 m (P < 0.05); (b) percent developed land within 500 m (P < 0.001); (c) river depth (P < 0.001); (d) river width (P < 0.001). Black line indicates model regression line; shaded gray area is the 95% confidence interval.***

*Predictors of overall species richness*

Species richness was best predicted by distance to the Bronx River Parkway and percent artificial green space within a 500m buffer around the sample site (Table 7). Species richness was lower at sites that had a higher percent cover of artificial green space within 500 meters (estimate: -0.012, *P*=4.0 E-03; Fig. 6A); for every 1% increase in artificial green space within 500 meters, the number of species at a site decreases by 0.012. Species richness was higher at sites that were closer to the parkway than sites that were further from the parkway (estimate: 1.4 E-03, *P*=8.7 E-03; Fig. 6B); as the distance to the Bronx River Parkway increases by 100 meters, species richness at a site decreases by 0.014. At the 100 m scale, none of the land cover classes were significant predictors of richness.

| Predictor | Estimate | SE | z value | *P* | Interpretation |
|---|---|---|---|---|---|
| % Artificial green space within 500 m | -0.012 | 4.2 E-03 | -2.9 | 4.0 E-03 | % Artificial green space within 500 m ↑ Species richness ↓ |
| Distance to parkway | -1.4 E-03 | 5.2 E-04 | -2.6 | 8.7 E-03 | Distance to parkway ↑ Species richness ↓ |

***Table 7. Best supported model for species richness considering land cover within a 500 m radius. Distance to the Bronx River Parkway and percent artificial green space within 500 m are negatively associated with species richness.***

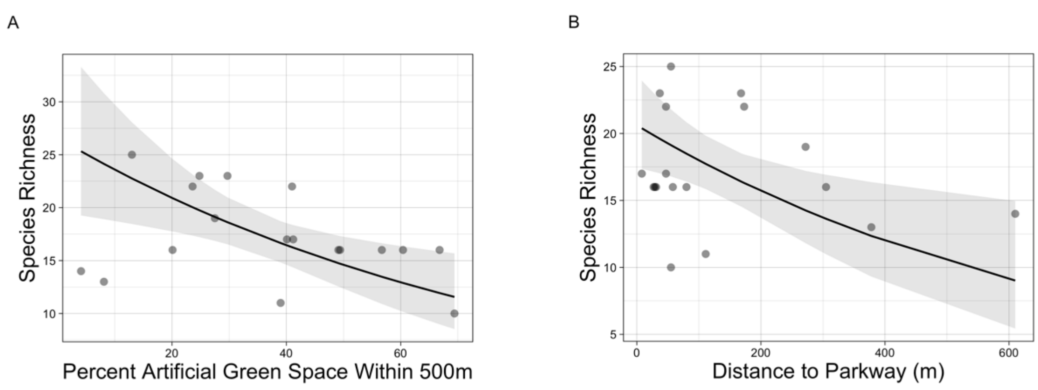


***Figure 6. Association between avian species richness and (a) percent artificial green space within 500 m (P < 0.05); (b) distance to the Bronx River Parkway (P < 0.05). Black line indicates model regression line; shaded gray area is the 95% confidence interval.***

*Predictors of overall Shannon-Wiener diversity*

Four variables significantly predicted Shannon diversity: (1) percent developed land within 100 m, (2) percent artificial green space within 500 m, (3) distance to the Bronx River Parkway, and (4) distance to the nearest train (Tables 8A-B). Shannon diversity was higher at sites that had a greater percent cover of developed land within 100 meters (estimate: 0.012, *P*=2.8 E-03; Fig. 7A); for every 1% increase in developed land within 100 m, Shannon diversity increased by 0.012. Conversely, Shannon diversity was lower at sites that had a higher percent cover of artificial green space within 500 meters (estimate: -0.013, *P*=8.1 E-03; Fig. 7B). I also found that Shannon diversity was significantly higher at sites along the Bronx River that were closer to the Bronx River Parkway (estimate: -2.5 E-03, *P*=6.2 E-03; Fig. 7C), and it was lower at sites that were closer to the nearest Metro-North train tracks (estimate: 6.9 E-04, *P*=6.7 E-03; Fig. 7D).

| Predictor | Estimate | SE | t value | *P* | Interpretation |
|---|---|---|---|---|---|
| % Developed land within 100 m | 0.019 | 3.3 E-03 | 3.6 | 2.8 E-03 | % Developed land within 100 m ↑<br>Shannon Diversity ↑ |
| Distance to parkway | -2.5 E-03 | 5.7 E-04 | -4.4 | 6.2 E-04 | Distance ↑<br>Shannon Diversity ↓ |
| Distance to train | 6.9 E-04 | 2.2 E-04 | 3.2 | 6.8 E-03 | Distance ↑<br>Shannon Diversity ↑ |

***Table 8A. Best supported model for Shannon diversity considering land cover within a 100 m radius. Distance to the Bronx River Parkway is negatively associated with Shannon diversity; distance to train and percent developed land within 100m are positively associated with Shannon diversity.***

| Predictor | Estimate | SE | t value | *P* | Interpretation |
|---|---|---|---|---|---|
| % Artificial green space within 500 m | -0.013 | 4.4 E-03 | -3.0 | 8.1 E-03 | % Artificial green space within 500 m ↑<br>Shannon Diversity ↓ |
| Distance to parkway | -2.0 E-03 | 5.4 E-04 | -3.7 | 2.3 E-03 | Distance ↑<br>Shannon Diversity ↓ |

***Table 8B. Best supported model for Shannon diversity considering land cover within a 500 m radius. Distance to the Bronx River Parkway and percent artificial green space within 500m are negatively associated with Shannon diversity.***

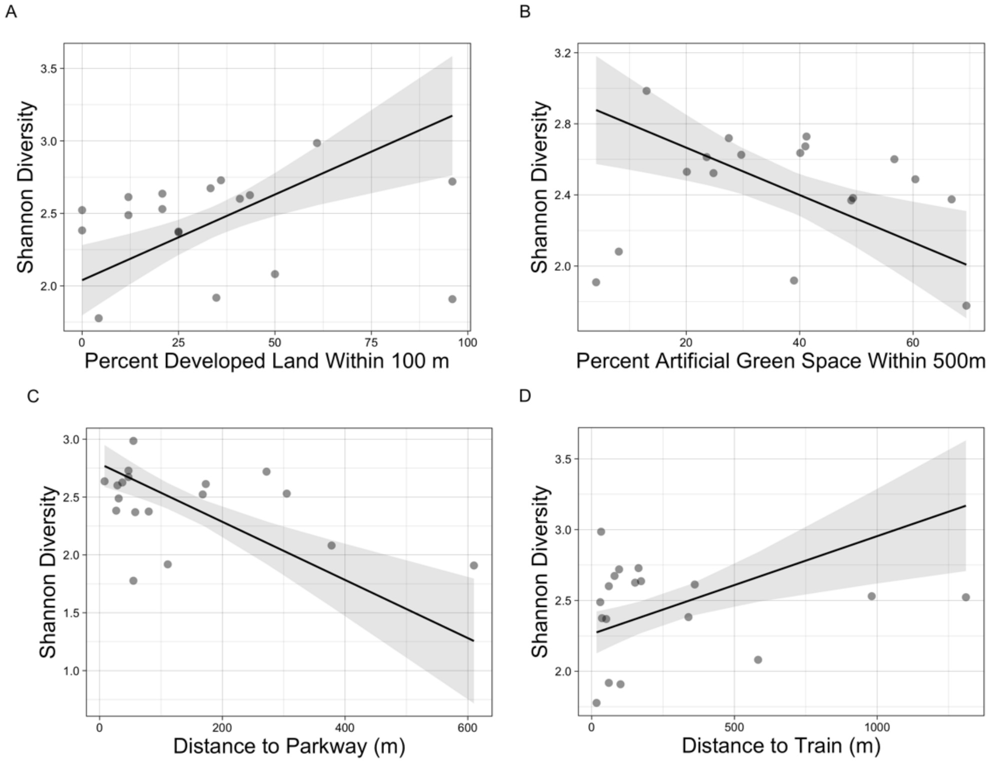


***Figure 7. Association between Shannon diversity and (a) percent developed land within 100 m (P < 0.05); (b) percent developed land within 500 m (P < 0.05); (c) distance to parkway (P < 0.05); (d) distance to train (P < 0.05). Black line indicates model regression line; shaded gray area is the 95% confidence interval.***

*Predictors of overall evenness*

Species evenness of birds along the Bronx River was best predicted by four variables: (1) percent developed land within 100m, (2) distance to the Bronx River Parkway, (3) distance to the nearest train, and (4) river width (Table 9). Evenness was higher at sites that had a higher percent cover of developed land within 100 meters (estimate: 2.2 E-03, *P*=1.8 E-03; Fig. 8A); for every 1% increase in developed land within 100 m, species evenness increased by 0.0022. Evenness was also higher at sites that were closer to the Bronx River Parkway (estimate: -5.1 E-04, *P*=1.9 E-04; Fig. 8B). However, sites that were closer to the nearest Metro-North train tracks had lower species evenness than sites that were further away from the train (estimate: 1.7 E-04, *P*=2.2 E-03; Fig. 8C).

In addition, species evenness was lower at sites where the Bronx River was wider (estimate: -5.1 E-05, *P*=5.7 E-03; Fig. 8D). At the 500 m scale, none of the land cover classes were significant predictors of evenness.

| Predictor | Estimate | SE | t value | *P* | Interpretation |
|---|---|---|---|---|---|
| % Developed within 100 m | 2.2 E-03 | 5.7 E-04 | 3.9 | 1.8 E-03 | % Developed within 100 m ↑ Evenness ↑ |
| Distance to parkway | -5.1 E-04 | 9.9 E-05 | -5.2 | 1.9 E-04 | Distance ↑ Evenness ↓ |
| Distance to train | 1.7 E-04 | 4.5 E-05 | 3.8 | 2.2 E-03 | Distance ↑ Evenness ↑ |
| River width (m) | -5.1 E-05 | 1.6 E-05 | -3.3 | 5.7 E-03 | River width ↑ Evenness ↓ |

***Table 9. Best supported model for species evenness considering land cover within a 100 m radius. Species evenness is higher at sites with more percent developed land within 100 m and at sites farther from the Metro-North train tracks. Species evenness is lower at sites farther from the Bronx***

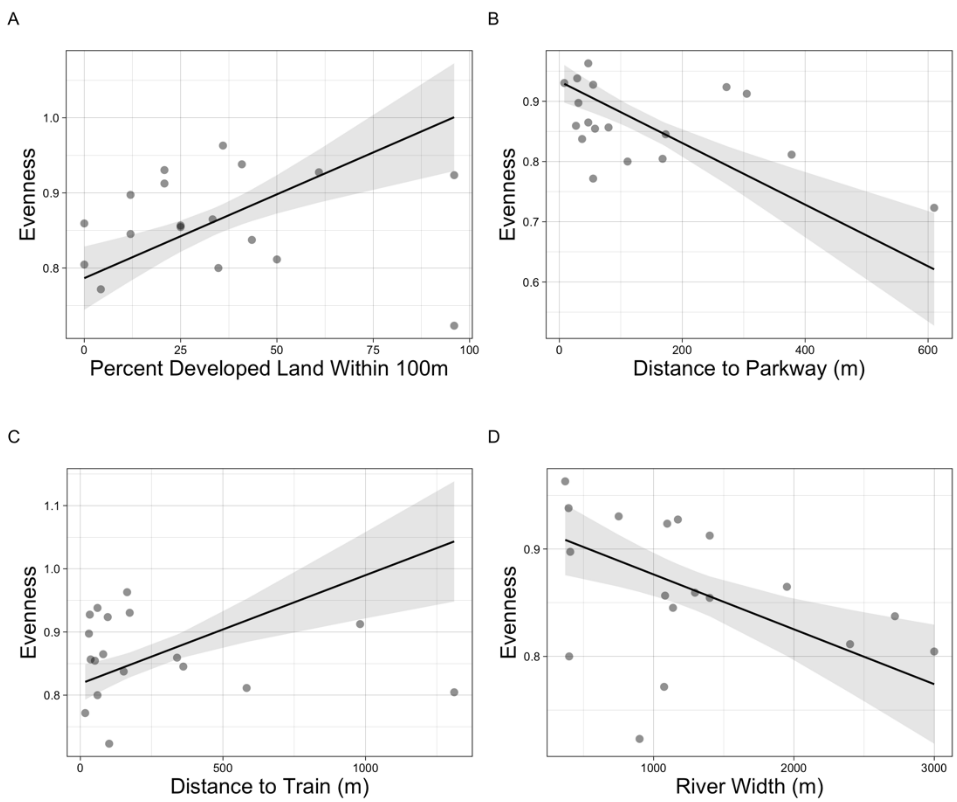


***Figure 8. Association between avian species evenness and (a) percent developed land within 100 m ($P < 0.05$); (b) distance to parkway ($P < 0.001$); (c) distance to train ($P < 0.05$); (d) river width (m) ($P < 0.05$). Black line indicates model regression line; shaded gray area is the 95% confidence interval.***

*Predictors of avian diversity within guilds*

**Neotropical migrants**

Avian diversity of Neotropical migrant, native, and non-native bird guilds differed in a few ways from the avian diversity of the overall dataset. Three variables best predicted Shannon diversity of Neotropical migrants: (1) artificial green space within 500 m and (2) natural green space within 500 m (Table 10). Similar to overall Shannon diversity, sites with more artificial green space within 500 m (estimate: -8.9 E-03, *P*=0.017) were associated with lower Shannon diversity of Neotropical migrants; as artificial green space increased by 1%, Neotropical Shannon diversity decreased by 0.0089. Shannon diversity of Neotropical migrants was higher at sites with higher percent natural green space within 500 m (estimate: 0.015, *P*=8.1 E-03). Furthermore, four variables best predicted Neotropical migrant species evenness: (1) natural green space within 500 m, (2) distance to the Bronx River Parkway, (3) distance to the Metro-North train, and (4) river width (Tables 11A-B). Migratory bird species evenness was also similar to the evenness of the overall dataset; evenness was higher at sites with higher percent natural green space at 500 m (estimate: 2.0 E-03, *P*=7.6 E-03) that were closer to the Bronx River Parkway (estimate: -2.7 E-04, *P*=2.5 E-04). Species evenness of migrants was lower at sites that were closer to the train (estimate: 8.7 E-05; *P*=0.011) and where the river was wider (estimate: -5.9 E-03, *P*=1.4 E-03).

| Predictor | Estimate | SE | t value | *P* | Interpretation |
|---|---|---|---|---|---|
| % Artificial green space within 500 m | -8.9E-03 | 3.3E-03 | -2.7 | 0.017 | % Artificial green space within 500 m ↑ Shannon Diversity ↓ |
| % Natural green space within 500 m | 0.015 | 4.8E-03 | 3.1 | 8.1E-03 | % Natural green space within 500 m ↑ Shannon Diversity ↑ |
| Temperature ($^{o}$C) | -0.13 | 0.021 | -6.2 | 2.5 E-05 | Temperature included in model as control |

***Table 10. Best supported model for Shannon diversity of Neotropical migrants. Percent artificial green space within 500 m is negatively associated with Shannon diversity. Percent natural green space within 500 m is positively associated with Shannon diversity.***

| Predictor | Estimate | SE | t value | *P* | Interpretation |
|---|---|---|---|---|---|
| Distance to the Bronx River Parkway | -2.7E-04 | 5.5E-05 | -5.0 | 2.5E-04 | Distance ↑ Evenness ↓ |
| Distance to train | 8.7E-05 | 3.0E-05 | 2.9 | 1.1E-02 | Distance ↑ Evenness ↑ |
| River width (m) | -5.9E-03 | 1.5E-03 | -4.0E | 1.4E-03 | River width ↑ Evenness ↓ |
| Mean wind speed | 7.6E-03 | 3.8E-03 | 2.0 | 6.4E-02 | Wind speed included in model as control |

***Table 11A. Best supported model for the species evenness of Neotropical migrants considering land cover within a 100 m radius. Distance to the Bronx River Parkway and river width are negatively correlated with evenness. Distance to train is positively correlated with species evenness.***

| Predictor | Estimate | SE | t value | *P* | Interpretation |
|---|---|---|---|---|---|
| % Natural green space within 500 m | 2.0 E-03 | 6.4 E-04 | 3.1 | 7.6E-03 | % Natural green space within 500 m ↑ Evenness ↑ |
| Distance to the Bronx River Parkway | -2.4 E-04 | 5.3 E-05 | -4.6 | 3.9E-04 | Distance ↑ Evenness ↓ |
| River width (m) | -3.4 E-03 | 1.1 E-03 | -3.1 | 7.6E-03 | River width ↑ Evenness ↓ |

***Table 11B. Best supported model for the species evenness of Neotropical migrants considering land cover within a 500 m radius. Percent natural green space within 500 m is positively correlated with species evenness. Distance to the Bronx River Parkway and river width are negatively correlated with evenness.***

### Year-round residents

Two variables predicted Shannon diversity of year-round residents: (1) distance to the Bronx River Parkway and (2) distance to the Metro-North train (Table 12). Shannon diversity of year-round residents was similar to the overall dataset, with sites closer to the Bronx River Parkway having higher diversity (estimate: -1.7 E-03, *P*=9.7 E-03), and sites closer to the nearest Metro-North train having lower diversity (estimate: 4.8 E-04, *P*=0.047). Five variables predicted species evenness of year-round residents: (1) percent developed land within 100 m, (2) artificial green space within 500 m, (3) distance to the Bronx River Parkway, (4) distance to the Metro-North train, and (5) river width (Tables 13A-B). Evenness of year-round residents was also similar to the overall dataset; it was higher at sites that had a higher percent cover of developed land within 100 meters (estimate: 3.0 E-04, *P*=1.3 E-03) and that were closer to the Bronx River Parkway (estimate: -6.1 E-04, *P*=4.5 E-04). I also found that evenness of year-round residents was lower at sites that had a higher percent cover of artificial green space within 500 meters (estimate: -0.030, *P*=0.033), that were closer to the nearest Metro-North train tracks (estimate: 2.3 E-04, *P*=1.7 E-03), and that were wider (estimate: -6.5 E-03, *P*=6.6 E-03).

| Predictor | Estimate | SE | t value | *P* | Interpretation |
|---|---|---|---|---|---|
| % Developed within 100 m | 7.1E-03 | 3.3E-03 | 2.1 | 0.051* | % Developed within 100 m is not a significant predictor of Shannon Diversity |
| Distance to the Bronx River Parkway | -1.7E-03 | 5.9E-04 | -3.0 | 9.7E-03 | Distance ↑ Shannon Diversity ↓ |
| Distance to the train | 4.8E-04 | 2.2E-04 | 2.2 | 0.047 | Distance ↑ Shannon Diversity ↑ |

*Table 12. Best supported model for Shannon diversity of year-round residents. Distance to the parkway is negatively correlated with year-round resident Shannon diversity, and distance to the train is positively correlated with year-round Shannon diversity. Percent developed land within 100 m is not a significant predictor of Shannon diversity of year-round residents.*

| Predictor | Estimate | SE | t value | *P* | Interpretation |
| --- | --- | --- | --- | --- | --- |
| Distance to the Bronx River Parkway | -6.1E-04 | 1.3E-04 | -4.7 | 4.5E-04 | Distance ↑<br>Evenness ↓ |
| Distance to the train | 2.3E-04 | 5.9E-05 | 3.9 | 1.7E-03 | Distance ↑<br>Evenness ↑ |
| % Developed within 100m | 3.0E-03 | 7.5E-04 | 4.1 | 1.3E-03 | % Developed within 100m ↑<br>Evenness ↑ |
| River width (m) | -6.5E-03 | 2.0E-03 | -3.2 | 6.6E-03 | River width ↑<br>Evenness ↓ |

***Table 13A. Best supported model for species evenness of year-round residents considering land cover at 100 m. Distance to the parkway and river width are negatively correlated with year-round resident evenness, and distance to the train and percent developed land within 100 m are positively correlated with year-round resident evenness.***

| Predictor | Estimate | SE | t value | *P* | Interpretation |
| --- | --- | --- | --- | --- | --- |
| % Artificial green space within 500m | -3.0E-03 | 1.3E-03 | -2.4 | 3.3E-02 | % Artificial green space within 500m ↑<br>Evenness ↓ |
| Distance to the Bronx River Parkway | -4.0E-04 | 1.4E-04 | -2.8 | 1.5E-02 | Distance ↑<br>Evenness ↓ |
| River width (m) | -4.9E-03 | 2.3E-03 | -2.2 | 4.8E-02 | River width ↑<br>Evenness ↓ |

***Table 13B. Best supported model for species evenness of year-round residents considering land cover at 500 m. Percent artificial green space, distance to the parkway, and river width are negatively correlated with year-round resident evenness.***

### Native species

Two variables predicted native species abundance: (1) distance to the Bronx River Parkway and (2) river width (Table 14). Similar to the overall dataset, native species abundance was higher at sites closer to the Bronx River Parkway (estimate: -7.9 E-04, *P*=2.2 E-04) and where the river was wider (estimate: 4.1 E-04, *P*<2E-16).

| Predictor | Estimate | SE | z value | *P* | Interpretation |
| --- | --- | --- | --- | --- | --- |
| Distance to the Bronx River Parkway | -7.9 E-04 | 2.6 E-04 | -3.1 | 2.2E-03 | Distance ↑<br>Abundance ↓ |
| River width (m) | 4.1 E-04 | 4.2 E-05 | 9.9 | <2E-16 | River width ↑<br>Abundance ↑ |

***Table 14. Best supported model for abundance of native species. Distance to the parkway is negatively correlated with native species abundance. River width is positively correlated with native species abundance.***

### Non-native species

Seven variables predicted non-native species abundance: (1) percent artificial green space within 100 m, (2) percent developed land within 500 m, (3) distance to the Bronx River Parkway, (4) distance to the Metro-North train, (5) river depth, and (6) river width (Tables 15A-B). Abundance of non-native species was lower at sites that had a higher percent cover of artificial green space within 100 meters (estimate: -0.042, $P$<2E-16). Abundance of non-native species was higher at sites that had a higher percent cover of developed land within 500 meters (estimate: 0.055, $P$=1.9E-15). In addition, abundance was lower at sites closer to the Bronx River Parkway (estimate: 2.1 E-03, $P$=8.6E-05) and higher at sites that were closer to the nearest Metro-North train (estimate: -3.2 E-03, $P$=1.6E-07). Finally, non-native species abundance was higher at sites where the river was deeper (estimate: 9.3 E-03, $P$=5.1E-05) and wider (estimate: 1.1 E-03, $P$=4.2E-09).

| Predictor | Estimate | SE | z value | *P* | Interpretation |
|---|---|---|---|---|---|
| % Artificial green space within 100m | -0.042 | 5.0 E-03 | -8.5 | <2E -16 | % Artificial green space within 100m ↑ Abundance ↓ |
| Distance to train | -3.2 E-03 | 6.1E-04 | -5.2 | 1.6E-07 | Distance ↑ Abundance ↓ |
| River depth (m) | 9.3 E-03 | 2.3 E-03 | 4.0 | 5.1E-05 | River depth ↑ Abundance ↑ |
| River width (m) | 1.1 E-03 | 1.9 E-04 | 5.9 | 4.2E-09 | River width ↑ Abundance ↑ |
| Temperature ($^{\circ}$C) | 0.14 | 0.027 | 5.2 | 2.6E-07 | Temperature included in model as control |

***Table 15A. Best supported model for abundance of non-native species considering land cover at 100 m. Percent artificial green space and distance to the train are negatively correlated with non-native species abundance. River depth, river width, and temperature are positively correlated with non-native species abundance.***

| Predictor | Estimate | SE | z value | *P* | Interpretation |
|---|---|---|---|---|---|
| % Developed within 500m | 0.055 | 6.9 E-03 | 7.9 | 1.9 E-15 | % Developed within 500m ↑ Abundance ↑ |
| Distance to the Bronx River Parkway | 2.1 E-03 | 5.2 E-04 | 3.9 | 8.6 E-05 | Distance ↑ Abundance ↑ |
| River width (m) | 4.0 E-04 | 1.4 E-04 | 2.6 | 8.9 E-03 | River width ↑ Abundance ↑ |

***Table 15B. Best supported model for abundance of non-native species considering land cover within 500 m. Percent developed land within 500 m, distance to the parkway, and river width are positively correlated with non-native species abundance.***

*Land cover analyses at 1 kilometer*

Land cover within 1 kilometer of the study sites was not a significant predictor of avian abundance, species richness, Shannon diversity, or species evenness.

## *Discussion*

In an urban ecology study on predictors of avian diversity along New York City's only freshwater river, I found that land use factors considerably affect diversity (see Table 16 for a summary of major predictions, results, and possible explanations for this study's findings). The variable that best predicted avian abundance, Shannon diversity, and species evenness was percent developed land within 100 meters. Meanwhile, the variable that best predicted species richness was percent artificial green space within 500 meters, and natural green space within 500 meters best predicted Neotropical migrant Shannon diversity and evenness. Contrary to my predictions, higher developed land cover was associated with higher diversity, and higher artificial green space was associated with lower diversity. The effects of the Bronx River Parkway and the Metro-North Railroad on avian diversity opposed each other: distance to the parkway was negatively correlated with avian diversity, whereas distance to the train was positively correlated with avian diversity. In addition, river morphology affected avian diversity and abundance along the Bronx River. In support of my predictions, deeper and wider reaches of the river were associated with higher bird abundance. Finally, I found that Neotropical migrants and non-native bird species responded differently from the overall dataset to certain variables; specifically, Neotropical migrant diversity was positively correlated with natural green space, while non-native abundance was positively correlated with distance to the Bronx River Parkway and negatively correlated with distance to the Metro-North Railroad. These results provide evidence that contributes to a growing body of literature on the importance of urban green spaces within a densely developed urban matrix, in addition to the influence of edge effects on patterns of avian diversity.

*The association between land cover and avian diversity*

Contrary to my prediction, urbanization in the form of heightened levels of developed land surrounding survey locations along the Bronx River was associated with higher overall Shannon diversity, species evenness, and abundance; furthermore, it was the best predictor of these variables. This result was observable at both the 100 m scale (for each of the three response variables) and at the 500 m scale (for abundance). My results differ from other studies of avian diversity along a riparian urbanization gradient that have found that bird diversity tends to be higher at locations surrounded by less development (Hennings and Edge 2003; Pennington et al. 2008; Pennington and Blair 2011; Petersen and Westmark 2013; Keten et al. 2020), or at locations surrounded by intermediate levels of development (Allen and O'Connor 2000; Larsen et al. 2010). I propose three possible explanations that might explain these differences.

First, the New York metropolitan area is possibly unlike other urban riparian survey locations. Researchers hypothesize that urban riparian corridors within different cities across the United States are more similar to each other than they are to the city in which they are located (Litteral and Shochat 2017). While this may be true for cities that are similar in population density and development intensity, due to differences in urban structure and green space, it is not probable that the Bronx River riparian corridor is more similar to corridors in other cities than it is to the New York metropolitan area. The New York metropolitan area is truly unique; while it is home to over 19 million citizens (U.S. Census Bureau 2019) and includes areas of extremely dense development, within New York City alone there exist over 10,000 acres of forest and 124 parks with natural areas consisting of forests, wetlands, and grasslands (Natural Areas Conservancy, 2020). Other urban areas where studies are located (e.g., Portland, OR: Hennings and Edge 2003; Cincinnati, OH: Pennington et al. 2008; Boise, ID: McClure et al. 2015) have smaller populations, and while they have areas of development, they are not as densely developed as New York City (U.S. Census Bureau 2019). Even cities that are similarly intensely developed as New York City, such as Mexico City (Ortega-Álvarez and MacGregor-Fors 2009) are not comparable because they do not have several large urban parks composed of natural habitats such as in New York City. Second, some studies might not be commensurate with the present study because they only used species richness to measure avian diversity (e.g., Pennington et al. 2008; McClure et al. 2015; Keten et al. 2020). Using multiple indices of diversity is preferable to using only one index, because this promotes a better understanding of the intricate factors that drive diversity (Morris et al. 2014); therefore, I opted to use Shannon diversity, richness, and evenness in my models. I found additional associations between Shannon diversity and species evenness and variables including percent developed land cover and distance to the Metro-North Railroad. My results might have been similar to those found in other studies had they included multiple metrics of diversity. Lastly, contrary to other studies, my results suggest that urban parks can be oases for many bird species. In support of this hypothesis, Callaghan et al. (2019) found that there was significantly higher bird richness and Shannon diversity in urban areas compared to natural green areas throughout the contiguous United States. This result is likely due to the increased habitat heterogeneity of urban green spaces; other researchers have found similar results, stressing large patch size as critical for avian diversity in urban natural areas (Ikin et al. 2013; Nielsen et al. 2014; Kang et al. 2015; Shih 2018; Yang et al. 2020; Zorzal et al. 2020). Parkland surrounds the Bronx River on its banks throughout its entire course; in Westchester, the Bronx River Reservation surrounds the river in a narrow buffer zone, and in the Bronx, the Bronx River Greenway forms a large shield from the urban matrix within parks such as Bronx Park and Starlight Park. Bronx Park is a highly heterogeneous and large habitat patch of 718 acres, consisting of freshwater wetlands, streams, forests, open fields, animal enclosures within the Bronx Zoo, and cultivated areas with the New York Botanical Garden. This park along with other heterogeneous bands of green spaces of varying width surrounding the Bronx River are likely oases from the intense development surrounding some of the survey locations. The site with the highest Shannon diversity was located in Bronx Park (site 26, Shannon diversity=3.0) and surrounded by a large percentage of developed land within 100m (61%), supporting the concept of urban parks as oases. While I cannot rule out the possibility that birds are habituated to development and that is why avian diversity and abundance are positively correlated with percent developed land in the vicinity of the Bronx River, scientists have found a similar trend of increased abundance of mammals in urban refuges in the New York metropolitan area. Stark et al. (2020) found that mammalian carnivore abundance was higher in green spaces surrounded by dense development compared to green spaces surrounded by less development. Although this result is within a separate taxon, it indicates a similar trend within a unique urban area, and it shows the potential for large green spaces within highly developed areas in the New York metropolitan area as biodiversity refuges.

Interestingly, sites with a higher percent artificial green space within 500 meters had lower Shannon diversity, species richness, and Neotropical migrant Shannon diversity; this was the best predictor for species richness. For every 1% increase in artificial green space within 500 meters, the number of species at a site decreases by 0.012. Artificial green spaces are areas that consist of vegetation in the form of lawn grasses, including homeowners' yards, parks, golf courses, and country clubs. Maintenance of these areas often involve mowing grasses, removing leaf litter, and applying pesticides and herbicides, all of which reduce overall biodiversity and therefore may impact avian diversity (Marzluff and Ewing 2001; Aronson et al. 2017). Reductions in mowing frequency (e.g., once per year) have been found to increase plant functional and phylogenetic diversity compared to areas that are subject to moderate and high mowing frequencies (Chollet et al. 2018). This increased plant diversity likely translates into higher insect diversity, as L. S. Smith et al. (2015) found that lawn plots that were mowed monthly as opposed to mowing as frequently as needed to maintain a 2-centimeter lawn height had more insects and higher levels of diversity. In addition, insect abundance was higher on native and mixed native/non-native grass-free plots compared to turf grass and non-native grass-free plots (L. S. Smith et al. 2015). Twenty-seven of the 57 species (47%) observed along the Bronx River were insectivores. Therefore, it is likely that artificial green spaces within 500 meters of the Bronx River have a negative effect on bird diversity because of the negative ramifications of intense maintenance on lawns, golf courses, and country clubs, which includes frequent mowing and planting of non-native ornamental species, reducing overall biodiversity compared to more natural habitats.

Another important result is that percent natural green space within 500 meters of the Bronx River positively predicted Neotropical migrant Shannon diversity and evenness; this was the most important predictor for Neotropical migrant diversity. This is likely because the Atlantic Coast migration route consists of highly developed cities with minimal habitat for migrants (Seewagen et al. 2011), so as birds look for stopover sites, they choose locations that have more green space in the vicinity. 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 down (Schuler and Forrest 2016; Loeb 2011). While flying overhead, Neotropical migrants likely view Bronx Park as an attractive stopover site. In fact, several studies demonstrate that this park is a key stopover site for migrating birds (Seewagen and Slayton 2008; Seewagen et al. 2011; Seewagen et al. 2013; Bricklin et al. 2016). Seewagen and Slayton (2008) found that Neotropical migrants gained up to 2.5% of their mean body mass per hour while replenishing their energy stores during their stopover in Bronx Park. My results add to a small body of literature showing that Bronx Park is an important habitat for Neotropical migrants. However, my results did not show significant effects of natural green space on overall or year-round resident diversity, which might indicate that the resident birds along the Bronx River include a lot of city-adapted species that are not affected by natural green space in general. Based on the effects of all three land cover categories on overall avian and Neotropical migrant diversity along the Bronx River, it is possible that minimally managed green spaces are important for avian diversity.

*The association between distance to the Bronx River Parkway and avian diversity*

Contrary to my prediction, I found that sites closer to the Bronx River Parkway had higher species richness, evenness, and Shannon diversity for the overall dataset; in addition, these locations also had higher Neotropical migrant evenness and higher native species abundance. This diverges from the literature describing the negative effects of major roads on bird abundance and diversity, including habitat fragmentation, vehicle collisions, pollution, physical barriers, traffic noise, and artificial lighting (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). The Bronx River Parkway is highly unique because it is forested along nearly its entire length. Roads neighboring forests create edge habitat, which insectivores, long-distance migrants, cavity nesters, and understory gleaners prefer, possibly due to increased resource accessibility from small-scale changes in vegetation structure in these areas (Terraube et al. 2016). In support of this alternative hypothesis, my results show that non-native species abundance was lower at sites closer to the Bronx River Parkway, possibly because they are generalists that do not need edge habitat for food sources. In addition, while traffic on the Bronx River Parkway may contribute to noise pollution especially at sites on the Bronx River located closer to the road (personal observation), studies indicate that bird species richness (McClure et al. 2015; Summers et al. 2011) and nesting site choice (Wiącek et al. 2014) are unaffected by road noise. Therefore, the Bronx River Parkway may create quality edge habitat that attracts native species and Neotropical migrants, resulting in higher diversity at sites that are closer to this major road.

*The association between distance to the Metro-North Railroad and avian diversity*

In support of my predictions, I found that Shannon diversity and species evenness for the overall dataset, as well as Shannon diversity of Neotropical migrants, was higher at sites farther from the Metro-North train tracks. Birds tend to avoid railroads because of the noise pollution that trains produce (Dorsey et al. 2015), or due to the risk of collision with either the train itself or components associated with the train (Malo et al. 2017). While birds may benefit from the edge habitat created by railroads similar to the effects of roads (Morelli et al. 2014; Wiącek et al. 2015), the Metro-North train tracks are typically surrounded by rocks and gravel, whereas the Bronx River Parkway is typically surrounded by vegetation, so the parkway forms preferable edge habitat for birds and the railroad does not. Based on my results, the Metro-North Railroad creates a hindrance that is not conducive to higher levels of avian diversity.

*The association between river morphology and avian diversity*

River width and depth were positively correlated with higher avian abundance, possibly because sections of rivers that are deeper and wider support more diverse food sources for birds including fish, aquatic vegetation, and macroinvertebrates (Ivicheva et al. 2019). Interestingly, overall species evenness and Neotropical migrant evenness were negatively correlated with river width, possibly because only species that benefit from riparian food sources are found in higher numbers at sites with wider sections of the river. These results show that abundance is positively correlated with wider and deeper sections of the river possibly due to the greater levels of food sources in larger rivers.

*The importance of scale*

Several researchers discuss the importance of studying varying spatial scales when observing how different land cover classes affect avian diversity because responses across scales may be dynamic (Hennings and Edge 2003; Pennington et al. 2008; Pennington and Blair 2011; McClure et al. 2015). My results show that developed land is most important within a radius of 100 m rather than within a radius of 500 m, which may be because birds are more affected by development on a local scale; in a highly developed area, they need to convene in the closest green space that can provide necessary resources (e.g., Stark et al. 2020). Meanwhile, associations between avian diversity and percent artificial green space or natural green space along the Bronx River show the opposite result, with their significance on the 500 m scale and not the 100 m scale. This is possibly because birds search for quality habitat to land in as they fly overhead, and natural green spaces provide more attractive habitat compared to areas that consist of heavily maintained grasses that are essentially homogeneous. Furthermore, large patch size is important for avian diversity (Ikin et al. 2013; Nielsen et al. 2014; Kang et al. 2015; Shih 2018; Yang et al. 2020; Zorzal et al. 2020), so it is understandable that natural green spaces such as sizeable forests appeal to birds, while artificial green spaces including lawns that are comparatively quite small do not attract birds. My results support other research that shows that patterns of avian diversity vary with land cover changes on differing scales (Hennings and Edge 2003; Pennington et al. 2008; Pennington and Blair 2011; McClure et al. 2015).

**Land cover on a 1-kilometer scale**

Land cover within 1 kilometer of the combined "super sites" was not a significant predictor of avian abundance, species richness, Shannon diversity, or species evenness. Other studies show that land use at larger scales than 500 m may also result in distinctive effects on avian diversity (Oneal and Rotenberry 2009; Pennington and Blair 2011). However, based on this study's results, land use effects on the Bronx occur on small (100 m) and moderate (500 m) scales, and large-scale land use (1 km) does not affect avian diversity. This finding may be due to three reasons. First, combining groups of three sites into one "super site" reduced 18 sites to 6, dramatically limiting sample size. Second, the "super sites" had similar levels of diversity, lessening the effects land use may have on diversity across these six sites. Finally, it is possible that land use 1 kilometer away from a survey location does not affect avian diversity at that site. While land cover within 100 meters and 500 meters predicts avian diversity and abundance along the Bronx River, land cover on a landscape level does not.

| Prediction | Result | Explanation | Source |
|---|---|---|---|
| Avian diversity would be higher at sites with more natural and/or artificial green space surrounding the Bronx River at multiple spatial scales. | - Overall avian diversity was lower at sites with more artificial green space within 500 meters.<br>- Neotropical migrant diversity was higher at sites with more natural green space within 500 meters. | - Within artificial green spaces, human modifications and maintenance may result in decreased plant and insect diversity, leading to lower avian diversity.<br>- While selecting stopover sites, Neotropical migrants are attracted to large green spaces because they are quality habitat. | - Chollet et al. 2018; L. S. Smith et al. 2015; Marzluff and Ewing 2001; Aronson et al. 2017<br>- Seewagen and Slayton 2008; Seewagen et al. 2011; Seewagen et al. 2013; Bricklin et al. 2016 |
| Avian diversity would be lower, and abundance would be higher at sites with more developed land surrounding the Bronx River at multiple spatial scales. | Overall avian diversity and abundance were higher at sites that had more developed land within 100 meters. | Diversity was measured within green spaces along the Bronx River, so urban parks and rivers within a densely developed urban matrix may serve as oases that harbor avian diversity. | Callaghan et al. 2019; Shih 2018; Yang et al. 2020; Zorzal et al. 2020 |
| Avian diversity would be lower at sites closer to the Bronx River Parkway and the Metro-North Railroad. | Avian diversity was higher at sites closer to the Bronx River Parkway.<br>Avian diversity was lower at sites closer to the Metro-North Railroad. | The Bronx River Parkway creates quality edge habitat for foraging, but the Metro-North Railroad does not. | Morelli et al. 2014; Terraube et al. 2016 |
| Avian abundance would be higher where the Bronx River is deeper and wider. | Avian abundance was higher at sites where the Bronx River was deeper and wider. | Deeper and wider sections of rivers might have more abundant food sources. | Ivicheva et al. 2019 |

*Table 16. Summary of major predictions, results, and possible explanations for this study's findings.*

*Limitations*

Several limitations are associated with the current study. First, my results are not necessarily generalizable to other urbanized riparian areas because sampling occurred on one relatively small river during one season. However, my study does provide insight into the anthropogenic and abiotic variables that predict avian diversity along the entire Bronx River, which has never been studied before. Future research may expand on my study by surveying other water bodies in the New York metropolitan area throughout several seasons. Another limitation is that I was not able to sample consistently at each site because of the inaccessibility of certain sections of the river due to dense invasive vegetation such as Japanese knotweed (*Polygonum cuspidatum*) and Multiflora rose (*Rosa multiflora*) on the riverbank. Regardless, I was as consistent as possible, and excluding the sites from the models where I was unable to walk on portions of the riverbank did not significantly alter the results. Additionally, sample size was limited in this study because I was the only researcher recording the birds present, and one person cannot detect all of the birds at one site with only twenty minutes to survey both sides of the river. However, the purpose of this study was to compare avian diversity along the Bronx River between sites, not to create a census of birds in the area. Regardless, future studies may involve surveying the Bronx River more frequently to attain enough information to compare individual species and foraging and nesting guilds. In addition, in my efforts to randomize the site locations, I did not survey all sections of the river equally. For example, the sites in the Bronx are clustered together, with five of the six sites in Bronx Park (see Fig. 1); future studies should ensure even surveying across all reaches of the river. Finally, future research to test the oasis effect would require comparing bird surveys within the riparian corridor of the Bronx River and surveys extending into the more developed areas surrounding the Bronx River. Despite these limitations, my study addresses a previously unanswered question regarding the variables that affect avian diversity along a critical urban water body in the New York metropolitan area.

## *Conclusion*

This study is among the first to look at how urbanization affects avian diversity surrounding the Bronx River. A critical result is that the most significant predictor for Neotropical migrant diversity is natural green space; as natural green space within 500 meters increases by 1%, Neotropical migrant Shannon diversity increases by 0.015. To ensure that areas surrounding the Bronx River provide quality habitat and continue to attract migratory birds, land managers should preserve forested areas and create more areas consisting of natural green space. Additionally, artificial green space within 500 meters was the best predictor for species richness and had a negative effect on both richness and Shannon diversity; as a result, local organizations and governments should advocate for homeowners and managers of country clubs and golf courses to reduce mowing frequency, plant more native species, and reduce pesticide usage (Marzluff and Ewing 2001).

In addition, contrary to the prediction that avian diversity would be lower in areas surrounded by higher percent developed land, this study found that avian diversity was positively correlated with developed land. This may be the result of an oasis effect, where urban parks harbor higher diversity within a dense urban matrix due to the inhospitable habitat surrounding the parks. Furthermore, urban parks might exhibit higher habitat heterogeneity (Callaghan et al. 2019; Yang et al. 2020), which supports more niches and therefore leads to higher avian diversity (MacArthur 1958; Tews et al. 2004). Another hypothesis may explain the observed higher avian diversity at sites surrounded by higher development: birds in New York City are habituated to high levels of development and are adapted to living in cities. However, I propose that the more parsimonious explanation for the positive correlation between avian diversity and developed land is that urban parks are oases that provide heterogeneous habitat, supporting a plethora of avian species. Future studies are necessary to test the oasis effect and the habitat heterogeneity effect to explore the possibility that large urban green spaces within New York City promote avian diversity within a densely developed urban matrix. While more research is needed to elucidate the importance of urban parks as oases, my study demonstrates how anthropogenic and abiotic factors affect avian diversity along New York City's only freshwater river.

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## *Supplementary Materials*

| Land cover type | Description |
|---|---|
| **Open water** | Areas that consist of open water, usually with less than 25% cover of soil or plants. |
| **Developed – open space** | Areas that consist of mostly vegetation in the form of lawn grasses, possibly with some development. These areas often include large single-family housing units, parks, golf courses, and planted vegetation. Impervious surface cover is less than 20%. |
| **Developed – low intensity** | Areas that consist of a mixture of built materials and vegetation; usually including single-family housing units. Impervious surface cover is from 20% to 49%. |
| **Developed – medium intensity** | Areas that consist of a mixture of built materials and vegetation; usually including single-family housing units. Impervious surface cover is from 50% to 79%. |
| **Developed – high intensity** | Areas that consist of high levels of development, where many people live or work, including apartment complexes or commercial/industrial buildings. Impervious surface cover is from 80% to 100%. |
| **Barren land** | Areas that consist of accumulations of earthen material. Vegetation usually is less than 15% of land cover. |
| **Deciduous forest** | Areas that consist of trees that are taller than 5 meters and are greater than 20% of plant coverage. More than 75% of the tree species shed leaves in response to change in season. |
| **Evergreen forest** | Areas that consist of trees that are taller than 5 meters and are greater than 20% of plant coverage. More than 75% of the tree species keep their leaves year-round. |
| **Mixed forest** | Areas that consist of trees that are taller than 5 meters and greater than 20% of plant coverage. Neither deciduous nor evergreen species are greater than 75% of total tree cover. |
| **Shrub/scrub** | Areas that consist of shrubs that are less than 5 meters tall and are greater than 20% of plant coverage. |
| **Grassland/herbaceous** | Areas that consist of graminoid or herbaceous vegetation that are greater than 80% of total plant coverage. These areas are not tilled but may be grazed upon by livestock. |
| **Pasture/hay** | Areas of grasses, legumes, or a mix of both planted for livestock grazing or the production of crops. Pasture/hay vegetation is greater than 20% of total plant coverage. |
| **Woody wetlands** | Areas that consist of forest or shrubland vegetation that is greater than 20% of total plant coverage and the soil is periodically saturated with or covered by water. |
| **Emergent herbaceous wetlands** | Areas that consist of perennial herbaceous vegetation that is greater than 80% of plant coverage and the soil is periodically saturated with or covered by water. |

***Table S1. Description of National Land Cover Database cover types.***

| Model Parameters | ΔAICc | Weight | Log likelihood |
|---|---|---|---|
| **Shannon diversity (100 m)** | | | |
| distance to parkway + wind speed | 0 | 0.294 | -2.191 |
| distance to parkway + wind speed + % artificial green space | 0.65 | 0.213 | -0.554 |
| wind speed + temp | 1.38 | 0.147 | -2.883 |
| distance to train + temp | 1.75 | 0.123 | -3.065 |
| distance to parkway + wind speed + % artificial green space + river depth | 1.91 | 0.113 | 1.133 |
| wind speed | 1.97 | 0.11 | -4.856 |
| **Shannon diversity (500 m)** | | | |
| % natural green space + % artificial green space + temperature | 0 | 0.286 | 2.749 |
| % natural green space + % developed + temperature | 0.08 | 0.275 | 2.708 |
| % natural green space + % artificial green space + distance to parkway + temperature | 0.51 | 0.222 | 4.813 |
| % natural green space + % developed + distance to parkway + temperature | 0.57 | 0.216 | 4.784 |
| **Species evenness (100 m)** | | | |
| distance to parkway + distance to train + wind speed + river width | 0 | 0.267 | 38.549 |
| distance to parkway + % natural green space + river width | 0.13 | 0.251 | 36.166 |
| distance to parkway + distance to train + river width | 0.31 | 0.229 | 36.077 |
| distance to parkway + % natural green space + wind speed + river width | 1.38 | 0.134 | 37.861 |
| distance to parkway + distance to train + wind speed + river width + river depth | 1.63 | 0.118 | 40.516 |
| **Species evenness (500 m)** | | | |
| distance to parkway + % natural green space + river width | 0 | 0.688 | 37.786 |
| distance to parkway + % natural green space + river width + wind speed | 1.58 | 0.312 | 39.313 |

***Table S2A. Best supported models (ΔAICc <2) for Neotropical migrant diversity along the Bronx River.***

| Model Parameters | ΔAICc | Weight | Log likelihood |
|---|---|---|---|
| **Shannon diversity (100 m)** | | | |
| distance to parkway | 0 | 0.345 | -0.343 |
| intercept | 0.1 | 0.328 | -1.852 |
| distance to parkway + distance to train + % developed | 1.24 | 0.186 | 2.679 |
| distance to parkway + % artificial green space | 1.78 | 0.142 | 0.449 |
| **Shannon diversity (500 m)** | | | |
| distance to parkway | 0 | 0.382 | -0.343 |
| none | 0.1 | 0.363 | -1.852 |
| distance to parkway + % artificial green space | 0.81 | 0.255 | 0.931 |
| **Species evenness (100 m)** | | | |
| distance to parkway + distance to train + % developed + river width | 0 | 1 | 30.753 |
| **Species evenness (500 m)** | | | |
| intercept | 0 | 0.232 | 20.52 |
| distance to parkway + % artificial green space + river width | 0.1 | 0.221 | 25.572 |
| distance to parkway | 0.45 | 0.185 | 21.753 |
| river width | 0.98 | 0.142 | 21.486 |
| distance to parkway + % artificial green space | 1.39 | 0.116 | 22.962 |
| temperature | 1.6 | 0.104 | 21.178 |

*Table S2B. Best supported models (ΔAICc <2) for year-round resident diversity along the Bronx River.*

| Model Parameters | ΔAICc | Weight | Log likelihood |
|---|---|---|---|
| **Abundance (100 m)** | | | |
| distance to parkway + river width | 0 | 0.534 | -76.967 |
| distance to parkway + river width + river depth | 1.43 | 0.261 | -76.001 |
| distance to parkway + %developed + river width | 1.91 | 0.205 | -76.241 |
| **Abundance (500 m)** | | | |
| distance to parkway + river width | 0 | 0.193 | -76.967 |
| distance to parkway + % developed + river depth + river width | 0.16 | 0.178 | -73.404 |
| % artificial green space + river width | 0.69 | 0.137 | -77.31 |
| % developed + river depth + river width | 1.06 | 0.114 | -75.816 |
| distance to parkway + % developed + river width | 1.17 | 0.108 | -75.868 |
| % artificial green space + river depth + river width | 1.42 | 0.095 | -75.994 |
| distance to parkway + river depth +river width | 1.43 | 0.095 | -76.001 |
| distance to train + % developed + river depth + river width | 1.78 | 0.08 | -74.212 |

*Table S2C. Best supported models (ΔAICc <2) for native abundance along the Bronx River.*

| Model Parameters | ΔAICc | Weight | Log likelihood |
|---|---|---|---|
| **Abundance (100m)** | | | |
| distance to train + % artificial green space + river depth + river width + temperature | 0 | 0.422 | -51.303 |
| distance to train + wind speed + % artificial green space + river depth + river width | 0.19 | 0.384 | -51.397 |
| distance to train + wind speed + % natural green space + % artificial green space + river depth + river width | 1.55 | 0.195 | -49.294 |
| **Abundance (500m)** | | | |
| distance to parkway + % developed + river width | 0 | 0.17 | -49.502 |
| distance to parkway + % developed + river depth | 0.15 | 0.157 | -49.579 |
| wind speed + %developed + temp | 0.5 | 0.133 | -49.75 |
| distance to parkway + % natural green space + % artificial green space + river depth | 0.87 | 0.11 | -47.978 |
| distance to parkway + % developed + river depth + river width | 1.17 | 0.095 | -48.125 |
| distance to parkway + % natural green space + % artificial green space + river width | 1.18 | 0.094 | -48.129 |
| distance to parkway + % natural green space + % artificial green space | 1.23 | 0.092 | -50.115 |
| wind speed + % natural green space + % artificial green space + temperature | 1.37 | 0.086 | -48.224 |
| wind speed + % natural green space + % artificial green space + river depth + temperature | 1.98 | 0.063 | -46.211 |

*Table S2D. Best supported models (AICc <2) for non-native abundance along the Bronx River.*