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The Impact of Land Use and Human Population Density on Benthic Macroinvertebrate Diversity in a Highly Urbanized River

Many studies have documented the detrimental effects of urbanization on aquatic ecosystems. What is less known is how "super urban" centers—areas with unusually high human population densities and immense infrastructures—impact biodiversity. Specifically, freshwater streams and rivers that are situated in highly urbanized metropolitan areas might be more susceptible to anthropogenic disturbance. Here, we evaluated the impacts of land use and human population density on benthic macroinvertebrate diversity along the Bronx River, a freshwater river situated in one of the largest urban centers in the world: the New York metropolitan area. We addressed the following research question: How does (1) high intensity development, (2) distance to the Bronx River Parkway, and (3) human population density impact benthic macroinvertebrate diversity along the Bronx River? To answer this question, we sampled benthic macroinvertebrates from 18 study sites, and calculated five measures of benthic macroinvertebrate diversity: (1) family richness, (2) Ephemeroptera-Plecoptera-Trichoptera (EPT) family richness, (3) Simpson's diversity index, (4) invasive species abundance, and (5) family dominance. Our study yielded three main results. First, benthic macroinvertebrate diversity was extremely low. Across study sites, family richness ranged from two to seven and EPT family richness ranged from zero to one. Indeed, only four of 18 sites harbored pollution-sensitive mayflies (Ephemeroptera) or caddisflies (Trichoptera), and zero sites supported stoneflies (Plecoptera). Second, two measures of land use, high intensity development (80 to 100% impervious surface cover) and distance to a major highway (Bronx River Parkway) were associated with reduced biodiversity. Specifically, high intensity development was negatively associated with family richness and Simpson's diversity, and positively associated with invasive species abundance. Study sites located closer to the Bronx River Parkway harbored more invasive species than study sites located further away. One invasive species, the Asian clam (*Corbicula fluminea*), was the second most dominant taxon on the Bronx River. Finally, we found that high human population density was negatively associated with family richness and positively associated with invasive species abundance. Our results suggest that "super urban" centers are especially vulnerable to anthropogenic pressures and that large urban areas warrant special attention for mitigating the decline of benthic macroinvertebrates.

Keywords
Bronx River, metropolitan area, urbanization, biodiversity indices, invasive species

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INTRODUCTION

Urbanization can have severe impacts on wildlife (Murray et al. 2019). Aquatic ecosystems are particularly sensitive to changes associated with urbanization (Paul and Meyer 2001; Walsh et al. 2005). In many cities, freshwater rivers have undergone extensive modification due to changes in land cover, industrialization, and development (Gál et al. 2019). These changes have had profound consequences on benthic macroinvertebrate communities (Roy et al. 2003). Although many studies have documented the detrimental effects of urbanization on biodiversity (e.g., Wheeler et al. 2005; McKinney 2008), their impact on "super urban" centers, that is, areas with unusually immense infrastructure and extremely high human population density (DeCandia et al. 2019), are less well known. Two factors thought to contribute to patterns of benthic macroinvertebrate diversity are land use (Weijters et al. 2009; Herringshaw et al. 2011) and human population density (Waite et al. 2010). The impacts of these factors are thought to be especially pronounced in larger cities (Cuffney et al. 2010).

Anthropogenic land use is one major stressor associated with declines in benthic macroinvertebrate diversity (Stendera et al. 2012). High intensity development within a river's watershed can alter benthic macroinvertebrate community composition (Paul and Meyer 2001; Walsh et al. 2001). More specifically, impervious surface cover can have extensive effects on local rivers leading to increased runoff, nutrient loading, and the deposition of various contaminants, including metals, industrial compounds, and pesticides (Paul and Meyer 2001; Bell et al. 2019). Accordingly, several studies have documented a negative relationship between percentage of impervious surface and benthic macroinvertebrate taxa richness (e.g., Stepenuck et al. 2002; Moore and Palmer 2005; Sterling et al. 2016). One factor related to impervious surface cover that might alter benthic macroinvertebrate community composition is proximity to major roads and highways (Maltby et al. 1995; Gál et al. 2020; Petrin et al. 2023). For example, Gál et al. (2020) found a negative association between distance to roads and native benthic macroinvertebrate abundance and diversity, and a positive association between distance to roads and invasive species abundance. Because anthropogenic land use is associated with declines in benthic macroinvertebrate diversity (Stewart et al. 2000; Cooper et al. 2006; Du et al. 2021; Gholizadeh et al. 2021), it is especially important to evaluate the extent of these declines in highly urbanized cities.

Human population density can alter benthic macroinvertebrate community composition in several ways. First, cities with high levels of human population density often exhibit higher levels of water pollution than less densely populated areas (Tu et al. 2007). Certain pollution-sensitive taxa, including the orders Ephemeroptera, Plecoptera, and Trichoptera, can be more susceptible to degraded water quality (Hilsenhoff 1987). For example, Olson et al. (2016) found that EPT richness declined with increasing human population density in a study of several urban watersheds in Iowa. In contrast, pollution-tolerant taxa, including Asellidae, Chironomidae, and Tubificidae, are more likely to thrive in highly disturbed rivers (Hilsenhoff 1987). In support, Jones and Clark (1987) found a positive association between human population density and the presence of pollution-tolerant taxa (e.g., chironomids). Second, increased human population density can result in corresponding increases in watershed erosion (Pimentel and Kounang 1998). Indeed, human activity has been estimated to cause ten times more erosion than all other natural processes combined (Wilkinson and McElroy 2007). Increased erosion contributes to increased pollutant loading (Lammers and Bledsoe 2019) and degraded water quality, which in turn can result in altered benthic macroinvertebrate communities (Mahler and Barber 2017). Finally, increased human population density is often associated with accelerated rates of invasive species introductions (Castañeda 2012). As human population increases, ecosystems become more degraded, which creates habitats favorable for invasive species (Francis and Chadwick 2015). Moreover, increased human activity often results in repeated introductions of invasive species leading to a greater likelihood of their establishment (Borden and Flory 2021). Invasive species often outcompete native species for limited resources disrupting the growth and survival of native biota, sometimes resulting in local extinction (Mooney and Cleland 2001). Indeed, many North American urban rivers are dominated by invasive species (Francis et al. 2019), including Asian clams (*Corbicula fluminea*), rusty crayfish (*Faxonius rusticus*), and zebra mussels (*Dreissena polymorpha*) (Wilson et al. 2004; Sousa et al. 2008; Strayer 2009; Ilarri and Sousa 2012). Because human population density can alter benthic macroinvertebrate community composition in numerous ways, understanding how these effects play out in a densely populated city is important for managing urban biodiversity.

The aim of this study was to assess the impact of land use and human population density on benthic macroinvertebrate diversity in a river located in the most densely populated region in the United States (Weckel et al. 2015): the New York metropolitan area. To accomplish this aim, we conducted our study in the Bronx River, New York City's only freshwater river, which runs through Westchester County and the Bronx (de Kadt 2011). Despite undergoing several years of anthropogenic disturbance, the Bronx River remains an important refuge for macroinvertebrates (Bode et al. 1998, 2003; Natural Resources Group 2008; Smith et al. 2015; Baladrón and Yozzo 2020; Lundquist and Scott 2023; Mahmud et al. 2023), birds (Goldstein et al. 2022), fishes (Rachlin et al. 2007), and plants (Frankel 1999; Natural Resources Group 2008). Because the Bronx River is situated in one of the most highly urbanized cities in the world, it is especially important to assess how extreme urbanization impacts benthic macroinvertebrate diversity. To address the aim of this study, we evaluated the following research question: How does (1) high intensity development, (2) distance to the Bronx River Parkway (a major highway adjacent to the Bronx River), and (3) human population density impact benthic macroinvertebrate diversity along the Bronx River? To answer our research question, we sampled benthic macroinvertebrates from 18 study sites, and calculated five biodiversity indices (family richness, EPT family richness, Simpson's diversity index, invasive species abundance, and family dominance). We predicted that benthic macroinvertebrate diversity would be higher in study sites surrounded by less development and situated further away from the Bronx River Parkway. We also predicted that benthic macroinvertebrate diversity would be higher in areas surrounded by lower human population densities.

METHODS

Study Area

The study area encompassed 18 locations situated in the Bronx River located in New York State (Figure 1; Table 1). The river is approximately 36 km, extending from its source in Westchester County through Bronx County where it meets the East River tidal estuary (Natural Resource Group 2008; de Kadt 2011; Mahmud et al. 2023). The upper reaches of the river flow through suburban and lightly developed areas while the lower reaches flow through highly urbanized areas (Goldstein et al. 2022). Throughout its course, the Bronx River is flanked by a major highway: the Bronx River Parkway (Figure S1). The Bronx River Parkway is forested for most of its length creating a modest buffer between the river and the parkway (Goldstein et al. 2022).

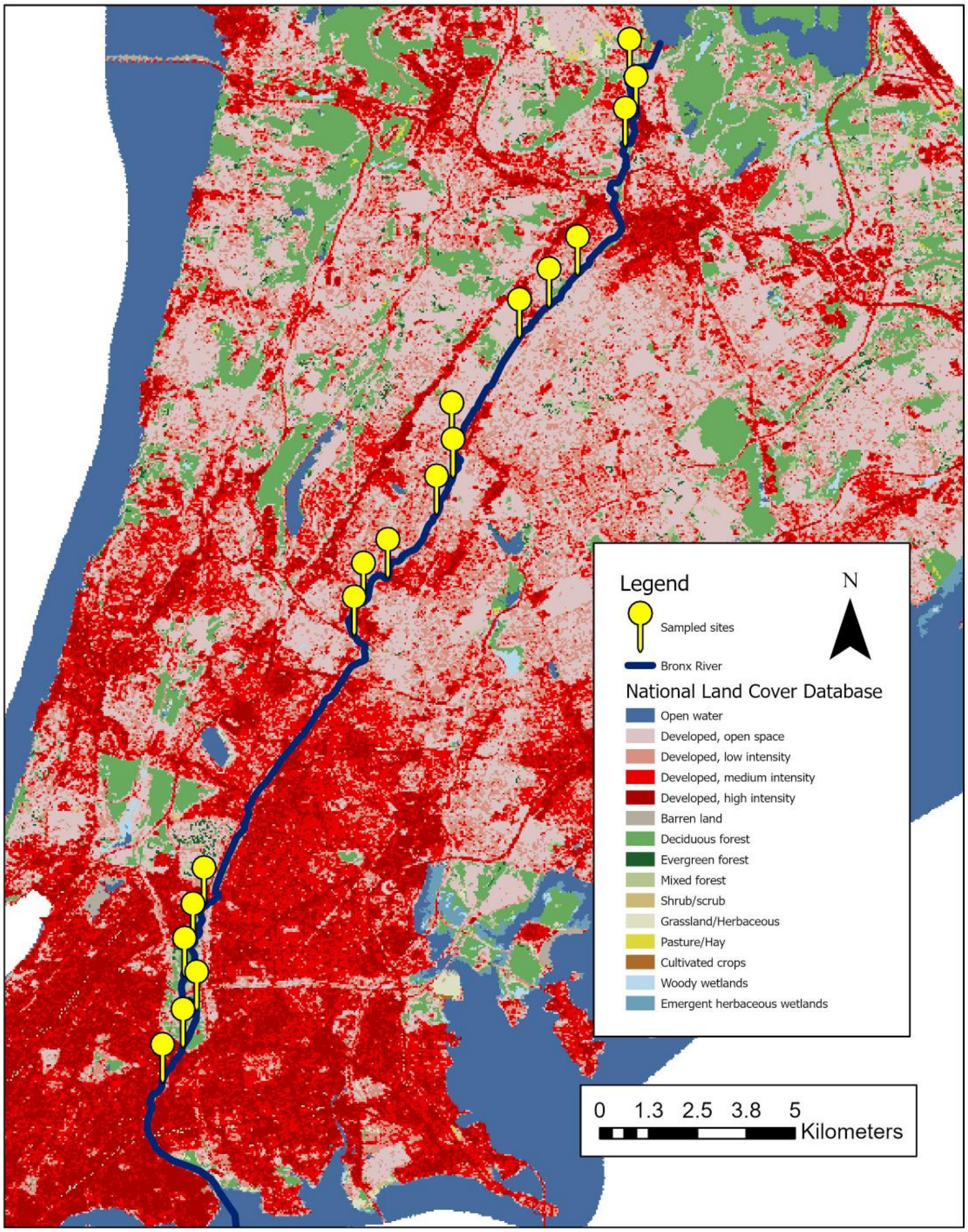

Figure 1. Map of the 18 study sites (yellow pins) and surrounding land cover along the Bronx River. Colored rectangular boxes represent different land cover types.

Table 1. Locations, latitude, and longitude of 18 study sites surveyed for macroinvertebrate diversity along the Bronx River.

Study sites	Location	Latitude, longitude
Site 1	Valhalla	41.0662462, -73.7739390
Site 2	North White Plains I	41.0576192, -73.7724645
Site 3	North White Plains II	41.0504071, -73.7749422
Site 4	Scarsdale I	41.0208320, -73.7859043
Site 5	Scarsdale II	41.0134625, -73.7924570
Site 6	Greenville	41.0063952, -73.7992765
Site 7	Eastchester I	40.9825942, -73.8148279
Site 8	Eastchester II	40.9742089, -73.8145430
Site 9	Crestwood	40.9657551, -73.8183175
Site 10	Tuckahoe	40.9511473, -73.8295238
Site 11	Bronxville I	40.9457037, -73.8351403
Site 12	Bronxville II	40.9379084, -73.8372519
Site 13	Bronx Park I	40.8755822, -73.8717961
Site 14	Bronx Park II	40.8673237, -73.8743247
Site 15	New York Botanical Garden	40.8593842, -73.8762586
Site 16	Mitsubishi Riverwalk	40.8516295, -73.8734651
Site 17	River Park	40.8430418, -73.8766247
Site 18	Starlight Park	40.8349188, -73.8813172

Historically, the Bronx River has experienced extreme environmental degradation stemming from many anthropogenic sources, including combined sewage overflows and municipal separate stormwater systems (Figure S2; de Kadt 2011). The development of industry, the construction of railroads and dams, river straightening, and a half century of population increase has also contributed to declines in water quality (Cox and Bower 1998; Bode et al. 2003). As a result, the biodiversity, hydrology, morphology, and water chemistry of the Bronx River have been altered substantially (Natural Resource Group 2008). Additionally, the surrounding land cover has also been modified over time (Zahmatkesh et al. 2015).

Benthic Macroinvertebrate Sampling, Sorting, and Identification

We sectioned the Bronx River into three distinct reaches based on geographic location: (1) upper reach (0-12 km), (2) middle reach (13-24 km), and (3) lower reach (25-36 km). Each reach was comprised of six locations for a total of 18 study sites. On a given sampling date, we randomly sampled three consecutive sites located one km apart. We organized study sites from 1 to 18 extending from the upper reach to the middle and lower reaches (Figure 1). We sampled benthic macroinvertebrates from 10 May 2019 to 29 June 2019. We used a D-frame net (500 µm mesh; 45.7 cm [length]; 20.3 cm [height]; 25.4 cm [depth]) to collect samples along the river bottom using the 3-minute traveling kick method (Environment Canada 2012). We obtained samples by kicking the benthic substrate in a zigzag pattern moving from downstream to upstream for approximately 20 m. This allowed us to sample multiple habitat types and microhabitats (Silva et al. 2016). All benthic macroinvertebrates collected during sampling were included in subsequent analyses (no sub-sampling).

We preserved collected samples in jars containing two-thirds 95% ethanol and one-third river water (Mahmud et al. 2023). We cleaned collected samples in the laboratory using tap water and a U.S. No. 40 standard sieve. We placed rinsed samples in a Petri dish, and we used a dissecting stereomicroscope (Zeiss Stemi 2000-C; Munich, Germany) to sort specimens. Sorted specimens were then preserved using 70% alcohol. With the exception of Nematoda, which was identified to phylum level, we identified all other preserved specimens to the family level using two identification keys (Pennak 1978; Voshell 2002). When calculating family richness, we conservatively counted Nematoda as one family. We identified the two invasive species found in our samples to the species level: Asian clam (*C. fluminea* [O. F. Müller]) and rusty crayfish (*F. rusticus* [Girard]).

Biodiversity Indices

We used five biodiversity indices to evaluate benthic macroinvertebrate diversity:

(1) *Family richness*. The number of different benthic macroinvertebrate families collected at each site (Xu et al. 2014; Mahmud et al. 2023).

(2) *EPT family richness*. The total number of mayfly (Ephemeroptera), stonefly (Plecoptera), and caddisfly (Trichoptera) larvae families collected at each site (NYSDEC-DOW 2019; Mahmud et al. 2023).

(3) *Simpson's diversity index*. A biodiversity indicator that accounts for both taxa richness and evenness; defined as the probability that two randomly sampled individuals represent the same taxon (Simpson 1949).

(4) *Invasive species abundance*. The total number of invasive species sampled at each study site.

(5) *Family dominance*. The percentage of the most prevalent family present at a given study site.

Anthropogenic Variables

For each of the 18 sites, we used ArcGIS Pro 2.6 (Esri, Redlands, CA) and the National Land Cover Database to measure land use, and we used open access data (see below) to measure human population density (Dewitz 2019; Goldstein et al. 2022; Figure 1). We define each of the anthropogenic variables as follows:

(1) *Percentage of high intensity development*. Percentage of land within a 500-m circular buffer that was comprised of high intensity development (80 to 100% impervious surface cover) (Dewitz 2019).

(2) *Distance to Bronx River Parkway*. Distance (m) of each study site from the Bronx River Parkway (Goldstein et al. 2022).

(3) *Human population density*. We measured human population density per sq. km for each of the study sites. To determine population density at each site, we calculated the number of individuals per km in the zip code situated in the study location using data derived from the United States Postal Service, United States Census Bureau, and Internal Revenue Service as described in Bradfield et al. (2022).

Statistical analyses

For each multiple linear regression model, we included one of the following biodiversity indices as a response variable: (1) family richness; (2) Simpson's diversity index; and (3) invasive species abundance. Two response variables, family richness and invasive species abundance, were modeled using the ‘glm’ function with Poisson error distributions. One response variable, Simpson’s diversity index, was modeled using the ‘glm’ function with Gamma error distribution. Three anthropogenic factors were modeled as predictor variables: (1) percentage of high intensity development; (2) distance to Bronx River Parkway; and (3) human population density. We also included river depth (measured in cm at the midpoint of the river), river width (cm), and water temperature (°C) as explanatory variables to control for variation among study sites.

For model selection, we used the *MuMin* package (Bartoń 2020) to compare all possible parameter combinations. We selected all models with ΔAICc < 2 as these models are defined as equally parsimonious (Burnham and Anderson 2002). We conducted model averaging using the summed weight method (Burnham and Anderson 2002, 2004) and calculated model-averaged coefficients using conditional R^2 (Nakagawa and Schielzeth 2013). Finally, we used the *car* package to calculate generalized variance inflation factors (GVIFs), which allowed us to diagnose for multicollinearity (Fox and Weisberg 2011; Fox 2015). Because all VIFs were <5, we found no evidence of problematic multicollinearity (Sheather 2009). All analyses were completed using R version 4.3.1 (R Core Team 2023). We used the *vegan* package (Oksanen et al. 2022) to calculate biodiversity indices and the *stats* package to conduct multiple linear regressions (R Core Team 2023). We used the ggeffects package (Lüdecke 2018) to calculate marginal effect sizes holding covariates at their mean values, which allowed us to generate figures.

RESULTS

Family Richness

We observed a total of 18 benthic macroinvertebrate families across the 18 study sites (Table 2). Family richness ranged from two to seven (Table 3). Four study sites (sites 1, 3, 5, and 11), all located in Westchester County, exhibited the highest family richness (n = 7). Three study sites (sites 14, 15, and 18), all located in Bronx County, exhibited the lowest family richness (n = 2).

EPT Family Richness

EPT family richness was almost always zero, except in four cases, one (Table 3). Across the 18 study sites, we observed one Ephemeropteran family (Baetidae), zero Plecopteran families, and one Trichopteran family (Hydropsychidae). Fourteen of 18 study sites had an EPT family richness of zero while four sites (4, 6, 7, and 10), all located in Westchester County, had an EPT family richness of one.

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Table 2. Benthic macroinvertebrate families sampled along the Bronx River in 2019. The Order is capitalized in the first column followed by family name(s). The phylum Nematoda is also capitalized.

Family Name	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	Site 7	Site 8	Site 9	Site 10	Site 11	Site 12	Site 13	Site 14	Site 15	Site 16	Site 17	Site 18
AMPHIPODA																		
Gammaridae	49	31	50	48	32	0	0	18	14	81	35	31	17	49	2	12	76	100
ARCHITAENIOGLOSSA																		
Viviparidae	0	0	4	0	1	0	0	0	0	0	2	0	0	0	0	0	0	0
BASOMMATOPHORA																		
Planorbidae	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
Physidae	0	0	0	0	0	0	0	0	0	0	4	1	0	0	0	0	3	0
DECAPODA																		
Cambaridae	0	1	1	3	3	2	4	3	0	0	0	0	1	2	0	0	1	0
DIPTERA																		
Psychodidae	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0
Tipulidae	3	1	0	0	1	2	0	1	0	0	0	0	0	0	0	0	0	0
EPHEMEROPTERA																		
Baetidae	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
HAPLOTAXIDA																		
Naididae	10	3	2	0	1	3	2	0	5	2	0	1	0	0	0	1	1	1
LUMBRICULIDA																		
Lumbriculidae	1	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
NEMATODA	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
ODONATA																		
Aeshnidae	3	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Calopterygidae	4	1	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
RHYNCHOBDELLIDA																		
Glossiphoniidae	0	0	1	2	1	0	1	0	0	0	2	1	0	0	0	0	0	0
SPHAERIIDA																		
Sphaeriidae	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
TRICHOPTERA																		
Hydropsychidae	0	0	0	5	0	2	2	0	0	0	0	0	0	0	0	0	0	0
UNIONIDA																		
Margaritiferidae	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
VENERIDA																		
Corbiculidae	12	0	163	9	155	61	7	26	49	27	23	0	65	0	11	3	0	0
Total Abundance	82	39	222	68	194	70	17	48	68	111	68	34	84	51	13	17	81	101

Simpson's Diversity

Simpson's diversity indices ranged from 0.27 – 0.78 (Table 3). The study site (site 7) with the highest Simpson's diversity index (0.78) was located in Westchester County whereas the study site (site 18) with lowest Simpson's diversity index (0.27) was located in the Bronx.

Invasive Species Abundance

Invasive species abundance ranged from zero to 164 individuals per study site (Table 3). We identified two invasive species across the 18 study sites: (1) Asian clam (*C. fluminea* (O.F. Müller); Family Corbiculidae; mean = 33.94, SD = 50.02, range: 0 – 163) and (2) rusty crayfish (*F. rusticus* (Girard); Family Cambaridae; mean = 1.06, SD = 1.35, range = 0 – 4).

Family Dominance

The two most dominant families found in the Bronx River were Corbiculidae and Gammaridae (Figure 2). Corbiculidae was present in 13 of 18 study sites and Gammaridae was present in 16 of 18 locations. Across all study sites, the proportion of taxa comprised of Corbiculidae ranged from 0.00 – 0.87 (mean = 0.37, SD = 0.34) while the proportion of taxa comprised of Gammaridae ranged from 0.00 – 0.99 (mean = 0.51, SD = 0.35). The proportion of Corbiculidae was negatively correlated with the proportion of Gammaridae (Pearson's $r = -0.92$, $P < 0.0001$).

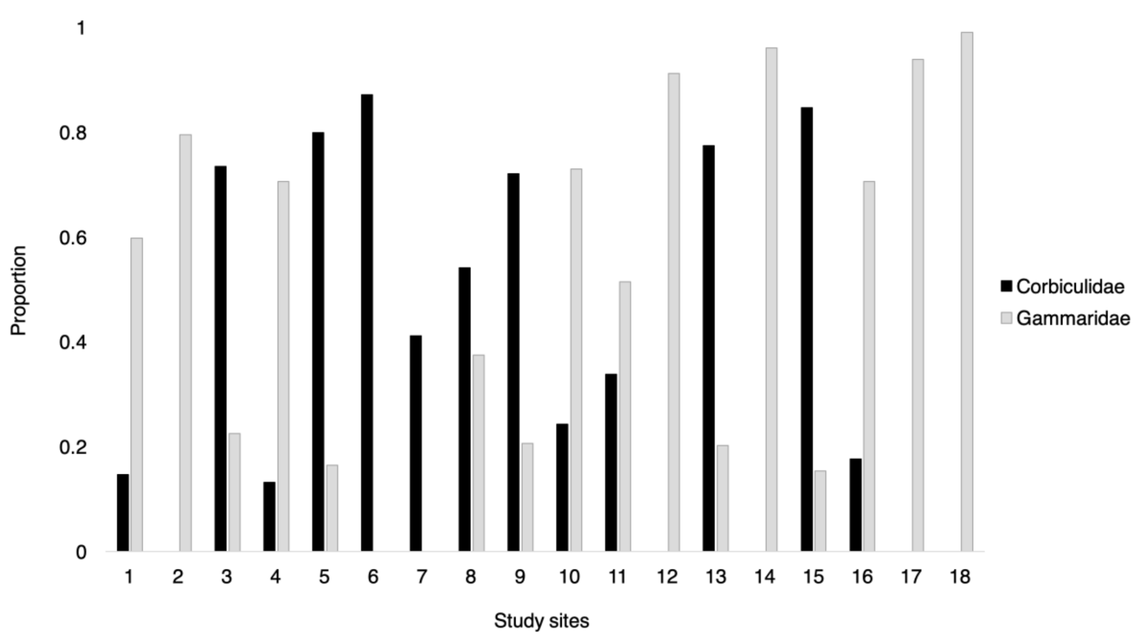

Figure 2. Proportion of the two most dominant benthic macroinvertebrate families sampled across study sites.

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Anthropogenic Variables

Land use (high intensity development, distance from Bronx River Parkway) and human population density varied across study sites (Table 3). The percentage of high intensity development ranged from 0.00 percent to 53.81 percent. Distance from the Bronx River Parkway ranged from 8 m to 610 m. Human population density ranged from 530 – 24388 people per sq. km.

Table 3. Mean, minimum, maximum, and standard deviation (SD) of biodiversity indices and anthropogenic variables across 18 study sites.

Biodiversity indices	**Mean**	**Min**	**Max**	**SD**
Family richness	4.67	2	7	1.78
EPT family richness	0.22	0	1	0.43
Simpson's diversity	0.50	0.27	0.78	0.14
Invasive species abundance	33.56	0	164	50.88
Anthropogenic variables				
High intensity development	11.79	0	53.81	14.66
Distance from the Bronx River Parkway	138.39	8	610	159.40
Human population density	7024	530	24388	8002.82

Predictors of Family Richness

The model parameter that best predicted family richness was human population density (Figure 3; Table 4; Table S1). Specifically, we found a negative correlation between benthic macroinvertebrate family richness and human population density. However, there was no significant association between family richness with either percent high intensity development or distance to the Bronx River Parkway.

Predictors of Simpson's Diversity Index

The model parameter that best predicted Simpson's diversity was high intensity development (Figure 4; Table 4; Table S1). Specifically, study sites surrounded by higher levels of high intensity development exhibited lower Simpson's diversity than study sites surrounded by lower levels of high intensity development. We found no significant association between Simpson's diversity with either human population density or distance to the Bronx River Parkway.

Predictors of Invasive Species Abundance

The model parameters that best predicted invasive species abundance were human population density and distance to the Bronx River Parkway (Figs. 5A-5B; Table 4; Table S1). Invasive species abundance was positively associated with human population density. Study sites located closer to the Bronx River Parkway exhibited higher invasive species abundance than study sites located further away. When we excluded human population density as a predictor variable, we found that percentage of high intensity development was positively associated with invasive species abundance (estimate: -0.037; SE = 0.006; z-value = 5.963; $P < 0.001$).

Table 4. Best supported models for predictors of benthic macroinvertebrate diversity along the Bronx River.

Response variables	Fixed effects	Estimate	SE	Adjusted SE	z-value	*P*-value
Family richness	Population density	-0.00004	0.00002	0.00002	1.965	0.0495 *
Simpson's diversity index	High intensity development	0.027	0.010	0.010	2.458	0.014 *
Invasive species abundance	Population density	0.0001	0.00001	NA†	9.766	< 0.001 ***
	Bronx River Parkway	-0.013	0.001	NA†	-13.529	<0.001 ***

Note: Statistical significance * $P<0.05$, ** $P<0.01$, *** $P<0.001$. † Model averaging was not required for these analyses as there was one best supported model.

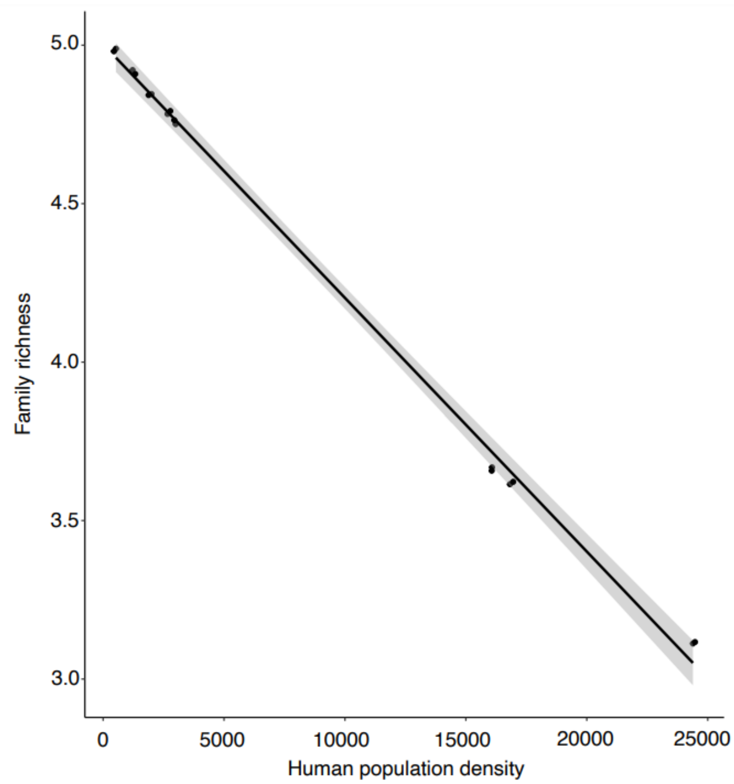

Figure 3. Association between benthic macroinvertebrate family richness and human population density across 18 study sites. Shaded gray area represents 95% confidence interval.

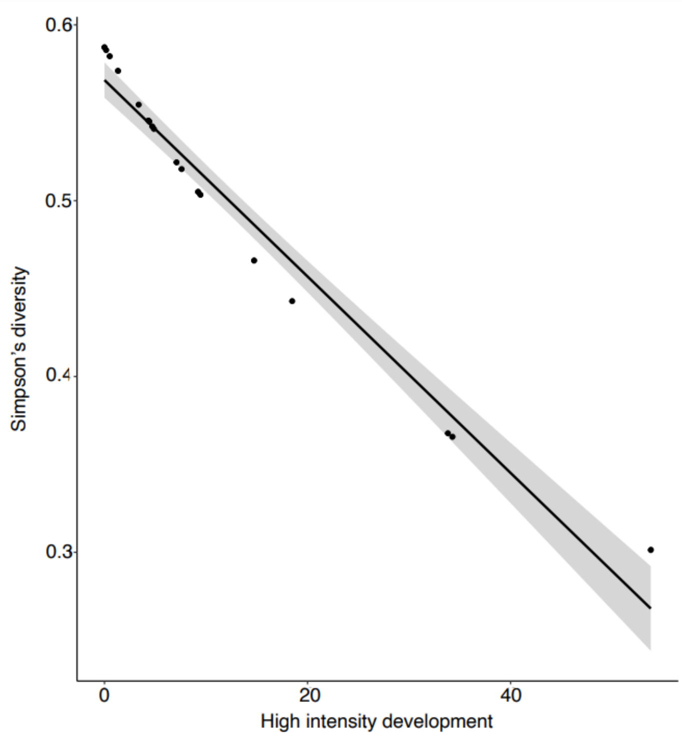

Figure 4. Association between Simpson's diversity index and percentage of high intensity development across 18 study sites. Shaded gray area represents 95% confidence interval.

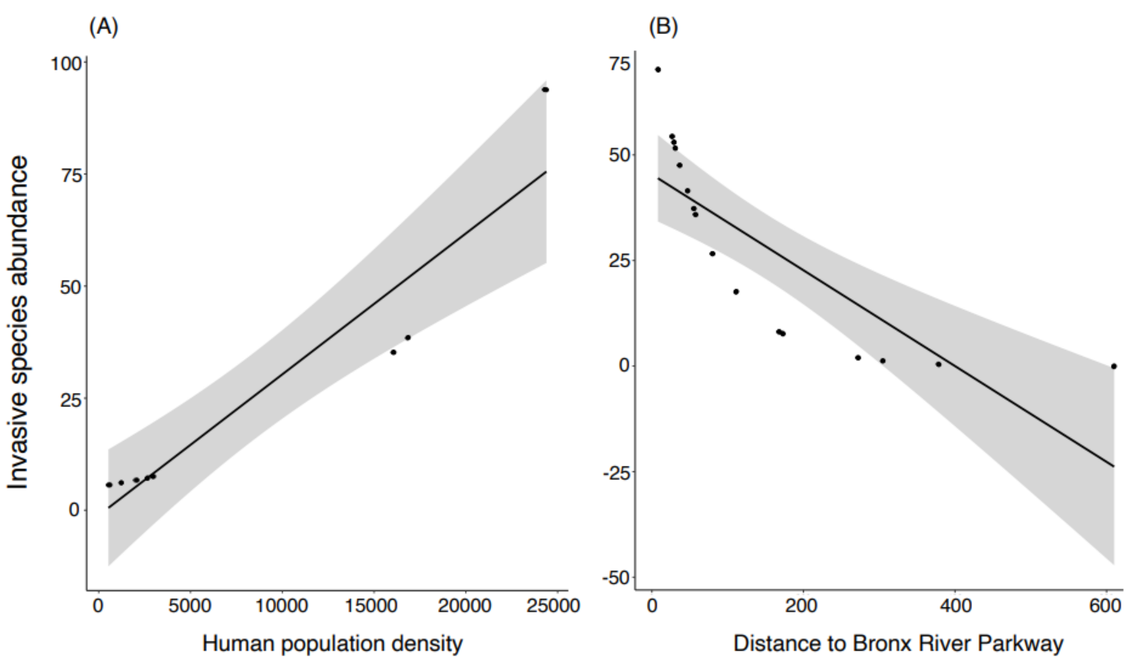

Figure 5. Associations of invasive species abundance with (A) human population density and (B) distance to the Bronx River Parkway across 18 study sites. Shaded gray area represents 95% confidence interval.

DISCUSSION

In support of our predictions, benthic macroinvertebrate diversity along the highly urbanized Bronx River varied based on different anthropogenic variables. We found that study sites surrounded by more humans per square kilometer exhibited lower benthic macroinvertebrate family richness than study sites surrounded by fewer humans. We also found a negative correlation between Simpson's diversity and high intensity development. Additionally, we found that different anthropogenic variables were associated with invasive species abundance. Study sites situated closer to the Bronx River Parkway and surrounded by high human population densities and more development, harbored higher invasive species abundance compared to study sites located further away from the Bronx River Parkway, and surrounded by low human population densities and less development. The Bronx River was dominated by two benthic macroinvertebrate families: Corbiculidae and Gammaridae. Corbiculidae was represented by only one species, the invasive Asian clam, whereas Gammaridae was comprised of pollution-tolerant amphipods. EPT richness was strikingly low across study sites as only four of 18 sites harbored pollution-sensitive mayflies (Ephemeroptera) or caddisflies (Trichoptera), and zero sites supported stoneflies (Plecoptera). Collectively, these results suggest that anthropogenic variables are major drivers of benthic macroinvertebrate diversity, and that rivers located in highly urbanized metropolitan areas are particularly vulnerable in terms of supporting healthy biological communities.

Influences of Land Use Variables

High intensity development, as measured by 80 to 100% impervious surface cover, was associated with reduced biodiversity as well as increased invasive species abundance. Impervious surface cover surrounding a watershed can increase the amount of stormwater runoff, which can cause erosion of streambanks and streambeds leading to nutrient loading, degraded habitat conditions, and reduced benthic macroinvertebrate diversity (Coles et al. 2012; Nguyen et al. 2023). Consistent with these patterns, Huang and Gergel (2023) found a negative correlation between impervious surface cover surrounding a river's watershed and percentage of EPT taxa. Notably, because 14 of 18 of our study sites did not harbor any EPT taxa, we could not conduct a correlation. Nonetheless, we also documented extremely low EPT richness and high levels of impervious surface cover across most study sites.

The conditions created by high intensity development, including changes in water temperature and nutrient loading, can be ideal for some invasive species as well as pollution-tolerant taxa (Riley et al. 2005; Whitehead et al. 2009; Strayer 2010; Cadotte et al. 2017; Ezenwa et al. 2023). Furthermore, invasive species, such as the Asian clam, possess several life history traits, including high reproductive rates, early maturity, rapid growth, and dispersal ability, that allow them to thrive in poor water conditions (Sousa et al. 2008). The high abundance of Asian clams documented in this study might be attributed to these traits. In addition to invasive species, some pollution-tolerant native taxa can also survive in highly urbanized rivers. Accordingly, we found that Gammaridae, a taxon known to thrive in polluted waters (Natural Resources Group 2008; Xu et al. 2014), was the most dominant benthic macroinvertebrate family sampled in the Bronx River. Consistent with this result, Medupin (2020), observed increased Gammaridae abundance with increasing urban cover surrounding a river in the UK. Notably, we found a strong negative correlation between Corbiculidae (Asian clam) and Gammaridae abundance. Although Corbiculidae and Gammaridae are both pollution-tolerant taxa (NYSDEC-DOW 2019), their habitats and diets differ, which might explain this negative association. Corbiculidae are filter feeders and reside in sandy and muddy substrates (Blalock and Herrod 1999; Minchin 2014) whereas Gammaridae are mostly shredders and collector-gatherers, and are commonly found under rocks, and in gravel or coarse substrates (MacNeil et al. 1997; NYSDEC-DOW 2019). Together, our findings support the idea that a highly urbanized river surrounded by high intensity development supports low levels of biodiversity but can also create conditions amenable to invasive species and pollution-tolerant taxa.

Invasive species abundance was also positively associated with proximity to the Bronx River Parkway. Specifically, study sites located closer to the Bronx River Parkway exhibited higher invasive species abundance than study sites located further away. Dispersal of invasive species is often mediated through human activities (Anderson et al. 2015). The spread of non-native species by human vectors might be accelerated if humans have increased access to otherwise inaccessible reaches of a river (Trombulak and Frissell 2000). The positive association between proximity to the parkway and invasive species abundance may have also resulted from increased propagule pressure (Johnston et al. 2009). If study sites located closer to the Bronx River Parkway experienced higher frequencies of invasive species introductions by humans, then this mechanism might explain these results. While studies have found that distance to roads is associated with reduced benthic macroinvertebrate diversity (e.g., Gál et al. 2020; Petrin et al. 2023), we found no significant association between distance to the Bronx River Parkway with two measures of biodiversity: family taxa richness and Simpson’s diversity. These null results might be explained by the greenspace flanking the Bronx River Parkway. Because the Bronx River Parkway is often forested along its length, this creates a buffer between the parkway and the Bronx River (Goldstein et al. 2022). These swaths of greenspace might therefore buffer against some of the negative impacts related to distance to roads. Indeed, several studies have documented a positive association between benthic macroinvertebrate diversity and riparian greenspace (Sponseller et al. 2001; Roy et al. 2003; Moore and Palmer 2005; Trovillion et al. 2023). Taken together, our findings suggest that a river’s distance to a road might be a proxy for river accessibility and propagule pressure, possibly impacting the likelihood of invasive species introductions.

Influences of Human Population Density

Three factors, nutrient loading, watershed erosion, and combined sewer systems might explain the negative association we found between family richness and human population density. First, elevated human population density within a river’s watershed can result in increased nutrient loading from road runoff and pet waste, which can in turn negatively impact habitat quality (McDonald et al. 2016; Müller et al. 2020). For example, Peralta et al. (2020) found a positive relationship between elevated human population density and increased phosphorous loading. Second, high levels of human population density can result in increased watershed erosion, which can further accelerate sedimentation and degrade water quality (Chen et al. 2015). Indeed, several studies have found a negative relationship between sedimentation and benthic macroinvertebrate diversity (e.g., Kaller and Hartman 2004; Larsen et al. 2011; Jones et al. 2012). Finally, the combined flow of wastewater and stormwater can overwhelm combined sewer systems (Dittmer et al. 2020). In cities with high human population density, sewers fill up at accelerated rates increasing the likelihood of overflows, even during light rain events (Botturi et al. 2021). Notably, the combined sewage overflows situated along the Bronx River are located in the most densely populated neighborhoods (Mahmud et al. 2023).

While increased human population density was negatively associated with family richness, we found the opposite pattern with invasive species abundance. Specifically, elevated human population density was positively associated with invasive species abundance. This finding suggests that increased human activity associated with high population density might contribute to invasive species abundance (Luck 2007; Pyšek et al. 2020). The two invasive species identified in this study, the Asian clam and the rusty crayfish, might have spread as a result of increased human activity (Wilson 2002; Ferreira-Rodríguez et al. 2019; Laffitte et al. 2023; Modesto et al. 2023). For example, Richardson and Selby (2020) hypothesize that the expansion of the Asian clam throughout lakes and rivers of New Hampshire has resulted from increased recreational activity due to increased human population density. Moreover, Puth and Allen (2005) observed that humans can act as vectors for rusty crayfish to travel between several lakes in Northern Wisconsin, facilitating their spread to locations that are otherwise inaccessible to them. Overall, our results suggest that human population density can be an important driver of benthic macroinvertebrate diversity particularly in the context of a large metropolitan area.

CONCLUSIONS AND FUTURE DIRECTIONS

While it is established that increased urbanization is associated with reduced biodiversity (e.g., Wheeler et al. 2005; McKinney 2008), our results suggest that these impacts might be more pronounced in a large urban center. The New York metropolitan area where the Bronx River is situated is the most densely populated region in the United States (Weckel et al. 2015). DeCandia et al. (2019) classify the New York metropolitan area as a “super urban” center because of its unusually immense infrastructure and human presence. Our findings indicate that three measures of urbanization—high intensity development, distance to a major parkway, and human population density—are associated with extremely low levels of benthic macroinvertebrate diversity as well as increased invasive species abundance. These findings are striking when you consider that the Saw Mill River, a freshwater river approximately 48 km north of the Bronx River headwaters and situated in a much less urbanized area, harbors nearly two-thirds more family richness than what we sampled in the Bronx River (Warkentine and Rachlin 2015).

One limitation of our study is that our analyses focused on one river with a limited sample size. We therefore recommend that future studies expand these analyses to other “super urban” areas. A second limitation of our study was the use of family level classification to analyze our data. Although the NYSDEC-DOW (2019) has specific protocols for the assessment of benthic macroinvertebrates at the family level, we recognize that more specific levels of analysis might be more informative. We recommend that future studies also consider incorporating DNA barcoding technologies for species identification (Hajibabaei 2019). On a regional level, ecologists could collect and analyze data on additional urban rivers in the New York metropolitan area. On a broader scale, we recommend that researchers aggregate data from other “super urban” areas to compare measures of biodiversity globally. Although it might not be feasible to rectify all damages associated with extreme urbanization, conservation measures, including the preservation of riparian forest, the reduction of impervious surface cover, and the expansion of greenspace, can be implemented to mitigate the impacts of anthropogenic stress on urban rivers.

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