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Cover Photograph: Blacks Run at Liberty Park, near downtown Harrisonburg VA, has undergone restoration efforts to buffer the stream from nearby parking lots and roads. Photograph © Julia Portmann.

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Case Study on Blacks Run: A Novel Approach to Assessing Urban Stream Restoration

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Abstract - Urbanization has required widespread restoration efforts to regain natural ecosystem function. Continued monitoring of diverse ecosystem characteristics is needed to assess the progress of such efforts. We conducted a multi-taxa monitoring approach using birds, tree carbon, and aquatic macroinvertebrates to assess urban restoration efforts. Tree carbon increased with greater distance from the urban core, while a pollution tolerance index decreased, indicating improved water quality ($R^2 = 0.823$, $p = 0.012$; $R^2 = 0.682$, $p = 0.043$). Assessing restoration progress using taxonomic diversity, carbon, and water quality allows for a comprehensive understanding of the efficacy of restoration projects. Future monitoring adopting this multi-taxa approach will help inform best practices for restoration implementation.

Introduction. By 2030, the extent of urbanization across the globe is projected to triple from that of the extent in 2000 (Seto et al. 2012, Threlfall et al. 2017). As urbanization is one the most prominent drivers of landscape degradation, this dramatic increase will likely have severe environmental consequences, from reduced forest cover and biodiversity to impaired water quality (Forman and Woo 2016). To mitigate such damages and improve the ecological resilience in growing urban spaces, efforts to restore human-dominated landscapes have begun (Lehmann 2021). However, the effectiveness of said restoration efforts depends on numerous factors and outcomes of restoration projects vary widely (Brudvig and Catano 2021). Furthermore, many projects lack the necessary, comprehensive follow-up assessments needed to ensure that their effectiveness is optimized (Aronson et al. 2014, Bash and Ryan 2002). In part, this lack of follow-up on projects could be because funding for ecological restoration is often not prioritized and/or is lacking (Cortina-Segarra 2021). As such, novel assessments of restoration efforts that consider a broad range of ecosystem characteristics, from water quality to wildlife biodiversity, while also including those that offer supplemental funding opportunities such as carbon sequestration, are essential (Lehmann et al. 2021).

Urban areas consist of a myriad of unnatural landscapes with varied, unnatural characteristics. However, some natural spaces, such as riparian areas, often remain in a degraded state. Impervious surfaces, such as roads, parking lots, and buildings, do not allow water to drain through them and instead direct it elsewhere (Sauer et al. 1983). Stormwater runoff, occurring when high water levels are channelized through impervious surfaces, increases fecal coliform bacteria concentrations through urban waterways for several days following a rainfall event (Green et al. 2019, Jeng et al. 2005). These impervious surfaces also transport pollutants through runoff, alter stream flow, impact stream geomorphology, and cause harmful impacts on aquatic systems (Klein 1979, Meyer et al. 2005, Walsh et al. 2005).

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Roadway runoff alone contributes over 50% of the annual metal and solid pollutants found in urban waterways (Hoffman et al. 1985). An effective way of assessing water quality and the effects of urban pollutants is to examine aquatic macroinvertebrate communities. These reflect stream health beyond the conditions present while sampling due to their multi-year aquatic larval stages and sensitivity to local habitat differences, as well as sensitivity to changes in water conditions (Berkman et al. 1986). Establishing a baseline for water quality in urban streams can help identify where restoration efforts should be focused, as well as monitor progress post-restoration.

Assessing faunal diversity is another important component of monitoring restoration projects, including those in urban areas. In particular, avian species presence is a known indicator of habitat quality and is useful to compose a holistic model of ecosystem functionality. Quantifying bird species diversity, along with abundance and richness, is necessary to fully understand bird species composition in urban habitats. Bird species diversity has been shown to increase with greater habitat diversity, while decreasing with increased impervious surfaces and increased proximity to the urban core (Dallimer et al. 2012, McKinney 2008). Bird species richness may peak in areas of moderate urban growth, with most of this increase occurring in urban generalist species (those species, both exotic and native, that have breeding populations in urban centers and are more abundant in city centers than in surrounding rural habitats) (Beissinger and Osborne 1982, Blair 1999, Concepción et al. 2016). These species, such as *Passer domesticus* Linnaeus (House sparrow), *Sturnus vulgaris* Schieffelin (European starling), and *Columba livia* Gmelin (Rock pigeon) are able to thrive in urban environments, with populations twice as dense as those in rural landscapes, while the presence of ecological specialists is often reduced (Jokimäki et al. 1996, Moller 2009). While urban areas may have high species abundance, the richness and diversity of native, ecological specialists is often reduced, highlighting the importance of considering species composition for ecological assessments of urban areas.

In addition to diminished water quality and biodiversity, urban areas often suffer a dearth of vegetation, particularly trees, which can have cascading environmental consequences ranging from degraded microclimate conditions to a loss of habitat that further drives the degradation of the ecosystem (Bounouna et al. 2015, Briber et al. 2013, Zipperer et al. 1997). A particular consequence that has become increasingly urgent under the growing climate crisis is the reduction in vegetation carbon storage within human-dominated landscapes (Just et al. 2018, Bounouna et al. 2015, Ren et al. 2011). Restoring urban landscapes offers the opportunity for rapid biomass accumulation as a by-product of regenerating flora, thus creating the potential for improved carbon sequestration and contributing essential natural carbon mitigation to climate change goals (Griscom et al. 2017). The high potential for carbon storage, particularly in urban trees, may also have the potential to act as a continuous source of funding for restoration efforts through carbon and ecosystem service credit payments (Richards and Thompson 2019). Furthermore, quantifying aboveground carbon storage in woody plant species can allow for a rapid assessment of the status of regenerating vegetation and ecosystem functioning in previously ecologically barren spaces (Zhou et al. 2020).

Collecting metrics such as water quality, wildlife diversity, and carbon sequestration following the implementation of restoration efforts are largely dependent upon the types of restoration management that are implemented. Restoration can be conducted passively, by removing a stressor and allowing the landscape to recover on its own, or actively, by implementing direct measures to improve habitat quality (Kauffman et al. 1997, Wohl et al. 2015). One way to help actively restore urban waterways is through the creation of protected green spaces. While urban green spaces can include any vegetated areas, those that are managed to prioritize environmental functioning can contribute to restoration that extends throughout an urban area. In turn, this can support higher biodiversity and provide ecosystem services such as cleaner water (Aronson et al. 2017, Dallimer et al. 2012). For our study, we are referring to green spaces as those that occur in small patches, like parks, or following riparian corridors in the form of greenways and focusing specifically on green spaces that have implemented either passive or active restoration around riparian areas. Although greenways and green spaces alone are not sufficient to consider an urban area restored, greenways are known to reduce the impacts of habitat fragmentation by connecting pockets of green space within a city matrix, which aids in the facilitation of gene flow and species diversity, reductions in urban runoff, and improving aboveground carbon storage and habitat diversity (Aronson et al. 2017, Griscom et al. 2017, Beninde et al. 2015, Bryant 2006, Dallimer et al. 2012).

Implementing multi-taxa assessments of restoration projects, rather than single-taxon, is becoming a more widely recognized approach to restoration monitoring (Aronson et al. 2014, Boetzl et al. 2021, Dallimer et al. 2012). Utilizing water quality, biodiversity, and carbon sequestration in concert is an effective means for examining the status of restoration efforts, as they are all indicators of ecological functioning and can be measured relatively quickly and at a low cost (Berkman et al. 1986, Brooks et al. 1998, Carignan and Villard 2001, Dallimer et al. 2012, Rockwell et al. 2020). Managing a landscape for these organisms encompasses a wide variety of ecological processes and habitat needs for other members of the ecosystem.

Blacks Run, a small stream in Harrisonburg, Virginia, is an ideal location to study the impacts of urbanization and restoration on water quality, bird diversity, and carbon sequestration. Blacks Run's headwaters are located north of Harrisonburg City limits, and the stream flows into Cooks Creek shortly after leaving the city limits. From there, Cooks Creek drains into the North River and eventually into the Chesapeake Bay (an economically and ecologically important body of water), emphasizing the importance of maximizing its water quality (Morimoto et al. 2003, Phillips and McGee 2016). Blacks Run has a history of disturbance, starting with tanning factories dumping effluent in the 1800s, and followed by the town dumping raw sewage in the 1900s, but the past few decades have seen extensive restoration efforts occur (Hagi 2019). In 1996, Blacks Run was declared impaired by the Virginia Department of Environmental Quality (VA DEQ) due to elevated fecal coliform bacteria levels and poor benthic habitat quality (VA DCR and VA DEQ 2006). In 2006, a water quality implementation plan was developed, with a goal of completely reducing pollutants by 2016, which has included restoring several sections of Blacks Run within city limits along with construction of a greenway (VA DCR and VA DEQ 2006). Although many efforts are underway, Blacks Run is still impaired with a ranking of 4A, on a scale of 1–5, with 5 representing the most impaired streams (VA DEQ 2020).

Considering the history of Blacks Run, our goals were to (i) assess water quality of Blacks Run using macroinvertebrates as indicators, (ii) analyze the species richness of birds along Blacks Run, and (iii) quantify the carbon storage in Harrisonburg's green spaces along the riparian corridor. We predicted that (i) areas that were restored would have higher water quality (using aquatic macroinvertebrates as indicators), (ii) bird species diversity would be higher at sites that have been restored the longest, and (iii) sites that have been restored the longest would have the highest amount of carbon storage.

Methods. Survey sites (n = 6) were chosen in green spaces throughout Harrisonburg, Virginia along Blacks Run or major tributaries (Fig. 1). Sites were primarily on city property and spanned the length of Blacks Run within Harrisonburg city limits. All surveys were conducted between September and November 2021. Sampling sites had a range of restoration times. In this study, time since restoration is defined as the number of years since trees were actively planted or allowed to passively regenerate. Six sites were surveyed, five of which have been actively restored and one that has been passively restored (Table 1). Time since restoration spanned one to fourteen years with each site varying in distance from the center of downtown Harrisonburg, VA (Table 1; Fig. 1; J. Harold, City of Harrisonburg Public Works, Harrisonburg, VA, 2021 pers. comm.).

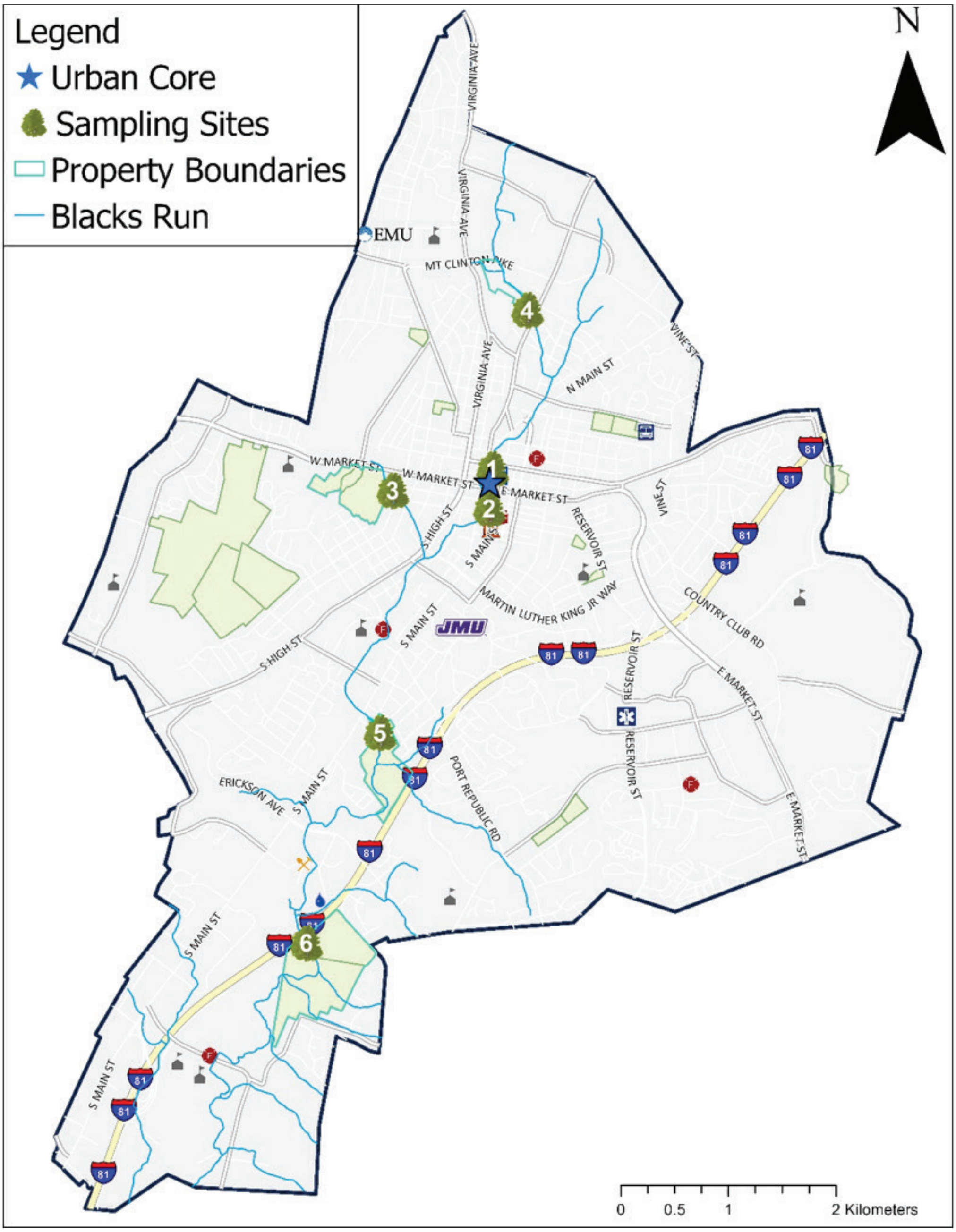

Figure 1. Map of sampling sites throughout Harrisonburg, VA. All sites were located in green spaces along Blacks Run. Sites are numbered in order of distance from the urban core (1 being the closest, 6 the farthest). Basemap from City of Harrisonburg GIS.

Riffles, areas of fast-flowing water over rocky substrate, were randomly selected to collect macroinvertebrates as indicators of water quality. Aquatic macroinvertebrates were collected using a one square meter kick net with a 0.02 inch (500 µm) mesh size placed at the downstream end of a riffle. Large substrate was scrubbed for one minute and all substrate disturbed for one minute. All macroinvertebrates were collected from the net and stored in 70% ethanol until being sorted and identified to family level. The Virginia Stream Condition Index (VSCI; Burton and Gerritsen 2003), Hilsenhoff Biotic Index (HBI; Hilsenhoff 1988), species abundance, richness, and Shannon diversity were calculated. The HBI is an index of pollution tolerance in which higher values indicate lower water quality, based on known tolerance values for each family of macroinvertebrate (Hilsenhoff 1988). The VSCI is a multi-metric index that includes the HBI, proportion of sensitive taxa (those that need clean water to survive), proportion of the dominant taxon (indicating low evenness in a community), and proportion of certain pollution-tolerant invertebrates (Chironomidae family) (Burton and Gerritsen 2003). Higher values of the VSCI indicate higher water quality. Bird species richness was established using traditional point count methods. Bird point counts were conducted 10.94 yd (10 m) away from the stream bank where macroinvertebrates were collected and all birds within a 27.34 yd (25 m) radius from this central point were recorded. One observer recorded all species present by sight and sound over a 10-minute period. Sound was recorded on a cellphone using BirdNet, an application produced by the Cornell Lab of Ornithology. All point counts were conducted between 7:30 and 8:30 am, during a time of day that is favorable for bird activity. The Shannon Diversity Index was used to calculate bird species diversity at all study locations.

Tree diameter at breast height (dbh) and species were recorded for all trees over 1.96 inches (5 cm) dbh in two streamside 32.81 × 10.64 yd (30 × 10 m) plots for four of the six sites. One plot was surveyed at the remaining two sites due to space restrictions. Wood density values obtained from the International Council for Research in Agroforestry wood density database. Carbon (Mg) per hectare was calculated using the following allometric equation (McPherson et al. 2016).

$$\text{Total carbon}(MgC)\text{ per tree} = \frac{0.0002835 * dbh^{2.310647} * \text{species wood density} * 1.28 * 0.5}{1000}$$

All geospatial analyses were conducted using ArcGIS Pro v2.8.3. Urban watersheds were created for each macroinvertebrate sampling site, percent impervious surface, percent tree/forest, road density within each watershed were calculated using the Virginia Geographic Information Network's 2014 land use land cover data and Harrisonburg roads from

Table 1. Urban restoration site characteristics. Sites are ordered by distance from the urban core.

Site	Size of riparian area (ha)	Distance from the urban core (m)	Time since restoration (years)
Liberty	0.059	132.008	14
Shenandoah Bicycle Company	0.021	221.564	11
Westover Park	0.597	906.325	9
Greenway	1.273	1655.256	1
Purcell Park	2.934	2539.303	12
Ramblewood Athletic Complex	3.565	4601.300	9

the US Census Bureau TIGER database. “Tree” was defined as patches of trees less than one acre, while “forest” was defined as patches of trees greater than one acre. The riparian area around the stream on each property was calculated as well. The urban core of Harrisonburg was defined as the area with the greatest road density, and the distance from this point (coordinates: 78.8697943°W 38.4500633°N) in meters was calculated for each site.

Shapiro-Wilk normality tests in R Studio v4.0.3 were used to check for normality of variables. Bird diversity was squared to improve normality, while total carbon was log transformed. All other variables used were normally distributed. Linear regressions were run for all variables individually, and the residuals were plotted to assess the validity of each. An alpha (α) of 0.05 was used to determine which trends were statistically significant.

Results. The Virginia Stream Condition Index scores ranged from 16.1–38.6, the Hilsenhoff Biotic Index (HBI) ranged 4.87–6.52, Shannon diversity ranged from 0.84–1.45, abundances ranged from 106–269 individuals, and species richness ranged from four to ten (Fig. 2). The best values for all metrics except for richness occurred at Ramblewood, while the lowest VSCI value occurred at Liberty Park and the highest HBI (representing worse water quality) occurred at the bike company. The HBI significantly decreased as distance from the urban core increased ($R^2 = 0.682$, $p = 0.043$; Fig. 3A).

Across all study sites, seventeen species of birds were seen and/or heard, three of which were urban generalists. Of the species recorded, the most abundant across all sites was an urban generalist (House sparrow). The highest Shannon diversity occurred at the Northend Greenway (H′ = 0.56) while the site with the lowest species richness occurred at Liberty Park (H′ = 0; Fig. 2). The highest proportion of urban specialists were found in downtown Harrisonburg (0.87/1.00). No variables were statistically significantly related to any bird metric used.

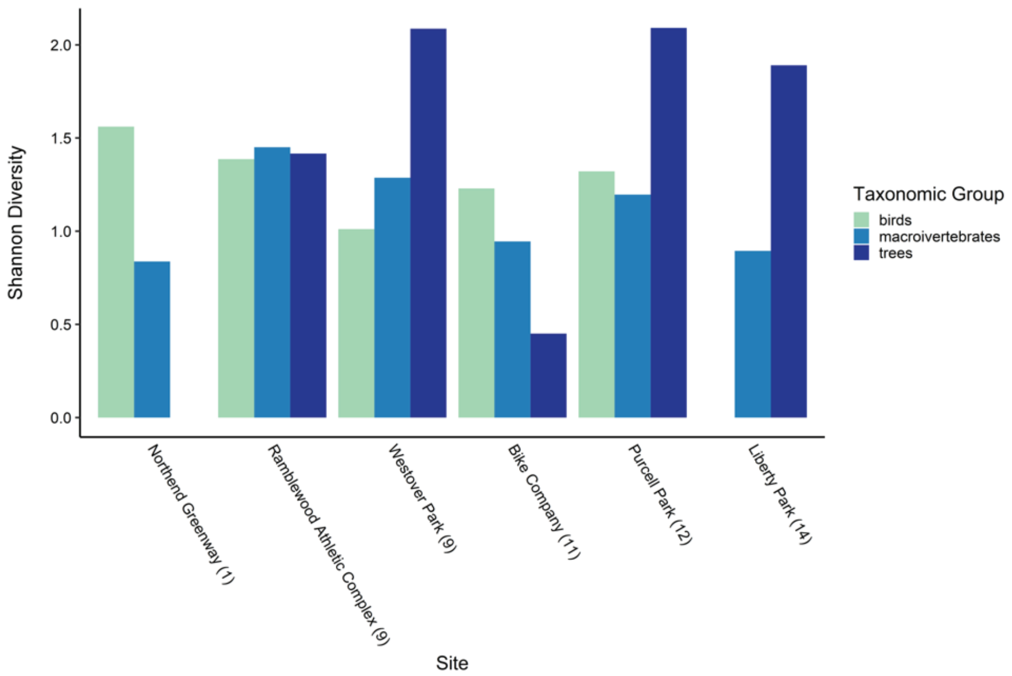

Figure 2. Shannon diversity values for all three taxa (teal = birds, macroinvertebrates = light blue, trees = dark blue) at each of the sampling sites. Sampling sites are arranged from most recently restored to longest restored, with the number of years in parentheses.

The highest Shannon diversity scores for tree species occurred at Purcell Park (2.09), and the lowest at the Greenway (0; Fig. 2). Carbon storage was greatest at Ramblewood (692.237 tn per hectare), while the lowest occurred at the downtown Harrisonburg site (48.541 tn/ha). Total tree carbon significantly increased as the distance from the urban core increased ($R^2 = 0.823$, $p = 0.012$; Fig. 3B).

Discussion. Our study presents a novel approach for assessing the efficacy of urban stream restoration. By examining floral and faunal characteristics and linking them to water quality, we can begin to identify the aspects of restoration that need additional focus and provide a more complete picture of restoration progress. Although other studies have taken multi taxa approaches (e.g., Bateman et al. 2015, Boetzl et al. 2021, Dallimer et al. 2012), studying tree carbon storage and bird communities along with water quality is a unique approach to this case study. Our initial predictions that length of time since restoration would be the most important explanatory variable for bird diversity, water quality, and carbon storage were not supported by our findings. Instead, distance from the urban core was the only statistically significant variable for our taxa of interest.

In areas with greater impervious surface cover, bird diversity was negatively affected overall. Although a few urban generalist species were found throughout the city (greater impervious surface cover, higher road density), overall species richness, and therefore di-

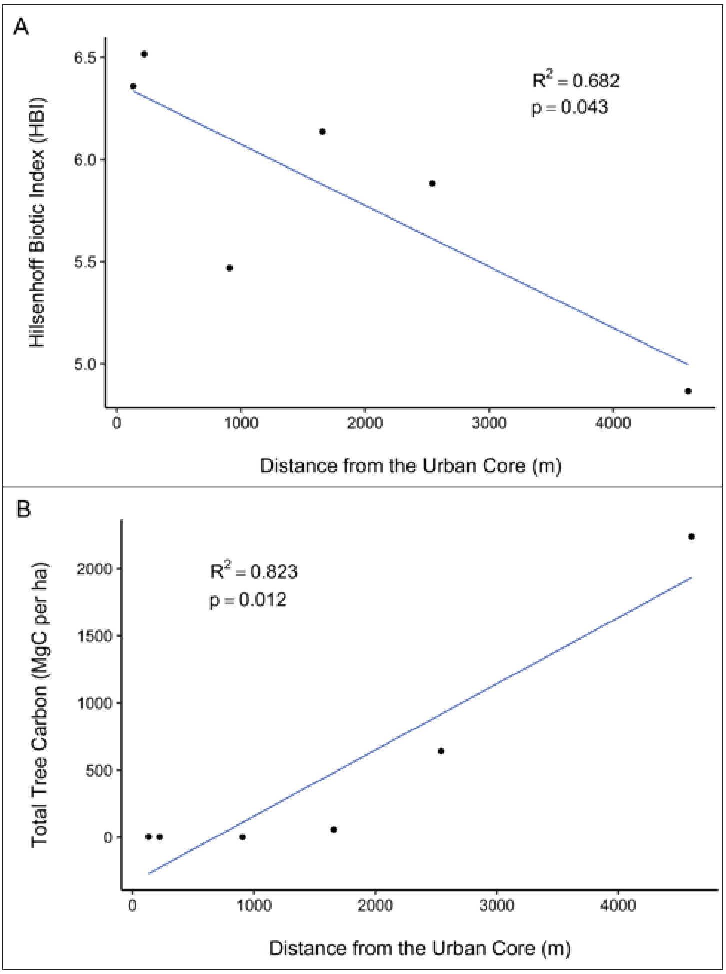

Figure 3. A) The Hilsenhoff Biotic Index is negatively correlated with distance from the urban core ($R^2 = 0.682$, $p = 0.043$). B) Total tree carbon is positively correlated with distance from the urban core ($R^2 = 0.823$, $p = 0.012$).

versity, was lower the closer to the urban core our study sites were. Urban specialists are able to outcompete native species in human dominated landscapes, shifting species composition greatly over time and lowering diversity. The more urbanized a location is, the more dramatic this biotic homogenization becomes (Beissinger and Osborne 1982, Concepción et al. 2016). This may explain why the passive restoration site had moderate species diversity, yet the highest abundance of urban generalist species. Although not statistically significant, distance from the urban core was an important metric for bird abundance, bird richness, and bird diversity. Another study focused on birds, plants, and butterflies found similar results (Dallimer et al. 2012). All three groups decreased in diversity and richness when impervious surface and road density increased, while distance from the urban core decreased. More comprehensive studies, utilizing a larger number of study sites throughout the year, are necessary to further explore how birds can be used as a valuable indicator taxon for urban restoration studies moving forward.

As was the focus of this study, gathering further information on non-breeding birds is imperative, as most current studies focus on species during the breeding season. Comparatively very little is understood about how urbanization impacts both resident bird populations and birds during the non-breeding season; although there appear to be clear differences in habitat and resource use (Jokimäki et al. 1996, Leveau and Leveau 2016, Rockwell et al. 2020, Zhou and Chou 2014). Additionally, data on herbaceous cover, shrub diversity and density, and soil composition will provide a more holistic picture of these greenways. At any given site, this can inform habitat availability for birds, as well as further clarify stormwater runoff mitigation and carbon sequestration (Hanberry and Thompson 2019). Thorough habitat assessments could strengthen the methodology presented here.

Aquatic macroinvertebrate communities displayed a trend of improving water quality as the distance from the urban core improved. Over time, improving urban habitat should also reflect on stream quality (Meyer et al. 2005, Walsh et al. 2005). A previous study in a nearby Virginia county found that restoration did not yield clear improvements in urban water quality; however, restoration improves stream bank degradation and improving habitat quality will eventually improve water quality (Selvakumar et al. 2010). Forest preserves, one type of green space, in urban areas have been shown to improve macroinvertebrate diversity, but not necessarily water quality, both within and up to two kilometers downstream of the protected area (Wilkins et al. 2015). Within urban areas with highly degraded waterways, there is no quick solution, but continued implementation of green spaces and restoration projects will improve conditions over time.

Despite the various restoration efforts throughout the city, tree carbon storage significantly increased with distance from the urban core. These findings are consistent with previous studies, which observed general tree carbon storage in relation to urban areas (Schreyer et al. 2014). These results likely reflect the distance of the restoration areas from the urban core as well, given that the closest site was over 109.36 yd (100 m) away. Integrating trees more closely into urban spaces could result in substantial carbon storage while also providing significant additional ecosystem services to the city of Harrisonburg. Street trees, a type of roadside urban tree commonly found in Harrisonburg, intercept over 10 million gallons of rainwater and sequester over 1.6 million pounds of CO_2 alone (Wiseman and Bartens 2012). The replacement value for these services is \$13 million, which breaks down approximately to \$374,000/year or \$53/tree annually. While these benefits were strictly measured in roadside trees, urban restoration efforts, such as riparian greenways, will only bolster these gains.

In addition to the abiotic ecosystem services, increasing urban green spaces and reducing the extent of impervious surface cover is essential for maintaining biodiversity. Specifically, vegetation is important for increasing connectivity (Aronson et al. 2017, Beninde et al. 2015, Bryant 2006, Dallimer et al. 2012, Von Thaden et al. 2021). Converting urban areas into green spaces improves vegetation cover, not only strengthening the resilience of older patches, but creating new ones as well (Aronson et al. 2017, Beninde et al. 2015, Bryant 2006, Dallimer et al. 2012). Healthy native vegetation improves soil nutrients and carbon storage, which further supports the ecosystem, compared to impervious surfaces, which reduce soil quality (Raciti et al. 2012). However, creating these self-sustaining habitats within urban spaces is not possible without substantial and prolonged management (Simmons et al. 2016). By implementing such efforts, corridors of healthy ecosystems, such as riparian greenways, will be established through urban centers, connecting them to source areas farther from the urban core.

Our findings provide a useful case study highlighting the benefit of simultaneously assessing birds (indicators of terrestrial biodiversity), macroinvertebrates (indicators of water quality) and trees (carbon sequestration potential). Diversity studies focusing on only one taxa or habitat often do not encapsulate the full story (Bateman et al. 2015, Dallimer et al. 2012). Broader studies are essential for furthering our knowledge of how urbanization can, and will continue, to impact many species. In addition to our results, other studies have shown that these continued efforts are essential to providing habitat connectivity, carbon sequestration, and improved water quality (Simmons et al. 2016). As urban areas continue to spread, we must increase urban green spaces, maximize ecosystem functioning within them, and regularly monitor the health of the environment.

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