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Fine-scale monitoring and mapping of biodiversity and ecosystem services reveals multiple synergies and few tradeoffs in urban green space management

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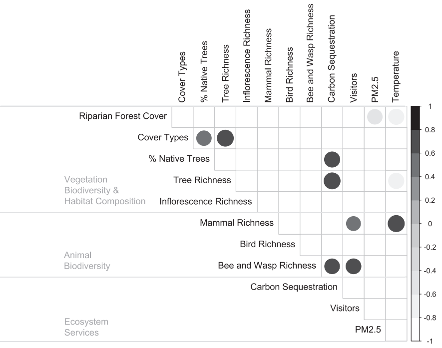
HIGHLIGHTS

- Urban watershed green spaces are critical for biodiversity and ecosystem services.
- We investigate habitat, biodiversity, and ecosystem service tradeoffs and synergies.
- Higher riparian forest cover supports lower $PM_{2.5}$ and air temperature.
- Tree richness and native trees can be optimized alongside carbon sequestration.
- Sites with high carbon sequestration also support pollinators and visitor access.
- Strategic urban green space management can advance multiple socioecological goals.

GRAPHICAL ABSTRACT



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ABSTRACT

Urban watersheds can play a critical role in supporting biodiversity and ecosystem services in a rapidly changing world. However, managing for multiple environmental and social objectives in urban landscapes is challenging, especially if the optimization of one ecosystem service conflicts with another. Urban ecology research has frequently been limited to a few indicators – typically either biodiversity or ecosystem service indices – making tradeoffs and synergies difficult to assess. Through a recently established watershed-scale monitoring network in Central Texas, we address this gap by evaluating biodiversity (flora and fauna), habitat quality, and ecosystem service indices of urban green spaces across the watershed. Our results reveal substantial heterogeneity in biodiversity and ecosystem service levels and multiple synergies (stacked benefits or “win-wins”). For example, we found that carbon sequestration positively correlated with tree species richness and the proportion of native trees in a green space, indicating that biodiversity goals for increased tree diversity can also provide carbon sequestration benefits. We also documented correlations between green spaces with greater riparian forest cover and lower particulate matter ($PM_{2.5}$) concentrations and cooler temperatures. In addition, we found that bee and wasp species richness was positively correlated with carbon sequestration and human visitation rates, meaning that urban green spaces can optimize carbon sequestration goals without

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losing pollinator habitat or access opportunities for city residents. Overall, our results indicate that many aspects of habitat quality, biodiversity, and ecosystem services can be simultaneously supported in urban green spaces. We conclude that urban design and management can optimize nature-based solutions and strategies to have distinct positive impacts on both people and nature.

1. Introduction

Urban areas are expanding globally and nationally, with an estimated 90 % of the U.S. population expected to live in cities by 2050 (United Nations, 2019). Given increasing population densities within urban areas, there is growing interest in understanding the status and drivers of biodiversity and ecosystem services in these landscapes (Bennett and Lovell, 2019; Dennis and James, 2017; Haase et al., 2014; Rocha and Fellowes, 2018). Environmental managers also have an expanding need to design and manage urban ecosystems in ways that enhance resilience and provide benefits to both people and nature (McPhearson et al., 2016). Ecosystem services (ES) comprise a diverse suite of processes through which natural systems support human life and well-being, including air purification, climate regulation, pollination, recreation, and cultural values, among many other services (Daily, 1997; Gómez-Baggethun et al., 2013; MEA, 2005; Potts et al., 2016). Outside of urban areas, past work on relationships between biodiversity and ecosystem services (BES) has indicated that biodiversity often positively correlates with ecosystem service delivery (Harrison et al., 2014; Isbell et al., 2011); however, there are relatively few studies that investigate a broad suite of biodiversity and ecosystem service indices, and their potential for optimization, within urban ecosystems (reviewed in Howe et al., 2014; Ziter, 2016).

In addition, given the increasing interest in BES within conservation research (Watson et al., 2020), recent efforts have highlighted the importance of evaluating synergies and tradeoffs between distinct biodiversity and ecosystem service indices (Lowe et al., 2022; Seppelt et al., 2011; Smith et al., 2013). A synergy describes a positive relationship between two indices, also known as a “win-win,” whereas a tradeoff describes a negative relationship between two indices, such that a “win” in one service occurs with a “loss” in another. These synergies and tradeoffs are especially relevant in urban ecosystems, where green infrastructure and green spaces are recognized as essential components for the management of resilient cities (McPhearson et al., 2015) and where there is an increasing need to simultaneously manage for multiple social and ecological dimensions (Perring et al., 2013). Further, urban ecosystems are subject to greater anthropogenic impacts compared to their non-urban counterparts, and therefore unexpected relationships between biodiversity, ecosystem services, and human well-being may emerge, expanding beyond the traditional understanding of BES relationships (Schwarz et al., 2017; Ziter, 2016). For example, urban systems often experience altered abiotic and biotic conditions, such as higher temperatures and greater habitat fragmentation (Alberti, 2015; Kuttler, 2008), as well as shifts in species composition, such as more non-native species, due to greater disturbances and human influences (Kowarik, 2011; Williams et al., 2009).

Despite these diverse human impacts, many previous urban ecosystem service studies have focused on quantifying single services, thus limiting the ability to effectively compare management strategies for multiple services within the same ecosystems (reviewed in Ziter, 2016). Outside of urban areas, past studies measuring multiple BES indices have shown that unexpected synergies can occur between distinct services. For example, enhancing habitat for pollinators can provide secondary biodiversity and ecosystem service benefits, such as reduced pest population densities and improved landscape aesthetic for humans (Wratten et al., 2012). Furthermore, the tradeoffs and synergies revealed from the quantification of BES indices are critical for developing management recommendations, many of which are implemented at smaller spatial scales (Ziter, 2016) and may be particularly important for the well-being of urban residents (Howe et al., 2014).

Local-scale habitat management is important to consider in urban green spaces, not only because decision-making often occurs at these scales (Aronson et al., 2017), but also because plant and animal biodiversity tend to respond directly to local management practices. Research from multiple urban ecosystems indicates that local-scale habitat characteristics strongly impact the abundance and composition of bird and pollinator communities (Belaire et al., 2014; Evans et al., 2009; Matteson and Langellotto, 2010). For example, increasing the diversity of flowers in urban green spaces leads to greater bee diversity (Ballare et al., 2019; Plascencia and Philpott, 2017) and increasing the native plants in urban yards results in greater bird diversity (Burghardt et al., 2009; Lerman and Warren, 2011). Further, a growing body of research indicates that green spaces, even those small in size, can contribute to ecosystem services within urban landscapes. For example, past work has shown that local increases in vegetation density and leaf area are associated with higher levels of ecosystem service provision in urban areas, such as air pollutant capture, carbon storage and sequestration, and heat mitigation (Nowak et al., 2016). Urban habitats with greater vegetation coverage and density are also likely to provide more carbon storage and sequestration (Davies et al., 2011) as well as greater heat island mitigation benefits to local residents (Davis et al., 2016). These studies illustrate the potential benefit of quantifying diverse BES indices for enhanced land management, especially in densely populated green spaces facing strong urbanization pressures.

Specifically, urban watersheds are critical systems for the study of tradeoffs in biodiversity and ecosystem services because humans tend to settle and focus their economic expansion along rivers and estuaries, and thus dense urban areas are very often located near or along water bodies (Kim et al., 2011). Urban streams and vegetated riparian areas often provide vital connectivity across developed landscapes and can be important hotspots for both biodiversity and local provisioning of ecosystem services (reviewed in Butler et al., 2022). For example, green space, especially along waterways, provides cooling benefits that mitigate urban heat island effects for many species (including humans) (Gunawardena et al., 2017), offer habitat connectivity across developed landscapes (Aronson et al., 2017; Keeley et al., 2018), and provide recreational greenways for local communities (Searns, 1995). For these reasons, urban watersheds offer a unique opportunity for understanding BES tradeoffs and synergies to better inform habitat management that supports both wildlife and human health and well-being.

In this study, we establish a uniquely multi-faceted urban watershed-scale monitoring network to investigate the relationships between habitat management, biodiversity, and ecosystem services in central Texas, one of the most rapidly urbanizing regions in the United States. Specifically, we measure key vegetation and habitat indices, multi-taxa animal biodiversity, and a range of ecosystem services to quantify important tradeoffs and synergies and develop data-driven management recommendations. We predict that we will observe 1) substantial fine-scale variation in habitat management and BES across the watershed, 2) patterns of increased forest cover and vegetation diversity corresponding to greater values in ecosystem services (reduced particulate matter, reduced temperature, and increased carbon sequestration), and 3) positive correlations between vegetation richness with animal biodiversity (e.g., greater bee and wasp richness in areas with greater floral richness).

2. Material and methods

2.1. Study area

This study was conducted in Austin, Texas, in the Waller Creek watershed. Texas is among the most rapidly growing states in the United States, with seven of the 15 fastest-growing large cities, including Austin (U.S. Census Bureau, 2018). Much of the growth in Texas is occurring along the Interstate

35 (I-35) highway corridor, which runs north-south through the major cities of San Antonio, Austin, and Dallas-Fort Worth. A substantial portion of the I-35 corridor in Texas parallels the Edwards-Trinity Aquifer, which covers >11,300 km^2 (Smith and Hunt, 2013) and is one of the most biodiverse groundwater systems in the world, providing habitat for many endangered species (Devitt et al., 2019; Smith and Hunt, 2013).

The Waller Creek watershed is the most urbanized watershed in Austin (~60 % impervious cover) (Clamann et al., 2019), and runs seven miles alongside I-35, through downtown Austin before it empties into Lady Bird Lake. The creek has a long history of challenges associated with flooding, water quality, and erosion and has been a management priority for the City of Austin's Watershed Protection Department, Parks and Recreation Department, NGOs, and private partners (Waller Creek Local Government Corporation, 2021). Additional goals for the watershed include providing recreation or cultural services, connecting people with nature, protecting or enhancing biodiversity habitat and native vegetation, expanding vegetated creek buffers, and improving resilience to climate change through activities like increased carbon sequestration and reduced urban heat island effects (City of Austin, 2014, 2016, 2018, 2019). Like many cities, Austin has a limited budget and capacity to achieve multiple management objectives and could greatly benefit from a better understanding of the synergies and tradeoffs between multiple priorities. Thus, the Waller Creek watershed is an ideal system for investigating BES relationships in urban green spaces given multiple diverse management objectives and great regional importance.

2.2. Establishing an urban watershed-scale monitoring network

We established a watershed-scale monitoring network across ten sites that span the geographic extent of the Waller Creek watershed (Fig. 1). Each study site is an urban green space adjacent to the creek. We intentionally selected study sites that spanned the extent of the watershed and represented design and management styles typical of urban green spaces. Of the ten sites, seven are owned by the City of Austin's Parks and Recreation Department (PARD) and three by The University of Texas (UT). Their total areas range from 2.5 acres to 59.4 acres (mean = 15.5 acres, sd = 21.0 acres) with a range of 7 % to 85 % mowed cover or maintained landscaping (mean = 54 %, sd = 24 %) (Table S1). Here we define ‘mowed’ as having regular (at least 3× per year) herbaceous biomass removal and ‘maintained’ as intentional landscaping, often designed for visual appeal with both woody and herbaceous plant species. At each site, we collected multiple datasets, as described below, during the same timeframe (late Spring 2018) to provide a snapshot of ecological conditions that would allow us to evaluate tradeoffs and synergies.

2.2.1. Vegetation biodiversity and habitat composition

We quantified seven indices related to vegetation biodiversity and habitat composition at each site: percent riparian forest cover, number of cover types, tree species richness, tree density, percent native trees, inflorescence abundance, and inflorescence species richness. Specifically, the *percent riparian forest cover* was quantified within a 1 km radius of the site center using geospatial data from US EPA EnviroAtlas, which estimates the percent woody cover within a distance of 15 m from the creek on both banks as a minimum buffer size for bank stability (Pickard et al., 2015). The *number of cover types* was calculated by categorizing and mapping land cover types within each green space based on the level of maintenance or management intensity. Specifically, we classified eight cover types: riparian unmaintained woodland, riparian mowed herbaceous, riparian not-mowed herbaceous, upland maintained woodland, upland unmaintained woodland, upland mowed herbaceous, upland not-mowed herbaceous, and upland maintained mixed (herbaceous and woodland) (details in Appendix B). These cover types were mapped with a combination of aerial imagery and ground-truthing with a GPS at each site. The total number of cover types in a site was then divided by the total area to standardize for variation in site sizes. This index is analogous to the patch richness density index, which is also standardized by area, and serves as a proxy for the diversity of resource types available to wildlife (McGarigal et al., 2012).

To estimate tree canopy composition in upland maintained portions of each site, we surveyed all trees which were identified to the species level and measured for diameter at breast height (DBH). From these data, *tree density* and *tree species richness* were calculated by summing the total number of individual trees and tree species, respectively, and then standardized by area of land surveyed per site. We used this data to calculate the *percent of native trees* in each site. Because tree species richness and tree density were highly collinear, we focused only on tree species richness for the remaining analyses.

Lastly, we quantified two variables describing floral resources in each green space: *inflorescence species richness* and *inflorescence abundance*. These variables were recorded along a 27 m transect within the largest patch in each cover type present at the site. On these transects, 1 × 1 meter quadrats were placed every three meters for a total of 10 quadrats per transect. In the few cases where transects had to be shortened to 18 m due to the size of the patch, quadrats were placed two meters apart. Within each quadrat, the total number of inflorescences flowering per species was recorded (as in Ballare et al., 2019). We focused on just inflorescence species richness for further analyses because inflorescence abundance and species richness variables were highly collinear.

2.2.2. Animal biodiversity

We quantified three indices related to biodiversity richness at each site for mammals, birds, and bees and wasps. We measured *mammal species richness* using motion-triggered wildlife cameras set up near the center of each site and adjacent to Waller Creek, as per methods developed by the Lincoln Park Zoo for the Urban Wildlife Information Network, in which Austin is a partner (Magle et al., 2019). Wildlife cameras were set out for one month per winter, spring, summer, and fall season. This paper focuses on data from the spring sampling season (April 2018) as it most closely aligns with the vegetation and other biodiversity sampling efforts. To estimate *bird species richness*, birds were surveyed two separate times for each site within the breeding season (late-May to mid-June 2018) as this captures peak activity and species richness for birds and pollinators (as per Belaire et al., 2014, Ballare et al., 2019). The five-minute point counts occurred between 7:30 a.m. and 10:00 a.m., and all birds seen and/or heard within 50 m of the wildlife camera were recorded using binoculars as an aid (Ralph, 1993).

To quantify *bee and wasp species richness* during the same season, we used standardized pan traps made from 3.25 oz Solo polystyrene plastic souffle portion cups. One-third of the cups were painted blue, one-third yellow, and one-third were left white (as per LeBuhn et al., 2003). The same 27 m transects (described above in the inflorescence survey) were used for pollinator surveys, but focused on the upland mowed herbaceous and upland not-mowed herbaceous habitats. These two habitats were the only ones suitable for pan-trap studies, which require minimal canopy cover. In each transect, we placed 15 bowls two meters apart if both cover types were present in the green space; if only one of the cover types was present, the 30 pan traps were staggered one meter apart along the 27 m transect. A soapy water mixture, created in a gallon water jug with a teaspoon of blue Dawn dish soap, was poured into each trap about two-thirds full (as per LeBuhn et al., 2003). Pan traps were picked up 24 h later and specimens were stored in plastic containers (one per site) with 100 % EtOH until they were washed, pinned, and dried. All bees and wasps (order Hymenoptera) were identified to species or morphospecies based on a reference collection and with assistance from taxonomic expert J.L. Neff. For all animal biodiversity analyses, we focused on species richness measures as these are straightforward to quantify from camera trap (Gallo et al., 2017) and point count data (Ralph et al., 1995), and because species richness can be particularly effective at capturing impacts of both local and landscape management, especially in urban areas (Ballare et al., 2019; Belaire et al., 2014).

2.2.3. Ecosystem services

We evaluated four indices that characterize ecosystem service conditions at each site: carbon sequestration, particulate matter concentration,

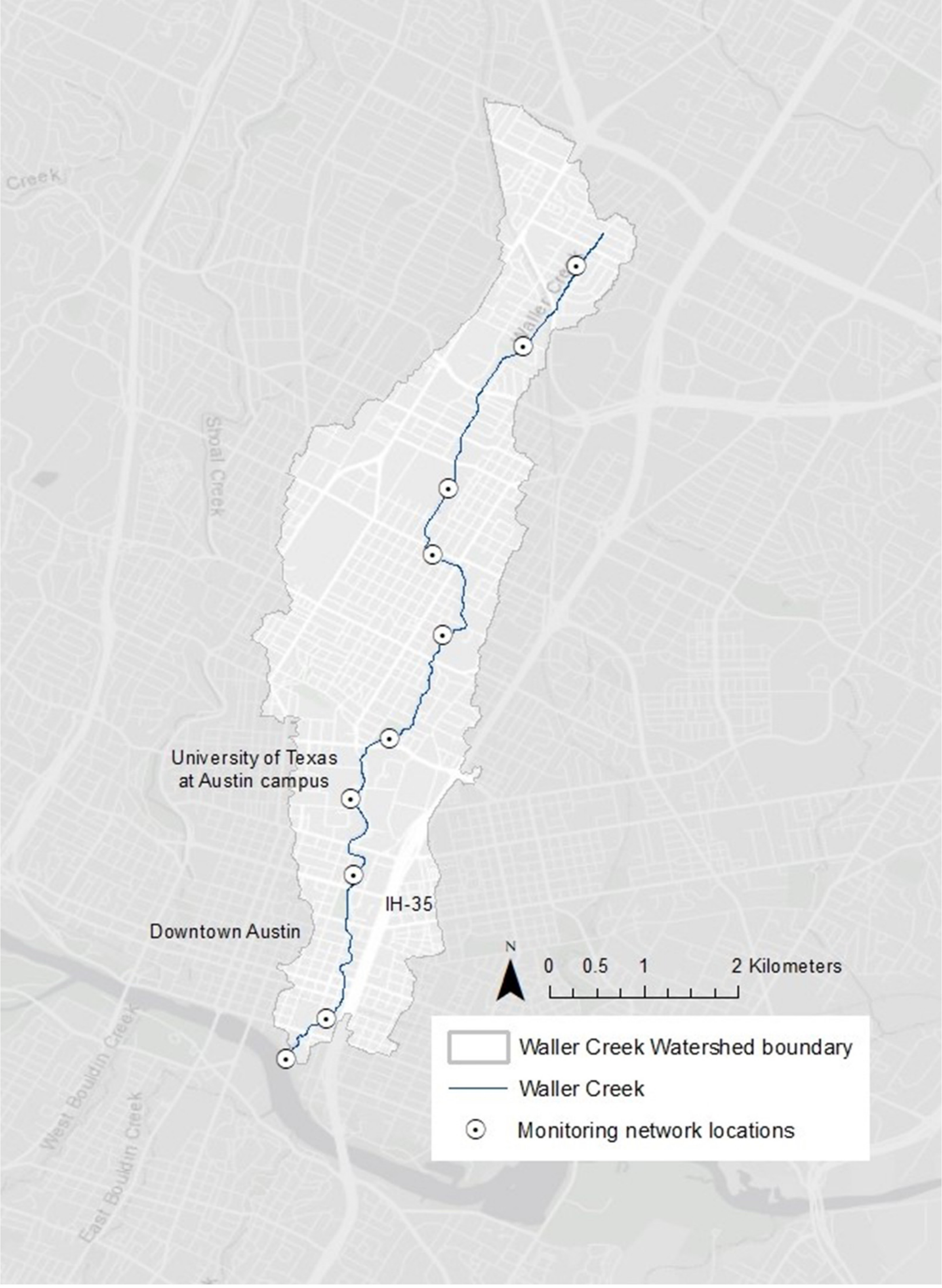

Fig. 1. Map of Waller Creek watershed in Austin, Texas. The watershed is highlighted in light grey. Waller Creek flows north to south and is depicted by the black line. Circles indicate the ten watershed-scale monitoring network sites. The locations of downtown Austin, The University of Texas at Austin, and Interstate 35 are noted for reference.

temperature, and human visitation. To estimate *carbon sequestration* rates, we used tree diameter at breast height (DBH) and species data (described above) and uploaded this into the I-Tree Eco v.6.0.10 software to calculate tons of carbon sequestration per year within each study site. This was then standardized by the area of land surveyed to account for variation in site sizes.

To estimate *particulate matter concentrations* and *temperature* at each site, we used a handheld AQ Trek Personal Air Monitor (PAM) device, developed by 2B Technologies (Ellenburg et al., 2019). Particulate Matter 2.5 ($PM_{2.5}$) is one of the six EPA regulated criteria pollutants that is associated with high vehicular activity and is particularly dangerous due to adverse health effects (e.g., cardiovascular impacts) that can occur from exposure (Crouse et al., 2012). Within each site, we surveyed a ~ 150 m transect with the AQ Trek PAM device directly adjacent to the riparian corridor of Waller Creek. During these surveys, $PM_{2.5}$ and temperature data were collected with the PAM device every second (walking at a rate of 1 m/s), and each transect was surveyed on four separate dates in the months of May and June 2018. All surveys occurred on weekdays during morning rush hour (7:00 a.m. – 9:00 a.m.). This time period is thought to have higher concentrations of $PM_{2.5}$ than evening rush hour (Gómez-Perales et al., 2007) and provides more accurate temperature readings before tree shade influences surface temperatures (Massetti et al., 2019).

Data collection during morning rush hour provided the opportunity to collect information on $PM_{2.5}$ during peak levels while simultaneously collecting accurate temperature readings in each green space. In addition, collecting data during a consistent early morning time interval allowed us to compare the air quality and temperature conditions between the green spaces in our sampling network. These datasets help characterized the abiotic conditions within each green space as experienced by humans, plants, and animals.

Lastly, to estimate *visitation rates* at each site, we adapted methods from the National Bicycle and Pedestrian Documentation Project, developed by Alta Planning & Design and the Institute of Transportation Engineers Pedestrian and Bicycle Council (Alta Planning and ITEPBC, 2016). Counts were conducted four times in June 2018, twice during the week (5:00 p.m. - 7:30 p.m.), and twice during weekends (9:30 a.m. – 12:00 p.m.), to coincide with estimated peak activity times (as recommended by Alta Planning and ITEPBC, 2016). Conducting surveys during peak activity intervals helps estimate total demand during high-volume use periods, which is an important metric for green space managers; it also helps characterize the conditions experienced by humans and by non-human biodiversity. Each sampling event occurred during a one-hour interval, where an observer sat in the center of the site (to maximize visibility of surrounding areas) counting the total number of visitors. This number was averaged across the four sampling dates to get the number of visitors per hour at each site.

2.3. Analysis

We first quantified variation and means for the three groups of indices: vegetation biodiversity and habitat composition, animal biodiversity, and ecosystem services. We then conducted pairwise Spearman correlations (as recommended for small sample sizes; Dytham, 1999) to identify tradeoffs and synergies between and across these three indices (Table S2). In this analysis, we defined a positive correlation as a synergy and a negative correlation as a tradeoff, as in past studies (Smith et al., 2013; Washbourne et al., 2020), focusing on correlations that were significant at the $p < 0.1$ level (e.g., Huang et al., 2020; Maas et al., 2021). All analyses were conducted in R Statistical Software (R Core Team, 2018).

3. Results

3.1. Summary statistics

Indices related to vegetation biodiversity and habitat composition varied substantially between the study sites, except for riparian forest cover, which was more consistent across sites (Table S3 and Fig. 2). Specifically, the species richness of flowering plants across the sites ranged from 0.3 to 2.0 per 10 square meters (mean = 1.1, sd = 0.8) of which 73 % of the species were native (49 % of individual inflorescences), while inflorescence abundance ranged from 0.6 to 16.0 per 10 square meters (mean = 5.7, sd = 5.3). Tree species richness ranged from 1.2 to 7.8 species per surveyed acre (mean = 4.0, sd = 1.9), of which 89 % of the species were native (87 % of individual trees), while tree density ranged 0.004 to 0.054 trees per square meter (mean = 0.038, sd = 0.042). Habitat heterogeneity also varied widely across all sites, ranging from a minimum of 0.1 cover types per acre to 1.4 cover types per acre (mean = 0.7, sd = 0.5). In contrast, riparian forest cover within a 1 km radius was relatively high across all sites (mean = 80.9 %, sd = 5.4 %, min = 72.1 %, max = 88.7 %).

Indices related to animal biodiversity also exhibited substantial variation (Fig. 2). Mammal richness ranged from 1 to 7 species per site (mean = 4.5, sd = 1.6), including domestic dogs and cats. When domestic dogs and cats were excluded from counts, all observed mammals were native to Texas and the species richness ranged from 0 to 5 species per site (mean = 3.0, sd = 1.3). Our remaining analysis of mammal richness excludes domestic dogs and cats. The more mobile taxa exhibited even greater variation; specifically, bird richness ranged from 5 to 11 species per site (mean = 7.1, sd = 2.3), while bees and wasp richness ranged from 8 to 14 species per site (mean = 10.6, sd = 1.8). In total, 86 % of all bird species and 94 % of all bee and wasp species observed across all sites were native to Texas.

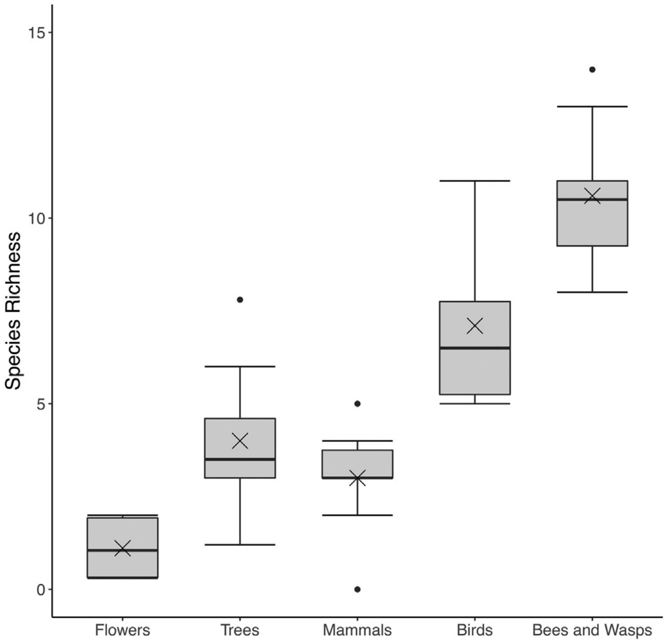

Fig. 2. Species richness of two habitat quality indices on the left (floral species richness per 10 square meters and tree species per acre surveyed) and three biodiversity indices on the right (mammals, birds, and bees and wasps). The top of the box represents the third quartile, the bottom represents the first quartile, the median line divides the box, the 'x' represents the mean, and the whiskers extend to represent variability outside the upper and lower quartiles. All data was collected in Summer 2018 except mammal data which was collected in April of 2018.

Ecosystem service indices were also distinct across sites (Fig. 3). $PM_{2.5}$ values ranged from 10.2 to 29.8 $\mu g/m^3$ (mean = 17.4, sd = 5.9), while temperature near riparian areas varied from 28.4 to 33.4 degrees Celsius (mean = 30.8, sd = 1.6). Carbon sequestration ranged from 0.1 to 1.0 tons per year/acre (mean = 0.4, sd = 0.3). The average visitation rates also varied considerably, ranging from 5 to 325 visitors per hour (mean = 72.5, sd = 95.4).

3.2. Tradeoffs and synergies

We found multiple synergies within the vegetation biodiversity and habitat composition indices (Fig. 4), with the number of cover types per acre being positively correlated with both percent native trees ($r = 0.60$) and tree species richness ($r = 0.72$). There were no positive correlations between the animal biodiversity and ecosystem service indices.

We found multiple additional synergies and one tradeoff between the groups of indices (Fig. 4). Results indicate two positive correlations between habitat quality and ecosystem services; specifically, the percent native trees and tree species richness were positively related to carbon sequestration ($r = 0.65$ and r = 0.72, respectively). We also found three synergies between habitat quality and ecosystem services; although these relationships appear negative on the correlation plot, it is important to note that they do in fact reflect synergies since $PM_{2.5}$ and temperature within the green space increase in benefit to humans as they decrease in value. Specifically, riparian forest cover at a 1 km scale was negatively correlated with two ecosystem service indices, average $PM_{2.5}$ and average temperature within the green space ($r = -0.60$ and $r = -0.65$,

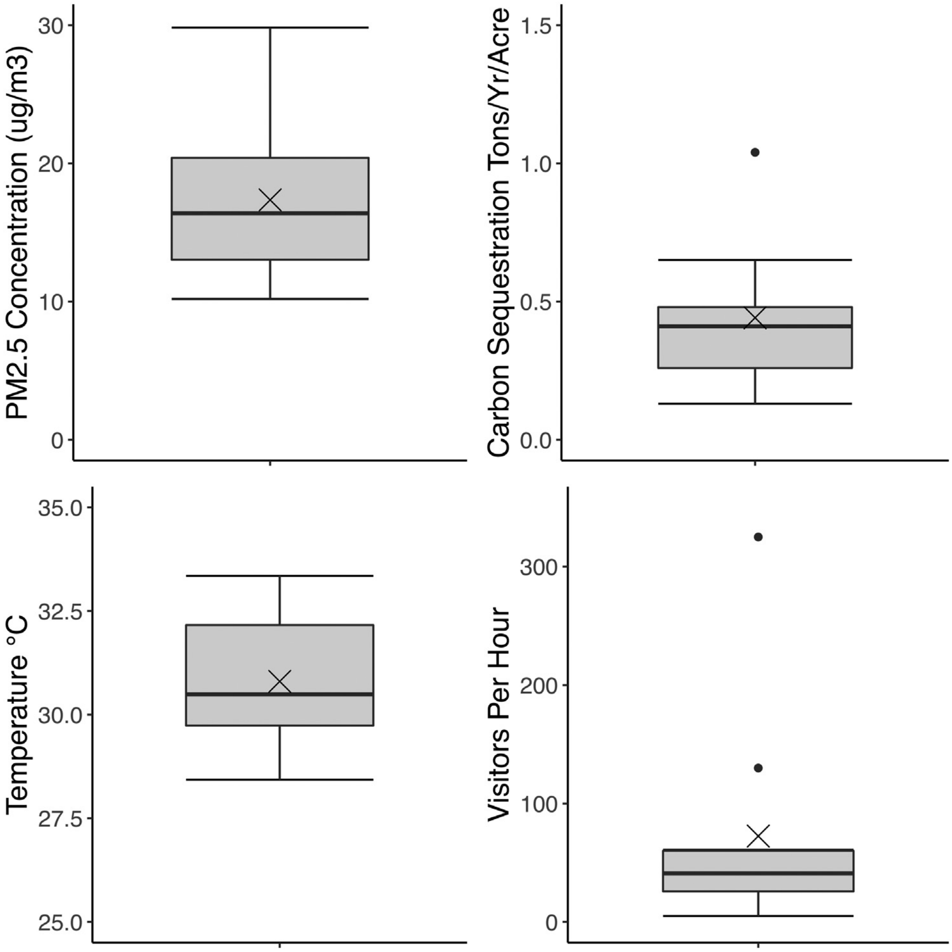

Fig. 3. Box plots illustrating the distribution of data for four ecosystem service indices: average PM2.5 concentration (ug/m3), carbon sequestration (tons per year/acre), average temperature (degrees C), and average visitors (per hour). The top of the box represents the third quartile, the bottom represents the first quartile, the median line divides the box, the 'x' represents the mean, and the whiskers extend to represent variability outside the upper and lower quartiles.

respectively). Tree species richness was also negatively correlated with the average temperature within the green space ($r = -0.65$).

Finally, we observed three synergies (positive correlations) between animal biodiversity and ecosystem services. Bee and wasp species richness was positively correlated with carbon sequestration ($r = 0.61$) and visitation rates ($r = 0.62$), and mammal species richness was also positively correlated with visitation rates ($r = 0.55$). In terms of tradeoffs, we found one tradeoff with a positive correlation between mammal species richness and average temperature within the green space ($r = 0.73$), indicating that warmer sites have higher mammal diversity (Fig. 4).

4. Discussion

By conducting a uniquely fine-scale spatial analysis of multiple biodiversity and ecosystem service condition indices, we reveal a dominance of synergistic relationships ("win-wins") between these indices within a major urban watershed. Specifically, across 12 indices – five measuring habitat quality and vegetation, three quantifying animal biodiversity, and four measuring ecosystem services – we documented ten synergies and one tradeoff in one of the nation's most rapidly growing metropolitan areas. Further, we show that sites within the same watershed can exhibit substantial variation in their vegetation and habitat management, with implications for animal biodiversity, human visitation, and ecosystem services. Thus, urban areas can offer a wide range of suitability for both wildlife and humans, depending on green space design and management. Taken together, these results indicate that urban green spaces can play an important role in supporting biodiversity and ecosystem services and that their design can be optimized to generate stacked benefits for both people and nature.

4.1. Green space vegetation relationships with ecosystem service indicators

Our results point to several important linkages between urban green space vegetation and ecosystem services that are important to city residents and wildlife alike. First, we documented a three-way synergy between riparian forest cover at the 1-km scale and two indices related to air quality and microclimate: $PM_{2.5}$ and temperature within green spaces. Specifically, as riparian forest cover increased, we found that both temperature and $PM_{2.5}$ levels within the green spaces decreased. This suggests that vegetated riparian areas may be providing services at fine spatial scales to reduce particulate matter and temperature within urban areas, benefiting both people and biodiversity within urban green spaces. These results align with past work demonstrating that vegetation cover, especially large trees, can reduce human-induced warming effects and provide fine-scale cooling services through evaporation from tree transpiration and shade (Nowak and Dwyer, 2007). This cooling service is particularly critical in cities, especially in light of urban heat island effects (Oke, 1997), where cities can register between 5 and 11 degrees Celsius warmer than surrounding areas due to high impervious cover (Kalnay and Cai, 2003). Not only do urban heat islands negatively affect human health (Kovats and Hajat, 2008; Tan et al., 2010), but urban heat extremes also impact animals (Chick et al., 2019; Merckx et al., 2018) and plant phenology (Luo et al., 2007).

Our results also align with past research highlighting the stacked benefits derived from vegetated riparian areas as important nature-based

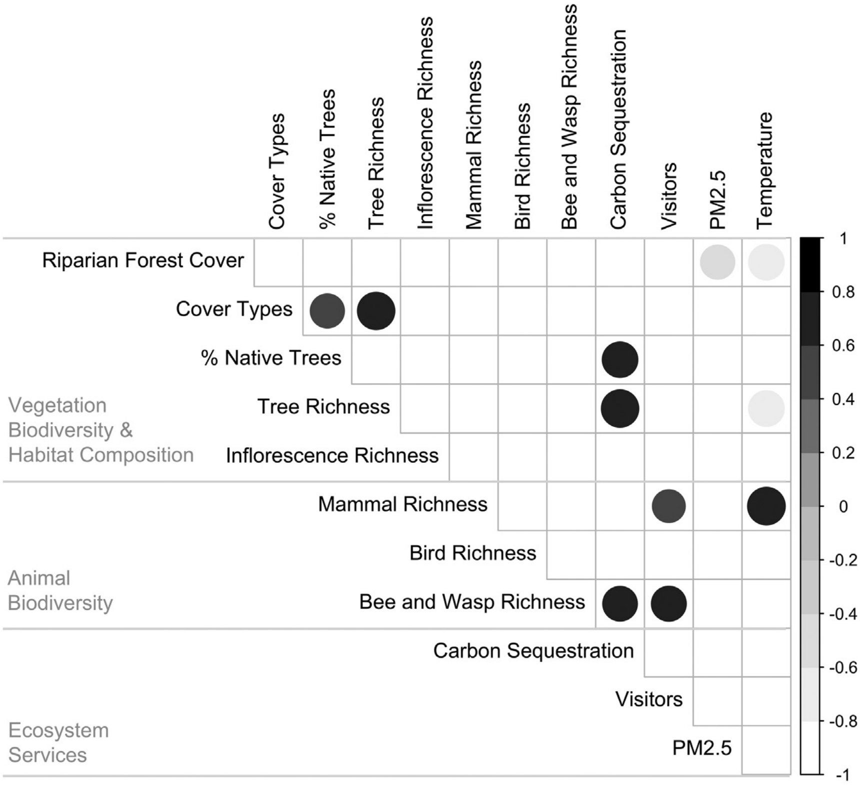

Fig. 4. Spearman correlation plot (*p*-value of 0.1) for 5 vegetation and habitat quality indices, 3 animal biodiversity indices, and 4 ecosystem service indices. The size of the circle indicates the absolute value of the corresponding correlation coefficient and the color indicates both strength and direction (white = negative, black = positive). Only correlations with p-value <0.1 are displayed.

solutions (Butler et al., 2022). While our study did not measure impacts on water quality and quantity, there is existing research establishing positive relationships between vegetated riparian areas and improved flood mitigation and water quality (Blanco-Canqui et al., 2006; Fischer and Fischenich, 2000; Groffman et al., 2003; Vidon et al., 2010). The City of Austin manages watersheds and creeks predominantly for water quality and quantity and has multiple programs around riparian restoration including a "Grow Zone" program with additional goals of enhancing species habitat and ecosystem services (City of Austin, 2021). For cities like Austin that use riparian vegetation to improve water quality and mitigate flooding, our study suggests that these efforts have additional benefits for local air quality and temperatures, which may help support other policy goals related to climate adaptation and human health.

We also found that cooler temperatures were also correlated with greater tree species richness. This relationship between tree species richness and temperature has been documented in a number of past studies (Nowak, 2010; Rahman et al., 2018; Wang et al., 2021). While this relationship has not been extensively explored in urban ecosystems, one study by Lin et al. (2018) did find that tree and shrub species richness in urban gardens was a significant predictor of mean temperature, where greater tree and shrub richness led to lower temperatures. One potential mechanism underlying this pattern could be that different tree species and their unique canopy structure can distinctively enhance climate buffering. Previous studies have demonstrated that sites with greater tree diversity often have greater functional complementarity through differential light capture strategies employed by the coexisting species (Schmid and Niklaus, 2017). In other words, complementary use of vertical space, in the form of multilayered stand structure and variations in tree crown architecture, can increase light capture and overall productivity across species within a community (Schmid and Niklaus, 2017), reducing temperatures below. Because different species often promote distinct ecosystem functioning in different places, at different times, and under different environmental conditions (Isbell et al., 2011), our results also align with past studies indicating that maintaining high tree species richness can be a key strategy for supporting ecosystem services in rapidly changing urban landscapes.

In addition, we found that sites with greater tree species richness and a greater percent native trees also had higher carbon sequestration values. These synergies provide further evidence that it is possible to increase ecosystem services without compromising vegetation biodiversity within managed urban green spaces. The benefit of increased tree species richness for carbon uptake aligns with a number of past studies, including those from both temperate (Buotte et al., 2020; Lecina-Diaz et al., 2018) and tropical systems (Liu et al., 2018), where increased tree species richness was associated with higher carbon stocks, carbon fluxes, and total carbon storage. While previous research suggests that non-native tree species are often fast-growing and can thus be important carbon sinks (Castro-Díez et al., 2019), our study sites were dominated by native trees – a total of 89 % of tree species (87 % of all individuals) – allowing us to explore their relationship with carbon sequestration. Given that high native tree diversity also provides greater foraging and habitat resources for native wildlife (Narango et al., 2017; Tallamy and Shropshire, 2009), as well as carbon, climate, and air quality services, we posit that enhancing native tree cover and richness is a critical and high-impact strategy for optimizing biodiversity and ecosystem services in urban green spaces.

Further, the City of Austin is among a large number of U.S. cities with established goals and programs associated with maintaining or increasing the urban tree canopy (Mullins and Fargo, 2008). Managing the urban tree canopy can be a stand-alone program, but is often connected with other projects related to watershed management, biodiversity, climate mitigation and adaptation, green infrastructure, and parks (Nowak and Greenfield, 2012). In response to tree canopy stressors like extreme weather, drought, and pests, many cities are diversifying species to help increase overall canopy resilience to shocks and stressors (Hauer et al., 2020). Our findings suggest that adding species richness and native species targets to urban tree canopy programs could help cities meet multiple management objectives related to resilience, biodiversity, and ecosystem services.

4.2. Biodiversity-ecosystem service relationships in an urban ecosystem

Interestingly, we found that animal biodiversity positively correlated with several ecosystem service indices, even when unrelated to putative ecosystem service providers. For example, we observed synergies between human visitation rates and both bee and wasp species richness and mammal richness. These synergies are intuitive when acknowledging that humans and wildlife often display preferences for the same habitat features in urban green spaces, such as diverse plant palettes (Fuller et al., 2007; Majewska and Altizer, 2020) and semi-natural spaces with more complex vegetation structure (Garden et al., 2007; Žlender and Thompson, 2017). Our results align with others indicating that human visitation will likely not be reduced, and instead increased, by initiatives to enhance pollinator abundance via restoration plantings (Lowenstein et al., 2014). Furthermore, the synergies we found between species richness and human visitation rates are notable in light of the growing body of research indicating that humans derive greater psychological benefits in green spaces that are more biodiverse (Fuller et al., 2007; Wood et al., 2018). Together, these findings suggest that we can support 'win-wins' for both nature and people in urban green spaces with a common set of strategies focused on plant diversity and structure.

An additional surprising BES synergy that we documented was between bee and wasp richness and carbon sequestration, given that bees and wasps are believed to prefer foraging in open habitat (Grundel et al., 2010; Majewska and Altizer, 2020), where carbon sequestration services may be limited. However, many bees and wasps nest in a variety of wood, cavity, and undisturbed ground sites, and this nesting habitat is often most available in forested areas (Roberts et al., 2017). Thus a diverse set of cover types that include both open space and forested habitat within urban green spaces could result in high bee and wasp diversity as well as high carbon sequestration services. Although we did not find a relationship between inflorescence richness and bee and wasp species richness, this may be due to the fact that the specific plant species in bloom at the time of the study may not have been high value for pollinators (as observed in Lowenstein et al., 2019), even if site-level herbaceous habitat in our system did provide valuable floral resources at other time periods.

Interestingly, we did not find positive or negative relationships between mammal, bird, and bee/wasp richness within our study sites. While the literature suggests that urban green spaces can positively affect species richness across a range of taxa (Goddard et al., 2010; Nielsen et al., 2014), there has been little consensus about how to best manage urban green spaces to support animal populations that may operate at different spatial scales, like birds and mammals (Lepczyk et al., 2017). For example, past work has demonstrated that birds and mammals often respond to nesting and food resources at distinct spatial scales, since birds have higher mobility and larger home ranges in comparison to mammals (Buchmann et al., 2013; Ottaviani et al., 2006). Other research has shown that mammals are more susceptible to physical barriers in the urban landscape like roadways, buildings, and increased human activity when compared to other taxa (Gallo et al., 2017). A recent study by Magle et al. (2021) found that urban intensity negatively correlates with diversity and richness measures for medium- to large-sized mammals. Although we did not find synergies between mammal, bird, and pollinator diversity, we note that the total species richness observed across the sampling network was relatively high. For example, we observed 5, 21, and 14 unique mammal, bird, and pollinator species during our surveys, which suggests that, collectively, green spaces in this watershed provide habitat resources for a variety of species.

Broadly, while a number of reviews have highlighted the potential relationships between biodiversity and ecosystem services (Balvanera et al., 2005; Cardinale et al., 2012; Harrison et al., 2014), only a few have been conducted specifically within urban systems, and these have demonstrated a tendency to focus on a single pair of biodiversity and ecosystem service measures, as opposed to multiple indices within a single urban system (Howe et al., 2014; Schwarz et al., 2017; Ziter, 2016). Similar to broader BES reviews (Harrison et al., 2014), urban-focused studies reveal that while the relationships between biodiversity and ecosystem service indices are often positive, not all urban ecosystem services are supported by biodiversity and not all biodiversity indices are related to ecosystem services (Schwarz et al., 2017). Additionally, recent studies highlight the importance of increasing biodiversity specifically with respect to multifunctionality, as opposed to simply increasing biodiversity regardless of function (Connop et al., 2016; Schwarz et al., 2017).

4.3. Management and policy implications

Cities are continuously faced with competing environmental management priorities, limited staff and funding, and external shocks and stressors. Thus, establishing management strategies and practices with stacked benefits for multiple objectives can help cities improve efficiencies and optimize investments. One innovative strategy that the City of Austin recently adopted is a commitment to achieve the Sustainable SITES Initiative certification for all park projects (City of Austin, 2022); SITES is a comprehensive rating system and framework for developing sustainable landscapes. In addition, we identify several policy opportunities and management practices that promote both biodiversity and ecosystem services within urban green spaces. First, because we found that higher riparian forest cover was associated with microclimate buffering and reductions in particulate matter, we suggest that urban land managers prioritize the conservation of existing riparian habitat and also work to restore and expand riparian forests where possible. Our findings, combined with previous research indicating that vegetated riparian areas provide critical habitat connectivity (Bryant, 2006; Groffman et al., 2003) and serve as "hotspots" for ecosystem services and biodiversity (Naiman and Decamps, 1997; Savard et al., 2000), suggest that conserving and restoring riparian vegetation may be a highly effective nature-based solution for biodiversity and ecosystem services within urban areas.

Second, our findings highlight the importance of tree species richness, particularly native tree species, as a management priority for urban green spaces. Our study indicates that areas with higher tree species richness have cooler temperatures and that carbon sequestration increased with tree species richness and percent native tree species. These findings are complemented by scholarship documenting the synergies between native tree species and increased native wildlife (Narango et al., 2017; Tallamy and Shropshire, 2009), emerging research on the positive relationships between exposure to trees and physical health (Wolf et al., 2020), and correlations between tree species richness and mental health improvements (Wolf et al., 2017). Together, these suggest that optimizing native tree species richness in urban green spaces may help land managers meet multiple city priorities related to biodiversity, climate mitigation and adaptation, and public health.

Finally, because we found that bee and wasp species richness was synergistic with carbon sequestration and human visitation, we show that it is possible to increase the quality of urban habitat for pollinators (e.g., increasing no-mow zones that promote flowers), while still managing for high carbon sequestration and human well-being. Indeed, promoting pollinator habitat in urban areas has the added benefit of reducing the expense of mowing in some patches, indicating that these goals can often be met with reduced management costs (Baldock et al., 2019).

5. Conclusion

Our study highlights the important role that urban green spaces can play in helping cities meet multiple objectives related to biodiversity, ecosystem services, and resilience. Across our watershed-scale monitoring network, we document substantial variation in multiple vegetation and habitat cover indices, specifically flowering plant and tree species richness, native plant cover, and habitat cover types per acre. This finding aligns with a number of studies highlighting heterogeneity within urban ecosystems (Belaire et al., 2016; Pickett et al., 2008) and provides less support for the notion that urban areas experience biotic homogenization, in which localized native species are replaced with increasingly widespread non-natives, and leading to similar biota across space (McKinney, 2006). We did not document this pattern in our study, given that the vast majority (> 70 %) of the plant and animal species we recorded were native to the region. Here, it is important to remember that Waller Creek flows through downtown Austin and is the most urbanized watershed in the city. Replicating this study in less urbanized locations in Austin could provide important nuance or additional insights given that there would likely be more native species and perhaps distinct tradeoffs and synergies.

Overall, the high level of variation we documented in vegetation and habitat composition indices indicates the important role that humans play in providing diverse resources for native species across urban areas. At the same time, we documented a dominance of "win-win" or synergistic relationships, indicating that many aspects of habitat quality, biodiversity, and ecosystem services can be simultaneously supported in urban green spaces. We highlight key management and policy opportunities for cities that are striving to achieve multiple environmental and social objectives within urban landscapes. Our results suggest that urban green spaces have the capability, under the right management decisions, to contain the fine-scale heterogeneity needed to support animal biodiversity and maximize ecosystem services and function.

CRediT authorship contribution statement

J. Amy Belaire: Conceptualization, methodology, analysis, resources, funding acquisition, project administration, writing - original draft, writing - review & editing. **Caitlin Higgins**: Investigation, analysis, writing - original draft. **Deidre Zoll:** Visualization, writing - original draft, writing - review & editing. **Katherine Lieberknecht:** Writing - review & editing, funding acquisition. **R. Patrick Bixler:** Writing - review & editing, funding acquisition. **John** L. **Neff**: Investigation, analysis, writing - review & editing. **Timothy H. Keitt:** Writing - review & editing, funding acquisition. **Shalene Jha:** Conceptualization, methodology, analysis, resources, funding acquisition, writing - original draft, writing - review & editing, supervision.

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Data availability

Data will be made available on request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Green space site management

Parks and Recreation Department sites	Waller Creek mouth (Delta), Palm Park, Eastwoods Neighborhood Park, Hancock Golf Course, Shipe Neighborhood Park, Reilly School Park, and Highland Park & Reznicek Field
University of Texas sites	UT Dell Medical Center, UT Campus (Alumni Center), and UT Wright-Whitaker Fields

Appendix B. Description of green space cover types

Cover Type	Description
Riparian Unmaintained Woodland	These areas have continuous canopy cover with no >20 ft. in between canopy edge (though, in most cases, riparian woodland areas were far more dense). In most cases, these areas are thick with poison ivy.
Riparian Mowed Herbaceous	This is characterized by maintained, mowed grasses without canopy cover. The distance between canopy edge cover must be >20 ft.
Riparian Not-Mowed Herbaceous	This is characterized by un-maintained tall grasses without canopy cover. The distance between canopy edge cover must be >20 ft. In most cases, grasses grow above ankle-length (6 in. or more).
Upland Maintained Woodland	These areas feature continuous canopy cover with no >20 ft. between canopy edges. The grass growing within these areas has been mowed, or, in some cases, these areas feature bare ground or dead litter as cover.
Upland Unmaintained Woodland	These areas feature continuous canopy cover with no >20 ft. between canopy edges. Any grass growing within these areas is un-maintained and often above ankle-height (6 in. or more). Some areas feature poison ivy.
Upland Mowed Herbaceous	This is characterized by maintained, mowed grasses without canopy cover or with sparse canopy cover in which the distance between canopy edge is >20 ft.
Upland Not-Herbaceous	These areas feature sparse canopy cover in which the distance between canopy edges is >20 ft. Grass in these areas is overgrown and often above ankle-height (6 in. or more).
Upland Maintained Mixed (Herbaceous and Woodland)	These areas are characterized by maintained, intentional landscaping and often include woody and herbaceous plant species in combination. Generally, these vegetation types are designed for visual appeal and line buildings and walkways. In some cases, such as the rain garden features at Dell Medical Center, these sites are also designed for stormwater management. There are very few of these at the green spaces we sampled.

Appendix C. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2022.157801.

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