Assessing urban tree taxonomic diversity, composition and structure across public and private green space types: a community-based tree inventory

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complies with the regulations of the University and meets the accepted standards with respect to originality and quality.

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ABSTRACT

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Kayleigh Hutt-Taylor

The urban forest is a crucial component of the city landscape, providing communities with countless benefits we refer to as ecosystem services. Trees improve urban air quality, decrease city temperatures, provide spaces for recreation and promote mental wellbeing. To properly quantify the benefits the urban forest provides, we require a strong baseline understanding of forest structure, diversity, and composition. To date, fine-scale work considering urban forest diversity has been commonly limited to trees on public land, considering only one or two green space types. However, the governance of green spaces in cities means tree species composition is being influenced by management decisions at various levels, including by institutions, municipalities, and individual landowners responsible for their care. Using a mixed-method approach combining a traditional field-inventory and community science project, I inventoried the urban forest in the residential neighbourhood of Notre-Dame-de-Grâce, Montreal. I assessed four green space types in the public and private domain: parks, institutions, street rights of way and private yards to quantify how tree diversity, composition and structure varies across multiple land management types at local scales. I additionally considered how patterns of service-traits (traits related to managers preference and ecosystem services) differed across green space types, with implications for the distribution of ecosystem services across the urban landscape. I found that green space types displayed meaningful differences in both tree diversity and structure. For example, the inclusion of private trees contributed an additional 52 species (30% of total species) not found in the local public tree inventory, and private land was dominated by smaller trees compared to the public domain. I found patterns of richness, size and abundance extend to differences in tree composition and service-traits at local-scales, particularly in the street right-of way and private yards. Composition varied considerably across street blocks; however, block

were very similar in terms of mean service-based traits. Contrastingly, species composition was similar from yard to yard, however, yards differed significantly in mean service-trait values. Overall, my work emphasizes that public tree inventories are unlikely to be fully representative of urban forest composition and structure, with implications for urban forest management at larger spatial scales.

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Land Acknowledgement

This research was conducted on the Island of Montreal, which is located on the unceded Indigenous lands of the Mohawk and Haudenosaunee People. The Kanien'kehá:ka Nation is recognized as the custodians of these lands and waters. Tiohtià:ke/Montréal is historically known as a gathering place for many First Nations. Today, it is home to a diverse population of Indigenous and other peoples.

For more information please consult Concordia's land acknowledgement with history and resources:
https://www.concordia.ca/content/dam/concordia/images/indigenous/Territorial%20Acknowledgement%20Resource%20July%202017.pdf

1. General Introduction

1.1 Urban Biodiversity and the Urban Forest

Managing biodiversity in cities that are experiencing population growth and continued urbanization is a primary goal in urban ecology research and planning (Knapp *et al.* 2021). Supporting biodiversity within urban green spaces promotes ecological resilience – providing insurance value against environmental threats (Knapp *et al.* 2021) – and supports the delivery of ecosystem services (ES), defined as the benefits people derive from ecosystems (MA 2005). The importance of supporting the sustained provision of ES in our cities is widely acknowledged. The Millennium Ecosystem Assessment Report (MA) noted that 60% of ecosystem services were being overused globally or were being consistently deteriorated (MA, 2005). The 2019 Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services report more recently concluded that building sustainable cities to meet our critical needs will require nature conservation, biodiversity restoration, and ecosystem service enhancement (IPBES 2019). Given that the majority of North Americans reside in urban areas, protecting biodiversity and ecosystem services in urban green spaces thus has important implications for human health and wellbeing (Barton & Pretty 2010; Endreny *et al.* 2017).

Knowledge around broad-scale biodiversity loss, biodiversity metrics (taxonomic, functional, phylogenetic, genetic), and their relationship with ES provision has been steadily growing within urban ecology (Ziter 2016; Aronson *et al.* 2017; Schwarz *et al.* 2017; McDonald *et al.* 2020). However, work considering how compositional, structural, and trait-based patterns vary across heterogeneous urban landscapes at finer-scales remains limited (Ziter 2016). For example, differences in management across green space types may lead to fine-scale differences in composition that influence species survival, the characteristics they possess, and thus the ecosystem services they provide (Cadenasso *et al.* 2007; Zhou *et al.* 2017). The composition and structure of green spaces may also prioritize provision of specific ES, while promoting or threatening diversity (Avolio *et al.* 2021). Generally, maintaining multifunctional landscapes through green space management has important outcomes for the sustained provision of ecosystem services in cities (Madureira & Andresen 2014). Using management based approaches to support urban tree diversity, will however, require a more fine-scale understanding of tree diversity and structure across a variety of green space types (Kowarik 2011; McDonald *et al.* 2020).

1.2 Urban Forest Management Across Green Space Types

Much of urban forest management practices have promoted low diversity communities that meet the demands of stressful urban conditions (Paquette *et al.* 2021), however, we know these communities are more susceptible to threats like climate change and disease. Researchers and practitioners are increasingly focusing on the need for more biodiverse urban forests. Ecologists in particular are increasingly interested in exploring how urban forest diversity varies across multiple spatial scales, and how these patterns extend to ecosystem service provision (Zhou *et al.* 2017). Furthermore, determining how diversity metrics beyond species richness differ in multiple green spaces can aid urban managers in supporting a diverse, resilient urban forest while also considering which green spaces hold the most potential for intervention and management (Avolio *et al.* 2021; Paquette *et al.* 2021).

Despite mounting interest in promoting a diverse urban forest across multiple green spaces, most urban forest research is limited to trees on public land using one or two land-use types (e.g., green spaces). Private land in particular can account for over half of city-wide green space, predominantly in residential yards (Larouche *et al.* 2019). Private trees have remained largely inaccessible for urban ecological work due to barriers to data collection, where sampling private land requires resident approval and takes time which leads to high costs and logistical challenges for research groups (Dyson *et al.* 2019). Cities however, tend to inventory public trees as they are planted and maintained, meaning data is easy access for researchers to investigate patterns of diversity in the public domain (Ossola *et al.* 2020). Understanding how both public and private land contributes to patterns of urban forest composition and structure is an essential step towards developing a more complete understanding of urban forest resilience and long-term ecosystem service provision. In order to quantify and manage the benefits provided by the urban forest, we must first have a strong baseline understanding of urban tree structure, diversity and composition.

1.3 Thesis Objectives

In the following two chapters I explored patterns of urban forest structure and composition using a mixed-methods approach combining traditional field inventory and community science. Broadly, I explored two research questions:

1. How does urban forest diversity and structure differ across multiple green space types, including public and private land?
2. Beyond tree diversity and structure, how do species and service-trait composition differ across multiple urban green space types?

The first chapter of my thesis quantifies differences in tree diversity (richness, evenness, species abundance) and structure between four green space types (parks, street right of way, private yards and institutions) in the public and private domain. I explore differences in the tree diversity and structure on private and public land and discuss the implications for urban forestry-based management targeting specific green space types. In my second chapter I build on patterns of public and private tree diversity by extending these findings to the composition of both species and service-based traits linked to ecosystem services and human preference, with implications for landscape multifunctionality and service provision.

Manuscript: Chapter 1

Title: Private trees contribute uniquely to urban forest diversity and structure: a community-based study of the urban forest

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Highlights

- Public tree inventories are not fully representative of urban forest composition and structure.
- Private land contributes unique tree species that represent 30% of total tree richness and is dominated by smaller trees compared to public land.
- Per unit area, the street right-of-way was the most tree dense and species rich green space type and contained the largest trees. Municipalities may be over-reliant on the street right-of-way for tree-based ecosystem services.
- We found that the scale at which a green space is managed and the scale at which diversity metrics vary are not always aligned.
- Overall, the unique species and structure of trees on private land shown in our work emphasize that targeting individual residents' attitudes and actions should be a key management strategy for urban forest diversity and resilience.

Abstract

The urban forest is made up of the trees and associated green spaces in parks, streets, private land and natural areas within the city. A diverse urban forest can provide resilience to environmental change (such as climate change, or insect outbreaks) while also providing numerous benefits to people. As part of the urban landscape, trees are a key contributor to biodiversity and ecosystem services like temperature regulation, pollution reduction and recreation. To quantify, map, and manage the benefits provided by urban forests – of interest to citizens, private organizations, and municipalities alike – a strong baseline understanding of urban tree structure and diversity is essential. Across many cities, approximately half of all trees are growing on privately managed land. Yet, we still lack an understanding of the characteristics of these private trees (e.g., species, size). Using a mixed method approach, combining a traditional field inventory and community science project, we built a tree inventory in Notre-Dame-de-Grâce Montréal, Canada across four green space types in the public and private domain. We found that the inclusion of private trees contributed an additional 52 species (30% of total species) not found in the local public tree inventory. Per unit area, the street right of way (ROW) and private yards held the highest tree densities and were the most species rich green space types. Street ROW dominated large tree sizes, while private yards had characteristically small tree species. These results suggest municipalities may be over-reliant on the street right of way for tree-based ecosystem services compared to parks, institutions and private residences. We also found that the scale at which a green space is managed and the scale at which tree diversity metrics vary do not always match. The scales at which ecologists study biodiversity patterns may mask broader patterns that emerge as a result of management. Determining best practices for effective approaches to analysis that consider the scale of management while also controlling for differences in area should be an area of further investigation in urban ecological work. Overall, the unique species and structure of trees on private land shown in our work emphasize that targeting individual residents' attitudes and actions has strong potential to improve urban forest diversity and resilience.

Keywords: Urban forestry; community science; citizen science; urban green spaces; species diversity; fine scale

1. Introduction

As cities continue to expand globally, urbanization and land use transformation have resulted in large-scale changes in biodiversity (van Vliet 2019; McDonald *et al.* 2020). More than 82% of North Americans live in urban areas (United Nations *et al.* 2019), thus, maintaining the functions and ecosystem services urban green spaces provide has important implications for both the ecology of urban landscapes as well as human health and wellbeing (United Nations *et al.* 2019). Within urban landscapes, trees are a key component of city-wide biodiversity (Grimm *et al.* 2008). Together, all of the trees in our cities make up the urban forest, which comprises the trees in green spaces such as parks and natural areas, institutions, private yards, street right of ways and vacant lots within the city (Larouche *et al.* 2019). The urban forest provides a host of benefits to humans through the delivery of ecosystem services like regulating temperature, reducing air pollution and stormwater runoff, and providing recreational space for physical activity and mental wellbeing (Bowler *et al.* 2010; Cadotte *et al.* 2011; Escobedo *et al.* 2011; Kirnbauer *et al.* 2013; Nowak *et al.* 2013). The composition of trees within the urban forest has the potential to influence both the variety and amount of services we receive as well as overall forest health and resilience (Grimm *et al.* 2008; Mace *et al.* 2012; Lovell & Taylor 2013; Goodness *et al.* 2016; Pearse *et al.* 2018). For example, a diverse urban forest can provide insurance value by maintaining ecosystem functions (and their associated services) in the face of environmental change and disturbance (Paquette *et al.* 2021). As species respond to change or stress, some will maintain overall function, while others may fail (Kowarik 2011). Generally, sustaining and enhancing diversity in our urban forests can help protect the benefits they currently provide our communities and promote their sustained deliverance through a multifunctional landscape.

Despite mounting evidence of the numerous benefits and value of urban forests, our understanding of urban forest diversity remains incomplete - particularly considering metrics beyond species richness. Many urban tree diversity studies have focused on patterns of species richness along urban to rural gradients, with tree species richness typically increasing in urban areas relative to their natural counterparts (Jim & Liu 2001; Cornelis & Hermy 2004; Nowak & Walton 2005; Nock *et al.* 2013; Aronson *et al.* 2014; Blood *et al.* 2016; Morgenroth *et al.* 2016). However, species richness alone gives an incomplete picture of an urban forest – as many rare species may inflate the overall number with minimal effects on overall forest composition (Morgenroth *et al.* 2016; Larouche *et al.* 2021). To combat this, the widely cited 10-20-30 rule states that no species should account for more than ten percent, no genus more than 20 percent and no family more than 30 percent of the tree community (Santamour 1999; Kendal *et al.* 2014). However, many cities are falling short of this benchmark and tend to over-rely on certain genera and species to maximize landscape suitability or ecosystem services (Doroski *et al.* 2020). Beyond species composition, forest structure (e.g., tree size, age, density) also has important implications for urban forest management and ecosystem services. For example, large, mature trees can increase ecosystem service provision (Song *et al.* 2020), however, an urban forest dominated by mature trees will be under threat when those trees die off or need to be removed (McPherson *et al.* 1997). Therefore, considering composition, structure and diversity can provide a more integrated picture of urban forest resilience and capacity to sustain long-term ecosystem service provision (Kendal *et al.* 2014; Morgenroth *et al.* 2016).

Patterns of urban tree diversity across green space types are also influenced by a multitude of factors related to management decisions and demography, including socioeconomic status, land-use legacies, resident attitudes and municipal policies (Berland *et al.* 2011; MacGregor-Fors & Ortega-Álvarez 2011; Dallimer *et al.* 2012; Roman *et al.* 2018). Patterns of diversity related to human-mediated drivers and structural inequality are now well-documented in urban ecology literature (Kowarik 2011; Aronson *et al.* 2017; Leong *et al.* 2018; Schell *et al.* 2020). Tree diversity and canopy cover tend to have a positive relationship with increasing levels of wealth, although this relationship is not ubiquitous (Gerrish & Watkins 2018; Leong *et al.* 2018; Landry *et al.* 2020). Tree composition and diversity can also be dependent on nursery availability and which species are being sold within the area (Avolio *et al.* 2018). Furthermore, municipal policies regarding public tree management also vary considerably across municipalities in their focus on planting, monitoring, native planting programs and removal (Conway & Urbani 2007).

Beyond neighbourhood-scale drivers, individual residents also influence tree diversity directly through activities like the introduction of new species. High levels of species richness in urban areas occur due to the addition and management of these new species into the landscape. Plant communities in particular experience more direct influence by human management compared to other taxonomic groups. Consequently, management decisions by individuals involved in the governance of urban green spaces can scale up to influence which species are present and what role they play in the urban landscape (Cadenasso *et al.* 2007; Kowarik 2011; Pham *et al.* 2013; Zhou *et al.* 2017). Overall, management of both public and private green spaces are driven by these social, cultural and municipal factors that result in differences in composition and structure across the urban landscape (Aronson *et al.* 2017).

Despite the influences of individual land manager decisions on both public and private land affecting urban tree species, urban forestry research is largely represented by work conducted on public land, at large-scales, pooling the entire species pool to address city-wide patterns in urban forest diversity (Jim and Liu 2001, Nagendra and Gopal 2011, Sjöman et al. 2012). However, some recent efforts have increased work incorporating trees on private land. For example, the introduction of the FIA program (in the United States) to inventory urban trees on public and private land (USDA Forest Service 2015) and more fine-scale work examining private residents role and preferences for tree planting and barriers to sampling on private land (Shakeel & Conway 2014; Avolio *et al.* 2018; Dyson *et al.* 2019; Ossola *et al.* 2019b). The dominance of work in the public-domain is mostly due to barriers in data collection and the inaccessibility of private land for sampling (Dyson *et al.* 2019). Many studies combine land-use types across the entire urban landscape (all public trees) or have focused on land-use types specific to public land (Bourne & Conway 2014; Larouche *et al.* 2021; Paquette *et al.* 2021; Wood & Dupras 2021). Yet, it’s clear that the different actors involved in the management of different green space types will result in varied personal preferences, plantable area use, and decision making, which in turn influence tree species composition (Pearse et al. 2018, Avolio et al. 2018). For example, Bourne and Conway (2014) found significant differences in tree species diversity across six urban land-use types where private residential plots exhibited the highest alpha diversity (site level local diversity) compared to public land-use types. Similar work in Australia found that residential neighbourhoods had significantly higher vegetative richness compared to golf courses, parks and remnant land (Threlfall *et al.* 2016). Trees on private land may be contributing unique species and structure to the urban forest that are not currently captured in public inventories. Work incorporating private land use types highlights the importance of differentiating landscape composition and scales of management when assessing diversity patterns, especially in an urban context, where numerous groups are responsible for green space management (Aronson *et al.* 2017).

Trees on private land - where individual preferences have a strong influence on tree choice - are particularly important as a result of their abundance within the urban forest. Municipalities worldwide have found that trees on private land account for upwards of half of all urban trees (Pataki *et al.* 2013; Avolio *et al.* 2015; Monteiro *et al.* 2020). In Toronto, Canada, for example, it's estimated that private trees represent 60% of the urban forest, while in our study area in Montreal they are estimated to account for close to 50% of all trees (CDN-NDG 2011; Larouche *et al.* 2021). Thus, continuing to rely solely on public tree data means we are excluding a crucial component of the urban forest which may contain species not currently represented in public tree datasets. Determining whether widely used public tree inventories are truly representative of the structure and composition of the citywide urban forest requires that research extend beyond city-owned land.

Here, we investigate how tree diversity and structure varies between public and private green spaces. The goal of our work was to improve our current understanding of the urban forest through a neighbourhood scale tree inventory in Notre-Dame-de-Grâce (Montreal, QC) in four green space types: street right-of-way (ROW), institutions, parks, and private yards. We asked two research questions:

1) How do green space types differ in tree species diversity and structure at the neighbourhood scale?

2) How do green space types differ in tree richness, evenness and abundance when compared at equal units of area?

Since public and privately managed green spaces serve different purposes in the urban landscape, we expected tree diversity metrics to differ among green space types at both the neighbourhood scale and at equal units of area. Overall, we expected tree species richness to be highest in residential yards (private land) where individual preferences for specific species likely increases species richness at local scales. We expected the street right of ways to have the lowest species richness since tree species are often selected for specific purposes in the; landscape, thus limited species choice (stress tolerance, tree shape) (Cowett & Bassuk 2017). We expected the street ROW to exhibit low species evenness, since street trees are often managed for block wide consistency for ease of maintenance and aesthetic value which leads to street blocks being dominated by a subset of species which decreases local-scale evenness (Asirifi 2020). We expected species evenness to be lowest in residential yards where rare and exotic species that occur infrequently are likely present due to resident choices which will decrease overall evenness at local scales by increasing rare species.

3. Methods

3.1 Study Area

Our study was conducted on the island of Montreal in the borough of Cote-des-Neiges-Notre-Dame-de-Grâce (CDN-NDG). Our tree inventory took place in the neighbourhood of Notre Dame-de-Grâce (NDG) within CDN-NDG, west of the downtown core (Fig. 1). The City of Montreal is the second most populated city in Canada, with approximately two million residents (Statistics Canada, 2017). Montreal is composed of 19 boroughs (administrative units, with their own mayor and council) that are characterized by a gradient of population densities, demographics and urban development that each contain a range of urban green space types including public parks, institutions, private commercial land and private residential yards. Each borough functions independently in the areas of urban planning, the environment, park management and budgets. NDG is characterized as a residential neighbourhood dominated by low-rise apartments (less than 5 stories), semi-detached homes, duplexes and single-family homes (Statistics Canada, 2017). The neighbourhood has a population of 31,782 individuals and over fifty percent of its residents are above 35 years of age. In 2011, NDG-CDN became the second Montreal borough to adopt an urban forestry plan (CDN-NDG 2011). The forestry plan has six broad goals: 1) placing the urban forest at the center of urban planning, 2) improving general understanding of the urban forest, 3) preserving existing urban forest components, 4) improving public satisfaction of public trees, 5) developing the urban forest (through planting) and 6) encouraging public engagement with the urban forest.

3.2 Tree Data and Green Space Types

We conducted a tree inventory of green space types common throughout NDG, and representative of residential neighbourhoods across Montreal and similar cities. The core area sampled within the broader neighbourhood boundaries covered approximately 2 km² (Fig. 1) in close proximity to Concordia University's Loyola Campus to facilitate ease of surveying and the re-use of data for teaching and learning applications. In response to the COVID-19 pandemic there was a need for safer methodologies to collect tree data from private dwellings within our study area, as well as a desire to engage the community in the process of science. Due to this necessary change in approach, submissions from private yards were opened beyond the original 2 km^2 study area to ensure adequate participation (Fig. 1). Within the core area (2km^2), we classified green spaces into four distinct categories representative of the broader green space types commonly found in urban neighbourhoods: parks, institutions (schoolyards and places of worship), private residential yards and street rights of way (see appendix I, Table A1.1). The boundaries of each green space were categorized based on the scale of management and land ownership. For example, an individual park, residential yard, or institutional ground was defined by its parcel boundaries (boundary of land ownership), while street rights of way (ROW) were defined as the portion of public plantable area along each side of a street segment, excluding the cement sidewalk along roadways (Figure 1).

3.3 Data

3.3.1 Public Tree Inventory

Between July-September 2020 we surveyed public parks (n=7), institutions (n=16) and street rights of way (n=109) within our study area through field collection. We accessed NDG-CDNs public tree inventory available through the city of Montreal's open data portal to locate all public trees (Ville de Montreal, 2020). Most tree species on public land (e.g., in parks and along streets) are classified in this inventory and include GPS coordinates (latitude, longitude), location classification, a diameter at breast height (DBH) measurement and in some cases planting date. All public trees were re-surveyed to correct inaccuracies (e.g., missing, dead, or misidentified trees) and update outdated DBH measurements.

We considered institutional green spaces as publicly accessible private land for our inventory. Institutional green spaces are rarely included in public tree inventories in Canadian cities because they are managed much like private land by individual managers. However, institutional land is often accessible to the public in some capacity through courtyards, public sitting areas or pathways. Although institutional green space may be accessible to the public, the actual management and planting decisions for an institution in our region are more reflective of the private domain (Bourne & Conway 2014). Institutional green spaces within our study area were identified using Google Maps and borough level administrative information on public institutions. We sampled sixteen institutional spaces (6 places of worship and 10 educational institutions).

Within each publicly accessible green space type: parks, street right of way and institutions, all live trees and large shrubs > 5 cm diameter at breast height (DBH) (Nowak *et al.* 2008; Nock *et al.* 2013) were inventoried. Trees were identified to the species level and geo-located. To ensure consistency across all sampled land cover types, cultivars were classified at the species level unless they were visually distinct (tree habit or leaf colour) in which case we noted the physical difference (e.g., maroon leaves) and treated the species as a separate species (see appendix). These unique species accounted for only 10% of the species pool. Finally, DBH was measured at 1.3 meters from the base of the tree and dead trees were noted and excluded from further analysis.

3.3.2 Private Residential Tree Inventory

Beginning in May 2020, we launched a community science project across the neighbourhood of Notre-Dame-de-Grâce named “The NDG Community Tree Project” (Dunlevy, 2020). The private tree inventory represents a subset of residential parcels (n= 89), which represents approximately 1.5% of all households with trees in the neighbourhood submission boundary and 4% of the estimated households within the 2 km^2 core area. This sampling effort is comparable to previous work incorporating residential yards in urban forestry work, particularly considering 37% of yards within the neighbourhood contained no trees (Bourne & Conway 2014; Avolio *et al.* 2018; Cavender-Bares *et al.* 2020)) (see appendix I). Using social and traditional news media (e.g., Facebook groups, community organizations, listservs, news articles and radio) we launched a project website which provided participants materials including “How-To” tutorial videos and worksheets to complete their inventory. To improve community awareness, we also conducted a targeted mail-drop of informational flyers (see appendix) within our study area between July and August 2020 in conjunction with our street tree surveys. Residents were asked to measure each tree's trunk circumference and submit three photos: (1) the entire tree, (2) the leaves/flowers and (3) bark, for identification or verification by our research team. For each submission, all trees were identified to species level and tree circumferences were converted to DBH to the nearest cm. Tree data were collected for private trees within both front and back yards to be representative of the entire residential parcel (excluding any public street trees that may be located in the front yard) and capture variation in front and backyard planting (Ossola *et al.* 2019a). Submissions that did not meet the initial requirements for submission to the community science project were excluded from analysis. For example, submissions from individuals in large apartment complexes, and community owned buildings were excluded since the ownership and management of these properties can involve multiple actors. Similarly, submissions that were located outside the NDG neighbourhood boundaries were not included in future analysis. Of the 98 resident submissions, 89 were selected as appropriate for analysis. All necessary ethical protocols were met to ensure participating residents’ privacy through Concordia University’s Human Research Ethics Committee (Certification Number: 30013987).

3.4 Controlling for Differences in Area

Due to the unique ways land is managed in cities, urban ecologists often struggle to reach consensus on comparable units of analysis. For example, we may expect differences in diversity and composition at the unit of management (the scale at which a green space is governed), such as a resident's private yard, an entire park or a school ground. As a result, many studies are choosing to employ parcel-level analysis to integrate these relevant scales of management within urban areas (Lepczyk *et al.* {2017; Kinzig *et al.* 2005; Avolio *et al.* 2015; Nitoslawski *et al.* 2016). However, ecological metrics (e.g. species richness, evenness) can also be influenced by differences in sampling area, meaning it's also important to compare these metrics on a per area basis (Staudhammer *et al.* 2018). Furthermore, if we're interested in understanding which green space types are contributing disproportionately to the urban forest or may have high potential for increased management, we must consider their differences on a per unit area basis. For example, per hectare, which green space holds the highest density of trees? Or the most species? We were interested in these effects of scale on our understanding of metrics of urban forest diversity, and thus chose to first consider differences at the scale of the neighbourhood pooling all trees in each green space (Objective 1), while also considering differences at equal units of area through subsampling (Objective 2).

First, to characterize the structure and diversity of the urban forest at a neighbourhood scale (Objective 1), we pooled trees in each green space type across the entire inventory. This provided us with general characteristics of the entire urban forest and coarse-scale differences between green space types. Second, to characterize the structure and diversity of the urban forest on a per-unit-area basis (Objective 2), we controlled for differences in area within our sampling sites as described below.

3.4.1 Public Parks and Institutions

Since the boundaries of parks and institutional green spaces differed within and across green space types (e.g., the size of each park differed from each other, and differed from other green space types), we chose to sub-sample and create subsites of equal areas for analysis (see Fig. 1). Each public park and institutional sample site (e.g. an individual park or place of worship) was delineated into subsites of approximately 400 m^2 (0.04 ha) following standard forest assessment protocol, including in i-Tree Eco, a peer reviewed software suite widely used for municipal and urban forestry applications (i-Tree 2021). This plot size (0.04 ha) was also consistent with the average sizes of street ROW and private yards in our sample, ensuring comparable units of area across all assessed green space types (Table 1). To ensure only plantable area was considered, first, we sourced a land-use classification polygon layer from the public data portal from the Communauté Métropolitaine de Montréal (CMM) (CMM 2020). Second, we sourced a building footprint polygon layer from Microsoft formatted for the entire island of Montreal (Microsoft 2019). Using both layers, any built infrastructure located on sample sites (e.g., washroom structures, maintenance buildings, school buildings) were removed to create a new polygon of 'plantable' area (green space in the absence of built infrastructure). This resulted in 314 park subsites and 126 institutional subsites for analysis. Subsites which contained no trees accounted for approximately 28% of subsites (30% in parks and 25% in institutions) and were removed from further analysis. In most cases these areas were not truly plantable and were being used for other purposes such as gravel playgrounds, sport fields or paved seating areas. Since private yards and street blocks without trees were not included, we concluded that removing empty subsites (which may not be true plantable areas), would minimize bias and improve consistency across green space types - consequently, our results emphasize differences in tree diversity and structure *where trees are present*, but may be an overestimate of absolute tree abundances per green space type. Since some parks or institutional land parcels could not be perfectly divided into 0.04 ha subsites (ranging between 0.03 to 0.05) we included log transformed subsite area as a covariate in all subsequent linear mixed models to account for the effect of any remaining differences in area.

3.4.2 Street Right of Way and Private Residential Yards

Street Right of Way (ROW) and Private Residential Yards varied only slightly in area, with mean sample unit areas of 0.04 (±0.01) and 0.03 (±0.01) hectares respectively (Table 1). Thus, we decided not to further subset these sites and retain the full area of each ROW or yard as a sampling site. However, since metrics of diversity can be sensitive to differences in area, we again included log transformed area (ha) as a covariate in all subsequent linear mixed models.

3.5 Tree abundance, richness and evenness and size structure

We calculated two indices of taxonomic diversity for each parcel and site within an urban green space type: species richness and Hurlbert's probability of interspecific encounter (PIE), a metric of species evenness. Species richness measures for green space type rarefaction curves were calculated under the framework of Hill numbers (Hill 1973). Hill (1973) introduced integrated species richness and species relative abundances into a class of diversity measures, now referred to as Hill numbers, or effective numbers of species. According to Hills framework, species richness, (q=0) counts species equally without regard to their relative abundances. Hurlbert's probability of interspecific encounter (PIE) ranges between 0-1 and estimates the probability of two randomly selected individuals from a sample belonging to different species (Hurlbert 1971). A community with ten individuals all belonging to the same species would thus be an evenness value of zero. PIE values were calculated for the combined species across an entire green space type (all parks, all institutional spaces), averaged across parcel scales and for individual sites of equal area. A value closer to 1 indicates higher evenness, while values closer to 0 indicate low evenness in the community. Tree abundance was calculated as the number of trees per subsite. In cases where multi-stemmed individuals were measured, stem measurements were consolidated and considered as one tree. For example, a multi-stemmed lilac (4 stems) was considered one tree (Magarik *et al.* 2020). Finally, to examine the composition of tree sizes across different green space types, we plotted size distribution curves (kernel densities) using DBH measurements. To determine whether DBH distributions were consistent with young trees or simply smaller tree species, we also examined maximum tree DBH values across the four green space types (see appendix III).

3.6 Statistical Analysis

3.6.1 Rarefaction Curves

We determined differences in species richness among green space types at the neighbourhood scale through individual-based rarefaction curves using tree species data compiled across an entire green space type (Colwell *et al.* 2012). Rarefaction curves are produced by repeatedly re-sampling the pool of N samples at random and plotting the average number of species with accumulating individuals. This means rarefaction curves are statistical expectations (through interpolation) of their expected accumulation curves as samples are re-sampled. Rarefaction curves allow us to compare diversity across different sized samples (different numbers of sites) through the calculation of expected richness at a standardized size (Staudhammer *et al.* 2018). However, in some cases, this requires down-sampling to reach the same number of observed individuals. The package “iNEXT” overcomes this limitation by offering a unified framework for estimating species diversity using rarefaction/extrapolation sampling curves integrated into one analysis which allow both rarefaction to smaller sample sizes and extrapolation to larger sample sizes guided by an estimated asymptotic species richness (Hsieh *et al.* 2016). Species richness curves were assessed for sample coverage: which is the proportion of the total number of individuals that belong to the species detected in the sample. The package employs the concept of Hill numbers for abundance data (Chao *et al.* 2014) and diversity calculations as explained above.

We constructed species richness individual-based rarefaction and extrapolation curves for each green space type using the R package “iNEXT” (Chao & Jost 2012; Colwell *et al.* 2012; Chao *et al.* 2014). Species incidence by subsite matrices for each green space type were used to estimate rarefaction and extrapolation curves. Species richness curves were created through 100 bootstrap replicates, extracting the mean of our replicates to estimate 95% confidence intervals for each curve. If confidence intervals of the different green space types did not overlap, we concluded that species richness differed significantly ($p<0.05$) from other green space types (Colwell et al., 2012). To confirm these patterns, and to ensure values of species richness were not overestimated, we also replicated this analysis using sample-based rarefaction, through spatially explicit rarefaction curves to evaluate the extent to which subsites, which are spatially autocorrelated (within parks and institutions) may have influenced estimates of species richness (see appendix III for detail).

3.6.2 Linear Mixed Models

To evaluate effects of green space type on species richness, tree abundance and evenness on a per unit area scale (using subsite data) (Obj 2), we used generalized linear mixed models using R's "glmer" and "lmer" function in the "lme4" package (significance level α= 0.05) (Bates *et al.* 2015). For all models, log transformed area was included as a covariate so that differences in area were integrated into the model. Species richness, tree abundance, and Hurlburt's PIE evenness were continuous variables describing the characteristics of each site, however, each differed in underlying distribution. To improve model fit, species (count) data were modelled using a negative-binomial distribution, while abundance data was log transformed. Evenness was fit using a linear mixed model using a standard gaussian distribution. For all models, subsites in parks and institutional green spaces were nested within each land parcel (e.g., an entire park) as a random effect to account for sub-sampling (non-independent samples) (Millar & Anderson 2004). All model residuals were visually inspected for normality using diagnostic plots. We then evaluated the significance of each green space type using the "Anova" function in the "car" package in R to generate p-values using Type II Wald chi-square tests. Mean estimates and associated 95% confidence intervals were calculated according to our model equations using the "predictInterval" function in R. Finally, we performed Tukey multiple pairwise comparisons using the "glht" function in the "multcomp" package to determine how specific green space types differed from each other according to each model estimate (richness, abundance and evenness) with single-step corrections for multiple comparisons. All statistical analyses were done in R 4.0.4 (R Studio, 2021).

4. Results

4.1 Urban Forest Plot Summary

In total, our work resulted in 4,272 trees for analysis across the four green space types including 155 tree species (see appendix for detail). Total species richness was highest in private residential yards (102 species) despite inventorying only 4% of yards with trees. Species rarefaction curves indicated that even with only including a proportion of all private yards in the study area, species captured were sufficient and comparable to other work in private yards (Fig. 2) (Bourne & Conway 2014; Avolio *et al.* 2018; Cavender-Bares *et al.* 2020). Species richness was lowest in institutional land (70 species) with intermediate numbers in parks and street ROW (83 and 85 respectively). The five most abundant tree species across the entire urban forest plot were Norway Maple (*Acer platanoides)* (14.4%), Eastern White Cedar (*Thuja occidentalis)* (13.4%), Silver Maple (*Acer saccharinum)* (11.9%), Littleleaf Linden (*Tilia cordata)* (5.5%) and Green Ash (*Fraxinus pennsylvanica)* (3.2%) meaning five species accounted for 48.4% of the entire inventory sample. The genus *Acer* accounted for over 30% of the tree population, meaning that our study area does not meet the 10-20-30 standard at any of the three levels. Considering the entire tree inventory, no single green space type contained more than 65% of all species in the total species pool. The addition of institutional and private green space types contributed an additional 53 species to the existing public inventory, meaning the current municipal inventory captured only 68% of neighbourhood tree species.

4.2 Tree Species Dominance

Private green space accounted for the highest proportion of all species (62%), while the street ROW accounted for lowest, only 43% of all species. There were some similarities in tree species composition across green space types. For example, *Acer platanoides* placed in the top two most abundant species in all green space types (Fig. 3). *Thuja occidentalis* was the most abundant species in both private residential and institutional green spaces (Fig. 3B) and accounted for over 40% of species abundances in private residential yards. The street ROW was dominated by three species, which when combined accounted for over 53% of individuals: *Acer platanoides* (accounting for 25% of individuals), *Acer saccharinum* and *Tilia cordata.* In parks, *Acer platanoides, Acer saccharinum* and *Thuja occidentalis* accounted for approximately 35% of individuals. Parks were less dominated by a few select species and displayed higher evenness with no species accounting for more than 15% of the species pool.

4.3 Tree Size Distribution

Tree size distribution differed across all green space types. Private residential green spaces had the largest proportion of small DBH measurements (<25cm) while street ROW had the largest proportion of large DBH measurements (>50cm) and displayed the most even distribution of DBH measurements across the entire range of values (Fig. 4). Generally, all green space types except for street ROW were left skewed towards a lower DBH distribution (<50cm), especially in parks, institutions and private residential green spaces (Fig. 4). Based on expected maximum DBH values, private yards still showed the lowest densities of large trees (above 35 cm) and larger trees were predominantly in parks and streets (see appendix 1). Both parks and institutions showed an additional proportion of large tree sizes not seen in current DBH distributions which indicated the presence of saplings that will eventually reach larger size classes once they have matured (see appendix I).

4.4 Species Richness

Species richness curves showed a clear trend of differences in species richness across green space types. After considering sample coverage (Fig. 2A), private residential yards had significantly higher tree species richness than the other green space types at the neighbourhood scale (Fig. 2B). The street ROW, parks and institutional green space types all had comparable levels of species richness which did not differ statistically (Fig. 2B). The shape of the accumulation curves suggests that the parks, institutions and street right of way were sampled exhaustively, while private residential green space has yet to reach a clear asymptote.

Species richness per unit area (subsites) also differed according to green space type. According to model estimates, green space type significantly affected tree species richness ($\chi^2_{(df = 3)} = 87.7$, $p<0.001$). Mean model estimates of species richness ranged from 2.1 [95% CI: 1.8-2.4] to 6.1 [95% CI: 5.0-7.5] species per equal unit of area (0.04 ha) and was highest in the street

ROW and lowest in park sites (Fig. 4B). According to pairwise comparisons, species richness in the street ROW was significantly higher than parks and institutions but not private yards ($p<0.001$). Private yards had the second highest tree species richness of 5.7 [95% CI: 4.1-8.3] and was significantly higher than parks and institutions but did not differ from street ROW. Parks and institutional green space types had similar estimates of species richness and did not significantly differ from each other.

4.5 Tree Abundance

According to our mixed models, green space type also significantly affected tree abundances (log transformed) ($\chi^2_{(df = 3)} = 262.0$, $p<0.001$). Mean estimates of tree abundance ranged from 3.5 to 14.5 trees per unit area (0.04 ha) and was highest in street ROW and lowest in parks (Fig. 5). Street ROW had significantly higher tree abundances than parks and institutions, with approximately four times the number of trees (Fig. 5A). According to pairwise comparisons, tree abundances in street ROW were significantly higher than all green space types ($p<0.001$). Tree abundance in private yards was significantly higher than parks and institutions ($p<0.01$) while parks and institutions did not differ from each other.

4.6 Evenness

Considering the entire inventory, (e.g., all parks, all institutions combined), parks had the highest species evenness, while private residential yards had the lowest (Fig. 5C). All green space types displayed generally high evenness values between 0.82 and 0.94. For example, despite high abundances of particular species, especially in the street ROW, parks and private yards the probability of encountering the same species considering the entire species pool was never more than 20%. However, at equal units of area (using subsite data), mean species evenness was highest in private residential yards 0.77 [95% CI: 0.66-0.87] and lowest in public parks 0.69 [95% CI: 0.62-0.75], while institutional and ROW green space types had comparable intermediate evenness values of 0.71 [95% CI:0.64-0.77] and 0.70 [95% CI: 0.63-0.76] respectively. However, these differences were not statistically significant ($p = 0.652$).

5. Discussion

Our work examined differences in tree diversity and structure among public and private green space types within the urban forest. Green space types throughout the urban landscape are managed in different ways according to preferences, management goals and individual planting motivations (Shakeel & Conway 2014; Avolio *et al.* 2015; Morgenroth *et al.* 2016; Nitoslawski *et al.* 2016). Our results matched our expectations that unique management goals and preferences would result in measurable differences in tree diversity across urban green space types (Fig. 5). Specifically, private green space types like residential yards are contributing species that were previously unaccounted for, meaning that relying only on public tree databases will not fully capture the tree community. Finally, our findings highlight the importance of scale when assessing diversity metrics as the nature of diversity patterns depended on the scale at which they were analyzed.

Across the entire neighbourhood tree inventory, the addition of private green space types (institutional and private residential) contributed 52 additional tree species, or 32% of all species in our neighbourhood inventory. Our sampling of private yards represented only a subset of all private residences in the study area, yet still contained the highest total number of tree species across all green space types. Private trees also differed in significant ways beyond species richness. For example, recent work on urban forest diversity in Montreal showed a lack of conifer trees on public land (Paquette *et al.* 2021). However, based on our findings, private land contains a high abundance of conifer species. For example, Eastern White Cedars (*Thuja occidentalis)*, Canadian Yew (*Taxus canadensis)* and Norway Spruce (*Picea abies)* were all within the ten most abundant species. Thus, private trees may not only increase overall species richness, but may be increasing representation of certain functional groups that are currently underrepresented in the urban forest (Paquette *et al.* 2021). By increasing a diverse functional representation of the urban forest we may increase its resistance to global change by ensuring species will respond differently to stressors and maintain ecosystem function (Díaz & Cabido 2001; Cadotte *et al.* 2011; Wood & Dupras 2021). Our findings highlight the need for more comprehensive urban forest inventories that include private trees – and show that community science may be a promising approach to collect this data more broadly. Our findings also support previous work that shows private spaces play a significant role in urban forest diversity (Bourne & Conway 2014) with patterns of tree composition and structure not well represented in current public tree inventories (Fig. 3).

Even with the inclusion of private trees, our study area remained dominated by a few tree species, most notably *Acer platanoides* (Norway Maple). *Acer platanoides* is the most abundant public tree species in Montreal (Paquette *et al.* 2021), and was similarly very abundant in private yards and institutions (Fig. 3B). We also observed that private land was dominated by smaller tree species, while the street ROW housed the majority of large trees (Fig. 4). Considering the anticipated maximum DBH of trees confirmed that private yards contained more smaller statured species (not just saplings) compared to other green space types, while parks contained a higher density of saplings that will eventually mature into larger height classes. The dominance of smaller trees on private land may be a result of relatively small yard sizes, or of individual preferences for smaller, more ornamental tree varieties that provide aesthetic value while also minimizing disservices related to large trees like branch loss, housing damage and debris (Roman *et al.* 2020).

Generally, however, the dominance of a few species or age structures across the urban landscape can threaten overall resilience to disease, pest outbreaks and environmental changes (Liu 2018; Bajeux *et al.* 2020), as certain trees are most vulnerable to stressors at specific ages. For example, drought poses a higher threat to seedlings than established trees. In addition to stressors, an urban forest dominated by large mature trees is threatened by the eventual die-off or removal of old species which can drastically reduce canopy cover and consequently ecosystem service provision (Nowak *et al.* 2008). Our findings indicate there is potential for improved management to increase the structural diversity of trees among different green space types to avoid one green space type accounting for an entire age class at any given time.

Unlike previous work, our inventory showed that at equal units of area, the street ROW and private yards were highest in species richness compared to other green space types (Fig. 5B). Other work considering site-scale differences has found that tree diversity was consistently lower in streets compared to private yards (Avolio *et al.* 2018). Since street trees are often planted and managed for ease of maintenance and street tolerance (dense canopy, stress tolerance), the specificity of their role in the urban environment has generally been found to result in lower species richness compared to other green space types (Kinzig *et al.* 2005; Cavender & Donnelly 2019). Our contrasting findings may be a result of the unique planting practices and specific borough-level goals to increase diversity in public spaces like the street ROW (CDN-NDG 2011). Higher street ROW richness may also be a result of high density of trees planted along street blocks in our study area which increase the likelihood of encountering a new species(CDN-NDG 2011). While private yards rarely contained more than 10 trees, the equivalent plantable area of a street block typically contained between 11 to 20 trees. This highlights just how heavily managed street blocks are, with some of the lowest plantable area, yet highest tree densities. Contrastingly, at equal units of area, parks and institutions had the highest potential for increasing species diversity. However, the low levels of diversity we observed in parks and institutions at equal units of area could be a result of the spatial clustering of species where tree planting must also accommodate other forms of green or non-green infrastructure like buildings, soccer fields, and playgrounds. One or two species may be planted in certain areas to accommodate the broader context of the park or for aesthetic appeal, resulting in lower local level diversity compared to larger scales. For example, a survey of various public land managers (municipal foresters, landscape architects, nursery owners) found that tree appearance was consistently more important than the surrounding diversity of other trees when making planting decisions (Conway & Vander Vecht 2015). Understanding the contexts where the differing needs of each green space type are most beneficial for increased management could improve the practicality and resource allocation for urban forest management efforts.

Despite differences in tree species richness, all green space types had comparable values of species evenness (Fig. 5C). Even with the dominance of Eastern White Cedars (*Thuja occidentalis)*, private yards had the highest species evenness at equal units of area while parks and institutions had the lowest, although these differences were not significant. Introduced and exotic species have previously been shown to decrease private yard evenness by increasing the number of rare species (Bourne & Conway 2014; Avolio *et al.* 2018; Ossola *et al.* 2019a). We expect that high species evenness in residential yards seen in our inventory are a result of individual planting decisions and preferences at the yard scale. Individual residents generally only plant a few trees in their yard and tend to avoid planting duplicate species (Shakeel & Conway 2014). This style of management increases species evenness at local scales by increasing the likelihood of encountering a new species creating a highly even community. High species evenness in private yards may also be related to nursery availability within the area. Species availability in retail nurseries and the number of that species found in neighbourhoods are strongly correlated (Avolio *et al.* 2018), indicating that residents may be relying on tree stock availability or nursery recommendations when making tree planting decisions. However, the driving force behind availability is likely a combination of both local nursery stock as well as nurseries responding to customer preferences or requests. Thus, untangling the causality between resident preference and availability should continue to be a focus of future work. The street ROW contrastingly had some of the lowest evenness values despite its high species richness. This indicates that at units of equal area, street blocks are often still dominated by relatively few species which is consistent with previous findings (Kendal *et al.* 2014; Cavender & Donnelly 2019). However, interestingly these patterns of species evenness do not scale-up to the entire neighbourhood since private yards had the lowest species evenness followed by parks, institutions and street ROW when considering the entire species pool (ignoring differences in area). In the case of species evenness, it’s possible that subsampling below scales of management may have masked more relevant patterns of species evenness in our study area. For example, our analysis of tree species at subsites of equal area (in parks and institutions) found no significant differences in evenness; however, more relevant patterns of species evenness may be discernible at a larger scale where trees are planted and managed (an entire park). These findings suggest that the scale of management and the scale at which diversity metrics like richness and evenness vary are not always aligned. Determining best practices for effective approaches to analysis that consider the scale of management while also controlling for differences in area should be an area of investigation in future urban ecological work.

Across all green space types, diversity metrics were compared at equal units of area (Fig. 1). In urban areas scales of management (parcel level) differ significantly in area, meaning urban ecologists must find meaningful ways to compare diversity at the scale at which green spaces are managed (an entire park or schoolyard) without ignoring the importance of controlling for area. Our findings show that when analyzing tree inventories, we may be missing key differences, or even observing opposing diversity patterns depending on the scale we consider. This has implications for the application and management of urban forestry research. If we are interested in the provision of ecosystem services, for example, the way we measure and interpret patterns of urban forest composition and structure may depend on the service of interest. For example, a tree’s contribution to carbon storage- a service that can be delivered remotely (e.g., outside of urban areas)- is expected to be similar regardless of its placement. However, services like temperature regulation which are strongly influenced by the trees in a specific area (e.g. a street block or neighbourhood) will require scale considerations (Ziter *et al.* 2019). Similarly, an urban planner interested in which green space types have the most potential for increased biodiversity and ecosystem service deliverance may be most interested in parcel-scale data, as this is the scale at which planting decisions and tree placement are most relevant. Understanding which scales are the most meaningful in relation to particular goals or decisions should be a priority in future work.

6. Conclusion

Overall, the unique species and structure of trees on private land emphasizes the potential that local scale management that targets individual residents' attitudes and actions has strong potential to improve urban forest diversity and resilience. We found that green space types displayed meaningful differences in both tree diversity and structure, emphasizing that relying solely on public tree inventories in urban forestry research will exclude a significant portion of tree species uniquely found in private spaces. Finding ways to integrate private land-use types and the importance of private landowners into our understanding of the urban forest will have important outcomes for our understanding of urban forest resilience as well as implications for the wellbeing of citizens who depend on the benefits urban trees provide. Our work also highlights the importance of scale in urban forest inventories. We showed that considering multiple scales can be important to make meaningful comparisons of urban forest diversity and structure across different green space types. Scales of green space management and scales of meaningful diversity patterns may not always be aligned. Future work is needed to determine effective approaches to analysis that consider scales of management while also considering differences in area, especially in urban ecology where management scales differ drastically in area.

Chapter 2

Title: Fine-scale differences in composition of tree species and service-based traits across urban green spaces

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1. Introduction

Urban landscapes are spatially heterogeneous and temporally dynamic systems that experience unique human-mediated factors that influence biodiversity (Kowarik 2011; Zhou et al. 2017; Avolio et al. 2021; Pickett et al. 2017). The governance of green spaces in cities means species composition is influenced by management at various levels, including by institutions, municipalities, and individual landowners responsible for their care. The range of individual goals and management systems involved in urban tree planting lead to differences in preference for specific species or characteristics which determine which species are present or absent within the landscape (Kowarik 2011; Aronson *et al.* 2017). Due to the many species we introduce and manage in our green spaces, cities tend to experience higher levels of plant species richness compared to rural counterparts (McKinney 2006). The heterogeneous nature of the urban landscape allows for a wide variety of species to persist, which is facilitated by human management of the green spaces which make up the broader city landscape.

Within urban green spaces, trees are a key component of biodiversity that provide us with a host of benefits we refer to as ecosystem services (UN, 2019). Urban trees improve air quality, promote mental wellbeing, mitigate high temperatures and provide crucial recreational spaces for local residents (Livesley *et al.* 2016; Salmond *et al.* 2016; Endreny *et al.* 2017; Wolf *et al.* 2020). For example, 94% of Canadian cities reported greater use of parks in 2020 due to the COVID-19 pandemic, and local residents are expected to continue, or increase, park-use in the upcoming post-pandemic years (Park People, 2021). The increased use of urban green spaces means urban tree biodiversity has significant implications for human health and wellbeing through the provision of ecosystem services. The long-term provision of these ecosystem services will rely on a resilient urban forest with multifunctional green spaces. (Lovell & Taylor 2013; Zhou *et al.* 2017).

An emerging approach to biodiversity management incorporates links of ecosystem functions to services through functional traits (Díaz & Cabido 2001; de Bello *et al.* 2010; Cadotte *et al.* 2011; Goodness *et al.* 2016). A trait-based approach recognizes that individual traits influence functions which in turn, may impact services (Hooper *et al.* 2005; Diaz *et al.* 2007; Mace *et al.* 2012; Balvanera *et al.* 2014). This may be particularly applicable in urban systems, where it's more often the composition of species and/or traits within our green spaces – rather than a specific biodiversity metric, like species richness – that promotes ecosystem service provision (Ziter 2016; Schwarz *et al.* 2017). Thus, it is the underlying composition of species and traits which determine the type and magnitude of ecosystem services provided by urban trees (Hooper *et al.* 2005; Díaz & Cabido 2001; Thompson *et al.* 2018) (see Fig. 1). For example, traits such as total leaf area combined with diameter at breast height (DBH) contribute to temperature regulation (a service). A small conifer species, with needles likely contributes less to temperature regulation than a large broad-leaved silver maple (de Bello *et al.* 2010). Understanding the distribution of species and traits across heterogeneous green spaces is thus important for understanding ecosystem service provision.

In highly managed and heterogeneous urban forests, the presence of different species and traits in green spaces are dependent on various human-mediated factors (Larouche *et al.* 2019). In cities, humans influence species composition and the distribution of traits directly and indirectly, through the introduction of species within urban green spaces and managing their success. Urban trees are selected and managed for various purposes within the urban landscape and tree species composition is highly governed by individual preferences and management systems (e.g. municipal governments, residents) (Conway *et al.* 2011; Aronson *et al.* 2017; Ossola *et al.* 2019a). For example, urban foresters may select street trees for their capacity to endure stressful conditions, or for a compact growth structure. By contrast, individual residents planting in their backyard may value more aesthetic-based traits like flowering or edible fruit production. As a result, a form of artificial rather than natural selection occurs in urban areas (Kowarik 2011). Consequently, while the functional traits we traditionally measure in forestry-based work can provide insight into forest function and resilience, they may not be as relevant to urban tree planting *decisions* compared to traits that are known to be preferred by humans. For example, wood density, a common proxy for growth rate in functional trait studies, may not be as important to whether a tree is planted, compared to traits like showy fall colour or flowers. Since human selection for tree characteristics plays a sizable role in the urban forest in ways that do not exist in the natural forest, integrating traits that are most relevant to preferences is a crucial step to understanding outcomes for species composition and service-trait links.

There is thus a growing recognition of the need to broaden our consideration of tree traits to include both traditional functional traits and what researchers in urban landscapes refer to as "service-based traits" such as growth rate and showy flowers which capture aspects of plant form and function that urban residents find beneficial (Pataki *et al.* 2013; Avolio *et al.* 2015, 2021). Such a framework can improve the relevance of traits to management decisions within urban ecosystems (Pataki *et al.* 2013; Avolio *et al.* 2018; Ossola *et al.* 2019a) and recognize the two-way interactions between nature and peoples' values that are involved in patterns of urban biodiversity (Avolio *et al.* 2021). Understanding if and how the distribution of preference or service-based traits differ among urban green space types will allow us to draw stronger conclusions about the type and magnitude of services these green spaces provide, providing relevant information for researchers and practitioners.

Focusing on service-based traits valued by individuals planting urban trees may allow urban ecologists to better understand and predict patterns of urban tree diversity, and direct research efforts towards avenues of inquiry relevant to tree planting decision makers (Avolio *et al.* 2018). However, whether, and how, patterns of species composition and service-based traits differ across various urban green space types remains underexplored in urban forestry work. Ibsen et al. (2020) recently observed few differences in service-traits among woody species in parks across various US cities, however, work considering differences across multiple green space types is noticeably missing. While a small number of studies of service-based traits have considered differences in publicly managed street blocks and privately managed yards, very few have also integrated other green space types like public parks and private institutions. The aim of our work is to explore how four common green space types (parks, street right of way (ROW), institutions and private yards) differ in composition of both tree species and service-based traits. For the purposes of our work, we will focus on traits that indicate the presence of ecosystem services (henceforth referred to as service-traits) and discuss the implications of their presence or absence in green space types for ecosystem service provision.

We address the research question:

1. Are there discernable patterns of tree species composition and service-traits that are explained by green space type (e.g., street ROW, public park, private residential yards and institutions)?

We expected that individual resident preference for specific tree attributes (aesthetics, shading) and exotic varieties would increase variation in service-traits in private yards above that of publicly managed green spaces and that public right of way will exhibit the lowest service-trait variation, since street trees are selected and managed for similar functional attributes across neighbourhood's (e.g., height, canopy shape). Finally, we expected that different preferences for service-traits between the public and private domain will result in clustering of 'ecosystem-service based traits' in private green spaces (residential yards) compared to public green space types (Shakeel & Conway 2014; Avolio *et al.* 2018)**.**

2. Methods

2.1 Study Area and Data Collection

Our study was conducted on the island of Montreal in the borough of Cote-des-Neiges-Notre-Dame-de-Grace (CDN-NDG) using the urban forest inventory in Chapter 1, please see sections: study area, urban forest plot for additional detail.

Between July-September 2020 we surveyed public parks (n=7), institutions (n=16) and street right of ways within our study area through a traditional field collection. Tree data were collected as in Chapter 1, using a mixed method approach including traditional field inventory and community science. See Chapter 1 methods: *tree data* for additional detail. As in Chapter 1, institutional and park sample sites were divided into subsites to create equal units of area for analysis using QGIS. Since some parks or institutional sites could not be evenly divided into precise 0.04 ha subsites (ranging between 0.03 to 0.05) we again included log transformed area per subsite as a covariate in all subsequent linear mixed models to account for the effect of any remaining differences in area. To control for large differences in area and sample size, we chose to maintain equal units of area for our multivariate analyses'. For more detail see Chapter 1 methods: *creating equal units of area*.

2.1.1 Service-Based Traits

We used an ecosystem service-based trait classification framework adapted from work by Pataki et al. (2013) to select eleven service-based traits linked to human preferences (Pataki *et al.* 2013; Avolio *et al.* 2015). Service-based traits reflect tree characteristics that are selected for and desired by urban residents and land managers. Each service-based trait is linked to the potential delivery of a service or need in human-based management. Therefore, while ecosystem services are not measured directly, by assessing patterns amongst service-traits we can discuss their possible implications for certain ecosystem services. For all tree species identified in this work, trait classifications were determined from a variety of landscape-based sources (Table 2). Traits based on aesthetic characteristics were treated as categorical variables to describe their nature (Table 2). For example, flowering had two categories: showy or inconspicuous, or fruiting considered: edible or not edible. Other service-traits like average maximum height were treated as continuous to properly capture variations in tree size (see Table 2). Finally, we quantified additional ecosystem-service based traits of trees that were not specifically linked to either a general service or disservice but that influence the suitability of an urban tree species for specific locations or uses; for example, these traits may be selected for specific needs of the green space type. These traits included growth rate, shade and drought tolerance.

2.4 Statistical Analysis

To visualize differences in the composition of species and service-traits, we used the "ape" package in R to conduct principal components analysis (PCoA). We chose PCoA over other multivariate analyses' (e.g., PCA, NMDS) due to its flexibility to various distance measures which were required in our dataset since it contained both continuous and categorical variables. PCoA visualizes a Euclidean representation of distance relationships between species and trait values. We first conducted a PCoA of species composition to observe differences among green space types (parks, institutions, private yards and street ROW). Species data was compiled to calculate the abundance of each species per subsite (of equal area) which was then overlaid with service-traits using the *envfit* function in vegan. We performed a Hellinger transformation to account for heavily abundant or rare species and Bray-Curtis dissimilarity matrices to account for species identity across different subsites. We then performed a second PCoA using community weighted means (CWM) of service-trait values. Community weighted means are calculated by averaging service-trait values for each tree within a subsite while also weighting for species abundances. When comparing sites, CWMs are frequently used in service-trait work (Pataki *et al.* 2013; Avolio *et al.* 2018). Other forms of weighting, such as by size or dominance exist, however species abundances account for highly dominant or rare species within a subsite which we chose to reflect subsite service-trait values. PCoA was conducted on Gower's distance dissimilarity matrix which accounts for different types of trait data (continuous, categorical) by assigning appropriate metrics for the specific data types. For each PCoA, we used the "gllvm" package to perform general mixed models akin to PERMANOVA that are robust to random effects, in this case to account for subsites within a sample site that are not independent (Hui 2014). Models were used to test for differences across green space types in either species or service-trait composition. All statistical analyses were conducted in R (R Development Core Team 2010).

3. Results

For each multivariate analysis, the first two axes of species PCoA ordination were used to explain variation in species and service-trait values among sites using subsite data in institutions and parks. Since the third species axis only explained <5% of additional variation and did not meet the scree test cut-off, it was not included in the final analysis (Cattell 1966; SAS Institute 2021). A total of 155 species and 11 service-based traits across 638 subsites were used in all subsequent multivariate analyses.

3.1.1 Species-based PCoA ordination

For species-based analysis, points more distant from each other indicate increased dissimilarity in species composition among sites (according to subsite data of equal area) (Fig. 8). The first and second PCoA axis explained 15% and 14% of species variation respectively. Species composition overlapped considerably across the four green space types, and three species: *Acer platanoides, Acer saccharinum and Thuja occidentalis* correlated to specific green space types. Private yards covered the smallest ordination space in species composition across sites (Fig. 8). Composition in private yards was highly correlated with the Eastern White Cedar, *Thuja occidentalis,* a coniferous species. (Fig. 8). The street right-of-way (ROW) similarly covered small ordination space in species composition compared to parks and institutions. Street ROW was associated with two species: *Acer saccharinum* and *Acer platanoides.* Parks and institutional green space types covered the widest ordination space in terms of species composition across sites (using subsite data) but were similarly associated with *Acer saccharinum* and *Acer platanoides.* These two species are highly abundant in public green space types. Finally, to interpret overlap between green space types, we used a mixed model approach to multivariate analysis using the "gllvm" R package. Pairwise comparisons indicated that the street ROW significantly differed from all green space types: private yards ($p < 0.001$), institutions ($p < 0.01$) and parks ($p = 0.01$). Institutions, parks and private yards, however, did not significantly differ from each other according to species composition.

3.1.2 *Service-trait based ordination*

For service-trait based ordinations, distant points indicated increased dissimilarity in weighted mean values of service-based traits among sites (using subsite data of equal area) (Fig. 9). The first and second PCoA axis explained 38% and 27% of service-trait variation respectively. Service-based traits similarly overlapped considerably across all green space types. Private yards displayed the most variation in weighted mean values of service-based traits and were highly correlated with several traits: leaf shape, bark texture, tree shape and species origin (native or non-native). The street ROW displayed the most similarity in weighted mean values in service-based traits indicating the street trees were highly similar in terms of average service-based traits from block to block. The street ROW was highly associated with growth rate, fall colour and to a lesser extent, maximum height. Ordination plots indicated that street ROW, parks and institutions had some similarities in service-based traits due to the overlap of green space type ellipses; however, generally, parks and institutions displayed a wider variety of weighted mean values compared to the street ROW (Fig. 9). According to our model-based analysis, the street ROW and private yards each significantly influenced service-trait composition ($R^2 = 0.25$, $p<0.001$ and $p<0.001$). According to pairwise comparisons street ROW service-trait composition significantly differed from private yards ($p<0.001$) however, did not differ from institutions or parks. By comparison private yards significantly differed from all green space types (p= <0.001, <0.001 and 0.01) while institutions, parks and street ROW did not significantly differ according to species composition.

4. Discussion

Our work explored fine-scale differences in composition of tree species and service-based traits across four green space types within the urban forest. A total of 155 species across 638 subsites were explored for patterns in species composition and service-based traits that are linked to human preference in urban areas. Trees within our urban green spaces are managed in diverse ways according to various preferences, management goals, planting motivations, and nursery availabilities (Kinzig *et al.* 2005; Shakeel & Conway 2014; Avolio *et al.* 2015, 2018; Morgenroth *et al.* 2016; Nitoslawski *et al.* 2016). We aimed to explore whether these distinct management systems resulted in visible patterns of species and service-trait composition across four green space types: street ROW, institutions, parks and private yards. Overlap across green space types was significant, however our results did show fine-scale differences in composition, notably between street ROW and private yards - likely related to differences in management goals and preferences. These differences have the potential to scale-up across the urban forest, with implications for ecosystem services. In addition to differences among green space types, it was clear both species and service-based traits across private yards and street ROW differed considerably. Specifically, our results show that although species composition differed across blocks in the street ROW (from block to block); they show fewer differences in mean values of service-based traits, likely providing a similar set of benefits regardless of species composition. Opposingly, private yards appeared to have similar species composition from yard to yard yet still varied considerably in mean values of service-based traits.

The street ROW had the highest similarity in weighted mean values of service-based traits (Fig. 8) across street blocks according to the 11 service-based traits considered. This similarity is unsurprising, given that the high stress environment is better survived for trees with particular characteristics, and therefore similar tree characteristics may be especially prioritized in this green space type (Kendal *et al.* 2012; Cavender & Donnelly 2019). The street ROW was highly associated with the service-traits of growth rate, fall colour and maximum height, and appeared to be prioritizing fast growing species that can establish quickly in the streetscape. These service-based traits are generally in alignment with known priorities in street tree planting, for example, selecting for large trees with fast growth that are intolerant of shade from adjacent planted trees (Cavender & Donnelly 2019). Interestingly, the high association of fall colour with street ROW implies that showy fall colours may be an important characteristic of streetscapes previously considered more relevant in private spaces like urban backyards (Avolio *et al.* 2018).

While trees with similar service-based traits may be beneficial for street tree maintenance and are aesthetically pleasing, characteristically similar communities within the street ROW may be more vulnerable to future environmental threats, and may be over representing a select subset of traits and services compared to other green space types (Díaz & Cabido 2001; Paquette *et al.* 2021). These results could be indicative of a tradeoff in ecosystem services, where fast-growing species - that store less carbon as they establish (Büntgen *et al.* 2019), particularly in an urban environment (Nowak *et al.* 2013; Tang *et al.* 2016), will also provide an established canopy earlier (linked to temperature regulation, shade provision). These tradeoffs become important for management decisions that prioritize the overall multifunctionality across all green space types.

Despite having similar trait-based characteristics, the street ROW still differed in species composition from block to block, contrary to the monocultures we tend to expect in the street ROW (Kendal *et al.* 2014; Avolio *et al.* 2018; Paquette *et al.* 2021). Perhaps these findings are related to the neighbourhood's commitment to increasing species diversity through tree planting initiatives on public land (CDN-NDG 2011). Importantly, however, the street ROW was still highly associated with two species: *Acer platanoides and Acer saccharinum* which indicates these species are likely present in most street blocks. Previous work has found that *Acer platanoides* and *Acer saccharinum* are very common street tree varieties across the island of Montreal (Wang & Akbari 2016) and similarly dominate the taxonomic diversity of the urban forests in other Canadian cities (Pham *et al.* 2013; Bourne & Conway 2014; City of Vancouver 2021).

Private yards covered the smallest ordination space in terms of species composition among all green space types, which indicated that yards house a similar composition of species from yard to yard across the neighbourhood. This may be indicative of similar species being present from yard to yard with only one or two species differing. For example, each yard may have a cedar hedge and Norway Maple, however, the additional species (which differs and increases richness) is not dissimilar enough to be captured by the ordination space. However, the high variation in service-traits across private yards indicated that mean values of service-traits differed more from yard to yard than other green space types. Despite similarities in overall species composition among yards, the species within yards still covered a wide service-trait space compared to other green space types. This may be a result of similar trees appearing from yard to yard, however, the species that differ are characteristically very dissimilar leading to a wider service-trait space. This may indicate that service-trait preference is highly individual and prioritized in different ways for different landowners. These findings are supported by previous work in Australia considering planting motivations of private residents. This work found seven classes of residents: aesthetes; spiritual tree lovers; practical tree lovers; arboriphobes; native wildlife lovers; tree hazard minimiser; and indifferent. This wide-variety of classes indicate the range of priorities important for urban residents that may be leading to more varied service-based traits compared to other green space types (Kirkpatrick *et al.* 2012).

Leaf shape, in particular, was highly associated with private yards, likely indicative of the higher proportion of conifer species (Fig. 8). We expect that the high proportion of conifer species is driven by a high density of hedges that are common along yard edges for aesthetics and privacy (Shakeel & Conway 2014; Ritcey-Thorpe 2018). This is contrary to previous findings which have shown that residents commonly prefer deciduous species to conifers when making planting decisions (Gerstenberg & Hofmann 2016). Although there has been work considering hedgerows contributions to ES, particularly, noise reduction (Van Renterghem *et al.* 2014; Blanusa, T, et al. 2019), the value of hedges, and the circumstances surrounding their selection within the urban forest is still poorly understood. The dominance of conifers in our study area implies that residents value plantings that maintain privacy, compactness and uniform aesthetics - a hypothesis that should be confirmed with future work addressing the motivation of urban residents more directly.

Private yards also appear to be contributing more so to native species than other green space types and therefore could be an important green space type for biodiversity conservation.

Higher densities of native species increase the abundance of many native insects and birds, providing important breeding habitat for certain insectivorous bird species (Burghardt *et al.* 2009; Narango *et al.* 2017). Moreover, yard management decisions at the local scale can aggregate up to the neighbourhood (Goddard *et al.* 2/2010). For example, if many private landowners are prioritizing native species, and are engaging in similar maintenance from yard to yard, then private yards have the potential to foster important habitat for native species that scales across the neighbourhood. The association of native species and private yards indicates that this green space type may be a good candidate for native species conservation efforts.

Perhaps unsurprisingly, we found that parks and institutions covered a wide ordination space in species or service-trait composition (Fig. 8 and 9). Although *Acer platanoides* and *Acer saccharinum* were associated with parks and institutions there were no evident service-based traits that were highly associated with these green space types. This may be a result of the roles that parks, and institutional green spaces play within the urban landscape. For example, parks and institutions may represent an intersection in terms of cultural versus biologically driven planting choices. Both municipalities (in parks) and private residents or community groups are involved in the tree planting choices within these green spaces, meaning both individual preferences and large-scale management goals are at play. Thus, we would expect to see selection for both aesthetic-based cultural services (fruiting, flowering, bark texture) as well as services related to more practical outcomes, such as growth rate or tree maximum height. For example, a park may contain many large wide-crowned tree species that contribute to shade and carbon storage, while also containing dissimilar species that provide aesthetic beauty like crab apples or hawthorns. We expect that this overlap in planting motivations may be contributing to the wide ordination space of species and service-traits within parks and institutions.

To our knowledge, the majority of service-trait based work to date has focused on one or two green space types, frequently private yards and street ROW. However, we know there are a multitude of actors beyond just municipalities and individual residents involved in the planting and management of the urban forest (Conway *et al.* 2011; Kendal *et al.* 2012; Nitoslawski *et al.* 2016). Our findings highlight the value of fine-scale work assessing tree composition and service-based traits which can direct urban ecologists towards management strategies that target planting decisions relevant to decision-makers. Using fine-scale information on species composition can inform land managers on which species are currently overrepresented in specific green space types and redirect planting efforts towards other species. For example, private yards are highly associated with *Thuja occidentalis, a* common coniferous hedge species. To further promote biodiversity in the urban landscape, homeowners could consider other coniferous species that could serve a similar role, like *Taxus canadensis* or *Juniperus communis*. Our results can also provide information on which green spaces are compositionally similar and how that may influence larger spatial scales. For example, yards seem to be more dissimilar to each other in terms of service-traits compared to street ROW. However, the species housed within yards are similar at local scales (from yard to yard) indicating that even with a large species pool, yards are consistently more similar to each other than other green space types. This could have important local-scale outcomes for connectivity, since compositionally similar yards can connect and expand habitats used by other taxonomic species (Goddard *et al.* 2/2010).

We chose to assess compositional and service-trait differences across green space types by comparing community weighted mean values, however, there are additional metrics worthy of exploring that emphasize other aspects of service-trait composition such as overall variation, tree size, etc. Using community-weighted mean values emphasizes differences across subsites by compiling variation of service-trait values within a subsite to an overall mean value. Considering metrics that emphasize variation within subsites in addition to mean values could improve our understanding of the differences within each green space type, including which services are present within an individual site and how service-traits differ at even finer-scales. Additionally, incorporating tree size distribution in future analysis, rather than number of individuals, could provide a stronger link between the known relationship between tree size and capacity for service provision. Large trees are known to provide more ecosystem services compared to smaller species (Turner-Skoff & Cavender 2019), thus, by weighting species by tree size researchers could incorporate the differences in service capacity among small and large trees.

Based on our findings, the street ROW is targeting species that grow quickly to large sizes and although composition varies from block to block, the characteristics of those trees are similar. Trees in the street ROW likely contribute most to services like temperature regulation and aesthetic value (specifically fall colour) due to their characteristic similarities. However, this means other green space types, particularly those in the public domain, are crucial to widening the variety of service-traits and species within the neighbourhood. In this case, park managers, for example, are playing an important role in maintaining the variation in species and service-traits across other public green space types. Overall, using approaches that incorporate these management structures in cities by exploring green space types can help determine the distribution of tree species and service-traits by acknowledging the individuals and land managers responsible for their care. Such work can help ecologists better understand the two-way interactions between nature, people's values and how these experiences shape behaviours, noted by Avolio *et al.* (2021) as some of the fundamental uncertainties that still exist in predicting patterns of urban biodiversity.

General Conclusions

Results of both chapters indicate that understanding the distribution of species and traits across heterogenous green spaces can tackle questions that have implications at larger scales in urban ecology. In this work, I explored differences in tree species diversity, composition, and structure across four different green space types to determine whether known differences in green space management result in notable differences in these tree diversity metrics.

I found that current reliance on public tree inventories in urban forestry research likely results in an underrepresentation of overall urban forest diversity, and in particular fails to capture notable differences in species richness and size structure across green space types. Considering multiple green space types can provide us with meaningful information on the overall urban forest. For example, within our study area, the street ROW contained the largest proportion of large trees (> 50cm DBH) whereas private residential yards were dominated by small trees (< 25cm). Private yards additionally contributed 52 new species to the current public tree species pool. Thus, if we assume green space types contribute equally to tree size (or diversity) we are missing crucial information that can improve urban forest management across neighbourhood's and cities at larger scales.

I similarly found that the fine-scale differences in richness and structure seen in my first chapter extended to patterns of tree service-based traits and species composition, particularly in street ROW and residential yards. Understanding differences in service-based traits and species among green space types can direct research efforts towards avenues of inquiry that are most relevant to land managers involved in tree planting decisions. Our findings can be used to inform which species and service-traits are dominating particular green space types to determine whether certain green space types have potential for increased or altered management. For example, we found that trees in the street ROW are prioritizing a specific subset of tree service-traits that are highly linked to temperature regulation and aesthetic value (fall colour). If we are aiming to create an overall multifunctional landscape that provides a variety of services, then other green space types need to prioritize services like carbon storage, food provision and other particular aesthetic preferences.

Our findings can also inform ecologists and planners alike on the species driving composition in specific green space types. For example, we found that private yards were highly associated with *Thuja occidentalis, a* common coniferous hedge species. Given their dominance in yards, management efforts to encourage planting other conifer species that serve a similar role like *Taxus canadensis* or *Juniperus communis* could ensure species aren't dominating specific green space types. Finally, determining whether the species or service-traits prioritized within specific green space types are consistent across different neighbourhood's and cities could inform city-wide planting decisions. Overall, determining service-based traits and species composition patterns that exist at these fine-scales has important outcomes for application and can improve our understanding of the most relevant factors associated with patterns of composition and ecosystem service deliverance.

Finally, dealing with issues related to spatial scale in urban forestry was a recurring theme in both chapters of my research. Within urban areas, we know that trees are managed for particular reasons within the landscape and experience increased management compared to other taxonomic groups. As a result, we expect to see these differences extend to patterns of diversity and composition within the urban forest. However, high heterogeneity and low land availability within cities (and even neighbourhood's) means certain green space types differ greatly in their overall area. For example, an individual borough may have parks that span less than half a street block, while another covers more than twice the same area. Other green space types like the street ROW and private residential yards are more consistent in area and don't cover the same wide range of sample areas like parks and institutions. However, if we want to explore differences in diversity metrics, the tools we employ using community ecology require equal units of comparison (or equal area). How we choose to approach these issues of area result in different tradeoffs. For example, comparing green spaces at equal units of area allows for robust comparison on a per unit area basis, however it may mask patterns of diversity that exist at the scale of management. As previously stated, a park is not managed in individual plots, but rather at the scale of the entire park or possibly neighbourhood and that unit of area will differ from park to park. Exploring useful approaches to manage these tradeoffs is an important avenue for continued work in urban forestry, or urban ecological work that employs a green space type framework.

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Figures and Tables

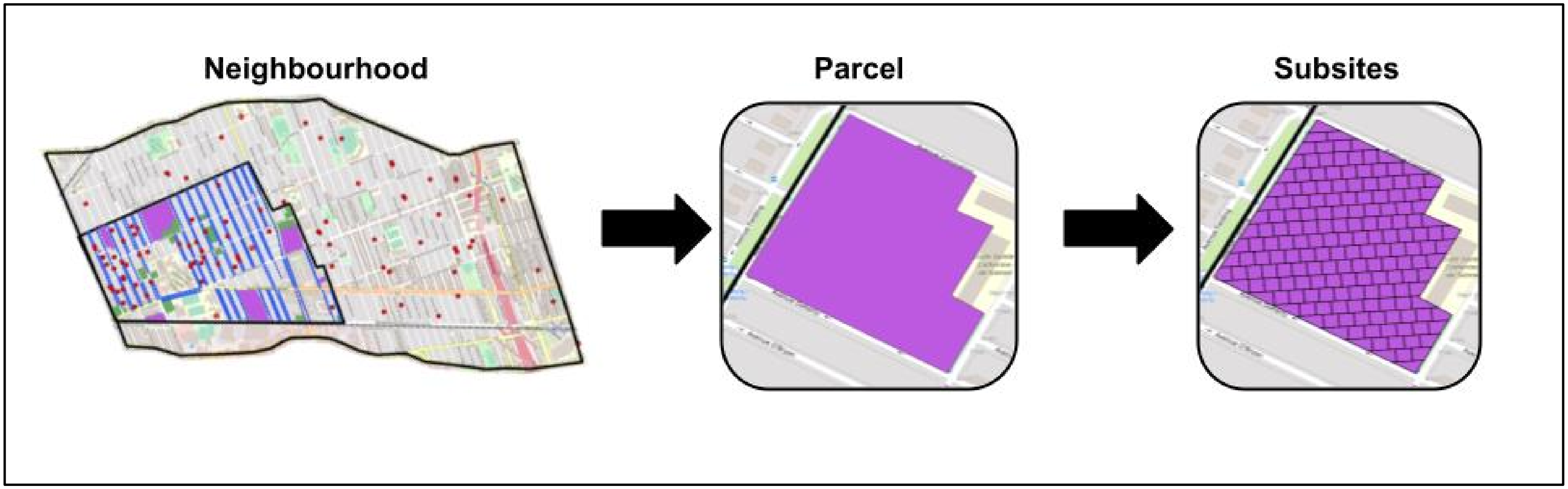

Figure 1. Visual representation of the scales of analysis for tree inventory data in Notre-Dame-de-Grâce in Montreal. Neighbourhood level: represents the two scales of data collection, the outer black line indicates the boundary for broad collection of private yard data and the core study area of 2 km². Blue polygons represent street block samples, purple polygons represent public parks, green polygons represent institutional spaces and red dots are private yards sampled. Parcel level: boundary of property ownership (an individual park, yard, institution). Subsite level: subdivided units of equal area (0.04 ha) within each park and institutional parcel.

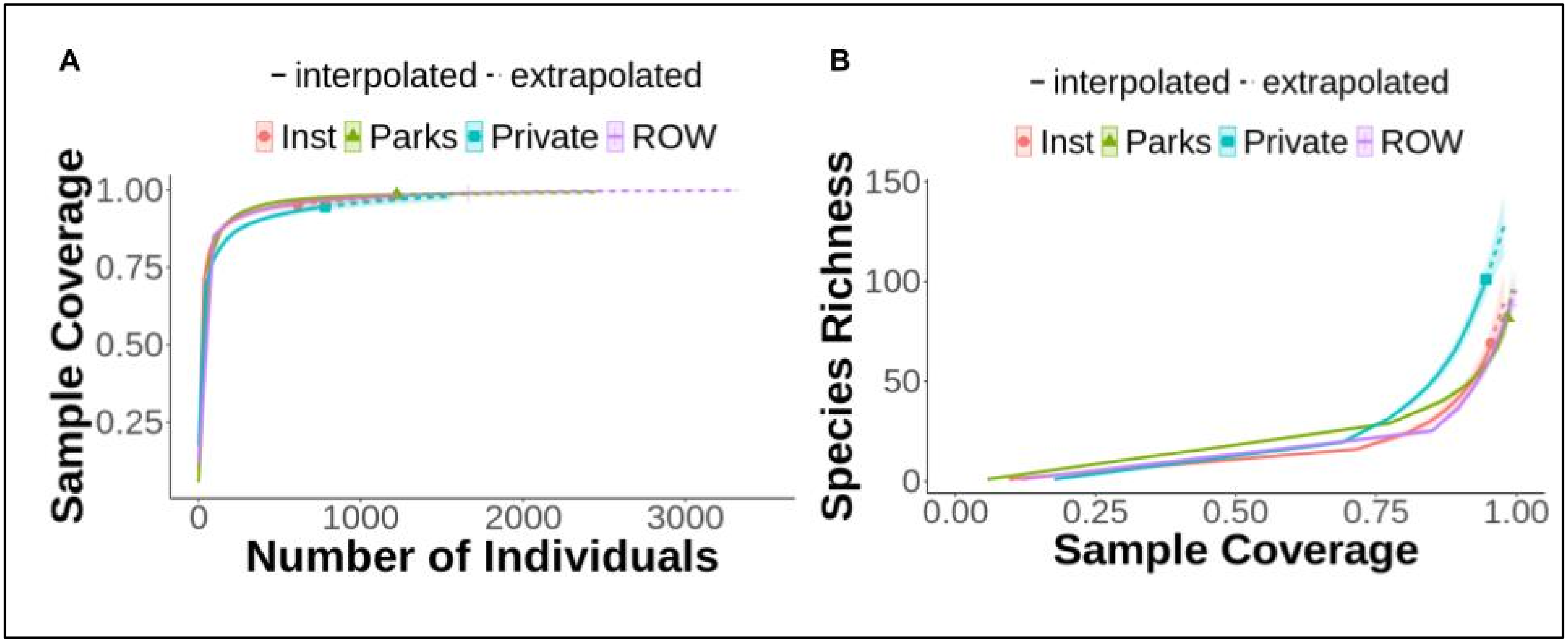

Figure 2. Individual based species rarefaction curves for four green space types where solid line indicates interpolation, and dashed line indicates extrapolation. Sample coverage is used to calculate the level of sampling effort for accurate comparison across green space types.

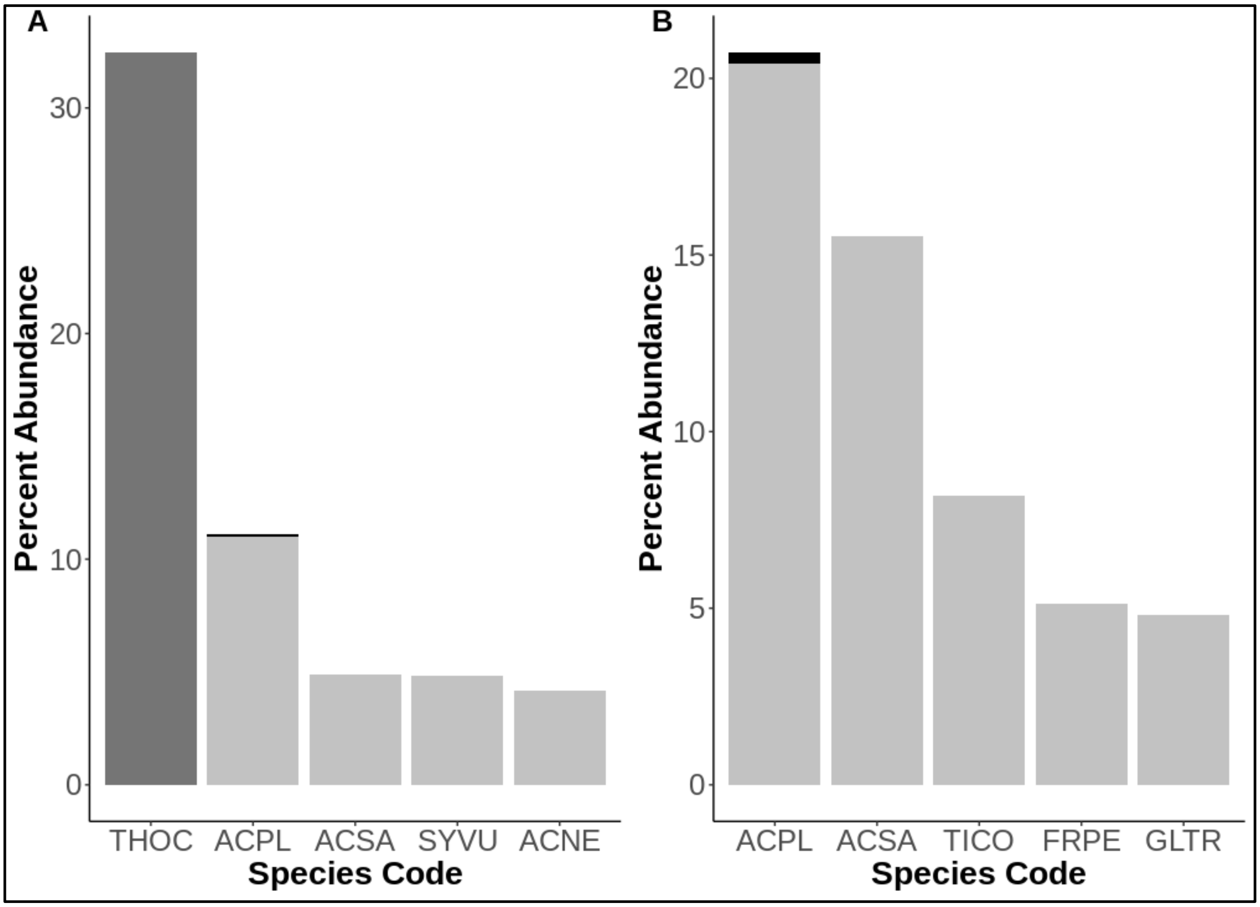

Figure 3. Percent abundance of the five most abundant tree species in (A) Private (residential yards and institutions) and (B) Public (parks and street ROW) green space types. THOC= *Thuja occidentalis*, ACPL= *Acer platanoides*, SYVU= *Syngria vulgaris*, ACNE= *Acer negundo,* ACSA= *Acer saccharinum*, TICO= *Tilia cordata*, GLTR= *Gleditsia triacanthos*, FRPE= *Fraxinus pennsylvanica*. Light grey represents deciduous tree species varieties, dark grey represents coniferous species, and, black represents the cultivar ACPLCK, a purple-leaved variety of *Acer platanoides*. While ACPLCK was considered taxonomically separate due to visually distinct traits, it still contributes to the dominance of *Acer platanoides* in the urban landscape.

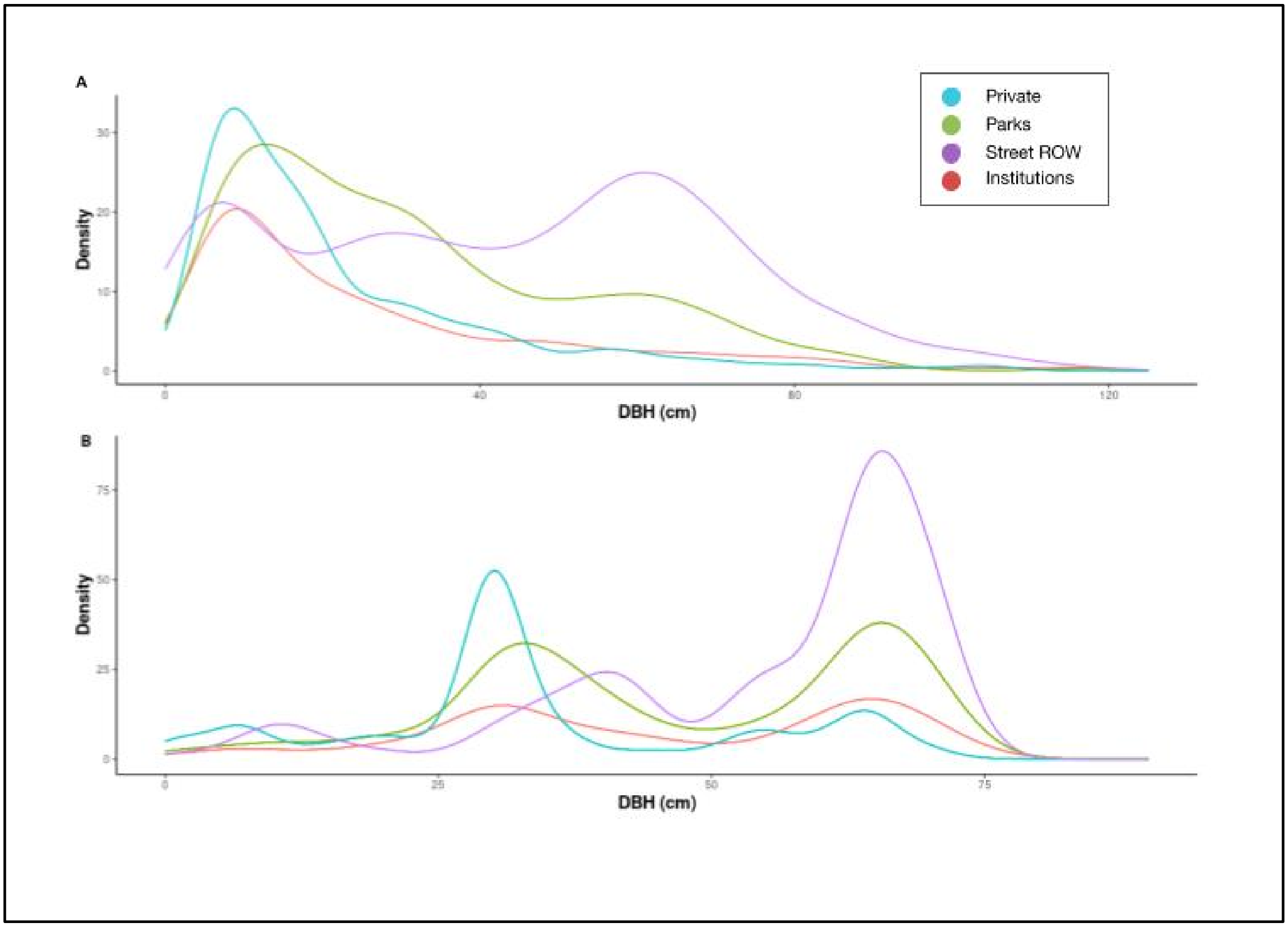

Figure 4. Scaled kernel density plot comparing the distribution of (A) Tree diameter at breast height (cm) and (B) Maximum diameter at breast height (cm) in each urban green space type. Distribution scaled to the number of trees sampled in the green space type (density times the number of data points).

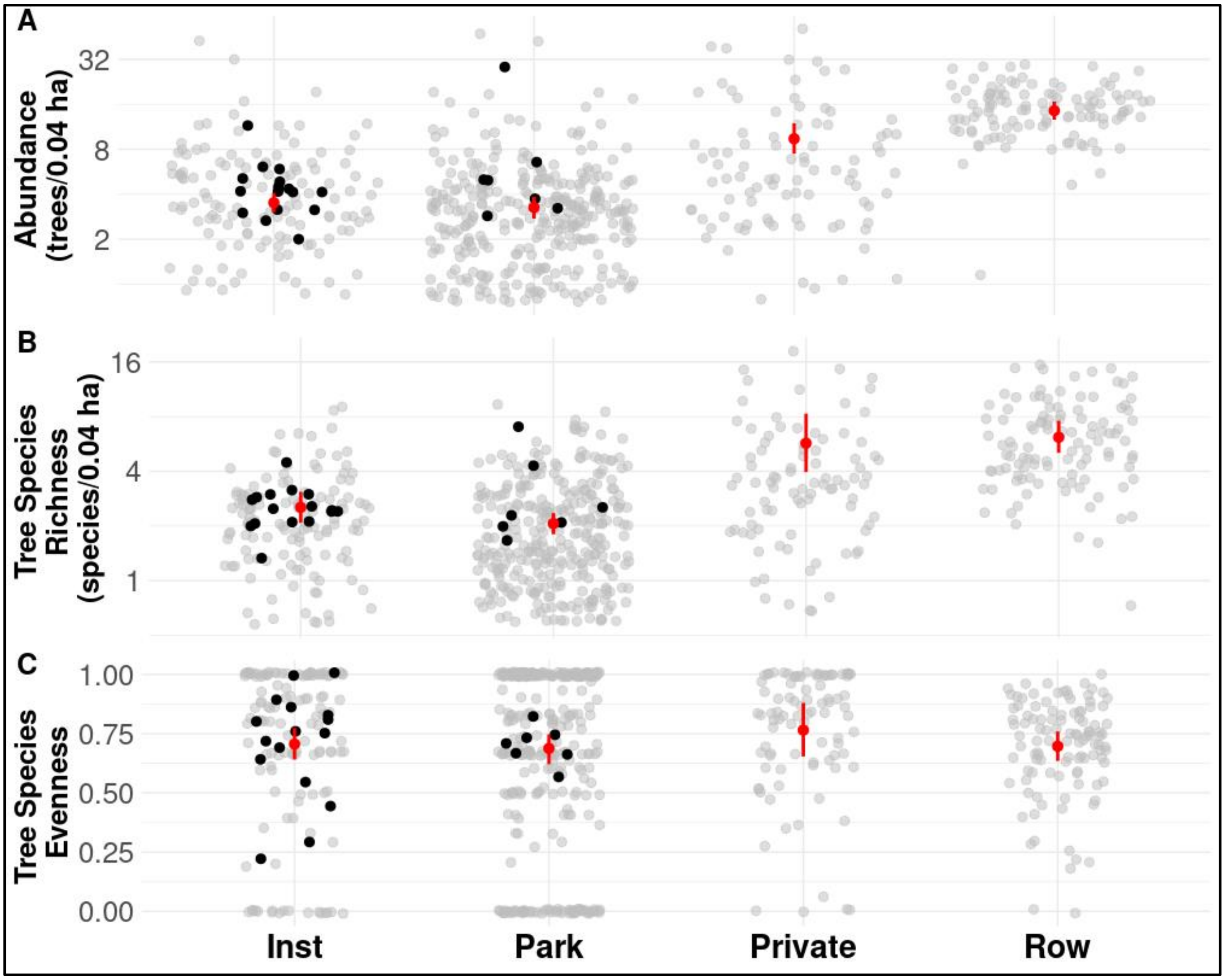

Figure 5. Variation in tree diversity and structure metrics (A) Tree abundance (trees per 0.04 ha), (B) Species richness (species per 0.04 ha), and (C) Hurlburt's PIE evenness across four green space types (Inst= Institutions, Parks, Private and Row= Street Right of Way) in NDG tree inventory. Tree abundance and species richness are $\log_2$ scaled. Grey data points represent raw data values of subsites (~0.04 ha) and black data points represent parcel means (e.g. the mean richness of all subsites in a park). Red data point ranges represent the model estimate means and 95% confidence intervals associated with mixed model estimates.

Table. 1 Description of public and private green space type classifications and site characteristics.

Green Space	Description	Samples (N)	Total Site Area (ha)	Subsites (n)	Mean Subsite Area
Parks	*Publicly managed parks*	7	16.6	314	0.04 (±0.000)
Institutions	*Publicly accessible school grounds and places of worship*	16	5.4	126	0.04 (±0.000)
Street Right of Way *(ROW)*	*Land allotment for street trees*	103	1.7	109	0.04 (±0.010)
Private Residential	*Single family homes, townhouses and semi-detached homes*	89	2.2	89	0.03 (±0.010)

Table 2. Explanation of ecosystem-service based functional traits used in our analysis.

Ecosystem Service Type	Ecosystem Service-Based Trait	Service Delivered	Rationale	Trait Source
Cultural	Native/Non-Native	Supporting other native forms of diversity (e.g. birds, insects)	Pataki et al. 2013 Helden et al. 2012	USDA Plants Database
	Flowering	Aesthetic beauty	Avolio et al. 2015 Pataki et al. 2013 Ibsen et al. 2020	Dirr 1990 Dirr 2011
	Fall Colour	Aesthetic beauty	Avolio et al. 2015 Pataki et al. 2013 Ibsen et al. 2020	Morton Arboretum 2021 University of Florida 2021
	Bark Texture	Aesthetic beauty	Avolio et al. 2015 Ibsen et al. 2020	Dirr 1990
Provisioning	Fruiting	Edible food production, aesthetic beauty	Avolio et al. 2015 Ibsen et al. 2020 Pataki et al. 2013	Dirr 1990 Morton Arboretum 2021
Regulating	Leaf Type	Shade provision, temperature regulation	Pataki et al. 2013	University of Florida 2021
	Shade Tolerance	Tree suitability for planting	Avolio et al. 2015	USDA Plants Database (Russell & Barbara 1990)
	Drought Tolerance	Tree suitability for planting	Avolio et al. 2015	USDA Plants Database (Russell & Barbara 1990)

Cultural and Regulating	Growth rate	Carbon storage and sequestration and time to maturity resident preference	Avolio et al. 2015 Pataki et al. 2013	Dirr 1990 University of Florida 2021
	Average maximum height	Provision of shade, aesthetic beauty	Avolio et al. 2015	Dirr 1990 Dirr 2011
	Tree Shape	Shade provision, temperature regulation and aesthetic beauty	Avolio et al. 2015	Morton Arboretum 2021 University of Florida 2021

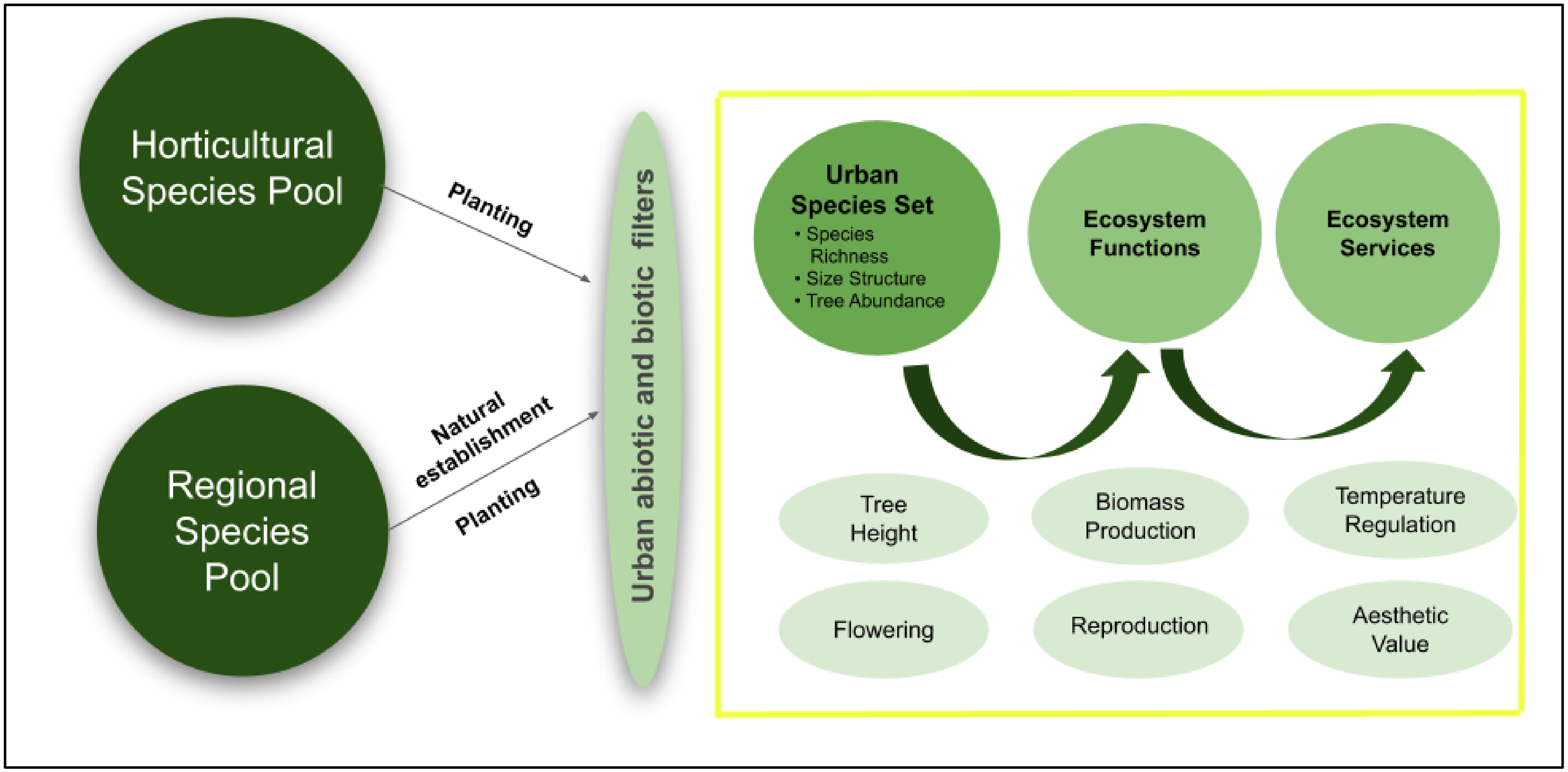

Figure 6. Simplified flowchart which visually depicts the process of urban tree establishment in green spaces and their links to ecosystem services adapted from (Goodness *et al.* 2016).

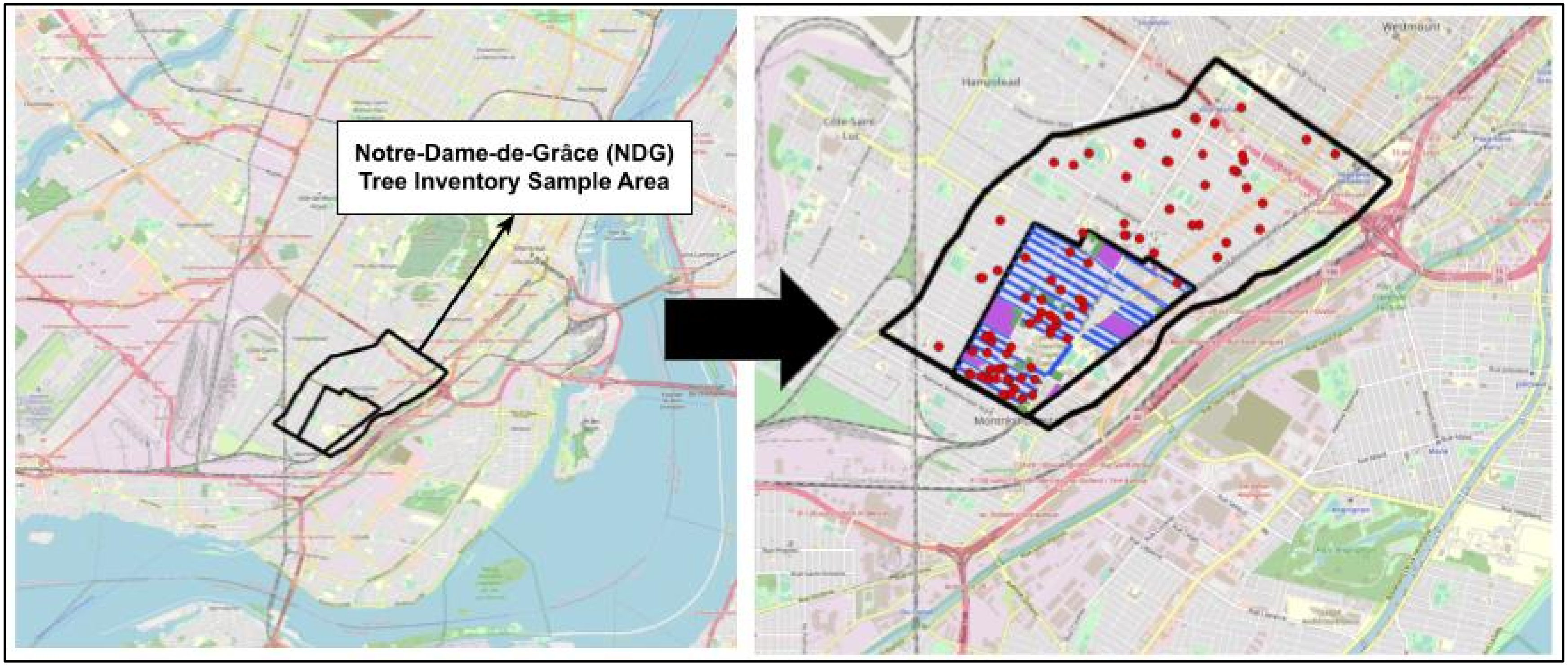

Figure 7. Outlines (in black) of sample area on the Island of Montreal in Notre-Dame-de-Grace neighbourhood scale outlines represent the two scales of data collection, the broad collection of private yard data and the urban forest plot. Blue polygons represent street block samples, purple polygons represent public parks, green polygons represent institutional spaces and red dots are private yards sampled.

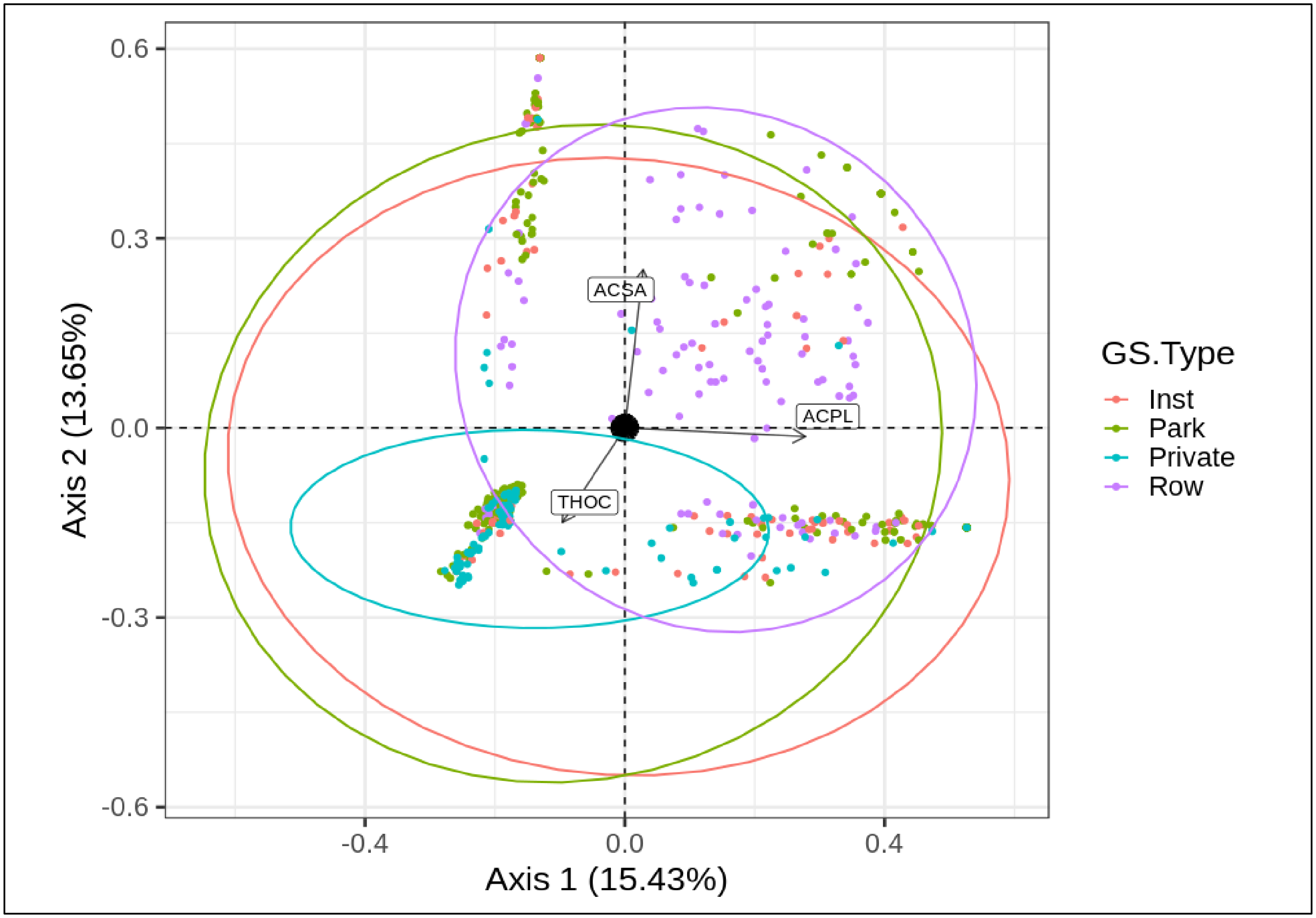

Figure 8. PCoA ordination plot showing distances among 155 tree species composition based on 638 subsites for the first two axes. The dispersion of species within four different green space types (parks, institutions, street ROW and private yards) are shown as ellipses using standard deviation of the point scores with a confidence limit of 0.90. Significant correlations ($p<0.001$) of traits with the first two PCoA axes are represented as arrows; the length of the arrows is proportional to their correlation coefficient, and they point in the direction of most rapid change. Arrows were scaled to improve visual representation of both subsite data points and vector arrows. THOC= *Thuja occidentalis*, ACPL= *Acer platanoides*, ACSA= *Acer saccharinum*.

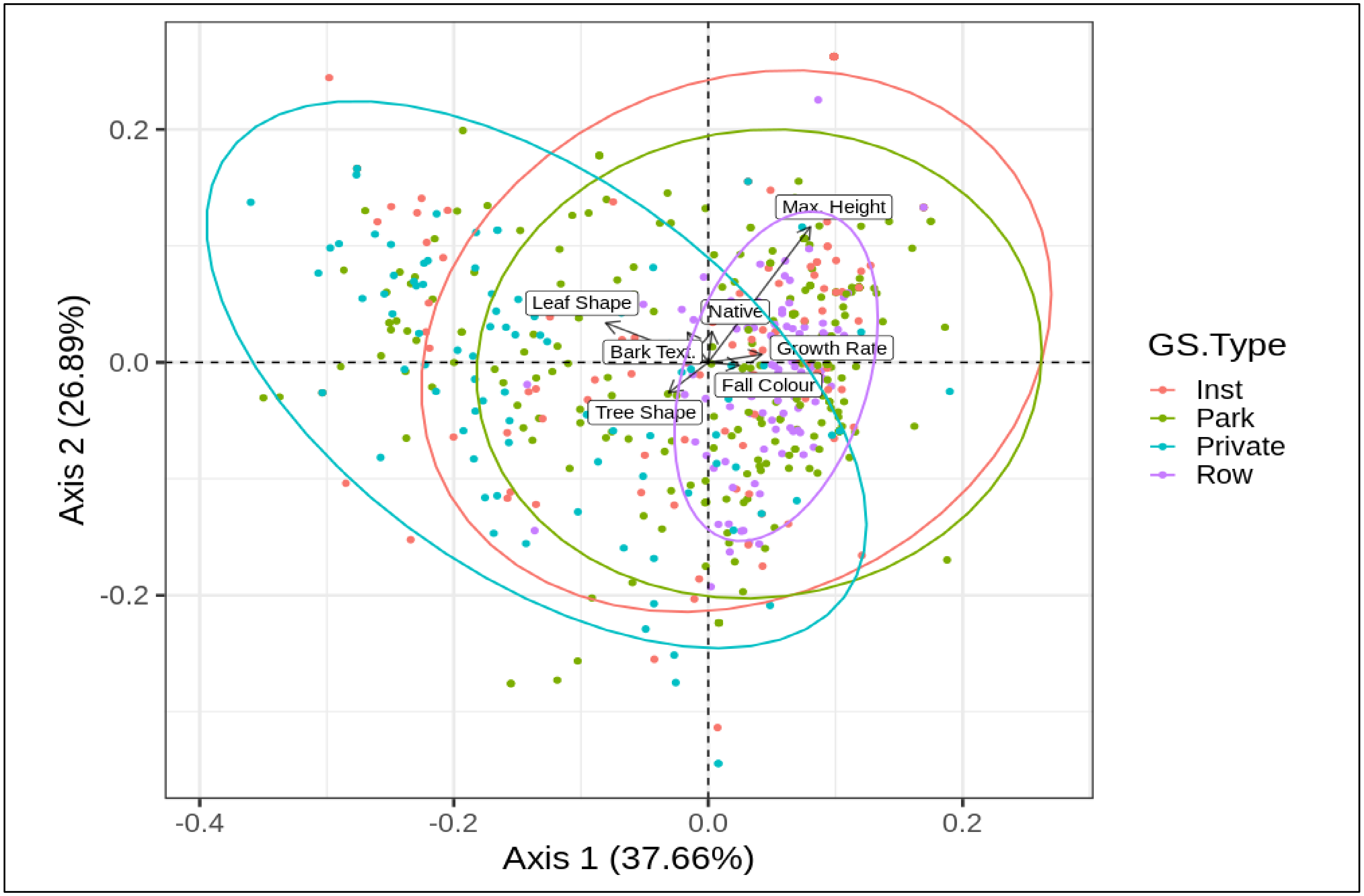

Figure 9. PCoA ordination plot showing distances among community weighted traits means of 638 subsites based on 11 traits for the first two axes. The dispersion of traits within four different green space types (parks, institutions, street ROW and private yards) are shown as ellipses using standard deviation of the point scores with a confidence limit of 0.9. Significant correlations ($p<0.001$) of traits with the first two PCoA aces are represented as arrows; the length of the arrows are proportional to their correlation coefficient, and they point in the direction of most rapid change. Arrows were scaled to improve visual representation of both subsite data points and vector arrows.

Appendix I: Linear mixed models

Table A1.1 Fixed and random effects results for mixed model analysis predicting species richness at the subsite level (N=638) for four green space types: institutions, parks, public right of way and private residential land.

Predictor	Estimate	Std Error	T value	P value
Institutions	2.93	0.828	3.54	***<0.0001***
Park	-0.210	0.126	-1.67	***<0.01***
Public Right of Way	0.881	0.148	5.95	***<0.0001***
Private Residential	0.805	0.221	3.65	***<0.0001***
	Random effect			
	0.619			

Table A1.2 Fixed and random effects results for mixed model analysis predicting tree abundance at the subsite level (N=638) for four green space types: institutions, parks, public right of way and private residential land.

Predictor	Estimate	Std Error	df	T value	P value
Institutions	3.95	0.524	513.9	7.53	***<0.0001***
Park	-0.07	0.118	16.3	-0.66	0.517
Public Right of Way	1.41	0.104	90.7	13.48	***<0.0001***
Private Residential	0.98	0.148	203.4	6.61	***<0.0001***
	Random effect				
	0.831				

Table A1.3 Fixed and random effects results for mixed model analysis predicting tree species evenness at the subsite level (N=638) for four green space types: institutions, parks, public right of way and private residential land.

Predictor	Estimate	Std Error	df	T value	P value
Institutions	0.71	-0.024	597.3	2.947	***0.003***
Park	-0.02	0.004	23.7	-0.417	0.680
Public Right of Way	-0.01	0.005	188.5	0.905	0.821
Private Residential	0.06	0.006	363.8	-0.226	0.366
			Random effect		
	$-4.02e^{-5}$				

Appendix II: Study area and community science project outreach

Table A2.1 *Land Use Classifications*

		Total Site Area			
Green Space	***Description***	***N***	***Total Area Sampled (ha)***	***Parcel Mean Area (ha)***	***Standard Deviation***
Parks	*Publicly managed parks*	*7*	*16.6*	*2.38*	*2.40*
Institutions	*Publicly accessible school grounds and places of worship*	*16*	*5.4*	*0.33*	*0.20*
Public Right of Way	*Land allotment for street trees*	*103*	*1.7*	*0.040*	*0.01*
Private Residential	*Single family homes, townhouses and semi-detached homes*	*89*	*2.2*	*0.025*	*0.01*

Table A2.2 *House Parcels with Tree Species*

Area	**Total House Parcels**	**Parcels with No Trees**	**Proportion**
NDG-CDN	10,319	3,852	37%
Urban Forest Plot Boundary	3,127	783	25%

1.3 NDG Community Tree Inventory Outreach Materials

Appendix III: Diversity, size class and cultivars

Cities contain a high density of tree cultivar species which have been bred for specific purposes in the landscape (e.g., drought tolerance, disease resistance, tree shape, vigor, flowering etc.). However, many of these species are clones of its parent species and therefore cannot be classified as a new separate species. For some species, visual differences are notably distinct, for example, purple rather than green leaves, or a compact columnar tree shape. Only species that contained these notable and distinguishable characteristics were classified as a separate species for analysis. We included these distinctions, which were related to tree planting motivations and decisions by land managers. For example, when deciding to plant a tree, within a private yard or along a street block, an individual may specifically choose a dark red leaf (not green) Norway Maple as seen below. Although, they may not understand this is the same species, and the aim of this work is to improve our understanding of management decisions and preferences and their outcomes for composition and diversity, it is integral I consider/include these small distinctions. Based on our data set we compiled a tree bank file which contains all cultivars related to a species and how it differs based on specific traits. See supplementary for spreadsheet.

Figure A1. Visual example of a Norway Maple (Acer platanoides) cultivar that was treated as a separate species for analysis. (A) 'Crimson King' Norway Maple variety with distinct purple leaves, (B) Norway Maple species.

Link to excel metadata on species cultivars within the public domain. Information includes known data on how cultivars differ on 11 service-based traits to parent species. See summary on sheet 1.

Tree Species and Cultivars Bank

Tree maximum diameter at breast height values

Tree maximum diameter at breast height (DBH) values were sourced from the Paquette Lab (PaqLab 2021) and adapted based on our tree species data. For all trees contained in the public tree database (Ville de Montreal 2021), maximum DBH values were calculated based on DBH values across the entire tree pool in Montreal. For each species, the maximum DBH was determined by assigning values equal to the 95th percentile value in the dataset for each given species. We followed the same protocol for all new species (not included in the public database) within our tree dataset. In order to calculate a value, the species had to have a minimum of ten individuals in the entire dataset. In situations where the genus was written (and there was a minimum of 10 individuals) but no species information, a genus average is also included.

For example:

Species	**DBH in 95th Percentile**
Norway Maple (Acer platanoides)	67 cm
Silver Maple (Acer saccharinum)	90 cm
Maidenhair (Ginkgo biloba)	36.2 cm

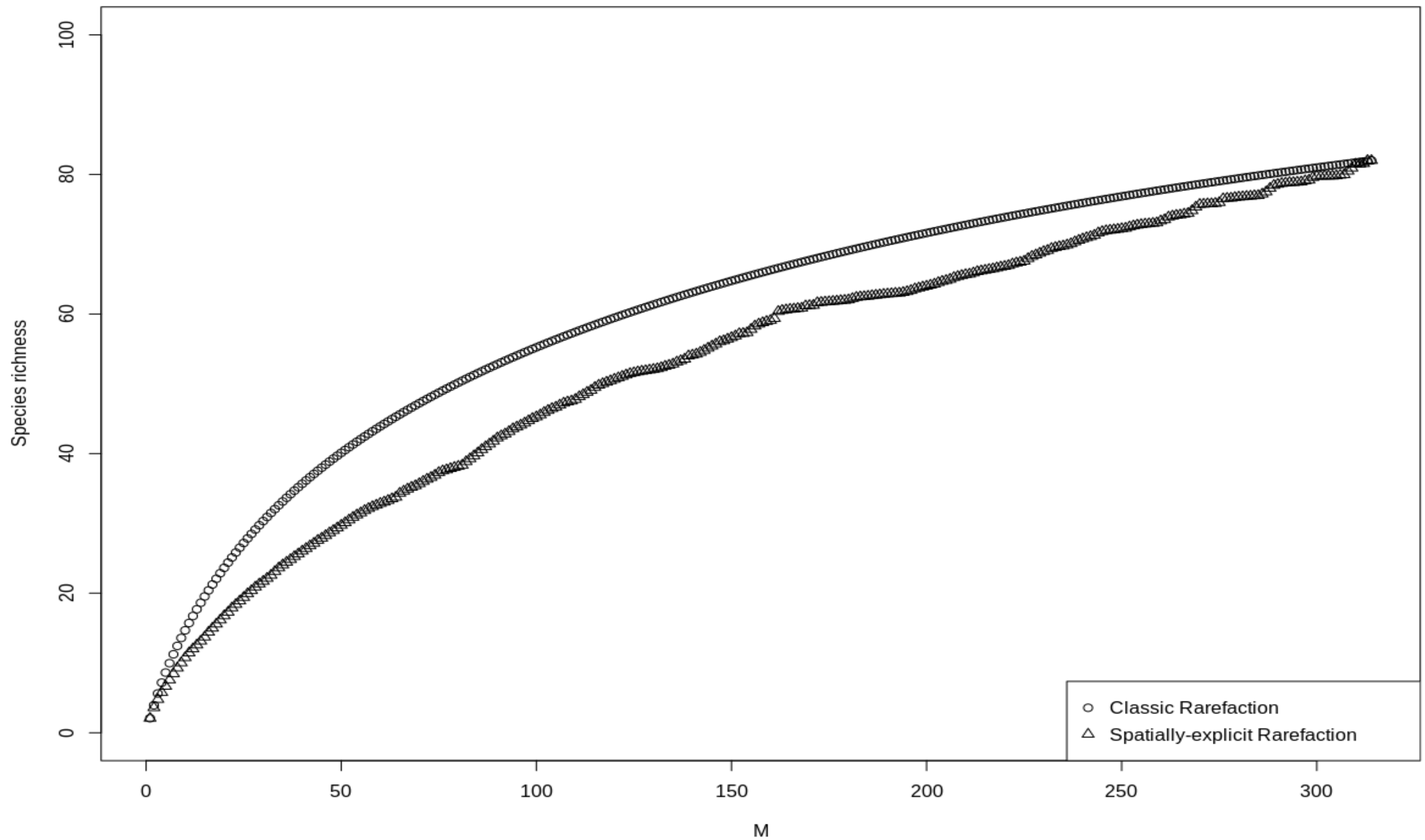

Figure A2. Spatially explicit and classic rarefaction curves for all park subsites (N=314) to explore the influence of sub-sampling on species richness estimation. Curves were created using a distance matrix which correlates sites which are located within the same park and adjusts for the impact of spatially autocorrelated sites.

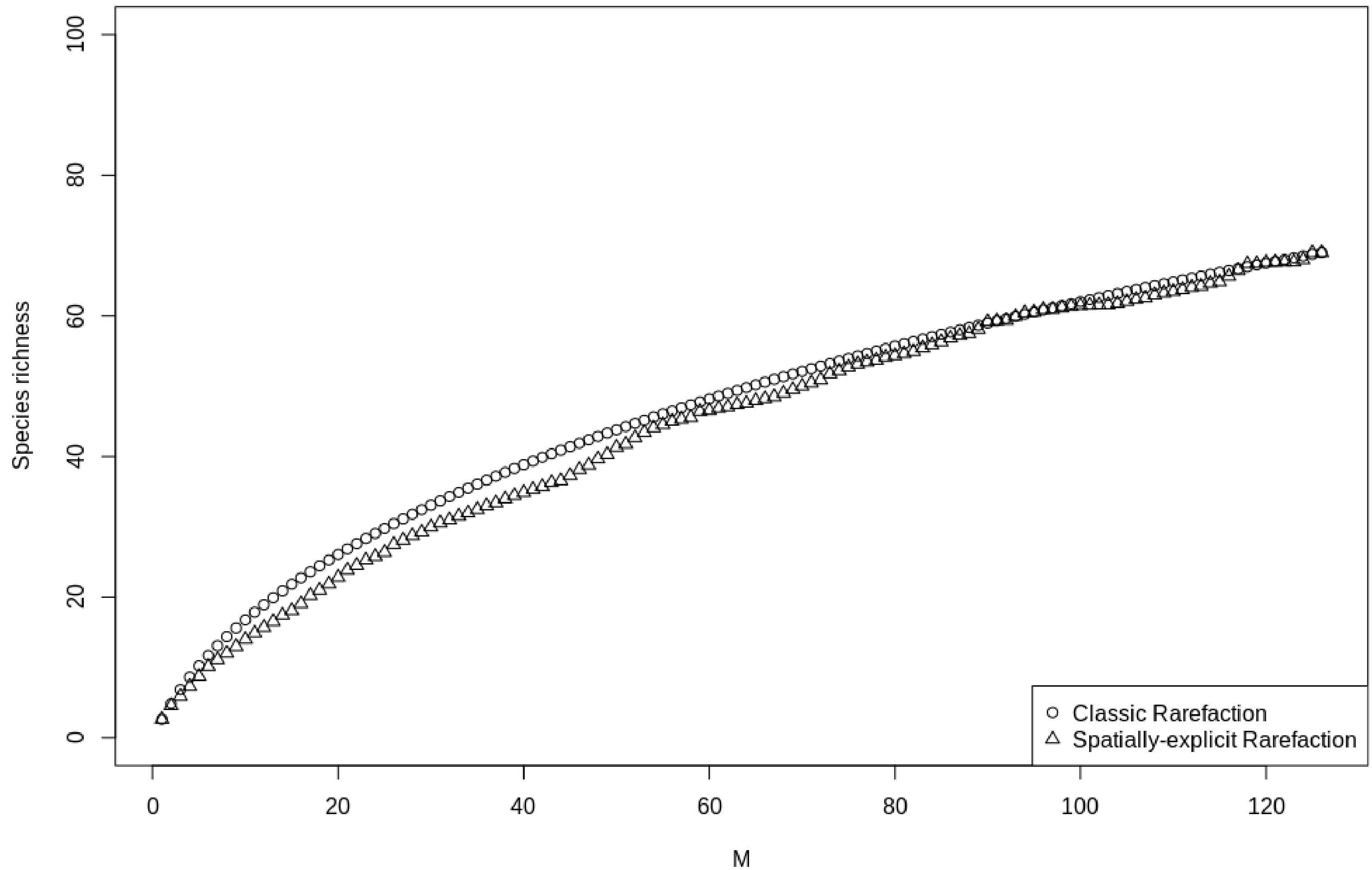

Figure A3. Spatially explicit and classic rarefaction curves for all institutional subsites (N= 126) to explore the influence of sub-sampling on species richness estimation. Curves were created using a distance matrix which correlates sites which are located within the same park and adjusts for the impact of spatially autocorrelated sites.

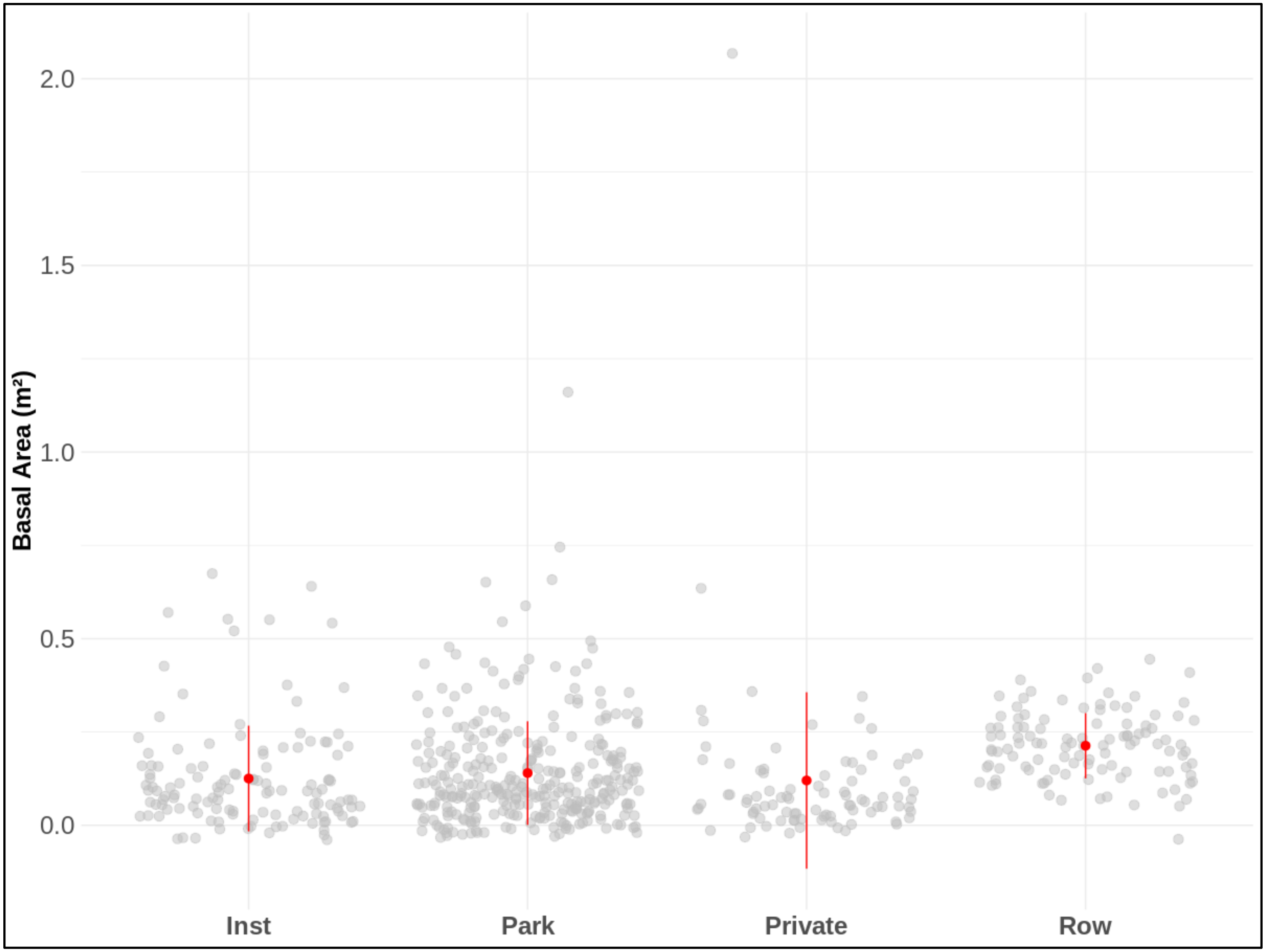

Figure A5. Mean basal area per subsite (grey dots) with mean basal area per green space type (red dots) and associated standard deviation.

Appendix IV: Mixed model analysis II

Table A4.1 Fixed effects results for mixed model analysis of PCoA axes based on species composition in 638 subsites, including random effect of subsites.

Predictor	Estimate	Std Error	df	T value	P value
Institutions	-0.15	0.26	120.91	-0.57	0.57
Park	-0.18	0.46	113.41	-0.39	0.70
Public Right of Way	-0.51	0.29	134.24	-1.80	0.07
Private Residential	1.02	0.28	132.06	3.66	***<0.001***

Table A4.2 Fixed effects results for mixed model analysis of PCoA axes based on service-trait composition in 638 subsites, including random effect of subsites.

Predictor	Estimate	Std Error	df	T value	P value
Institutions	-0.08	0.09	69.71	-0.82	0.41
Park	0.20	0.14	30.97	1.45	0.16
Public Right of Way	-1.12	0.13	177.58	-8.57	***<0.001***
Private Residential	0.54	0.13	158.32	4.35	***<0.001***