Temporal and spatial drivers of Canadian urban forests

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Introduction

Urban landscapes are a complex combination of natural, physical, social, and built elements[1] (see Table 1), resulting in extremely fine-scale heterogeneity[2,3]. Within this context, urban nature provides benefits to humans not received from built elements[4–6], improving urban residents' overall well-being, happiness, mortality rates, and more[7]. However, due to the complexity of cities, along with pressures of capitalism and settler-colonialism in the Global North, nature's benefits are delivered inequitably[8–10]. For example, management practices based in classism and white supremacy result in disproportionately less green space in neighbourhoods home to marginalized populations[8,11–13]. Ensuring equitable distribution of urban nature's benefits requires understanding mechanisms that produce inequalities using empirical ecological data, grounded in the historical context and social fabric of cities[14]. We must also adopt an approach of equity, compassion, and justice[15] surrounding urban greening, focusing on values that benefit our communities as a whole.

Managing urban nature to maximize human benefits can be approached through the integrated framework of *ecosystem services*[16–18]. For example, recreational access to water is a service that can improve mental health and aid in stress recovery[19,20]. Ecosystem service capacity, or the total potential of an ecosystem to provide a certain service, provides a framework that can be understood by various stakeholders and addressed at multiple scales. Thus, managing urban nature for production and delivery of ecosystem services is a common municipal goal. Regulating ecosystem services, defined as benefits that are provided through the regulation of the ecosystem, are particularly critical when managing cities because they often must be produced *in situ*[21,22]. Urban forests in particular provide many regulating services, but their capacity to do so varies due to many factors, such as species composition[21,23,24]. For example, a well-known regulating service provided by the urban forest is the ability of trees to reduce the urban heat island effect[25–27]. Shade and evapotranspiration by trees can reduce air temperatures from levels that are dangerous to human health[25]. Larger trees with thin, wide leaves may buffer temperatures more effectively than smaller trees with thick, narrow leaves and thus, the capacity of the urban forest to buffer heat at any particular scale is dependent on its species composition.

The capacity of the urban landscape to deliver ecosystem services is also spatially and temporally heterogeneous, driven by anthropogenic and natural factors. For example, stakeholders manage urban land differently, both on small scales, e.g., homeowners planting different species in their yards, and large scales e.g., different cities or neighbourhoods varying in tree governance[28,29]. Similarly, current ecosystem services can be significantly influenced by legacy effects[30–32], when a historical event carries over its effects to subsequent events[33,34]. For example, someone planting a backyard tree affects service capacity at the time of planting and for all subsequent homeowners. Thus, understanding the variation and distribution of urban ecosystem service capacity requires a multi-scale, spatiotemporal approach.

My proposed thesis will take a spatiotemporal approach to investigating the processes that influence urban forest characteristics and regulating ecosystem service capacity in Canadian cities. Historically, our inferences on ecosystem services have been limited due to most studies being conducted in a single city[32]. My multi-service, multi-city, spatiotemporal approach will contribute to theoretical and applied understanding of the ecology underlying urban ecosystem services, while incorporating the context, history, and social aspects of cities. My research will also contribute to quantifying the legacy effects of management decisions such as gentrification. Critically, some factors that impact ecosystem services, such as past environmental racism, are set by history and thus irrevocable[35,36]. However, clearly defining common and distinct current drivers of, and legacy effects on, urban forest ecosystem services will help us shape future urban landscapes to more equitably serve all residents.

Study Area & Positionality

My thesis work will use data and be completed upon lands across the country colonially known as Canada, the traditional and unceded territory of many Indigenous peoples and nations. I live, work, and will collect data for chapters 2 and 3 in Kawenote Teiontiakon (known as Montréal), the unceded and traditional lands of the Haudenosaunee and Kanien'kehá:ka (Mohawk) peoples[37]. Chapter 1 also includes data collected in 6 additional cities: Vancouver – the ancestral lands of the Coast Salish peoples; Calgary – the ancestral lands of the Niitsítpiis-stahkoii (Blackfoot/ Niitsítapi), Tsúūt'ínà, Ktunaxa, and Michif Piyii (Métis) peoples; Winnipeg – the ancestral lands of the Anishinabek, Michif Piyii (Métis), Očhéthi Šakówiŋ (Sioux), Cree, Dakota, and Dene peoples; Toronto – the ancestral lands of the Anishinabek, Haudenosaunee, Mississauga, and Wendake-Nionwentsïo peoples; Ottawa – the ancestral lands of the Omàmìwininìwag (Algonquin), Kanien'kehá:ka (Mohawk), and Anishinabek peoples; Halifax – the ancestral homelands of the Wabanaki and Mi'kma'ki peoples[37].

My thesis work integrates both qualitative and quantitative data in urban environments. I approach this work with many biases that stem from my identities and lived experience. Especially relevant to this work is my background as a white settler, socialized and trained using a Eurocentric worldview of the scientific method. My approach to science is thus based in reductionism. Further, I have lived my whole life in the Global North, which influences the nature of my scientific questions and approach. For example, my knowledge of the Global North leads me to test relationships between race and urban nature, whereas those questions may be less relevant, or approached differently, in the Global South.

Proposed Research

<u>Chapter 1: Cross-city drivers of urban forest regulatory ecosystem services</u>

Quantifying and understanding variables affecting ecosystem services can allow for holistic planning of cities that are healthy and equitable. If we identify consistent drivers of urban forest ecosystem service capacity, we can align management practices and decisions with stakeholder goals and priorities before ever planting a tree. Most studies assess ecosystem services in one city[38] (but see Landry et al. 2020[39], Galle et al. 2021[40] for multi-city approaches). A single city approach is useful for understanding fine-scale intricacies. However, it does not allow for the identification of consistent drivers of ecosystem service capacity, reducing our ability to generalize across landscapes.

Drivers of ecosystem service capacity are wide-ranging in scope and can vary in the effect they have[23,24,27,41,42]. The relative strength and importance of specific drivers also varies by scale. For example, the capacity of a single urban tree to provide temperature regulation to residents is partially driven by its leaf area[43], whereas at the neighbourhood scale, temperature regulation may be influenced by tree species composition[27]. Thus, a multi-scale approach is necessary to gain a better understanding of the drivers of ecosystem services on scales relevant to human health and well-being.

To test the strength and direction of drivers of ecosystem service capacity in the urban forest, we use a "city-specific" and cross-city" framework. We expect city-specific drivers to be unique to individual cities and influence services on a specific spatial scale (i.e., street, neighbourhood, city). For example, different property ownership trends and/or varying climatic conditions may lead to different tree sizes, resulting in a location-specific driver of aboveground carbon storage[39]. We define cross-city drivers as processes that influence ecosystem service provision across cities and scales. For example, we would hypothesize that tree size distribution affects temperature regulation, regardless of which city or at what scale we are investigating. Using publicly available street tree data, we use a multi-scale, multi-city approach to ask: what are the cross-city drivers of regulatory ecosystem services in Canadian cities?

<u>Approach</u>

Study Area. We will use publicly available data to test ecosystem services and their drivers in seven major (>400,000 people) southern (below 51°4'0"N), temperate cities that span a longitudinal gradient across Canada (Figure 1a). We will test three groups of drivers of three ecosystem services at three management-driven scales within and across the seven cities: fine-scale (street level), medium-scale (neighbourhood level), and large-scale (city level) using a Bayesian general linear model framework.

Ecosystem Services. We will quantify three regulatory ecosystem services provided by the urban forest: temperature regulation, air pollution mitigation, and carbon storage (Table 2). The dense, impervious design of cities make temperature and climate regulation, and air pollution uniquely problematic[25]. We will measure biophysical indicators of these services using remotely sensed data of air pollution and land surface temperature, along with allometric modelling to determine carbon storage.

Ecological Drivers. We will explore four independent ecological variables relevant to urban forest ecosystem service capacity using data on publicly owned street trees: tree species richness, functional diversity, size distribution, and density (Table 2). There is no consistently available data in Canada on privately-owned trees, thus incorporating private trees is out of the scope of this project. We also chose to exclude publicly owned park trees. Park trees data are not available for every city. Also, park trees often provide social and recreational services in addition to regulating and supporting services[11,44]. The differences in ecosystem service provision between street and park trees can result in very disparate managerial decisions for what species to plant and when, thus, to answer our specific research question we chose to focus on publicly owned street trees. This focus will also allow us to determine areas where public street trees are more influential, i.e., areas with less space for private tree planting may rely more on street trees, which is an important consideration for equity-based planning.

Built Infrastructure Drivers. Built infrastructure drivers, otherwise known as urban form drivers, refers to the physical configuration of an urban area[45].We selected built infrastructure variables with established relationships with our ecosystem services: road size, total impervious and green space, as well as building density, function, and height (Table 2). We will obtain data from the federal roads database, municipal LiDAR imagery, federal digital elevation models, and an open-source Microsoft building footprint layer.

Sociodemographic Drivers. We use multiple census-based measures to assess how income and class drive ecosystem service capacity across Canadian cities, with sociodemographic variables including population density, median income of residents, and dwelling type (Table 2). Our focus on public trees may influence relationships detected between the urban forest and sociodemographic drivers, as we expect less of a relationship between publicly owned trees and variables such as race and income in Canadian cities, however, we felt it was important to test these relationships regardless.

Controls. We will also include relevant controls in our analysis, such as housing market regulation, tree governance, and climatic variables.

<u>*Status of Chapter:*</u> We have cleaned and gathered relevant data for the socioeconomic and ecological drivers for all study cities at street, neighbourhood, and city scales. We are currently gathering and cleaning remotely sensed data for ecosystem service capacity as well as built infrastructure variables.

<u>Chapter 2: Legacy effects of previous land-use on regulatory ecosystem service capacity of park trees</u>

Legacy effects, or present-day impacts of past decisions or events[34], can affect ecosystem processes and functioning for decades to millennia[46,47], such that understanding today's ecosystem functioning is dependent on understanding the continuing influence of historical conditions. As cities are human-designed ecosystems, existing due to past human action[32,47], many urban legacy effects are caused by past anthropogenic disturbances. An example is land (re)development. Variation in past land use type influences current urban ecological processes and functioning. For example, areas that differ in whether they were previously forested vary in levels of soil nutrients[35] and recreational use today[48].

Cities are shaped by human activities and values. As a result, they have dynamic histories with high rates of land use change[2,31]. Urban development in North American cities results in expansion at city edges, where agricultural and forested land surrounding cities are converted to urban land-use types[49]. Due to intensification or land abandonment, urbanization also results in redevelopment of industrial, commercial, and residential land use within city borders[50]. For example, loss of manufacturing business in Pittsburgh led to the abandonment of the downtown core for decades, leading to a series of "revitalization" efforts which redeveloped former industrial areas to mixed-use areas with office buildings, hotels, green spaces, and residences[51]. This mix of new and re-development results in a wide array of past land use types in cities, including forested, industrial, and agricultural.

Land-use and (re)development patterns in cities are determined by societal context and are thus intertwined with injustice and inequity[52]. Urban planning is defined as a social endeavor that has a distinct set of goals designed to reach an "optimal strategy" determined by those in power[53]. Thus urban planning in post-colonial North America, inevitably and intentionally upholds inequity and injustice[54–58], ultimately structuring the ecology of our cities[8]. For example, present day urban forest resilience, a factor determined by past management decisions, is lower in areas where there are lower income communities with high rental populations[39]. Better understanding of the complex relationship between land-use legacies and environmental inequity is required to work towards just, equitable cities.

The long-lived nature of trees means their current functioning is strongly affected by legacy effects of past management decisions and socioeconomic circumstances[32,59]. Tree species composition and density are determined in part by cultural values, management practices, and community goals at the time of planting. These factors tend to differ depending on the area and land-use type, and the effects of planning decisions are often not experienced until decades later[32,59]. Different land-use types can also leave different physical legacies that influence ecosystem service capacity. For example, following development agricultural land accumulates carbon in the soil but former forests do not, potentially altering the tree growth and associated ecosystem services for years to come[60]. Differences in physical legacies from past-land use types can also determine which species may or may not be present in an area[61,62]. Parks provide an excellent study system, as they provide critical ecosystem services to residents, are often developed on different land-use types, have several tree species within them, and are developed based on cultural values and community goals. Quantifying the legacy effects of past land-use types on the ecosystem services of trees in current urban parks will allow us to better plan for equitable distribution of ecosystem services in the future. Here, we ask:

1) What are the legacy effects of past land-use types on current ecosystem service provision (carbon storage, temperature regulation) by urban parks?
2) Are certain past land-use types disproportionately represented in today's neighbourhoods and if so, is the relationship perpetuating systemic injustices?

We 1) hypothesize the previous land-use type will influence the type and quantity of ecosystem services currently delivered by urban trees in Montréal's parks. We predict past land-use types that resulted in an input of nutrients to the soil, such as agriculture, will result in increased tree size and canopy cover, in turn yielding higher ecosystem service capacity. We predict past land-use types associated with higher levels of anthropogenic contaminants, such as industrial waste, will result in lower ecosystem services. Finally, we predict the intensity of legacy effects will decrease with time since park development. We also hypothesize 2) that neighbourhoods which were historically inhabited by marginalized people will have disproportionate rates of past land-use types deemed "undesirable" (i.e. industrial land) due to environmental racism and thus, lower levels of ecosystem services. However, due to changing spatial dynamics in Montréal through processes such as gentrification in historically polluted areas of the downtown core, we predict the relationship between past land-use types and current community demographics will be weak.

Approach
We will investigate the legacy effects of the land-use type immediately prior to park development on today's ecosystem service capacity in Montréal, Québec (Figure 1b). Using historical archives, such as land-use maps, municipal documents, and aerial photographs, we will determine the former land use

type and year of establishment for parks in the city. We will classify previous land-use as previously forested, agricultural, or industrial. Using Montréal's Large Park Network and supplementing with smaller parks, we will select 10 parks of each former land-use that span a gradient of time since development (to account for effects of tree growth and maturation). To assess the impacts of past land-use on current forest composition and structure, we will use two scales of analysis at each park: 1) forestry plots and 2) entire park canopy cover. For 1), we will randomly assign three forestry plots stratified by current canopy cover within each park: sparse (cover < 30%), medium (cover > 30% but < 70%), or full (cover > 70%). Thus, if a park has all three canopy cover levels present, there will be nine plots total per park. Plots will be modelled after iTree sampling design, they will be 0.04 ha and assess tree density and individual tree attributes such as size and species[63]. For 2) we will assess canopy cover aggregated at the park scale using LiDAR data[64]. To measure the legacy effects of past land-use on current temperature regulation capacity of the parks, we will deploy a temperature sensor in one of the three forestry plots for each land cover type at each park. We will also measure carbon storage using allometric modelling. To assess how past land use type interacts with historical and current inequity and environmental racism, we will collect sociodemographic data for current and historical neighbourhoods using census data and historical accounts. Using Bayesian generalized linear models, we will test how the independent variables related to time since development, past land-use type, and sociodemographics influence current urban forest composition and ecosystem service capacity.

Chapter 3: Legacy effects of urban form on urban forest composition and structure

The widespread migration to cities following the industrial revolution in North America increased population and building density in urban centers across the world[65]. Such urbanization often negatively affects urban forests, mainly due to planning decisions such as increases in impervious cover that limit planting space[13,48]. However, urbanization is not a homogeneous process, with cities exhibiting distinct approaches at various spatial scales[66]. Neighbourhoods are an important scale that represent distinct patches of urbanization approaches[67]. Neighbourhoods also experience distinct trajectories following initial urbanization, which influences urban form[68–70]. Planning decisions which affect urban form dictate physical and social factors that subsequently impact urban forest composition and structure at fine-scales[41,71]. Urban form can influence the effects of urbanization on the urban forest through space constraints, modification to the microclimate, and population density[72–74]. For example, in Montréal, distance of a building from the road and proportion of households per building determine street tree cover[41]. Urban form decisions often persist through time, affecting neighbourhoods for decades.

In contrast to the persisting effects of urban form decisions made during urbanization, gentrification is a dynamic development process that occurs over time after an area has been developed which impacts the sociodemographic characteristics of a neighbourhood[75]. Alongside other factors, gentrification influences the ecology of the urban forest, with gentrified neighbourhoods often experiencing higher tree density, canopy cover, and biodiversity[8,76]. Gentrification is a common phenomenon across North America. Many North American cities experienced significant outmigration from downtowns starting in the 1950s[77,78]. Following outmigration, municipalities often invested in "reviving", or gentrifying, downtown neighbourhoods, which were traditionally high density, lower-class, and racialized areas[55]. Gentrification led to downtown areas being dominated by wealthy, white people, which would thus be expected to have a more robust and diverse urban forest[8,53]. However, gentrification's relationship with urban forest ecology is complex due to the competing influences of initial urban form decisions.

The urban form decisions made during initial urbanization efforts that do not easily change with redevelopment can be thought of as static factors, and they can make shifting neighbourhood urban forest composition and structure difficult regardless of gentrification. For example, a neighbourhood built with large roadways and buildings very close to the road will be constrained by those static factors reducing physical space for tree planting and affecting tree health, even after gentrification occurs. In contrast, we can think of urban form decisions that more easily change with redevelopment processes as dynamic factors. For example, building and population density change more easily than road width, as buildings are renovated for a different number of apartment units. In this dynamic vs static framework, we can assume that dynamic factors are often the driving force between the differences in urban forests across neighbourhoods that experience different levels of gentrification. Further, we can imagine that static factors, which are a result of past urban form decisions, constrain current and future urban forest composition and structure even when neighbourhoods experience gentrification.

It is currently unclear the extent to which legacy effects of past urban form decisions constrain current urban forest structure and composition. Determining the legacy effects of urban form decisions on the ecology of current urban forests and teasing out the static and dynamic factors that are driving the legacy effect, will allow us to better plan and manage our cities for more robust, resilient urban forests that are distributed equitably. Here, we ask:

1. What are the legacy effects of past urban form decisions and how do they constrain current urban forest structure and composition in neighbourhoods with varying gentrification trajectories?

We hypothesize that static initial urban form decisions will influence current urban forest structure and composition, across different neighbourhood trajectories. We hypothesize that varying trajectories of our selected development process, gentrification, will influence the urban forest through changing of dynamic urban form and social factors, but the effect will be smaller than the effect of the static initial urban form decisions. We predict that gentrified areas will have an urban forest that more diverse than ungentrified areas. However, due to the constraints of urban form, higher-density areas will have lower density of trees than lower-density areas regardless of gentrification status.

Approach

We will select 15 neighbourhoods in Montréal which will span gradients of current, static urban form characteristics and gentrification (Figure 1b). We will assess urban form characteristics using variables established as important determinants of urban forest composition and structure; road size, building setback, building density, and house size[79]. Using fieldwork, census data, and building plans, we will assess the mean and standard deviation for each urban form characteristic in selected neighbourhoods to assess the average condition and variation in conditions and establish a gradient. Urban form characteristics will span a gradient from "high density" neighbourhoods, with low building setback, high building density, low house size, and large road size to "low density" neighbourhoods, with high building setback, low building density, large house size, and small roads. We will use an open-access map-based tool designed to evaluate gentrification in Canadian cities to classify neighbourhoods as those which have experienced gentrification from 2006 to 2016, those which could have experienced gentrification from 2006 to 2016 but did not, and those which could not have experienced gentrification from 2006 to 2016[80]. We will select 5 neighbourhoods in each gentrification category that span the gradients of urban form characteristics. Using street tree data collected in chapter 1, we will assess urban forest composition and structure (tree size composition, density, diversity) in each neighbourhood. To incorporate privately owned trees, an important component of neighbourhood gentrification, we will assess canopy cover aggregated at the neighbourhood scale using LiDAR data[64]. Gentrification, considered as a categorical variable, and continuous urban form variables will be included as independent variables in Bayesian generalized linear models in order to tease out the effects of these phenomenon on current urban forest composition and neighbourhood canopy cover.

Figures

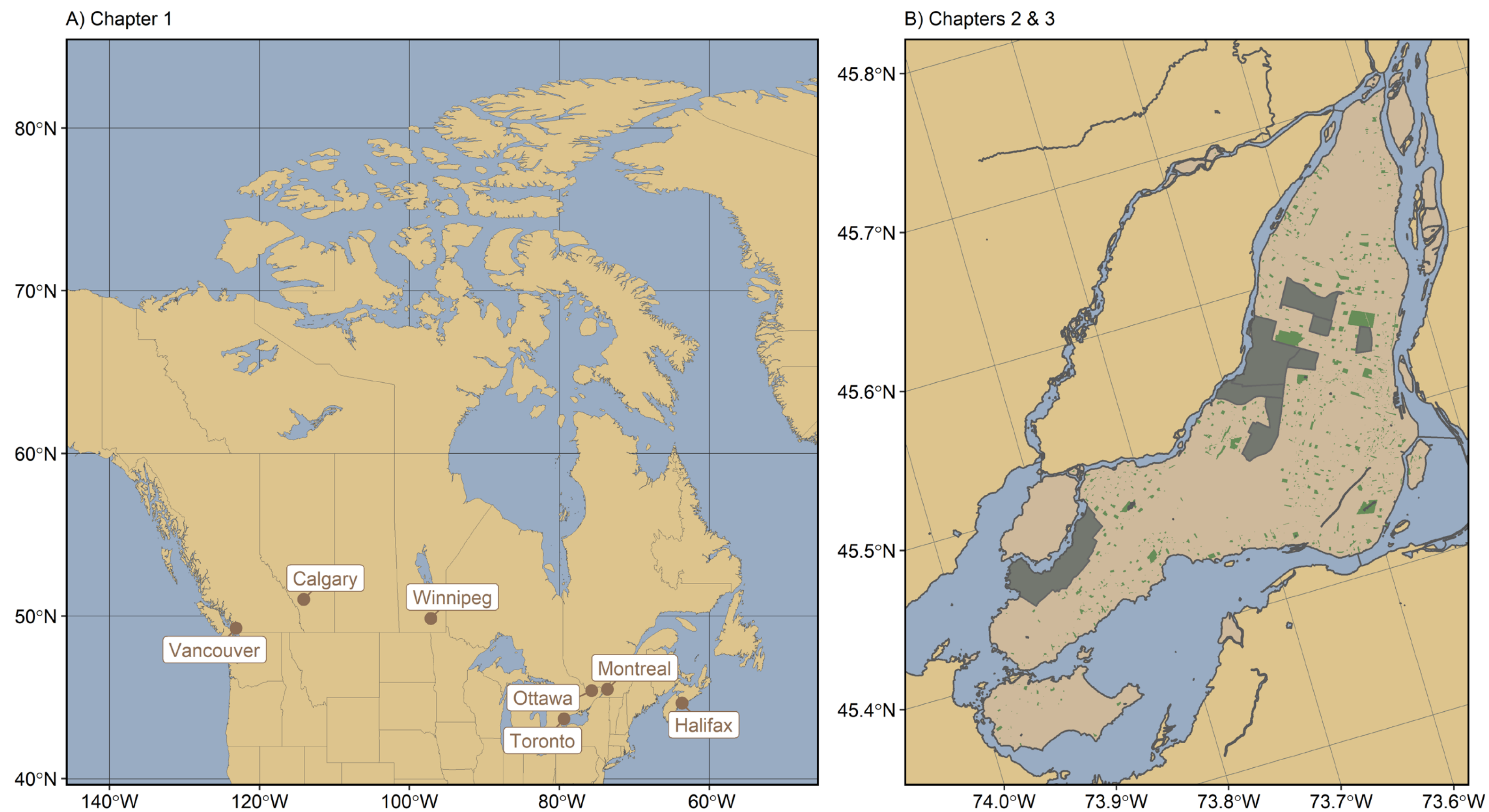

Figure 1. Proposed study systems. A) Seven study cities proposed for chapter 1. B) island of Montréal, with green polygons representing urban parks and grey polygons representing various potential neighbourhoods.

Tables

Table 1. Glossary of terms used

Term	Definition	Reference
Urban ecosystem/city	An ecosystem whose biological and physical characteristics are primarily engineered, modified, and constructed by humans. In urban ecosystems, human society influences the relationships among organisms and between organisms and the physical environment.	Des Roches et al. 2020[81]
Natural	The biotic, organic factors that are in a biome or ecosystem	Tansley 1935[82]
Built	All human-generated land modifications, buildings, infrastructure, and other artifacts	Pickett & Grove 2009[3]
Physical	Physical, inorganic factors that form the environment of the biome, habitat factors	Tansley 1935[82]
Social	Human generated social structures and interactions that are crucial to the functioning of ecosystems (e.g. government)	Pickett & Grove 2009[3]
Ecosystem services	The benefits that people derive from ecosystems	Millennium Ecosystem Assessment 2005[16]

Regulating services	Benefits obtained from the regulation of ecosystems	Millennium Ecosystem Assessment 2005[16]
Ecosystem service capacity	An ecosystem's potential to deliver services based on biophysical and social properties and functions	Villamagna et al. 2013[21]
Urban forest	Trees, forests, greenspace and related abiotic, biotic and cultural components in areas extending from the urban core to the urban-rural fringe	Tree Canada 2019[83]
Legacy effects	Manifestation of temporal autocorrelation within and across urban ecosystems. Carry-over effects on subsequent events in ecosystems.	Ossola et al. 2021[34]

Table 2. Ecosystem services, drivers, and their rationales for inclusion in this study.

Ecosystem Service	Indicator	Rationale
Temperature regulation	Land surface temperature (°C)	Heatwaves in Canadian cities can have tragic consequences. Most recently in British Columbia, during the summer of 2021, 569 people lost their lives due to heat-related causes[84].
Air pollution mitigation	O_3, SO_2, and NO_2 levels	The Canadian government estimates that over 15,000 Canadians die prematurely from air pollution every year[85]. Urban trees are most effective at removing sulphur dioxide and nitrogen dioxide from the environment[86]. The urban forest has a complex relationship with ozone, sometimes causing it to worsen by reactions with VOCs emitted by the trees, and sometimes removing it from the air[86,87].
Carbon storage	Tree carbon (C)	Carbon storage is an important contributor to climate regulation, with trees helping to decrease carbon dioxide (CO_2) in the atmosphere by storing it in their biomass[38], thus reducing the amount of greenhouse gasses in the Earth's atmosphere.
Driver	**Measure**	**Rationale**
Tree biodiversity (*Ecological*)	Species richness, functional diversity	Species richness, has mixed results regarding the relationships between biodiversity and ecosystem services[38,88,89]. Recently there is evidence that functional diversity may explain biodiversity-ecosystem service relationships because stakeholders often plant trees for specific purposes, resulting in urban forests with very few functional groups, even when species richness is high[90,91].
Tree size distribution (*Ecological*)	DBH distribution of tree community	Tree size distribution determines the shade provision and transpiration rate of the tree, both of which have a significant negative relationship with air temperature[92,93]. Tree size can also be related to rates of air pollution removal[94] but the relationship is species dependent[25,76,95]. Carbon storage and tree size have a linear positive relationship, with larger trees storing more aboveground carbon[96].
Tree density (*Ecological*)	Number of trees / km^2	Due to the increase in shading, transpiration, and biomass, an increase in tree density should be positively associated with temperature

		regulation and carbon storage. The relationship between tree density and air pollution may be negative depending on the crown and leaf structure, which can potentially trap airflow, increasing air pollution[95].
Road size (*Built Infrastructure*)	National road class	Road width has been previously shown have a significant negative relationship with street tree cover in Montréal[41]. Thus, we predict that road size impacts ecosystem service capacity in urban areas through the relationships between shading, transpiration, biomass, and airflow.
Impervious surface cover (*Built infrastructure*)	% impervious for a given area	Increased cover of impervious surfaces results in higher air temperatures and air pollution levels[26,97,98]. Impervious surface increases the production of ozone[98] while reducing wind levels and trapping other air pollutants[97,99]. Carbon storage is negatively related to impervious surface cover in cities which creates hostile growth environments and reduces space for growth[100].
Building density (*Built infrastructure)*	Area covered by buildings (km^2) / total area (km^2)	Increased building density is thought to increase urban temperatures and air pollution by increasing the area covered by impervious surfaces and by reducing air flow, trapping heat[26,101]. As building density increases, there will be less space for planting, therefore less carbon storage[102].
Building function (*Built infrastructure*)	% buildings for each function type (residential, industrial, commercial)	Different land-use types and urban form function manage their associated land differently leading to differences in how much space is available for planting, what type of planting occurs, and what species are planted[34,103].
Building height distribution (*Built infrastructure*)	Building height (m) distribution of a study area	Increasing building height increases impervious surface, therefore increasing temperature[26]. However, the increase in building height also produces shade, which can decrease air temperature[92]. Increasing building height reduces air flow and generally results in increased levels of air pollution[101]. The densification of cities using higher buildings is thought to reduce available planting space, therefore decreasing carbon storage[102].
Population density (*Human demographic*)	Number of residents / km^2	Population density was originally thought to have a negative relationship with tree cover and growth, and thus ecosystem service capacity[102]. However, the relationship is more complex and has different direction and magnitude depending on location[41,104].

Class/income (*Human demographic*)	% of population low income after tax, median income after tax	Income and economic class have been shown to be a major driver of ecosystem service demand and supply in many cities around the world, including in Canada[8,39,105]. Class privilege works through various mechanisms, with processes such as redlining in the United States resulting in historical legacies of inequitable ecosystem service distribution across race and class lines[9] and green gentrification resulting in modern exacerbation of inequity in ecosystem service delivery[106].
Race/ethnicity	# recent immigrants (2011-2016), visible minority population, Indigenous identity	Ecosystem services across North America have a positive relationship with the percent of white residents in an area, and a negative relationship with the percent of people of colour[8,39]. The number of recent immigrants in Montréal has a positive relationship with % street tree cover[41], and associated ecosystem services.
Dwelling type (*Human demographic*)	Count of each household type in study area	Dwelling type in Canadian cities can determine vegetation cover, with single-family homes and dwelling value having a positive relationship with tree cover in Montréal[41,79]. Dwelling type is an important indicator of generational wealth and privilege that captures social inequity in a way that median income does not. In a time of increasing housing prices and decreasing access to housing, generational wealth and parental home ownership becomes a major determinant in what kind of dwelling type people have[107].

Appendix

<u>Proposed Timeline</u>

	Year 1			Year 2			Year 3			Year 4			Year 4.5
	Winter 2021	Summer 2021	Fall 2021	Winter 2022	Summer 2022	Fall 2022	Winter 2023	Summer 2023	Fall 2023	Winter 2024	Summer 2024	Fall 2024	Winter 2025
MSc & BSc Publications													
Proposal													
Ruelles Vertes Collaboration													
Concordia Service*													
Qualifying Exams													
Chapter 1													
• Data Collection													
• Analysis													
• Write-Up													
• Journal Submission													
Chapter 2													
• Data Collection													
• Analysis													
• Write-Up													
• Journal Submission													
Chapter 3													
• Data Collection													
• Analysis													
• Write-Up													

• Journal Submission													
Pedagogical Training													
• Introductory Lectures													
• Advanced Lectures													
Course Requirement†													
Thesis													
• Compiling/ formatting													
• Submission/ evaluation													
• Defense													

* I volunteer as a graduate student representative on the Council of the School of Graduate Studies, Graduate Curriculum Committee, and Concordia Student Tribunal Pool.

† Dependent on course availability.

Anticipated Publications

I expect to have published the first two of my three chapters before thesis defense. I plan to submit my third chapter for publication around the same time as I submit my thesis for defense. I also plan to publish various side projects and collaborations, including projects with collaborators at uOttawa and McGill.

Anticipated Conferences

I anticipate attending one major conference a year to present one of my thesis chapters. Major conferences I would consider include the annual meetings for the Canadian Society and Ecology & Evolution (CSEE) and the International Association of Landscape Ecology. I will also plan to attend regional/online conferences once or twice a year, or as appropriate. Regional conferences I will consider attending include meetings of the Quebec Center for Biodiversity Science, The Nature of Cities, and Canadian Urban Forestry Conference.

In 2022, I plan to present the preliminary findings from my first chapter at the CSEE/Ecological Society of America joint meeting planned for August.

Pedagogical Training Plan

To fulfill program requirement BIOL 801, I must deliver four guest lectures in the department of Biology. Two lectures to introductory undergraduate courses and two lectures to advanced undergraduate courses. My proposed venues for completing this requirement include:

- One lecture in BIOL 226 “Biodiversity and Ecology”
- One lecture in BIOL 205 “Introduction to Sustainability”
- One lecture in BIOL 322 “Biostatistics”
- One lecture in BIOL 398 “Urban Ecology/Intermediate Topics in Biology”

I plan to reach out to course instructors of BIOL 226 and BIOL 205 in summer 2022 to establish a date, topic, and teaching plan for my first two guest lectures. In summer 2023 I plan to reach out to course instructors for BIOL 322 and BIOL 398 to establish a date, topic, and teaching plan for my final two guest lectures.

Course Requirement

My program requires me to take one course to fulfill course requirements. I have yet to fulfill this requirement, due to COVID-19 restrictions and lack of course offerings in my interest. I hope to complete a QCBS short course on biodiversity ecology or a bios2 quantitative training short course in the next year, ideally summer 2022, to fulfill this requirement.

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