Exploring causes and predictors of urban forest benefits in Canadian cities

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ABSTRACT

Exploring causes and predictors of urban forest benefits in Canadian cities

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Cities are complex landscapes composed of natural, built, and social elements, resulting in high levels of spatial and temporal heterogeneity. Urban nature provides benefits to human residents, increasing their quality of life. The urban forest specifically provides many benefits to residents, yet these benefits are currently delivered inequitably. My thesis explores the spatial and temporal distribution of benefits provided by the urban forest in Canadian cities. In chapter one, I show that historical land-use of Montreal parks causes differences in forest composition and structure, and ultimately nighttime cooling capacity, disproportionately affecting immigrants and low-income residents. However, current park management can overcome historical differences, resulting in similar levels of daytime cooling in all parks. In chapter two, I provide evidence from two Quebec cities that while green alley programs provide higher levels of biodiversity support than traditional alleys, they do not consistently provide higher levels of nature's benefits to residents – despite potential to do so. I suggest expert guidance on green alley design could lead to better outcomes for both nature's benefits and biodiversity. Finally, in chapter 3, I show the importance of scale-specific context when predicting urban temperature and air pollution levels using a multi-scale, multi-city study that incorporates street tree, urban form, and sociodemographic data. I found that the most important predictors of temperature and air pollution vary across scales, highlighting the need for scale-specific approaches when attempting to manage temperature or air pollution. Ecological variables are important predictors of temperature, nitrogen dioxide, and ozone at the city and/or neighbourhood scales, which are key scales of management for decision-makers. Overall, my thesis uses under-studied frameworks of historical ecology, interdisciplinary methodology, and cross-city analysis to contribute knowledge about the benefits of urban greenspaces. I highlight that urban forests – including trees in parks, green alleys, and along streets – improve quality of life for residents across various spatial scales in Canadian cities. However, my thesis also contributes to the growing body of evidence highlighting distributional inequity of nature in Canadian cities.

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To start off my expression of gratitude, I would like to say thank you Carly, my supervisor. I have had such a great time working for you for the past five years, a fact that I do not take for granted. I deeply admire the care you take when supervising students, and I have felt that care many times over the years. You are both supportive and trusting, in a combination that has allowed me to grow through trial and error, improving my confidence and abilities but never making me feel discouraged or alone. You are exceptionally good at your job, even when it includes things that are most definitely not in your job description (e.g., parenting a group of adults??). Thank you.

Next, is of course, the ZULE lab. This is a special group of people, often a very large group of people, that is dear to me in so many ways. We show up for each other, care for each other, and encourage each other always, whether it be work related or life related. Growth happens when you surround yourself with people better than yourself, and I have grown a lot with you all next to me. Thank you so much Kayleigh, Serena, Emily, Katie, Maya, Kieu-Nhi, Taylor, Mathieu, Gail, Meagan, Sarah OD, Nicole, Michael, Erica, Laura, Niraj, Caytee, Noa, Lingshan, Fatemeh, Lauren T, Chloe, Emma, Mackenzie, Evan, Johanna, Lauren B, Antonia, Cami, Sarah CF, Siena.

Thank you to my excellent committee, Hiên and Emma. You are both scientists I admire, and I am very grateful to have been able to learn from you both over the past several years. Thank you, Hiên for your generosity and always including me in your lab meetings and events, giving me an opportunity to develop and learn from the excellent scientists at UQAM.

I am extremely lucky to have had many wonderful collaborators over the past 5 years. A lot of them are in the long list of ZULE lab members above, but not all of them. It has been a great privilege to work with folks at UQAM, UdeM, UBC, UofT, Organisme Respire, McGill, MUN, and uOttawa during my PhD, thank you all. A special thank you to Lorien at UBC, who graciously welcomed me into her lab for a three-week exchange where I was lucky enough to learn about the amazing work her and her team do while also seeing the cherry blossoms, swimming in the Pacific Ocean, and meeting the *enormous* trees of Vancouver for the first time.

Starting a PhD in January of 2021 in a new city meant that I was utterly friendless for a while. However, thanks to Carly (see reference above to going above and beyond her job description and caring for her students), I was soon introduced to an extremely special person, Laura. I think of Laura as my PhD cohort, and I am eternally grateful to her for the support and camaraderie she has provided over the years. You are extremely funny, kind, generous, and smart and this PhD would have been much, much worse without you.

Perhaps unsurprisingly, the process of a PhD has made me a nerd. However, in a turn of events very surprising to me, it has made me somewhat of a stats nerd. I will blame this in large part on my friend Alec. When I started my PhD, Alec was a good friend and had taught me most of what I knew about coding. Now, Alec is a great friend and has taught me most of what I know about coding and statistics. Anything I did not learn from Alec, I probably learned from my friend Andrew. Thank you both, Alec and Andrew, for your unending generosity and patience. Collaborating and learning with you both has been one of the greatest joys of my PhD, even

when (especially when?) it led me down some very long rabbit holes. You are both geniuses in a lot of conventional ways, but in my opinion your true genius lies in the way you support your community and pull up the people around you, traits I strive to do as well as you every day.

For me, the opportunity to reflect on the truly incredible community of family and friends that I am lucky enough to surround myself with is the best part of writing this thesis. I am deeply grateful and humbled to love and be loved by this group of people. Thank you to my mom, who is the reason I love nature in the first place and the source of strength I draw on whenever I find myself in a tough situation. Thank you, Liv, Rebecca, and Lindsey, for always calling me during the workday at the exact time I need a break, that is some sort of sister magic. Thank you especially to Liv for the unwavering support, I have never known a moment where I doubted that there is someone in my corner, and that is thanks to you. Thank you to my niblings, Carter, Cohen, Logan, and Hallie for inspiring me to want to make this world a better place. Thank you to my grandparents and dad for being patient and encouraging while it took me 27 years to finish school, slightly longer than anticipated. Thank you to my best friends, Kayleigh, Julia, Ashley, Quinn for an uncountable number of dinners, phone calls, walks, and bike rides where you relentlessly built me up, I don't know who I would be without you. Thank you to Wren and James, for bringing me pure joy and laughter these past few years. Thank you to all the people I haven't named here but who I love deeply and support me in so many ways. Finally, thank you Haley, for always checking my math (usually wrong), doing fieldwork with me, editing my writing, brainstorming, coworking, and all the other thesis-related support you have given me over the last several years. More importantly, thank you for the life we have together.

Lastly, thank you to the taxpayers for funding this research. Thank you for gifting me the great privilege of being a scientist, I have strived to always do the best I can in all my work.

Positionality

My thesis work used data and was 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 collected data for chapters 1 and 2 in Kawenote Teiontiakon (known as Montréal), the unceded and traditional lands of the Haudenosaunee and Kanien'kehá:ka (Mohawk) peoples. I also collected data in the city now known as Trois-Rivières for Chapter 2, which is located on the unceded and traditional lands of the Nitaskinan and N'dakina peoples. Chapter 3 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.

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. Further, I have lived my whole life in the Global North, which influences the nature of my scientific questions and approach.

Contribution of Authors

I contributed to all aspects of research design, data collection, data analysis, data interpretation, writing, and editing of all thesis chapters. Dr. Carly D. Ziter contributed to research design, data interpretation, and editing of all thesis chapters. Kayleigh Hutt-Taylor contributed to research design, data interpretation, and editing of all thesis chapters, data analysis of Chapter 1, and data collection of Chapter 2. Alec L. Robitaille contributed to data analysis, data interpretation, and editing of Chapters 1 and 3. Michael A. Paulauskas, Erica Padvaiskas, and Laura C.G. Sinisterra contributed to research design, data collection, and editing of Chapter 1. Johanna Arnet contributed to research design, data collection, data interpretation, and editing of Chapter 2. Lauren Bianco, Antonia V. Zanella, Francois Bérubé, Paola Faddoul, and Étienne Perreault-Mandeville contributed to data collection and editing of Chapter 2. Nathalie Boucher and Thi Thanh Hiên Pham contributed to research design, data collection, data analysis, and editing of Chapter 2. Nicole Yu contributed to research design, data collection, data analysis, and editing of Chapter 3.

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All authors reviewed final drafts of manuscripts and/or thesis chapters and approved of the contents.

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I. General Introduction

The lives of people and nature in cities are, and have always been, deeply intertwined (Comberti et al. 2015, Reyers and Bennett 2025). In cities, humans actively manage most of the available space, cultivating and stewarding nature in intentional ways (Kendal et al. 2012, Campbell et al. 2022). In turn, the nature in our cities provides most of the world's population with their first and most frequent interactions with the natural world (Hartig and Kahn Jr 2016, Gu et al. 2021). Following the industrial revolution, North American cities were often viewed as dirty, polluted, and devoid of any nature (Cruikshank and Bouchier 2004, Bocking 2005, MacDowell and EBOUND Canada 2012). For example, Calgary's Bow River – now a cherished recreational space and the source of 60% of Calgary's drinking water – was viewed as a "junkyard" in the years after World War II (Nelles 2005). The Euro-centric conception of nature as separate from humans meant that nature in cities continued to be overlooked and undervalued for decades after most North Americans were living in cities (Niemelä and McDonnell 2011, Wu 2014). In the early 19th century, there were citizen and professional movements that attempted to "clean up" the rapidly expanding cities of the Western world (Eisenman 2013). For example, in North America women took on the role of city beautification, advocating and performing acts of tree planting, park establishment, and the beautification of yards (Dümpelmann 2015). Simultaneously, parks were being lauded as important public health initiatives in Britain and across Europe (Eisenman 2013). In France, urbanism movements that prioritized greenness through parks, green belts, and various urban planning strategies were underway, changing the landscapes of cities (Mehdi et al. 2012). In Germany, the ecology of cities and greenspaces was being studied and advocated for by naturalists (Lachmund 2011). These movements were imported to North America and led to major changes in the late 19th and early 20th centuries, where city leaders identified that successful cities would require both industrial strength and beauty, which signified the beginnings of the City Beautiful movement (Dümpelmann 2015).

The City Beautiful urban planning movement in North America emphasized adding parks and trees to cities to improve quality of life for city residents, albeit the process was fundamentally inequitable, with poor and working-class residents displaced to create public green spaces (Peterson 1976, Reece 2018). Since then, our relationship with urban planning and nature in cities has continued to evolve, with increasing emphasis on sustainable building and urban nature as a potential solution to issues caused by climate change (Watts et al. 2015, Cohen-Shacham et al. 2016, Cook et al. 2025). Urban nature can be a solution to many problems, in many ways (Diep and McPhearson 2025). For example, trees reduce heat related morbidity and mortality (Remme et al. 2021) and the presence of green vegetation can improve people's mental and physical health (Sousa-Silva et al. 2025, Soga and Gaston 2025). Today, urban nature is an important part of many urban planning processes and is often framed as green infrastructure, defined as a system of connected ecosystems, built infrastructure, and ecological-technological hybrids that provide social, environmental, and technological benefits (Grabowski et al. 2022). The study of urban nature and green infrastructure typically includes all nature living in cities, spanning across flora and fauna (Knapp et al. 2021, Rega-Brodsky et al. 2022), private and public land use types (Hutt-Taylor and Ziter 2022, Priya and Senthil 2025), and managed and

unmanaged areas (Sikorska et al. 2020, Stanford et al. 2024). However, urban planning does not always integrate ecological knowledge to provide the benefits of nature to city residents (Cheng et al. 2021, van Zyl et al. 2021). Given the important role that urban nature plays in the lives of urban residents and the urban planning process, understanding the ecology of our cities and the mechanisms linking urban biodiversity and structure to benefits for human residents is critical.

The value systems associated with nature are often sorted into three groups: intrinsic, relational, and instrumental (IPBES 2022). Intrinsic value systems value nature independent of people, relational value systems value nature as it exists in relation to people, and instrumental value systems value the benefits that nature brings to people (IPBES 2022). To date, scientific literature has focused an overwhelming majority of studies solely on instrumental values (IPBES 2022). However, there is an increase in work focused on relational values in scientific and policy spaces (Pratson et al. 2023, Chan et al. 2025). The skew towards instrumental values in previous work is in part due to the framework of ecosystem services, defined as the benefits that nature provides to people, which largely fall within the category of instrumental values (Millennium Ecosystem Assessment 2005). Thousands of research papers have been published within the field since the term ecosystem services was popularized in 2005 (Valencia Torres et al. 2021). The ecosystem service framework allows scientists to quantify and communicate the value of nature to rights holders and manage urban nature in a way that attempts to maximize human benefits (Millennium Ecosystem Assessment 2005, Bennett 2017).

The demand for ecosystem services by urban residents is dependent on the type of benefit, as well as local context (Villamagna et al. 2013). Ecosystem services are commonly split into four categories of services: provisioning, supporting, regulating, and cultural (Millennium Ecosystem Assessment 2005). Regulating services are the benefits people receive from the regulation of ecosystem processes and supporting services (Millennium Ecosystem Assessment 2005). Regulating services are the ecosystem service group that is most dominantly studied in urban ecology, as they are particularly critical to resident well-being because they often must be produced locally to be accessed (Villamagna et al. 2013, Sutherland et al. 2018). Commonly studied regulating ecosystem services include temperature regulation, water purification, and air quality control, all of which are examples of ecosystem services that must be provided locally to be accessed by residents (Villamagna et al. 2013, Sutherland et al. 2018). Ecosystem services, regulating and otherwise, are tied directly to human health and wellbeing (Millennium Ecosystem Assessment 2005). For example, temperature regulation provided by vegetation in cities can directly contribute to decreased levels of heat related mortality (Choi et al. 2021). Cultural ecosystem services, the non-material benefits that people receive through interacting with nature, have historically been understudied in cities and elsewhere, though that is beginning to change (Millennium Ecosystem Assessment 2005, Hirons et al. 2016, Yang and Cao 2022). The recognition of the value of nature, especially urban nature, for our collective mental health and wellbeing has driven this increase in research on cultural ecosystem services, especially following the onset of the COVID-19 pandemic (Beckmann-Wübbelt et al. 2021, Ciesielski et al. 2024). Despite the production and delivery of regulating and cultural ecosystem services being acknowledged by researchers and policy-makers as critical for the wellbeing of all urban

residents, their distribution in cities is currently inequitable, perpetuating environmental injustice across our landscapes (Pham et al. 2013, Villamagna et al. 2017, Landry et al. 2020).

Canadian cities are sites of environmental racism and injustice and were established as such by European colonizers (Cruikshank and Bouchier 2004, Pham et al. 2013, Landry et al. 2020, Dorries et al. 2022, Quinton et al. 2022). Initially treated as terra nullius, "land owned by no one", by colonizers, Canadian cities were developed to process the outputs of resource extraction, and many became highly industrialized in the 20th century (Cruikshank and Bouchier 2004, Bocking 2005). As industrialization increased and immigration to Canada began to expand, working class immigrants across the country lived in neighbourhoods with high concentrations of environmental hazards and had their access to nature for recreation and leisure stripped away (Cruikshank and Bouchier 2004). Urban planning to date has done little to combat environmental inequity, in fact, it has often exacerbated it (Boyer 1986, Hendricks and Van Zandt 2021). Today, the impacts of historical injustice continue to be felt, compounded with modern day inequities. Working class immigrants, especially people of colour, continue to experience environmental hazards at a higher rate than other groups and have less access to high quality nature (Jepson et al. 2022, Fong et al. 2022). Academics have introduced the term "The Luxury Effect" to describe the increased levels of greenery, biodiversity, access to parks, and more experienced by wealthy, white communities (Hope et al. 2003a, Aznarez et al. 2023). Municipal governments are increasingly considering integrating equity into urban greening and climate adaptation plans to ensure that nature benefits all residents but face many barriers (Nesbitt et al. 2019). Effectively improving green equity requires a strong understanding of current patterns and drivers of inequity, which requires an understanding of both urban nature and its benefits. Environmental injustice and inequity must be considered in urban ecology research and urban planning, as systemic inequity forms the foundation that our cities are built on (Schell et al. 2020).

A major component of urban nature and a critical provider of nature's benefits in Canadian cities is the urban forest, which encompasses trees and other vegetation growing in cities. Components of the urban forest include the vegetation found in parks, street trees, urban woodlands, and the vegetation found in people's private yards (Miller et al. 2015). Urban trees specifically provide many benefits to urban residents and contribute to human well-being through all four categories of ecosystem services (O'Brien et al. 2022). For example, trees are often integrated as a key policy initiative by local and regional governments to regulate high temperatures caused by the urban heat island effect, and have a disproportionately large impact when compared to other vegetation types (Schwaab et al. 2021, Nelson and Bigger 2022, Alonzo et al. 2025). Like forests located in non-urban areas, the ecosystem services that the urban forest can provide are dependent on ecological factors, such as forest composition and structure (Helletsgruber et al. 2020). For example, shade and evapotranspiration by trees can reduce air temperatures from levels that are dangerous to human health (Ziter et al. 2019). Larger trees with denser foliage buffer temperatures more effectively than smaller trees with sparse foliage (Speak et al. 2020, Tsoka et al. 2021, Alonzo et al. 2025) and thus, the capacity of the urban forest to buffer heat at any particular scale is dependent on its species composition. Additionally, birdwatching is an activity that provides many cultural ecosystem services, which are dependent

on the urban forest's structure such as vegetative complexity and species composition (Graves et al. 2019). Other aspects of forest composition and structure also contribute to its ability to provide ecosystem services, such as functional diversity, crown width, crown density, vegetative complexity, and tree size (Rahman et al. 2020, Speak et al. 2020, Wujeska-Klause and Pfautsch 2020, Paquette et al. 2021, Alonzo et al. 2025).

Understanding what conditions result in the most benefits being delivered to local residents depends not only on ecological factors but also on anthropogenic ones such as urban form or governance. Compared to non-urban forests, urban forests are much more strongly influenced by the structure and composition of built infrastructure, also known as urban form (Labrecque et al. 1993, Morakinyo et al. 2017). Impervious surfaces are the defining characteristics of cities (Wu 2014), and their presence and density impact both the physical conditions of the landscape as well as the ecological functioning of the urban forest (Nowak and Greenfield 2020, Hou et al. 2022). For example, the distribution of transportation networks throughout a city can affect air pollution levels by reducing (or increasing) road traffic and congestion and by influencing residents' transport behaviour (Wang et al. 2024a). The matrix of built and natural elements in the environment results in an extremely heterogeneous environment, where conditions can drastically change at a very fine scale (Gaston et al. 2013, Ziter et al. 2019). In addition to physical heterogeneity, cities have complex governance systems (Buffam et al. 2022). The responsibility of managing both built infrastructure and urban nature falls to many different groups within a city, resulting in even more spatial and temporal heterogeneity (McPhearson et al. 2016). Management decisions are made by individual landowners, companies, institutions, ENGOs, neighbourhood or borough administrations, city governments, and larger regional governments (Byrne 2022). The many levels and types of management result in many values and strategies being used to design and manage urban nature (Aronson et al. 2017).

Despite the high spatial heterogeneity and temporal dynamism that characterize urban ecosystems, there remain few studies that integrate multiple spatial and temporal scales (Kremer et al. 2016, Ziter 2016, Tappeiner et al. 2020). With respect to temporal trends, many studies explore a single snapshot in time, while ignoring historical conditions or trends over multiple time points (Ossola et al. 2021). Scholarship within the past five years has shown the previously underappreciated power of historical data in explaining current ecological patterns within cities (Roman et al. 2021b, Healy et al. 2022, Aznarez et al. 2023, Nix et al. 2023, Pregitzer and Bradford 2023). Given the legacies of inequity that form the foundations of our cities, integrating historical conditions allows us to better understand current conditions of urban nature. Similarly, many studies assess research questions at a single spatial scale, failing to evaluate how an effect may change across scales both within and among cities (Kremer et al. 2016, Ziter 2016). Using a single spatial scale can be a meaningful and necessary way to understand fine-scale trends, but to generalize results across a landscape and apply findings in different contexts, we must use multi-city, multi-scale studies (Kremer et al. 2016, McPhearson et al. 2016). These types of studies are increasing (e.g., Helletsgruber et al. 2020, Landry et al. 2020, Wang et al. 2024b) but still represent a small minority of urban ecology research overall. Given the complexity of cities,

evaluating research questions across multiple spatial and temporal scales is necessary to provide the context and knowledge we need to make good management decisions.

In addition to the high spatial and temporal heterogeneity of urban ecosystems, the integration of human and natural infrastructure in cities results in an ecosystem that must be viewed from multiple disciplinary lenses to be understood (Pickett et al. 2016). Environmental injustice is an interdisciplinary issue and trying to address it by approaching urban greening as a single discipline issue can result in harm (Frantzeskaki et al. 2025). As a result, interdisciplinary projects have repeatedly been identified as an important part of understanding our urban forests (Knapp et al. 2021, Frantzeskaki et al. 2025). Meaningful interdisciplinary collaborations can be difficult, often facing challenges of disciplinary differences, time constraints, and suffering from the rigid requirements of granting agencies (Lanterman and Blithe 2019, Neuenkamp and McGale 2023). However, given that the nature of cities is to integrate natural, physical, social, and built elements into a highly heterogeneous area, taking on interdisciplinary projects is necessary to understand all the factors influencing urban nature and apply the results of research to improve our cities moving forward.

Conducting meaningful interdisciplinary and/or transdisciplinary work in urban ecology includes studying areas and questions that communities identify as important to them (Frantzeskaki et al. 2024). Most of the work that has been done on urban forests to date has focused on trees in specific land-use types, mainly parks and street trees (Chatzimentor et al. 2020, Ying et al. 2022). However, other urban green infrastructure types that may be providing important habitat and are important community spaces remain overlooked (Pinho et al. 2021). Further, ecologists often make decisions about which ecosystem services to measure based on their own assumptions, rather than incorporating the needs and preferences of communities (Schröter et al. 2021, Chen et al. 2024). Knowledge about the contributions of the urban forest in areas that have not been traditional areas of study is key, especially as we attempt to find new and creative solutions in the face of climate change.

In this thesis, I use a framework of ecosystem services to assess how and why multiple benefits of the urban forest are distributed within and across Canadian cities, integrating approaches from landscape ecology and social-ecological systems. Scale is a focus of my work, integrating multiple spatial and temporal scales. In my first chapter, I blend historical ecology, ecological fieldwork, and environmental sensors to measure the impact of historical land-use on capacity for cooling in parks today. This chapter connects historical conditions to modern day issues of environmental injustice, highlighting the importance of considering temporal scale, and the need for community-based, thoughtful greening interventions. In my second chapter, I continue to explore connections between social and ecological systems, while shifting my focus on scale to that of spatial scale – I consider the impact of fine-scale distributed green infrastructure, while broadening the extent to consider two cities. Here, I focus on an understudied type of urban green infrastructure, green alleyways. In Montreal and Trois Rivieres Quebec, I test if establishment of a green alley results in an increase in biodiversity support and/or ecosystem services. This chapter is an interdisciplinary collaboration, using interviews with residents to inform what ecosystem services to assess, blending qualitative and quantitative

methodologies to provide analysis and conclusions that are meaningful to both scientists and residents. Finally, my third chapter expands my focus on scale, using a multi-service, multi-city approach that tests how well street tree, urban form, and sociodemographic variables predict ecosystem service capacity across seven Canadian cities at three spatial scales. My work uses the urban forest as a study system to test effects of inequity in Canadian cities, integrating interdisciplinary approaches and data types. Though different green infrastructure types, a throughline of my work is the impact of trees. Across all my chapters, I seek to explain or predict what variables related to trees as a part of green infrastructure result in an increased level of ecosystem services; I do this through using both causal and predictive statistical approaches.

We know that ecosystem services are critical for the wellbeing of urban residents. We also know that due to past and current injustice, the distribution of said ecosystem services is inequitable. While some factors that impact ecosystem services, such as past environmental racism, are set by history and thus are very difficult to reverse (Tomscha et al. 2016, Ziter and Turner 2018), clearly defining causes and predictors of the urban forest ecosystem services helps us shape future urban landscapes to more equitably serve all residents.

II. Chapter 1: *Land-use history causes differences in park nighttime cooling capacity and forest structure*

Abstract:

Cities are temporally dynamic ecosystems that experience continuous redevelopment over time. Urban parks, which provide critical benefits to resident wellbeing, are developed on different land-use types and contain natural elements that are susceptible to the effects of historical decision making. Thus, understanding the current day functioning of our city's ecosystems and planning for the equitable distribution of park benefits in the future requires incorporation and understanding of the impacts of historical decision-making. We measured neighbourhood socio-demographic composition, forest structure, and the cooling effect of 33 sites in parks across Montreal, each with a past land-use in one of three classes: agricultural, forested, or industrial. We asked: 1) what are the effects of historical land-use on current park forest structure, diversity, and consequently the capacity to provide cooling? 2) how do surrounding communities differ around parks of each historical land-use type, and what are the implications for equitable access to cooling? We found that forest structure and cooling capacity differed across past land-use type, and forest structure has complex relationships with park cooling capacity. Our results provide evidence of historical environmental injustice impacting current day cooling capacity for marginalized groups. Previously industrial parks had less cooling capacity at night, while simultaneously being surrounded by communities with higher proportions of immigrants, and lower median incomes than Montreal's average. However, daytime cooling capacity was similar across past land-use type, highlighting the importance of current management decisions to provide a critical ecosystem service, temperature mitigation, regardless of a site's history. Planting areas of small, dense forest stands with trees >= 5 cm DBH within urban parks can help augment daytime cooling benefits in the city but may hinder nighttime cooling. To provide both nighttime and daytime cooling, a mixed management strategy of park trees is required, where small and large trees are incorporated at different densities. Finally, we find evidence of gentrification surrounding all park sites, emphasizing the complex socioecological dynamics of green infrastructure and the need for community-led greening projects paired with social housing policies.

1.1 Introduction:

Urban greening is gaining popularity as a strategy to improve human wellbeing while combatting climate change and biodiversity loss (Haaland and van den Bosch 2015, Nelson and Bigger 2022). However, to more fully understand the benefits provided by urban natural ecosystems we must integrate historical conditions. Urban landscapes experience legacy effects, defined as the present-day impacts of past decisions or events (Ossola et al. 2019a), which can in turn affect ecosystem functioning for decades to millennia (Foster et al. 2003, Cramer et al. 2008). An important driver of legacy effects in cities is land (re)development, the process of changing one land cover type to another, often multiple times across decades (Raciti et al. 2011, Ziter and Turner 2018). Throughout the evolution of cities, patches of land are continually maintained, redeveloped, and abandoned, creating a complex history (Koebel 1996, Alig et al. 2004). For example, many cities in North America were deindustrialized in the mid-20th century, leading to

a series of "revitalization" efforts which redeveloped former industrial areas to mixed-use areas with office buildings, hotels, green spaces, and residences (Koebel 1996). Urban growth in North American cities also often results in expansion at city edges, where agricultural and forested land surrounding cities are developed into urban land-use types, including parks and green spaces (Dallimer et al. 2015). This mix of urban intensification and/or land abandonment in urban cores combined with the expansion of suburbs at city edges means that urbanization results in contemporary green spaces existing in a variety of spaces and incurring a variety of legacy effects (Alig et al. 2004, Dallimer et al. 2015).

Land-use and (re)development patterns in cities are determined by urban planning, a social endeavor with place and period-specific goals, determined by those in power (Pallagst 2009). Thus, urban planning and land development in post-colonial North America inevitably and intentionally upholds inequity and injustice (Alexander 1992, Ture and Hamilton 1992, Calmore 1997, Powell 2008, Goetz et al. 2020), ultimately structuring the ecology of our cities (Schell et al. 2020). Environmental injustice is a documented form of inequity across North American cities, and although urban nature is increasingly considered a type of infrastructure all communities deserve access to, decades of evidence demonstrates that urban planning benefits white, rich communities and endangers low-income communities of colour (Gelobter 1993, Maynard 2017, Goetz et al. 2020). Marginalized communities are often relegated to neighbourhoods that are poorly designed (Gelobter 1993), under serviced (Larsen and Gilliland 2008, Shah et al. 2016), and have environmental hazards that threaten public health (United Church of Christ 1987, Waldron 2018). For example, on the island of Montreal urban heat is correlated with the percentage of low-income residents and education level across neighbourhoods (Fan and Sengupta 2022). Low income and visible minority residents also experience inequity in access to vegetation (Pham et al. 2012), a key factor in combatting urban heat. Further, neighbourhoods surrounding industrial areas were historically inhabited by working class or impoverished immigrants working in the quarries (Ndiaye 2004, Héroux and Martin 2020). Today, populations with higher proportions of visible minorities and low-income households are more likely to live near highly congested parks in Montreal, reducing access to park benefits such as heat mitigation (Jepson et al. 2022). More broadly, areas of high social vulnerability in several Canadian cities have lower urban forest resilience (Landry et al. 2020), a key factor determining the longevity and health of urban nature.

Increasing the presence of urban forests and parks is often regarded as universally positive (Roman et al. 2021a). However, a concern of urban greening is the potential perpetuation of societal inequities (Sax et al. 2022, Kiani et al. 2023). This is particularly true for parks developed on industrial land in historically marginalized neighbourhoods. Without strong social housing policy, urban greening can lead to gentrification and displacement of residents (Anguelovski 2016, Anguelovski et al. 2019). In addition, legacies of historical inequity in neighbourhoods through various mechanisms such as environmental racism and presence of industrial lands has been shown to continue to impact key providers of ecosystem services such as current tree canopy and growth (Healy et al. 2022, Nix et al. 2023). The influence of historical land uses and inequity on current distribution of tree canopy has other important implications which have not yet been thoroughly studied, notably the distribution of urban heat.

Urban trees and forests are a critical component to consider in understanding the link between historical legacies and the benefits of green spaces. Park trees promote wellbeing in diverse ways, from physical relief through heat mitigation to mental health improvements via stress reduction and promotion of physical activity provided by exposing the brain to nature (Remme et al. 2021). Benefits of urban trees are often determined by the composition of tree species, size, and density (Ziter et al. 2013, Villamagna et al. 2013, Qiu et al. 2018). The long-lived nature of trees means their current state, and the functioning of forest ecosystems, is strongly affected by legacy effects of past management decisions (Roman et al. 2018, 2021b). Legacy effects may influence tree size and diversity due to legacies in soil properties and nutrient levels that continue to influence tree growth and functioning today (Aznarez et al. 2023, Pregitzer and Bradford 2023). For example, agricultural land may be depleted of nutrients following its use as farmland, influencing the soil structure and development over time (Pabst et al. 2016). Indeed, agricultural land often accumulates carbon in the soil following development whereas former forest remnants do not, which has the potential to bring about long-term changes in tree growth and associated ecosystem services (Raciti et al. 2011). Legacy effects from past land-use types can also determine which species may or may not be present in an area (Munteanu et al. 2015). For example, in residential areas in Haikou, China that were previously woodlands, there are 7 species of trees that are not found in residential areas that were previously open land (Yang et al. 2017).

An urban park is thus a complex web of past and current land-uses and understanding the physical influences of historical land-use on vegetation will allow us to tease out a piece of the puzzle when assessing the differences in our parks' benefits across space. Many cities are interested in pursuing restoration and altered management of urban green spaces. Quantifying the legacy effects of past land-use types on the benefits of trees in current urban parks will facilitate improved planning for equitable distribution of park benefits in the future. Here, we ask two research questions. First, what are the effects of historical land-use on current park forest structure, diversity, and consequently the capacity to provide cooling? Second, how do surrounding communities differ around parks of each historical land-use type, and what are the implications for equitable access to cooling?

We hypothesize that the historical land-use type will influence the quantity of temperature mitigation currently delivered by urban trees in Montreal's parks via differences in tree size, tree basal area, and tree species richness. Tree size and basal area are both factors that drive cooling in urban settings (Rahman et al. 2020, Helletsgruber et al. 2020). Additionally, tree species is a driving determinant in cooling efficacy (Helletsgruber et al. 2020) and higher species richness of trees can lead to an increase in cooling through an increase in canopy density (Gillerot et al. 2024). We predict that previously industrial sites will have the lowest levels of temperature mitigation due to smaller trees, lower basal area, and less species rich tree stands. We expect these differences in tree communities at previously industrial sites because of their association with high levels of heavy metals and low levels of carbon and nitrogen stocks as a result of soil contamination, removal, and treatment (Rooney et al. 2012, Clarke et al. 2015, Goyal et al. 2020, Ashwood et al. 2022). We predict previously agricultural sites will have higher capacity for temperature mitigation than previously industrial sites but less than previously

forested sites. Agricultural lands typically have higher levels of heavy metals and lower carbon stocks than forested sites, which can cause a decrease in woody plant species richness (McLauchlan 2006, Arao et al. 2010, Lachmund 2011, Shumi et al. 2018, Zwolak et al. 2019). However, they can have high levels of nitrogen stocks, which increases plant growth (McLauchlan 2006). Finally, we predict that previously forested sites will have the largest, densest trees and highest species richness, leading to the highest capacity for temperature mitigation due to their relatively less intense management (see Fig 1.1 for hypothesized causal relationships).

Regarding question two, we hypothesize that due in part to historical environmental injustice there will be differences in resident communities surrounding parks characterised by each past land-use type. We predict that proportions of marginalized populations, such as recent immigrants, people of colour, and residents with low incomes will be present at higher rates surrounding parks that have industrial land-use legacies (Gelobter 1993, Jolivet and Carré 2017, Gerrish and Watkins 2018, Landry et al. 2020). Due to the complex nature of these relationships, as well as historical data limitations, we do not have the ability to test the causal relationships between past land-use and current sociodemographic profile. However, we assess current differences among areas with different past land-use types using an exploratory data analysis so that we can better contextualize our results in terms of the capacity of cities to work towards green equity.

1.2 Methods:

1.2.1 Study Area

We sampled 33 sites spread across the island of Montreal (hereafter referred to as "Montreal") in the summers (May – August) of 2022 and 2023. Montreal houses Canada's second largest city, has 2.04 million residents (Gouvernement du Québec 2022) and is approximately 4,022 km2. Montreal is composed of the 19 boroughs of the city of Montreal, along with 14 independent municipalities (Association des municipalités de banlieue 2018, Ville de Montréal 2023a), and the level of urbanization, population density, socioeconomic status, and development varies greatly within and across these areas. The parks that we sampled spanned the island (Fig. 1.2), including 13 boroughs and three municipalities.

1.2.2 Explanatory Variables

1.2.2.1 Legacy Effects

To test how legacy effects influence park ecosystem service capacity, we identified the historical land-use type of 27 parks. We defined historical land-use type as the category of land-use that the park was developed on and is therefore dependent on the year the park was developed, which ranges in our study from 1887 to 2016 (Table A1.2). Through extensive searching of historical city archives, satellite imagery, and grey literature published by historical societies, municipalities, and historical enthusiasts, we reconstructed the history of each park to identify a) the age of the park, and b) the land-use type immediately prior to park development (Table A1.1). We sorted historical land-uses into three categories: agricultural, industrial, and forested. We sampled 27 parks, however, within parks each different historical land-use was treated as a

different study site, resulting in 33 study sites total (n = 11 of agricultural, industrial, and forested historical land-uses each, see Table A1.2 for historical land-use(s) of all parks). For parks with multiple historical land-uses, we digitized the different historical land-use boundaries using satellite imagery (Division de la géomatique and Ville de Montréal 2023) and historical map layers from the City of Montreal (Division Soutien Technique, Infrastructures, CESM and Ville de Montréal 2023, Ville de Montréal 2023b) using QGIS v3.16 (QGIS Development Team 2020).

1.2.2.2 Forest Structure

We assessed forest structure of our study sites in the summer of 2022 by assessing tree basal area, median size, and species richness. To sample each site representatively, we sampled plots in areas of low, medium, and high canopy. Prior to entering the field, we calculated the canopy cover across the parks in 0.04 ha pixels (Communauté métropolitaine de Montréal 2019). We then selected three low (10-30%), medium (31-80%), and high (81-100%) plots in each site to sample. If there were not enough low, medium, or high canopy areas to sample, we did as many as possible (n = 9 for study sites, with some exceptions when not possible, n = 279 sampling plots total). For each of the sampling plots, we conducted a forest inventory. Once arriving at the sampling plot, we walked 20 m in each cardinal direction and flagged the edge of the plot. The four cardinal points were then connected diagonally, creating a 0.08 ha square plot (Figure A1.1). We measured and identified every tree with a diameter at breast height (DBH) > 5.0 cm. For the first half of the field season, we also did a complete inventory of the 0.08 ha plot for trees with a DBH > 1.0 cm. Due to time constraints, we changed our methodology to a "mini-plot" of 0.005 ha for trees between 1-5 cm DBH halfway through the season, consistent with the Canadian Forest Inventory (Canadian Forestry Inventory Committee 2008). The mini-plot was placed in the most representative area of the larger sampling plot, and every tree under 5 cm DBH was identified and classified into a size category (1-3 cm DBH or 3-5 cm DBH, for more information see Figure A1.1). For trees with multiple stems, if the split in stems was above 30 cm we measured the DBH just below the split. If the split was below 30 cm, we measured each stem individually at breast height (Magarik et al. 2020). To identify trees to species level, we used National Audubon Society Field Guide to Trees: Eastern Region (Little 1980), Trees of Canada (Farrar 1995), and Seek (iNaturalist 2022). If identifying to species level was not possible, we identified to the genus level (< 0.1 % of trees).

1.2.3 Response Variables

1.2.3.1 Temperature Regulation

We collected temperature data the summer following the vegetative data collection. We deployed sensors during the hottest months of the year, collecting data between June 1 and July 31, 2023, recording a data point every 15 minutes. Sensors were CredoSense CSL-T0.5 temperature loggers, with an accuracy range of +/- 0.1-0.5°C (Figure A1.2). We placed temperature sensors in three plots within each site – one for each canopy level (Table A1.2). We installed sensors at approximately 1.5 m in height, in a location representative of the canopy cover of the plot,

typically near the plot center, attached to a tree branch or trunk if the tree was too large to reach the branches.

To assess the cooling effect of park vegetation as an ecosystem service, instead of raw values of temperature, we deployed control sensors in the neighbourhoods surrounding each study site and compared the temperature differences between the park and the surrounding built-up area. We selected control sensors to be at least 500 m away from study sites or other large greenspaces (Hamada and Ohta 2010, Vaz Monteiro et al. 2016). Control sensors were attached to poles in parking lots. If two study sites were very close together, and therefore have the same surrounding neighbourhood, only one control sensor was deployed for both sites. In total, we deployed 97 park sensors and 18 control sensors, for a total of 115 sensors. After collection, three sensors were malfunctioning and 14 were no longer at the site when we went to collect them, resulting in 98 full sensor datasets (see Table A1.2 for sensor location details). One agricultural site had all three sensors stolen, resulting in 11 sites with temperature data for previously forested and previously industrial land-use legacies, and 10 sites for previously agricultural. To deal with missing control sensors, we supplemented our data using a dataset collected in the same summer, using the same type of sensor, with similar criteria to us or used the data from the next closest control site. For the dataset provided to us by a similar project, the control sensor was placed on a roadside, not in a parking lot. We conducted a sensitivity analysis to ensure that the data followed the same trends as other control sensors in our study (Figure A1.3).

1.2.3.2 Neighbourhood Demographics

We calculated the neighbourhood demographics surrounding each study site using census data. Based on previous work on park access in Quebec (Apparicio et al. 2010, Robillard et al. 2023), we selected 1000 m as our buffer distance to include residents who may use the park regularly. Using census variables, we calculated population density, median income, proportion of people who are low income, recent immigrants, visible minorities, and those who have a bachelor's degree or higher for the neighbourhoods within 1000 m surrounding each of our study parks at the dissemination area level (Pham et al. 2013, Government of Canada 2021, Statistics Canada 2022). When dissemination areas crossed buffer boundaries, we calculated the area that intersected the buffer and used a spatially weighted mean for calculations. For each past land-use type, we calculated the mean of each of our variables of interest within the industrial, agricultural, and forested groups. We then collected the data for each of our variables of interest at the broader island level (Statistics Canada 2022). To obtain the difference between communities surrounding parks of each previous land-use type and the island of Montreal averages, we subtracted the values for the island from the mean values for the communities surrounding previously industrial, agricultural, and forested areas.

1.2.4 Statistical Analysis

We calculated tree species richness, basal area, and size composition at the plot level. We calculated all forest structure indices separately for trees < 5.0 cm DBH and trees > 5.0 cm DBH. Basal area was calculated by summing the cross-sectional area of each tree at breast height and then dividing the total by the plot size for a final unit of m^2/ha. By calculating basal area instead

of stem abundance, we were able to compare the density of trees < 5.0 cm even when plot size differed as they shared a common unit (m^2/ha). Size composition was calculated by assessing the median DBH across all trees within a plot. For mini-plots, where trees < 5.0 cm DBH were classified into bins of 1-3 cm and 3-5 cm, for each recorded tree we randomly sampled values within the size categories to produce a dataset of real numbers. We only calculated species richness for trees >= 5 cm DBH due to the differences in sampling methodologies across the season for trees < 5 cm DBH. Since all plots were sampled at 100% coverage, we calculated species richness by summing the number of unique species found at each site.

To assess the cooling benefits provided by each plot, we calculated average temperature of daytime and nighttime hours per date for each sensor. Using the date, latitude, and longitude of each sensor, sunrise and sunset times were calculated via the 'suncalc' package (Thieurmel and Elmarhraoui 2022). Sensors logged temperature every 15 minutes and we classified each logged point as daytime, if it was between sunrise and sunset, or nighttime, if it was before sunrise and after sunset. We then grouped the data by plot and date and calculated a mean temperature for daytime and nighttime. We did the same for each of the control sensors. We then calculated the cooling effect, separated by day and night for each date of sampling (n = 64 dates total). The cooling effect was calculated by taking the average temperature of each plot per day and subtracting the average temperature of the park's control site for that day. We built our models using the causal framework outlined in Fig. 1.1. We used 5 Bayesian general linear mixed effects models to assess the effects that we were interested in (full model equations found in Figure A1.4). We opted for Bayesian models due to their flexibility, generative nature, and production of probability distributions for effect sizes and comparisons instead of point estimates. To assess the total effect of past land-use on cooling effect, we modelled cooling effect as the response, with past land-use type time of day, and age of park as fixed effects. We also had an interaction effect between time of day, i.e., nighttime or daytime and past land-use type. Plot and park identification code (ID) were varying effects. To assess the total effects of past land-use type on forest structure, we produced three models with tree basal area, tree size, and tree diversity as response variables and past land-use type as a fixed explanatory variable for each. Then, to test the direct effects of forest structure on cooling, we modelled cooling effect as the response, with tree basal area, tree size, and tree diversity as fixed effects. We also included time of day, i.e., nighttime or daytime, as an interacting effect with each of the tree variables. Plot and park ID were included as varying effects. For all models, numeric variables were centered and scaled before modelling and weakly informative priors were selected. We define weakly informative priors as priors that increase the probability of biologically possible values for our variables while still allowing the possibility of extremely strong relationships. Setting weakly informative priors can improve chain convergence without affecting model performance or interpretation (McElreath 2020). For our models with tree structure as response variables, we computed the global mean contrasts between each group (i.e., agricultural, forested, industrial) to assess differences between past land-uses using the posterior distributions of each model. For temperature models, the continuous explanatory variables in the model were set to their average values when computing the contrasts. We performed prior predictive checks using 'tidybayes' (Kay and Mastny 2023) and 'ggplot2' (Wickham et al. 2024) packages to ensure that priors were appropriate (Figure A1.5). We assessed model convergence by ensuring that all Rhat values were

below 1.01, verifying that Markov chain Mont Carlo (MCMC) chains appeared well mixed through inspection of trace plots, and confirmed that there were minimal divergent transitions (< 0.5 %). To check if models were well specified, posterior predictive checks were completed. All model diagnostics can be found in Figure A1.6. Data preparation and cleaning, spatial analysis, and modelling was done using R 4.3.0 (R Core Team 2023, Pebesma et al. 2023, 2024, Bürkner et al. 2024).

1.3 Results:

1.3.1 Overview

We sampled temperature across 61 days from June 1 to July 31, 2023. The mean temperature difference between park and control sites averaged across all days was 1.36 ± 1.0℃, with park plots nearly always cooler than control sites (98% of measurements). The cooling effect per day across all plots ranged from -0.8℃ to + 7.8℃, with a positive cooling effect indicating park plots providing more cooling than control sites. For forest structure variables we measured a total of 11,053 trees across all parks. For trees >= 5 cm diameter at breast height (DBH) at the plot scale, mean basal area ranged from 0.29 to 55.0 m^2/ha, median size ranged from 6.4 cm DBH to 64.6 cm DBH, and mean species richness ranged from 1 to 11 species per park. Trees < 5 cm DBH ranged in basal area from 0.0 to 7.9 m^2/ha and median tree size ranged from 1.1 to 4.6 cm DBH.

1.3.2 Total Effect of Past Land-Use on Cooling

We found some differences in cooling effect across land use legacies (Figure 1.3). All past land-use types cooled more in during the day than at night (Figure 1.3). Previously forested plots cooled the most overall, with a mean daytime cooling effect of 1.5 ± 0.08 ℃ and a mean nighttime cooling effect of 1.4 ± 0.08 ℃. Previously agricultural sites were similar, with a mean daytime cooling effect of 1.4 ± 0.08 ℃ and a mean nighttime cooling effect of 1.3 ± 0.08 ℃. Previously industrial sites had the largest difference between daytime and nighttime cooling effects. Their daytime cooling effects were comparable to previously forested and agricultural sites, with a mean of 1.4 ± 0.09 ℃. However, previously industrial sites had the lowest nighttime cooling effects with a mean of 1.0 ± 0.09 ℃ (Figure 1.3).

1.3.3 Direct Effect of Past Land-Use on Forest Structure

We observed some differences in forest structure across different past land-use types (Figure 1.4). For large trees (DBH >= 5 cm), previously forested sites had the highest tree basal area. Previously forested sites had basal areas that were on average 0.72 ± 2.46 m^2/ha higher than previously agricultural sites and 2.72 ± 2.80 m^2/ha higher than previously industrial sites. Previously industrial sites had the largest trees >= 5 cm DBH, with a median DBH 8.8 ± 3.6 cm higher on average than previously forested sites and 3.9 ± 3.4 cm higher on average than previously agricultural sites. Previously agricultural sites were 4.8 ± 3.4 cm larger on average than previously forested sites (Figure 1.4). Similar to large tree basal area, species richness was highest in previously forested sites but differences were small overall (Figure 1.4) Previously forested sites had on average 0.8 ± 0.5 more species than previously agricultural sites and 1.1 ± 0.5 more species than industrial sites. Previously agricultural sites had on average 0.3 ± 0.5 more species than previously industrial sites. Regarding small (DBH < 5 cm) basal area, previously

agricultural sites had the highest basal area, with on average 0.56 ± 0.49 m^2/ha higher basal area than previously forested sites and 0.22 ± 0.55 m^2/ha higher basal area than previously industrial sites. Previously industrial sites had higher small tree basal area than previously forested sites, on average 0.33 ± 0.67 m^2/ha higher. Consistent with large trees, we found that previously industrial sites had the largest small trees (Figure 1.4). Previously industrial sites had on average 0.5 ± 0.2 cm larger trees than previously forested sites and 0.2 ± 0.2 cm larger trees than previously agricultural sites. Previously agricultural sites had 0.3 ± 0.2 cm larger trees than previously forested sites on average.

1.3.4 Direct Effect of Forest Structure on Cooling

We found evidence that differences in forest structure alter the levels of cooling provided by parks (Figure 1.5). For trees >= 5 cm DBH, we found a positive effect between tree basal area and cooling during the day and a negative effect between tree basal area and cooling at night. Large tree size and species richness had little to no effect on cooling. For trees < 5 cm DBH, the relationship between basal area and cooling switches – we found a positive relationship between small tree basal area and cooling during nighttime and a slightly negative effect between small tree basal area and cooling during the day. Small tree size had a weak positive relationship with cooling during the day and a weak negative relationship with cooling during the night (Figure 1.5).

1.3.5 Neighbourhood Sociodemographic Composition

Due to data limitations, we were not able to causally test the relationships between historical land-use and current community demographics. Instead, we offer descriptive summaries of the communities surrounding our sites using current census data. Using these data, we did find differences among communities surrounding past land-use types. However, we also found evidence for general systemic inequity in the immediate areas surrounding our parks, consistent with previous literature (Table 1.1). There was a higher proportion of residents with bachelor's degrees or higher, and a lower proportion of visible minorities in the areas immediately surrounding parks of all historical legacies than we would expect given the island of Montreal's averages (Table 1.1). Using census data, we found trends that support what we would expect regarding legacy effects of environmental injustice when looking at the areas surrounding previously industrial parks. Areas surrounding previously industrial parks had a lower median income and prevalence of single detached homes, and the highest population density when compared to Montreal's averages and other land-use types.

1.4 Discussion:

We leveraged historical archives, urban forestry fieldwork, and sensor data to answer two research questions in Montreal, QC. For our first question, we found support for our hypothesis that capacity for cooling differs across previous land-use types, most notably the cooling effect of previously industrial sites at nighttime is lower than at previously agricultural and previously forested sites. Further, we found that forest structure had some differences across land-use type. Previously forested parks had smaller trees with a higher basal area and a slight increase (~ 1 species on average) in species richness. In contrast, previously industrial sites had lower basal

area, but larger trees on average, while previously agricultural sites had the highest density of trees < 5 cm DBH. We also found partial evidence to support our hypothesis for our second question. We found that communities surrounding previously industrial parks had lower median incomes and higher population densities when compared to previously agricultural and forested parks and to the Montreal area average, indicating persistent effects of environmental injustice.

1.4.1 Effect of Past Land-Use on Cooling

Studies have shown canopy cooling effects are typically stronger during the day (Ziter et al. 2019, Wujeska-Klause and Pfautsch 2020). Accordingly, our findings revealed that all park types showed a stronger capacity for cooling during the daytime than during nighttime. The similar levels of daytime cooling across all park types are likely attributed to current park management and suggests that parks, regardless of history, can provide critical ecosystem services. However, we observed a difference in cooling capacity across past land-use types at night. This difference may reflect differences of the broader urban heat island effect, which is often felt most intensely at night (Iungman et al. 2023). Historical industrial sites are generally located in denser urban areas and transformed into smaller parks, which have lower transpiration rates and reduced shade provision, ultimately leading to less cooling at night (Ziter et al. 2019). As such, these parks may show a reduced ability to combat urban heat island effects. This is further supported by the nighttime cooling effect observed in previously forested parks, which are larger in size compared to previously industrial and agricultural parks and maintained the highest levels of nighttime cooling. Additionally, previously forested parks were more often located in lower density areas, which show less of an urban heat island effect, resulting cooler nighttime temperatures. Thus, we concluded that land use legacy effects on cooling capacity may manifest not only via changes to forest structure, but also the landscape context in which we typically find parks with different historical land uses. These nighttime differences in cooling capacity are especially important as nighttime temperature is often considered a better predictor of mortality and morbidity (Sarofim et al. 2016). Although our study demonstrated differences in park cooling capacity by historical land-use, there are also microclimatic variables that impact people's perception of, and response to, heat such as relative humidity and wind. Investigating how land-use legacies, along with influences of other microclimatic variables would be a useful addition to the literature.

1.4.2 Effect of Past Land-Use on Forest Structure

Forest structure also differed across past land-use types, especially in relation to basal area and tree size. Consistent with other studies that found temporal distance from anthropogenic disturbance is positively correlated with basal area, previously forested sites had smaller trees with higher plot-level basal area (Thompson et al. 2002, Pregitzer and Bradford 2023). One limitation when working with historical data is it is often not possible to find the complete history of a site. As such, we were unable to determine the logging and management history of the previously forested sites, though the small, dense stands suggest that these areas are relatively young forests (Thompson et al. 2002). Previously industrial sites were characterized by lower basal area but higher median tree size when compared to other past land-use types. Higher tree size in previously industrial sites may be due to the approach taken during park establishment.

Industrial sites have the topsoil replaced upon restoration and conversion to a park, and their woodlands often start with intentional planting of saplings due to low natural recruitment (Robinson et al. 1992, Ashwood et al. 2022). Newly planted saplings in Montreal are generally required to be between 5-7 cm DBH, which are larger than many of the naturally establishing saplings in the previously agricultural and forested sites (Rivière-des-Prairies–Pointe-aux-Trembles 2013, Saint-Laurent 2018, Anjou 2019). These results suggest that there is a density-size trade-off present in urban parks that is driving differences across past land-use types. This trade-off has been previously documented, as large trees can be difficult to maintain and manage especially in high volumes (McPherson et al. 1997, Endreny et al. 2017, Soto et al. 2018). Therefore, urban forest stands often alternate between two options: smaller, dense trees or larger, sparser trees, as a strategy to balance size, density, and cover.

One similarity in forest structure that we found across past land-use types was species richness, where previously forested sites had slightly higher levels than previously industrial and agricultural sites but only by an average of ~ 1 species. This finding is in contrast to a study that found species composition of New York City forests is dependent on land use history (Pregitzer and Bradford 2023). Our finding is a testament to the power of park management and shows that maintaining tree diversity is possible across a city with varying conditions through cohesive management (Aznarez et al. 2023). However, we recognize that species richness is not always the most meaningful measure of diversity and has no effect on cooling in our study. Future studies looking at how legacy effects influence functional diversity and the presence of native vs invasive species (Pregitzer and Bradford 2023) would be an interesting extension of this research.

1.4.3 Effect of Forest Structure on Cooling

For trees >= 5 cm DBH, cooling is driven mainly by plot basal area. We observed a positive relationship between cooling and basal area during the day, and a negative relationship between cooling and basal area during the night. This finding aligns with literature that shows higher tree density typically results in more tree cover and thus higher rates of transpiration and shade provision, which increases cooling during the day (Ziter et al. 2019, He et al. 2021, Zhao et al. 2023). However, we would expect this relationship to hold with tree size, and it does not. We found no relationship between tree size for trees >= 5 cm DBH and cooling. This is contrary to our predictions, as there are many studies that demonstrate that larger size of trees in parks results in greater cooling (Rahman et al. 2020, Helletsgruber et al. 2020). It is plausible that our contrary results are due to the density-size trade-off. Due to planting and maintenance strategies in urban park management, development patterns, and resource constraints, it is rare to find a park that has both large and dense trees (e.g., see Figure A1.8). Further, the largest trees in urban parks are often surrounded by mowed turfgrass, leading to a mitigation of the cooling effect, especially on hot days (Rahman et al. 2020, Kraemer and Kabisch 2022). In contrast, more "natural" or forest-like conditions in our study parks tended to have denser stands of small trees, surrounded by herbaceous vegetation. Our findings suggest that large trees alone are not enough to provide cooling in urban parks, with high tree density and/or cover providing stronger daytime cooling. Although we were not able to measure understory structure in our study, literature

suggests that it can also impact cooling (Fung and Jim 2019, Stickley and Fraterrigo 2021) and should be considered in the future as a potentially important component of urban park cooling capacity.

Increasing the basal area of trees in parks or creating more "naturalized" or rewilded areas may be good strategies to provide temperature regulation during the day. However, dense, forested parks may provide daytime cooling at the expense of nighttime cooling and the many other needs that parks serve (Gaston et al. 2013, Kremer et al. 2016). At night, high tree cover can actually trap heat, decreasing the cooling effect (Wujeska-Klause and Pfautsch 2020). Additionally, parks with only dense forest stands lose the opportunity to provide open space for recreation, community gardens for food provisioning, wildflower beds for pollinators, etc. To further examine the impact that forest structure can have, we suggest looking at the effects of forest structure within a single park to help inform the role of management on the capacity for cooling and balance this information with strategies to provide other desired ecosystem services.

We found that as the basal area of small trees increases, the nighttime cooling effect increases, and the daytime cooling effect is limited. This directly conflicts with what we would expect based on the literature and our results for trees >= 5 cm DBH. We hypothesize that this relationship is due to a trade-off between large and small trees in our system. Areas with a high basal area of trees < 5 cm DBH – i.e., dense, shrubby stands – are less likely to contain a large shade tree in the parks we studied, therefore heat can escape at night and results in a positive relationship between basal area of trees < 5 cm DBH and nighttime cooling. However, we do see the expected relationship with tree size given the literature, where larger trees increase daytime cooling because of increased shade provision but trap heat at night (Wujeska-Klause and Pfautsch 2020). We found that an increase in median tree size causes an increase in daytime cooling and a decrease in nighttime cooling.

1.4.4 Communities Surrounding Past Land-Use Types

Our second hypothesis was partially supported. Industrial areas in Montreal have a history of systemic inequity, with neighbourhoods surrounding areas that were used for quarrying, garbage dumping, and/or other industrial activities being inhabited by working class or low-income people, who are often recently immigrated, and are majority Black or Brown (Waldron 2018, Schell et al. 2020, Kikano et al. 2023). Our results provide evidence that park establishment in these areas can provide daytime cooling, though the critical service of nighttime cooling is lacking. With differentiated management that incorporates strategies to improve nighttime cooling while also maintaining daytime cooling, parks established on previously industrial land have the potential to counter a history of inequity in these neighbourhoods, as they are providing important natural benefits to people with lower median incomes living in denser populations.

A natural conclusion to draw from our results is that previously industrial areas should be priority sites for development of new urban green spaces, to increase nighttime cooling capacity and combat the urban heat island effect. However, we are wary of making that recommendation, as we found that communities immediately surrounding parks in all three of our past land-use types have lower proportions of visible minorities and higher proportions of highly educated

people than average for the island of Montreal. This finding supports the luxury effect – an established relationship across North America between wealth/privilege and plant diversity (Hope et al. 2003b) that has been expanded to include vegetation metrics beyond diversity such as greenness (Mennis 2006), vegetation cover (Clarke et al. 2013), and more (Schell et al. 2020). This indicates to us that efforts to provide urban nature, involving the establishment or restoration of urban green spaces, may fail in their mission and result in gentrification (Anguelovski 2016, Sax et al. 2022). Green gentrification is an issue that we commonly see in Canada and around the world, and which can only be solved by stronger housing regulations and community-led policies (Goossens et al. 2020, Parish 2020, Triguero-Mas et al. 2021). Further investigation into the connections between historical injustice, ecological capacity of greenspaces, and gentrification is warranted. We recommend that moving forward, urban greening is done in collaboration with housing and urban planning departments, and driven by community-led greening initiatives.

In conclusion, we found that incorporating historical context can be a useful way to understand differences in contemporary ecological and societal conditions. Building on this study by incorporating other key ecosystem services such as air pollution mitigation, recreation provision, cultural importance, and habitat provisioning is integral to discovering how our histories influence our current day service provision, as well as informing how our current decision making will influence our future service provision. We see through this work that the restoration of industrial sites has the potential to provide critical ecosystem services to equity-seeking groups and suggest this as a promising strategy to provide urban nature as long as it is done intentionally and led by the community it is serving. Finally, our results support that building greenspaces on all different types of sites, from forest remnants to quarries, results in the capacity for daytime cooling and comparable tree diversity, critical benefits to our cities.

1.5 Tables & Figures:

Table 1.1: Mean difference in socioeconomic variables between neighbourhoods surrounding each park type and island of Montreal's averages, for parks with each of three different historical land-uses. Positive values indicate a value higher than the island's average and negative indicate a value lower than the island's average. Standard deviations are presented beside means.

Past Land Use	Population Density (per km2)	Median Total Income ($)	Single Detached Homes (% residents)	Visible Minorities (% residents)	Recent Immigrants (% residents)	Attained a Bachelor's Degree or Higher (% residents)
Industrial	7683 +/- 2576	-1849 +/- 2440	-7.3 +/- 7.5	-10.4 +/- 10.4	3.5 +/- 2.0	6.8 +/- 13.6
Agricultural	2537 +/- 6041	1230 +/- 3855	28.3 +/- 39.6	-8.6 +/- 9.9	2.1 +/- 2.9	14.4 +/- 11.0
Forested	1571 +/- 3498	698 +/- 2908	21.2 +/- 28.6	-3.4 +/- 11.0	3 +/- 3.1	5.1 +/- 12.2

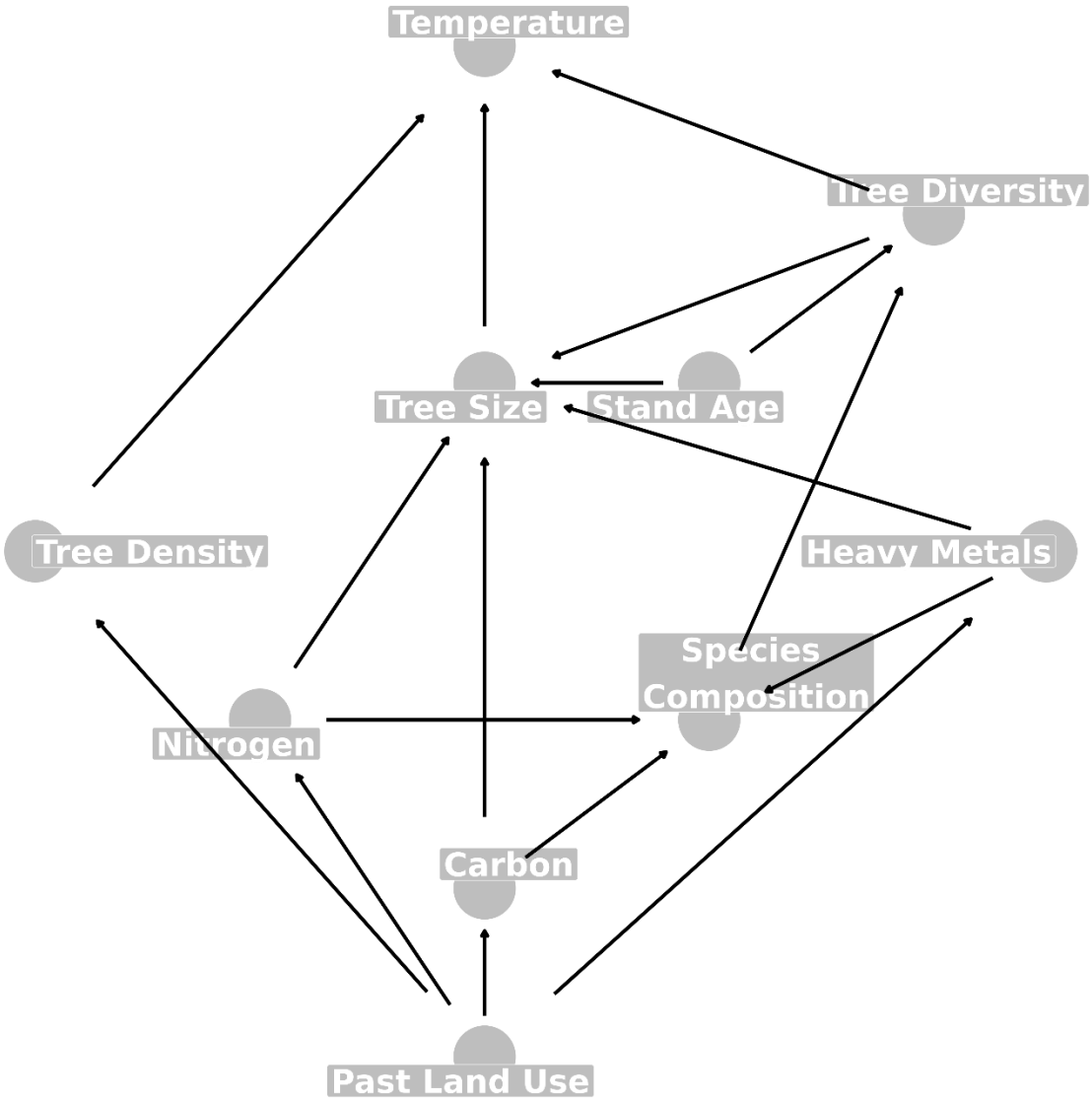


Figure 1.1: Directed acyclic graph depicting our hypothesized causal relationships between variables in our study system. Arrows in this graph indicate that the variable at the blunt end of the arrow directly affects the variable at the sharp end of the arrow (i.e., a causal relationship). For example, changing the past land-use will result in a change in nitrogen stocks. Temperature, tree density, tree size, tree diversity, past land use, and park age were all included in our models.

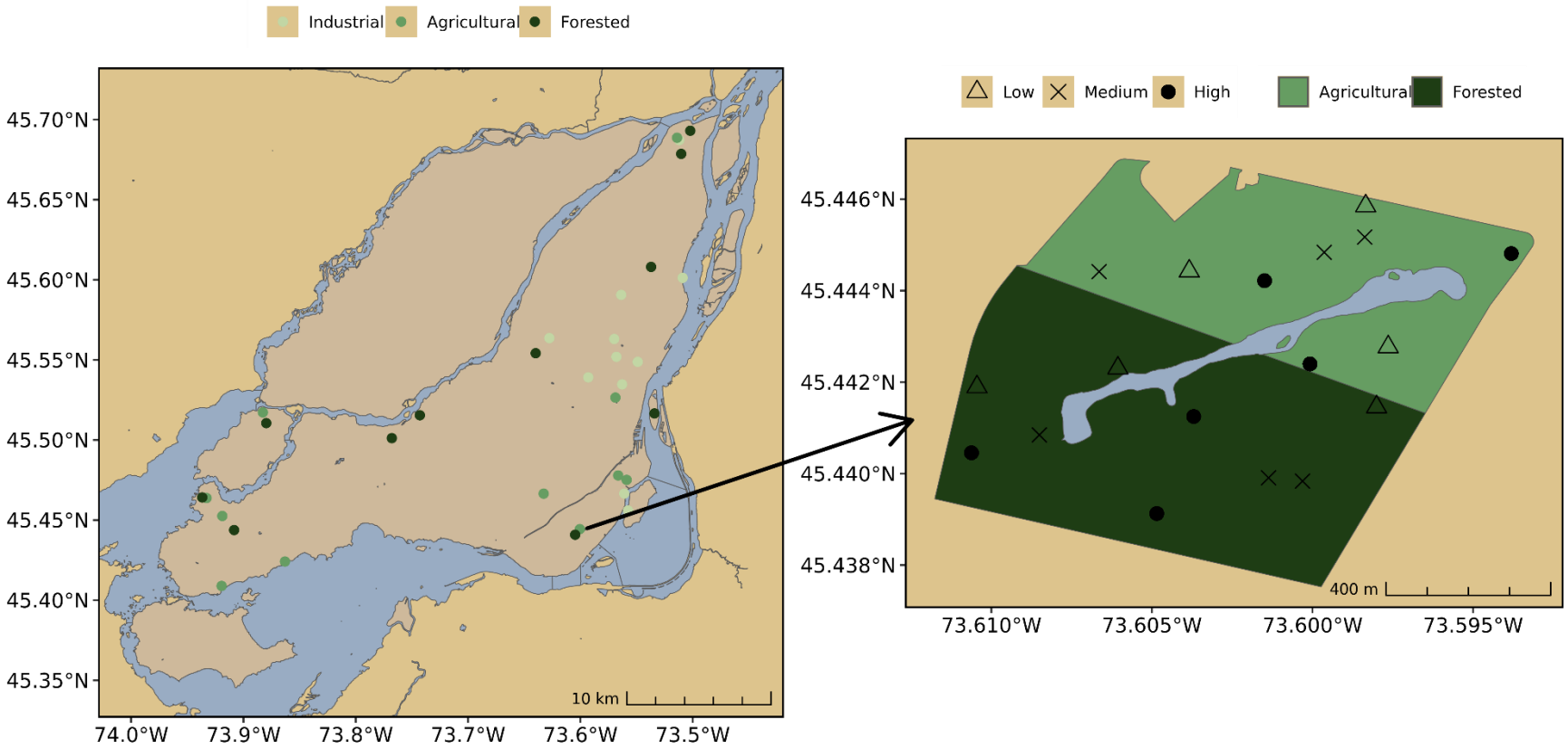


Figure 1.2: Left: Our study sites across the island of Montreal (n = 33, n = 11 per past land-use type). Different past land-uses were categorized into three main types, shown in different colour shades: industrial, agricultural, or forested. Right: Park Angrignon, one of our parks that had multiple previous land-use types. Each previous land-use type was considered a different study site and was sampled separately. Each study site had 15 potential sampling points (9 true sampling points), five in low canopy areas, five in medium canopy areas, and five in high canopy areas. For visual depiction of the sampling plots, see Figure A1.1. Maps were created using `sf`, `ggplot2`, `MetBrewer`, and 'osmdata' packages in R 4.3.1 (Mills 2022, R Core Team 2023, Padgham et al. 2023, Wickham et al. 2024, Pebesma et al. 2024).

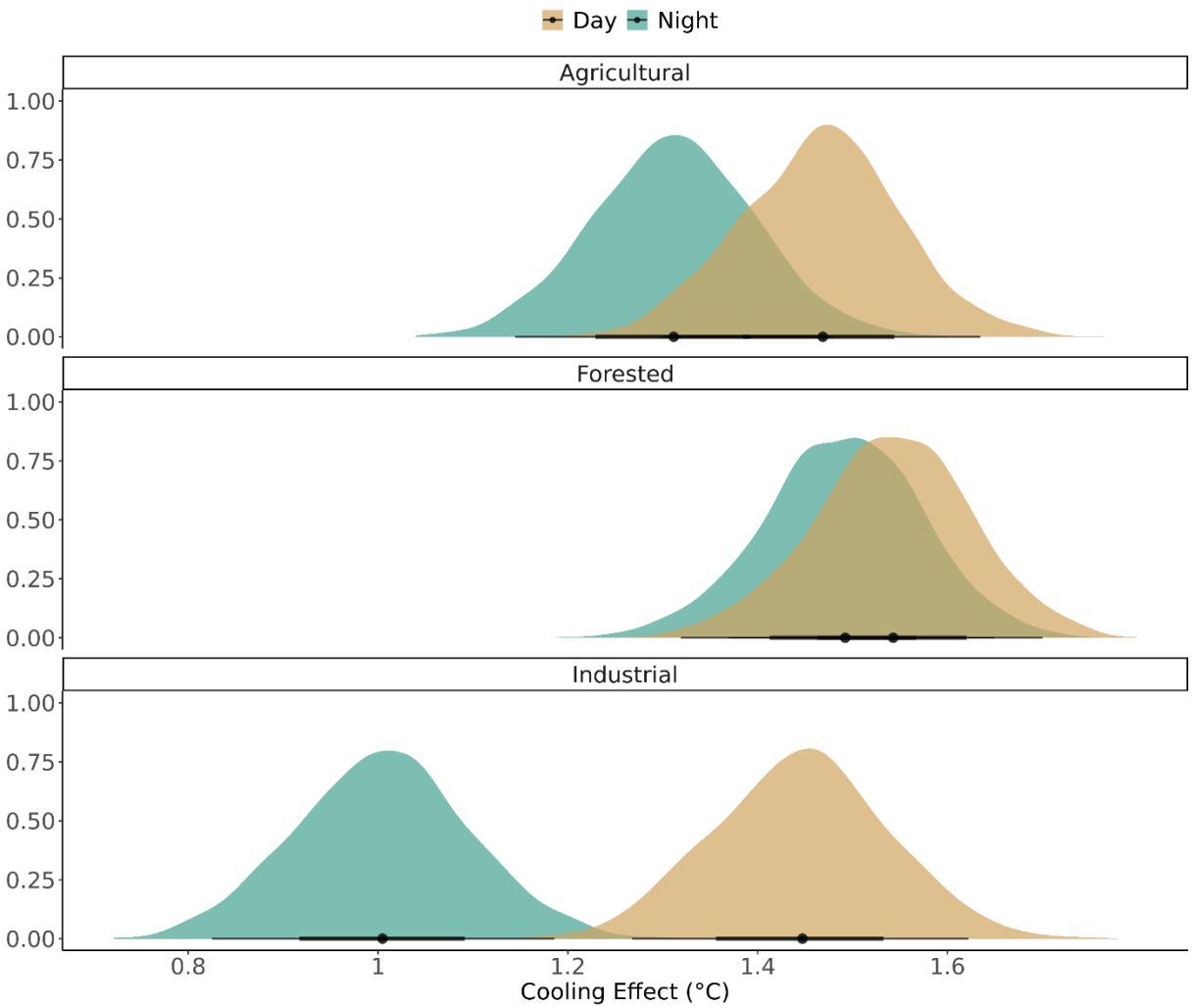


Figure 1.3: Visualization of the posterior draws for the model assessing total effect of past land-use on cooling effect of parks. Y-axis indicates density of the probability distributions, x-axis indicates relative cooling effect which is the cooling effect relative to the average cooling effect across the entire dataset Dot represents mean, linear intervals indicate 66% and 95% credible intervals. Night and daytime averages were calculated by categorizing each temperature measurement into day or night categories based on sunrise and sunset times of that day. Temperature was collected over 61 days in 2023.

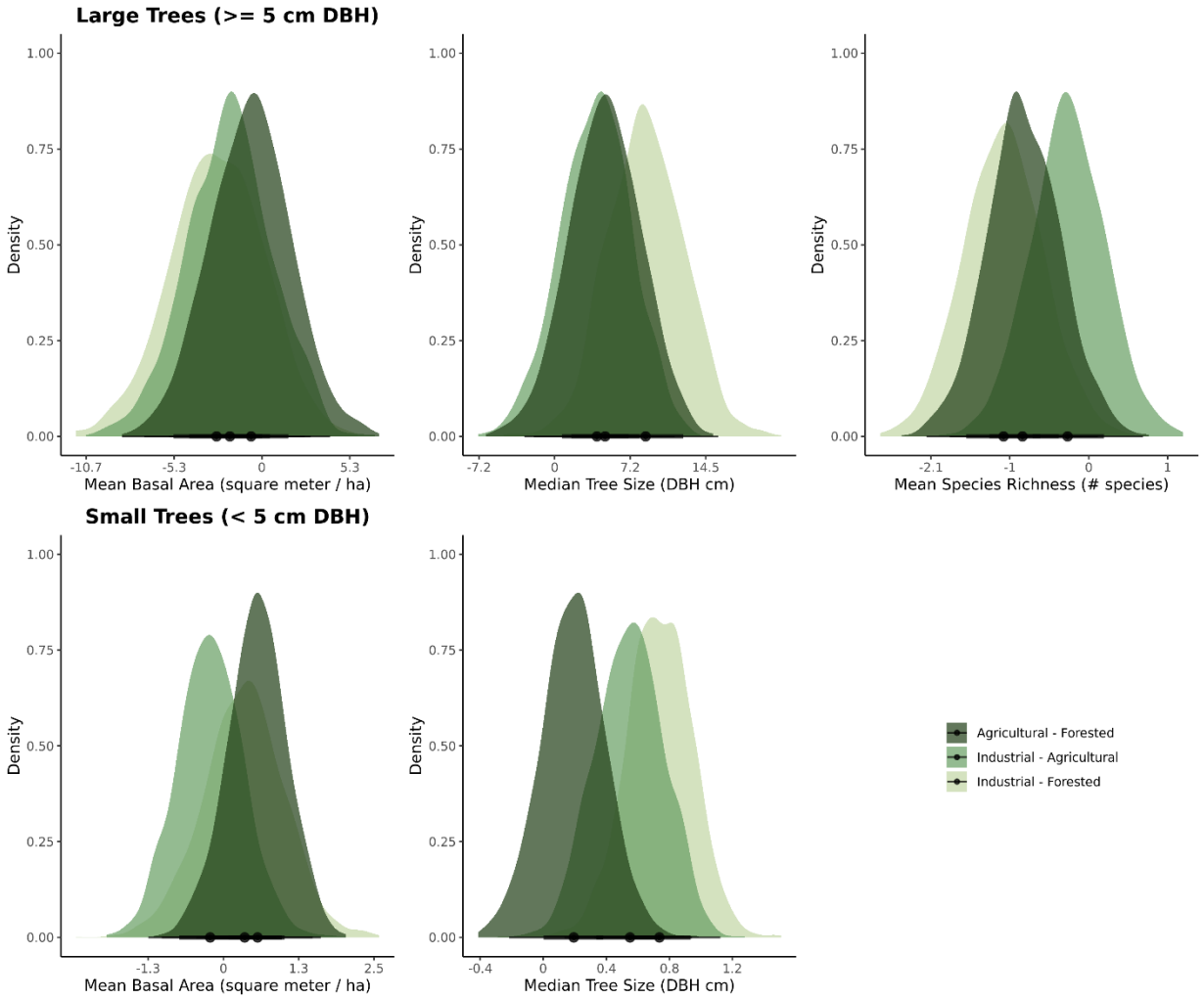


Figure 1.4: Visualization of the pairwise contrasts of the posterior draws for each combination of past land-use type to assess the direct effects of past land-use on forest structure of parks. Top 3 panels show the relationships between cooling and forest structure of large trees (trees with a diameter at breast height (DBH) of >= 5 cm). Bottom two panels show the relationships between cooling and forest structure of small trees (trees with DBH < 5 cm). Dot represents global mean of the contrast, linear intervals indicate 66% and 95% credible intervals. Contrasts can be interpreted as the effect of switching from the state on the right, e.g., forested, to the state on the left, e.g., agricultural.

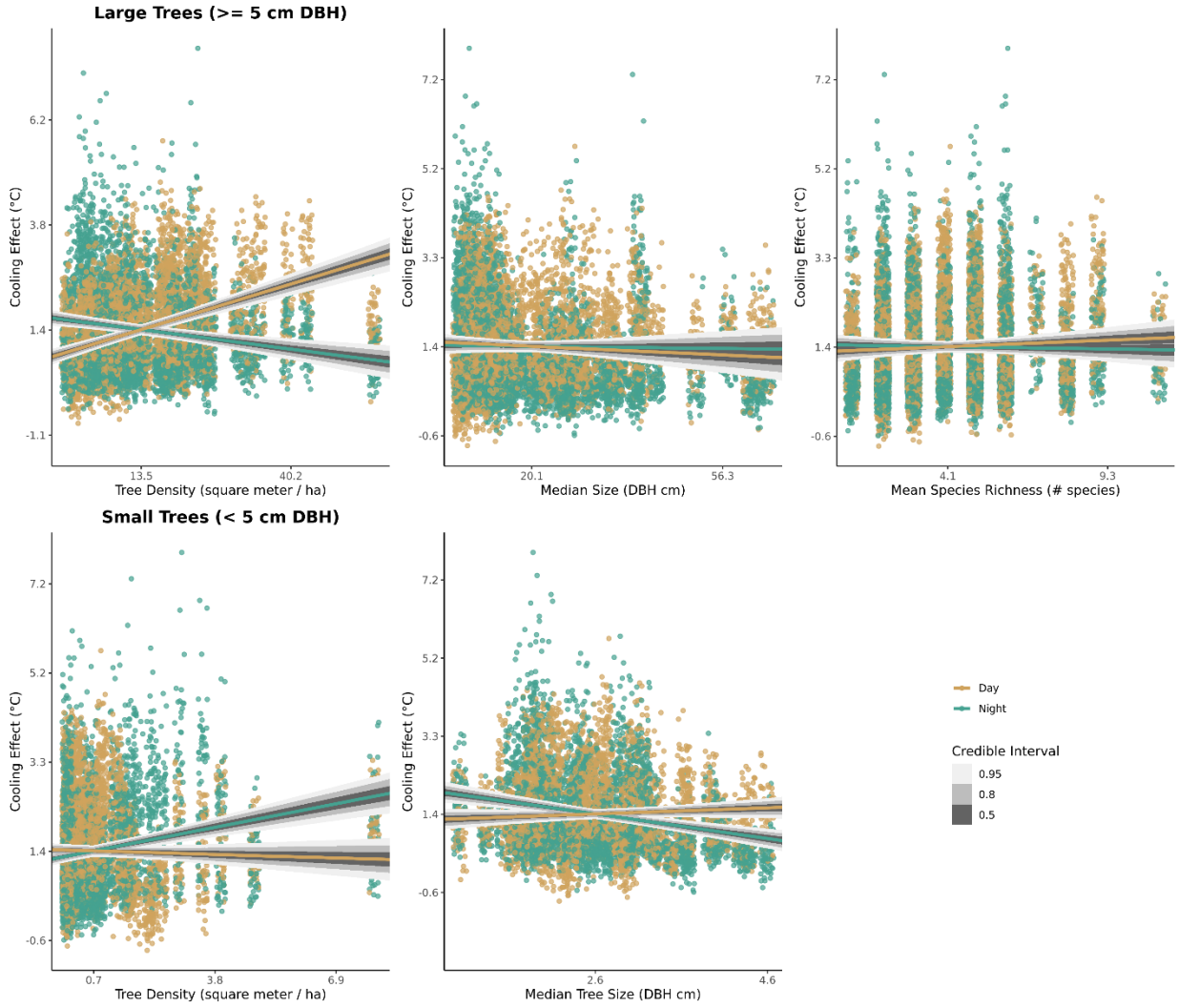


Figure 1.5: Visualization of the predicted relationships between forest structure and relative cooling effect, calculated while holding all other variables in the model constant and using time of day as an interaction effect. Predicted draws were calculated 1,000 times and then extracted and plotted. Coloured lines indicate the conditional expectation of the model to the data with grey credible intervals at 0.50, 0.8, and 0.95. Top 3 panels show the relationships between cooling and forest structure of large trees (trees with a diameter at breast height (DBH) of >= 5 cm). Bottom two panels show the relationships between cooling and forest structure of small trees (trees with DBH < 5 cm). Points represent raw data, coloured by time of day.

III. Chapter 2: *Green alleys in Quebec provide variable biodiversity support and ecosystem services*

Abstract:

Green infrastructure is increasing in popularity in cities globally because of its potential to improve urban sustainability and resident quality of life. In this paper, we studied green alleys in two Quebec cities, one with a resident-led green alley program and one with a municipally led program. Green alleys are conceptualized and promoted as green infrastructure that provide many benefits for urban residents. Using ecological methods supported by qualitative interviews, we assessed 53 green alleys' capacity to support biodiversity and provide ecosystem services, alongside 23 grey alleys and 76 streets. We interviewed residents to identify the ecosystem services that were most relevant to people living around green alleys and then measured indicators of ecosystem service capacity with ecological techniques, harnessing an approach that incorporated both ecological data and resident preferences. Green alleys provided more biodiversity support than grey alleys and adjacent street segments but did not consistently increase the capacity for ecosystem services. Vegetative complexity and proportion of native tree species are both higher in green alleys than traditional grey alleys and adjacent streets. The proportion of flowering trees was one indicator of ecosystem services that was consistently higher in green alleys. Resident-led vs municipally led creation and management of green alleys resulted in differences, where resident-led alleys were more able to target the needs of residents but had high levels of variation in both support for biodiversity and ecosystem services. We recommend ongoing funding paired with technical expert support to increase the impact of green alleys.

2.1 Introduction:

Green infrastructure is gaining popularity as a tool that can support cities' sustainability goals (Nelson and Bigger 2022). There is no consensus on the definition of green infrastructure (Matsler et al. 2021) but here we define green infrastructure as "an interconnected network of green spaces that conserves natural ecosystems values and functions and provides associated benefits to human populations" because we believe this definition outlines the infrastructure and context that we are discussing (Benedict and McMahon 2012). Urban sustainability goals and urban sustainable development have been incorporated into constitutions, laws, and urban development policies globally since the 1980s (United Nations Secretary-General and World Commission on Environment and Development 1987, Ruggerio 2021). One of the purposes of green infrastructure projects is to address urban sustainable development goals, but we often lack the empirical evidence to evaluate their objectives and performance (Cameron and Blanuša 2016, Jerome et al. 2019). For example, green roofs, pocket parks, living walls, green alleys, and other types of green infrastructure in cities often aim to provide several benefits such as air pollution reduction, temperature mitigation, improved social well-being, and biodiversity support. However, while there is broad consensus in the literature for specific benefits provided by specific green infrastructure types, such as temperature mitigation provided by green roofs (Zheng et al. 2023, Wang et al. 2023b), there are many benefits and green infrastructure types that lack evidence regarding the type and quantity of benefits they provide (Cameron and Blanuša 2016, Choi et al. 2021). Although a variety of benefits are plausible, on-the ground monitoring is crucial to establish the impacts of green infrastructure, especially small-scale green

infrastructure. Small-scale green infrastructure is currently understudied, though it provides a unique opportunity to green our cities in areas that have already been built (Navarrete-Hernandez and Laffan 2023). Given that green infrastructure focused policies are increasing as the impacts of climate change worsen, collecting evidence on how green infrastructure does and does not address policy goals is critical to informing greening projects.

When assessing the potential benefits of green infrastructure, we can build on the previously established biodiversity-ecosystem service framework to sort the benefits into two categories: "biodiversity support" and "ecosystem services" (Cardinale et al. 2012). We use these categories because green infrastructure is expected to deliver higher levels of ecosystem services than grey infrastructure (Escobedo et al. 2019) and public policies tend to focus on both ecosystem services and biodiversity support as separate entities (Newell et al. 2013). Here, we define biodiversity support as the benefits of green infrastructure that improve ecosystem functioning and environmental quality resulting in higher levels of biodiversity, essentially "nature for nature" (Kremen and Merenlender 2018). An example of biodiversity support provided by green infrastructure is increased habitat provisioning, which increases the faunal biodiversity of the ecosystem (Hanski 2011). By contrast, ecosystem services are the outcomes of green infrastructure that benefit human residents, such as temperature mitigation and increased access to nature for human residents (Millennium Ecosystem Assessment 2005), that we define as "nature for people".

In urban areas, previous studies support the claim that green infrastructure has the potential to deliver critical biodiversity support to cities. For example, green infrastructure can increase the green space abundance, diversity, and complexity present in dense urban areas that may otherwise be hostile to flora and fauna due to the amount of built infrastructure (Pinho et al. 2021). However, the design, management, and built environment surrounding different green infrastructure types will inevitably determine the quantity and quality of biodiversity support provided (Zuniga-Teran et al. 2020, Pinho et al. 2021). For example, developing school yards as small green space pockets across a city can significantly increase connectivity, by providing habitat and supporting biodiversity (Iojă et al. 2014). However, a single school yard within a matrix of heavily built-up land will not provide the same magnitude of biodiversity support as the network. To date, the influence of design and management on the levels of biodiversity support provided by green infrastructure has been focused on a small number of indicators, and thus we often do not have a strong ecological understanding of green infrastructure (Jezzini et al. 2023).

Turning to ecosystem services, they are a focus of city managers and planners as they increase the quality of life of urban residents in important and varied ways (Geneletti et al. 2020). Ecosystem services are diverse and can include regulating services such as air temperature regulation, cultural services such as opportunity for recreation, and provisioning services such as food production (Millennium Ecosystem Assessment 2005). In our opinion, one of the current gaps in ecosystem services studies is the connection between ecosystem services perceived or desired by residents and the ecosystem services that are most commonly quantified by scientists (van Oudenhoven et al. 2018, Schröter et al. 2021). Studies are often siloed by

discipline, measuring either residents preferences or ecological the capacity of the system to provide ecosystem services (Chen et al. 2024). There is a dearth of studies where researchers quantify the ecosystem services that residents have stated are desirable or preferred despite the fact that asking the local community for their input has been highlighted as an important methodological approach (van Oudenhoven et al. 2018; Schröter et al. 2021). Far more often, ecologists select ecosystem services to study based on factors that exclude resident experience or perception, such as data availability, prevalence in the literature, or human health impacts. Yet, residents often have complex relationships with nature that determine what they desire as ecosystem services and what are disservices for them (Roman et al. 2021a, Drew-Smythe et al. 2023) which are also dependent on a person's social and ecological context (Quintas-Soriano et al. 2018, Cebrián-Piqueras et al. 2020). The stated goals of green infrastructure are often to improve resident quality of life, and given that the delivery of ecosystem services to residents requires that residents value said benefits, understanding which services are desired by residents is a critical step in the implementation and management of local green infrastructure.

This brings us to a broader discussion about the rapport between humans and nature and the conceptualization of biodiversity and ecosystem services. In this paper we propose that biodiversity support can be seen as "nature for nature" and ecosystem services as "nature for people". Both concepts are needed in sustainability policies, they can however be opposing in terms of management needs (Nassauer 1995, Ziter 2016). The opposition occurs when human preferences and norms result in green spaces that do not have capacity for biodiversity support (Nassauer 1993, Larson et al. 2020, Lis et al. 2022). For example, people may prefer manicured turf grass lawns over wildflower meadows or native grasses due to aesthetic preferences and social pressures, despite wildflower meadows and native grasses supporting more biodiversity (Nassauer et al. 2009, Simmons et al. 2011). Another example is the emphasis on social cohesion, where people desire for their yard to look like their neighbours', regardless of ecological function or biodiversity (Nassauer et al. 2009). This said, the relationship between human desires and biodiversity support is not always antagonistic. Researchers and practitioners have also found synergistic relationships between desired ecosystem services and biodiversity support (Shen et al. 2020, Karimi et al. 2021, Khosravi Mashizi and Sharafatmandrad 2021). The increased research on synergies between biodiversity support and ecosystem services provided by green infrastructure can help cities meet multiple sustainability goals.

As a result of their potential capacity for synergies between biodiversity and ecosystem services, green alleys are a type of green infrastructure North American cities are increasingly investing in (Newell et al. 2013). Alleys provide an excellent case study to assess green infrastructure. Alleys have had many uses throughout history including ice/coal delivery, garbage pickup, and socializing (Wolch et al. 2010). A key benefit of green alleys is that alleys exist within even the densest parts of our cities, reducing the need for substantial modification of built infrastructure to incorporate green infrastructure. Further, given that alleys already exist as important social and recreation spaces (Forde et al. 2024), transforming an alley into a form of green infrastructure is often met with resident support, though it can depend on local context (Seymour et al. 2010, Brazeau-Béliveau and Cloutier 2021, Forde et al. 2024). The development and governance of green alleys varies across location, from exclusively municipal management

to entirely community driven (Newell et al. 2013), resulting in green alleys looking very different across and within cities (Pham et al. 2022, Forde et al. 2024). However, we have limited information on how the functioning of alleys differs in response to their variable appearances.

In Montreal, Canada, for example, green alley programs but are predominantly resident-focused though details of the programs vary depending on year of establishment and the borough in which they take place. Across programs, community participation is and has been essential, and residents provide input and their preferences when designing alleys, as well as participating in the manual labour. This format results in very variable management by residents, ranging from installation of planter boxes and trees to additions of wall murals and play equipment (Pham et al. 2022). On the other hand, municipally led green alley programs often have a specific goal, and thus more uniform designs (Newell et al. 2013). For example, the green alley program in Trois- Rivières, also in Quebec, is municipally led and focused mainly on delivering stormwater management (Ville de Trois-Rivières 2023). Given the unique form and variation in alley appearance, using established ecological methods for parks or yards and extrapolating information from other green infrastructure types is not appropriate (Dade et al. 2024). We expect that green alleys vary ecologically, but the variation in provision of biodiversity support and ecological services in green alleys is a question that, to our knowledge, has yet to be explored.

We currently lack studies demonstrating the benefits of small-scale green infrastructure and how those benefits change depending on management. Our study addresses this gap by assessing the capacity for a type of small-scale green infrastructure, green alleys, to provide multiple metrics of both biodiversity support and ecosystem services across two types of governance. We use publicly owned green alleys in two Canadian cities, Montréal and Trois-Rivières, where Montréal uses a resident-led (with municipal support) green alley program and Trois-Rivières uses a municipally led program. We selected a large, central city (i.e., Montréal) and a smaller, regional city (i.e., Trois-Rivières) within the same climatic zone to better understand the influence of governance type, funding differences, and community involvement in the benefits of green infrastructure. The two cities represent two ends of the spectrum in their approach to green alley implementation, and both have characteristics that are shared by other North American cities more broadly. We used qualitative interviews to guide our analysis of ecosystem service indicators measured using a previously collected ecological dataset that included tree and temperature data (Table 1). This ecological approach supported by qualitative interviews to measure ecosystem services that were identified as important to the residents surrounding the green alleys attempted to bridge the fields of human preferences and ecosystem services. Using this approach, we asked:

1. To what extent do green alleys provide more benefits, i.e., biodiversity support (i.e., “nature for nature”) and ecosystem services (i.e., “nature for humans), than comparable grey infrastructure such as grey alleys and streets?

Given that governance plays a key role in the management of green alleys, we also asked:

2. How does the capacity for green alleys to provide benefits change across program type, i.e., resident led (Montréal) vs municipally led (Trois-Rivières)?

We hypothesize that green alleys will provide higher levels of both biodiversity support and ecosystem services than grey alleys or streets due to active management initiatives and an input of funding. However, we predict that in areas where alley design and management is bottom-up, i.e., Montréal, the alleys will be more variable in their vegetation management and therefore have more variable levels of ecosystem services and biodiversity support than in top-down programs, i.e., Trois-Rivières.

2.2 Methods:

2.2.1 Site Selection

2.2.1.1 Montréal

Our study area was the Montréal borough of Villeray—Saint-Michel—Parc-Extension (VSMPE), composed of three distinct neighbourhoods and a total population of ~144,000 with a population density of 8,723 residents per km^2 (Montréal en statistiques et al. 2018). Parc-Extension is considered the most densely populated and poorest neighbourhood in Montreal. Saint-Michel is a low-income neighbourhood whose population is composed of 50% immigrants with low education levels. Villeray has a higher proportion of francophone residents than Saint Michel, with some high-income and highly educated areas (Centraide of Greater Montreal 2020).

In total, there are 72 green alleys in VSMPE (Regroupement des éco-quartiers 2023). We surveyed 40, spread across the three neighbourhoods geographically to represent each of the neighbourhoods and span a range of canopy cover (Figure 1). We also selected 10 grey alleys that do not have a green alley designation and were similarly spread across the three neighbourhoods and a range of canopy cover to act as control sites and facilitate comparison between the two groups (Figure 1). We selected a limited number, i.e., 10, control sites in VSMPE due to the high number of green alleys we were sampling, in addition to the dense nature of the neighbourhood which facilitated the use of a single control site for multiple alleys.

2.2.1.2 Trois-Rivières

Trois- Rivières (TR) is a city of ~ 139,000 people with a population density of 155 residents per km^2 within the Mauricie region of Quebec, approximately 139 km northeast of Montreal. TR has a mainly white, francophone population and residents with a range of income levels, with high proportions of low-income residents concentrated in the city centre (Statistics Canada and Government of Canada 2022). TR currently has a total of 13 green alleys, and we sampled each of them. We chose to sample 13 grey alleys as controls, a higher number than in VSMPE (Figure 1). We used a higher number of controls in TR because there were fewer sites overall and TR is a less dense city, meaning that neighbourhood context can greatly change between sites.

2.2.1.3 Street Segments

In both cities, we sampled the sidewalk and adjacent yards/boulevards parallel to the longest segment of each selected alley (hereafter "street segment") to facilitate comparison between alleys and streets which are somewhat similar in form but have different function and management regimes. Using satellite imagery, we identified the two potential street segments parallel to the alley, then selected the one which had the most green infrastructure, i.e., segments with street trees, garden squares, and vegetated curb cutouts. If both street segments parallel to the alley had similar levels of green infrastructure, we chose via coin flip (Supplementary Materials A, Table S1).

2.2.2 Biodiversity Support

2.2.2.1 Biodiversity Support Metric Selection

We use the framework of "nature for nature" to describe biodiversity support. We chose to focus on sampling trees and vegetative complexity, as trees play a key role in ecosystem functioning and biodiversity support (Manning et al. 2006). Additionally, trees are often important to municipal managers and residents alike (Pearce et al. 2015, Martin et al. 2025a). Because alleys are small, multiuse areas, we selected biodiversity support metrics that were appropriate given that context and which we could collect data on given time constraints. To calculate our first biodiversity support metric, canopy cover, we used existing, open-source data (Institut National de Santé Publique du Québec and Gouvernement du Québec 2022).

2.2.2.2 Tree Diversity

We sampled trees by identifying and measuring the diameter at breast height (DBH) of every tree (defined as a woody plant > 2 m tall) found at the site. We then assessed tree diversity in two ways. First, we calculated the species richness of each site by counting the number of unique tree species. We recorded a total of 75 species (Table A2.2). The second diversity metric was functional group richness. Using the original dataset and methodology from Paquette et al. (2021), we assigned a functional group, i.e., a group of species that share a similar set of biological traits, to each of the tree species present in our dataset and counted the number of functional groups present at each site (Belluau et al. 2021, Table A2.2).

2.2.2.3 Tree Species Composition

We also assessed the proportion of invasive and native trees at each study site by calculating the proportion of stems at each site that were native and invasive. We assigned a status of native or invasive to each of our study species (Philp 2024, Padvaiskas et al. 2025, Table A2.2) according to the native ranges of the St. Lawrence Lowlands ecoregion. We categorized invasive species based on Quebec-specific sources (Plant Dynamics Laboratory and Plant Biology Research Institute 2008, Lavoie and Ayotte 2019, Lavoie et al. 2022).

2.2.2.4 Vegetative Complexity

We measured vegetative complexity by walking linearly through each study site and taking measures every 10 m. At each stop, we counted how many of the 5 following vegetative layers were present as a proxy for complexity: ground cover, herbaceous vegetation, wall vegetation,

shrubs, or canopy. Average vegetative complexity of sites was then calculated by summing the total number of layers counted and then dividing by the number of points measured.

2.2.2.5 Firefly Survey

To assess the habitat quality of our study alleys, we selected a subset of alleys in VSMPE and performed a presence/absence survey of fireflies (Family: Lampyridae). Fireflies are known bioindicators in cities, as they require leaf litter, access to water, and low levels of light pollution (Picchi et al. 2013, Firefly Atlas et al. 2023). Due to time constraints, we were unable to sample fireflies in TR, however, we still believe this is a valuable metric. There is a need for approachable and feasible methodology to assess green infrastructure (Meixner et al. 2021, Dade et al. 2024). The status of fireflies as bioindicators paired with a global community science initiative with established methodology makes them a prime candidate to assess habitat quality in cities in an approachable and meaningful way (Picchi et al 2013; Firefly Atlas et al. 2023). To pilot the ability of fireflies to be used as a habitat quality metric in green alley projects, we selected the 28 green alleys with the highest canopy cover and most vegetative complexity for our subset, the five grey alleys with the least canopy cover and vegetative complexity as our controls, and the associated street segment for all 33 alleys surveyed. This approach is not representative of the true effect of green alley establishment as we chose those sites with the highest canopy cover, however, it does allow us to test the potential of green alleys to provide habitat. If the presence of a firefly was noted in any of the surveys, the site was assigned as having fireflies present. Additional details on methodology and data sources of the above metrics can be found in the supplementary materials (Supplementary Materials Section B).

2.2.3 Ecosystem Service Indicators

2.2.3.1 Interviews & Ecosystem Service Indicator Selection

In the summer of 2023, we did 28 semi-structured walking interviews to assess the perceived and desired ecosystem services present in green alleys in VSMPE and TR as part of a larger multi-university project. Interviews were conducted by research professionals (EPM, NB) and graduate students (FB, PF) in urban and environmental studies. All interviewers had experience conducting interviews and interviewed individuals in the language of their choosing, either French or English. Residents were contacted via flyers posted in their neighbourhoods and Facebook posts in community groups. After agreeing to participate, residents met with two interviewers, where they followed a pre-chosen route through green alleys, other nearby greenspaces and adjacent grey alleys. The lead interviewer asked a series of interview questions designed to connect perceptions and experiences of nature to ecological benefits and conditions (Hoyle et al. 2019) while the second documented everything the interviewee mentioned using photos (for interview script see Supplementary Materials B). Although walking interviews resulted in fewer participants than other methods such as surveys, they allowed a more in depth understanding of individual's preferences and desires (duration varying between 1 and 1.5 hours), described as they were experiencing them in the relevant context (in our case, by walking in the alleys and streets that they know well). Methods were approved by the university's ethics committee (Permit No. 2023-5054).

Our interviewees (n = 30) covered a diverse range of ages, immigration status, genders, countries of origin, employment status, housing types, and neighbourhoods to capture the

variation in resident composition of the study areas (Supplementary Materials A, Table S3). However, one notable bias was that most of our participants (76%) were highly educated. Multiple team members (FB, PF, EPM, NB) transcribed the interviews and used thematic content analysis coding with NVivo to sort interview contents into broad categories such as "relationship with nature" and "description of neighbourhood". We then went through all broad categories and inductively coded mentions of desired and perceived ecosystem services made by interviewees. We counted both how many individuals and how many times each interviewee mentioned each ecosystem service across all interviews (Supplementary Materials A, Table S4). Examples of perceived and desired ecosystem services include:

Cultural value of trees: "On the street, the trees are enormous, and I love streets that have a lot of trees"

Temperature regulation: "[About the green alley] It's so much more pleasing to the eye and even helps oxygenate the air and cool the summer too. Yes, I think it will do some good."

Aesthetic appreciation of flowers: "Well, you don't often see trees like this in the city. It's like, you stop and go wow! With the tree next to it with all the little white flowers, I don't know what it is, but it's beautiful."

Using the list of perceived and desired ecosystem services mentioned by interviewees, we selected ecosystem service indicators to quantify that were highly mentioned and overlapped with the ecological data we had previously collected via fieldwork. Because we were limited to ecological data that was collected concurrently with interview data, we were only able to assess ecosystem service indicators using tree-related and temperature data. Temperature mitigation, or cooling, was the ecosystem service that we were able to measure most directly, though we were still not able to incorporate residents' perception of the cooling effect. The rest of the ecosystem services were measured using indicators as proxies. Ecosystem service indicators included biological traits of trees that were connected to desired and perceived ecosystem services. For example, aesthetic appreciation of flowers was an ecosystem service commonly mentioned by residents. We assessed if green alleys had more capacity for appreciation of flowers by assessing if green alleys had a higher number of flowers present, using the indicator of proportion of trees that produce showy flowers. Due to the nature of the ecological dataset, there were several ecosystem services listed as desirable by residents that we were unable to measure due to data constraints. Ecosystem service indicators that could be assessed with tree inventory data were selected, whereas others that would have required another season of data collection were removed. For example, we could not meaningfully assess the provisioning of fruit and vegetables provided by green alleys as most food plants are herbaceous and thus this ecosystem service was removed. The final list of ecosystem service indicators selected includes temperature mitigation/cooling, the presence of trees, the presence of large trees, and the presence of flowering trees.

2.2.3.2 Cooling

To assess the capacity of alleys to provide temperature mitigation, we placed one Kestrel DROP D2 wireless temperature sensor (0.1°C resolution ± 0.5°C) housed within an AcuRite radiation

shield (Bailey et al. 2020) in every alley at approximately 1.5 metres off the ground attached to either a tree branch or a post, depending on availability. Sensors recorded the temperature every 15 minutes. Due to the highly heterogeneous nature of the alleys, we opted to place the sensors in the greenest part of the alley, to assess the maximum cooling potential. The greenest section was assessed on-site, typically chosen as an area with the highest canopy cover and vegetative complexity. We deployed sensors to all study alleys in Montréal on June 27-28 and retrieved them July 25-26, 2023. We then deployed the same sensors using the same methodology in Trois-Rivières on August 6-8 and collected all sensors on October 3, 2023. Due to the different dates of temperature collection, direct cross-city comparisons are not possible.

2.2.3.3 Tree Abundance

We calculated tree abundance by summing the number of individual stems in each of the study sites. We included dead trees in this metric.

2.2.3.4 Large Trees

We quantified two metrics to capture the presence of large trees. First, we calculated the mean observed tree DBH followed by the mean potential height for each study site. To calculate mean observed DBH, we took the average DBH of all the trees in an alley or street segment. More details on DBH measurements can be found in the supplementary materials (Appendix Section 2B).

To calculate the mean potential height of alley trees, we collected data on the maximum height for individual tree species included in our study (Table A2.2) using published data from previous studies (Hutt-Taylor and Ziter 2022) and other sources (The Morton Arboretum 2022, Missouri Botanical Garden 2024, United States Department of Agriculture and Natural Resources Conservation Service 2024, University of Florida 2024). We then took the average maximum height of all the trees at a site.

2.2.3.5 Flowering Trees

We calculated the proportion of flowering trees at each study site by identifying if each study species had showy flowers (Table A2.2, The Morton Arboretum 2022, Missouri Botanical Garden 2024, United States Department of Agriculture and Natural Resources Conservation Service 2024, University of Florida 2024) We then calculated the proportion of stems that did have showy flowers.

2.2.4 Statistical Analyses

Our statistical approach is based on a causal inference framework (Grace and Irvine 2020, McElreath 2020), which is increasingly called for in ecology (Siegel and Dee 2025). To test the effect of establishing a green alley on our various response variables, we constructed directed acyclic graphs (DAGs) representing our assumptions and hypotheses about the causal links between variables in our system (Laubach et al. 2021, Arif and MacNeil 2023). We hypothesized that there were many factors that influenced the establishment of a green alley in VSMPE. Because green alley designation in VSMPE is determined by the residents, there are many variables that are associated with the establishment of a green alley, that must be taken into

account such as socio-demographic and economic characteristics of the neighbourhoods (Brazeau-Béliveau and Cloutier 2021; Pham et al. 2022; Forde et al. 2024, Figure 2). We used the literature to construct relationships present in the system based on our hypotheses. In contrast, Trois- Rivières is a municipally led program and green alley creation is dependent only on the state of the pavement, thus we did not hypothesize any confounding relationships anddid not require DAGs. In VSMPE, we used DAGs in combination with do-calculus to identify the variables we needed to add to our model to deconfound our system and test the effect of alley type on our response variables in VSMPE (Pearl and Mackenzie 2018). This process identified income level and language spoken as necessary variables to be added to our models in order to test the effect of green alley establishment (Figure 2). Income level was represented using median after-tax income for the dissemination area and language was represented using the proportion of the population that had knowledge of each of the official languages (i.e., English, French, both, or neither).

To test the effect of implementing a green alley on biodiversity support and ecosystem services included in this study, we model each biodiversity support metric (n = 7) and ecosystem service indicator (n = 5) individually using generalized linear models. All biodiversity support metrics and ecosystem service indicators are modelled twice, once for each city (n = 23 models total, firefly abundance is measured only in VSMPE due to data constraints). To control for confounding of the system from the resident-led model in VSMPE (as presented in model-specific DAGs, Supplementary Materials C, Figure S1), we stratified our models by language spoken and median income and added neighbourhood as a varying intercept variable. Temperature models had a different structure as both date and site had to be included and thus are mixed effects models in both VSMPE and TR. Temperature models included neighbourhood, date, and site ID as varying intercept random effects. Two-way interactions were used to test the relationships between time of day, infrastructure type (i.e., green alley, grey alley, or street segment), and day of year. Full model equations with priors are presented in the supplementary (Supplementary Materials D, Equations 1-23).

To calculate the effect of implementing green alleys on the level of biodiversity support and ecosystem services, we computed the global mean contrasts between infrastructure groups (i.e., green alleys, grey alleys, street segments) using the posterior distributions of each model. For VSMPE models, the adjustment variables (i.e., language spoken and median income) in the model were set to their average values when computing the contrasts. For the temperature model, we graphically represented the contrast instead of computing mean values with credible intervals, due to its complex model structure. We estimated the posterior distributions using Hamiltonian Monte Carlo as implemented in the brms 2.21.0 and cmdstanr 0.8.1 packages (Gabry et al. 2024, Bürkner et al. 2024). We assessed model convergence by inspection of trace plots, R-hat values, and effective sample sizes. Prior predictive simulations as well as model diagnostics are presented in the supplementary (Supplementary Materials E, F) and all results can be replicated using the code available at https://github.com/zule-lab/infrastructuresvertes, archived at https://doi.org/10.5281/zenodo.15304732. We used R v4.4.3 for all data cleaning and analyses (R Core Team 2023).

2.3 Results:

2.3.1 Summary Statistics

2.3.1.1 Alleys

Alleys in our study system were on average 4.45 m wide, with a minimum width of 3 m and a maximum width of 6.8 m. Alleys varied greatly in length and had many configurations (e.g., L, T, I, or F shaped). In VSMPE, most alleys were paved but there was a range of up to 100% permeable surfaces. In TR, all green alleys had the same appearance with approximately 75% of the alley surface being permeable, crosshatched pavement (Figure S2).

2.3.1.2 Biodiversity Support

Canopy cover across all sites was on average 15% higher in VSMPE than TR (Table 1). Tree diversity and species composition were higher in VSMPE than TR, following the trends of canopy cover and tree abundance (Table 1). The proportion of native trees and invasive trees was higher in TR than VSMPE (Table 1). Vegetative complexity was slightly higher on average in VSMPE compared to TR (Table 1). Finally, in VSMPE, we recorded a total of 28 firefly sightings across 12 sites.

2.3.1.3 Ecosystem Service Indicators

Temperature data was collected across different dates for each city, inhibiting direct comparison of raw temperature values. VSMPE had a mean daytime temperature across all sites of 24.4 ± 3.6°C and a mean nighttime temperature across all sites of 21.9 ± 2.5°C. TR, measured two months later, had a mean daytime temperature across all sites of 20.3 ± 4.9°C and a mean nighttime temperature across all sites of 16.3 ± 4.1°C. Tree abundance and size was higher overall in VSMPE when compared to TR (Table 1). Our aesthetic measurement, proportion of trees with showy flowers, had higher levels in VSMPE than TR (Table 1).

2.3.2 Modeling & Contrasts

Overall, results were variable across biodiversity support metrics and ecosystem service indicators, as well as between cities. However, for most of the biodiversity support metrics, green alleys provide at least a slight increase in benefits when compared to grey alleys or street segments (Table 2). Ecosystem service indicators were very variable, and we found that their delivery in green alleys does not always align with the interests of the interviewed residents (Table 3).

2.3.2.1 Biodiversity Support

In VSMPE, where each alley is managed by the local community, we found high levels of variation in our models (Table 2). Biodiversity support was generally higher in green alleys, though by small margins for some variables (Table 2, Figure 3). The exceptions being canopy cover and tree diversity. Canopy cover was consistently lower in green alleys than grey alleys (global mean = - 11.8 %) and street segments (global mean = - 18.2 %). Tree species richness was similar across groups, with contrast means less than one species different. However, at the extreme ends of the 95% credible interval, green alleys could have up to 1 more species than

“grey alleys” and almost 2 (1.87) less species than street segments. The same trends held for functional group richness, with differences between green alleys and other infrastructure being less than 1 functional group but general trends indicating that green alleys have slightly higher functional group richness than grey alleys and slightly less functional group richness than street segments. Firefly presence was on average 2 % more likely in green alleyways when compared to grey alleyways, and 4 % more likely in green alleyways than street segments, with high levels of variation across both groups. Vertical complexity was higher in green alleys when compared to “grey alleys” (global mean = 0.15 increase in mean levels of complexity) and even more so when compared to street segments (global mean = 0.31). The percentage of native tree species in green alleys was notably higher than in grey alleys (global mean = 19.0% increase in percentage of native species) and street segments (global mean = 20.8%). Finally, the percentage of invasive species was correspondingly lower in green alleys than in grey alleys (global mean = - 11.3 % decrease in percentage of invasive species) and street segments (global mean = - 5.4%).

In TR, we see similar trends to VSMPE with respect to higher levels of vegetative complexity and native trees, and lower proportions of invasive trees in green alleys (Table 2, Figure 3). However, canopy cover in green alleys is slightly higher than in grey alleys (global mean = 0.7 % increase) and street segments (global mean = 7.2 % increase). There was no difference in tree species richness or functional group richness when comparing green alleys to grey alleys or street segments. There was an increase in average vertical complexity when comparing green alleys to both grey alleys (global mean = 0.20 increase in mean levels of complexity) and street segments (global mean = 0.31). There was a slight increase in the percentage of native trees in green alleys when compared to grey alleys (global mean = 4.8 % increase) and a larger increase when compared to street segments (global mean = 20.9 %). Finally, the proportion of invasive trees decreased slightly when comparing green alleys to grey alleys (global mean = -3.9 % decrease) and decreased notably when comparing green alleys to street segments (global mean = -17.0 %).

2.3.2.2 Ecosystem Service Indicators

The temperature models were our most complex models, and the results are presented in graphical form instead of being included in the results tables (Figure 4). It is important to note that temperatures were assessed across different time periods in each city, preventing direct cross-city comparison. When looking across the sampling period, temperature was similar between green alleys and grey alleys in both cities, with high variation across both infrastructure types (Figure 4). However, there are some key differences across infrastructure types when broken down by time of day. On average green alleys were cooler during the day than grey alleys (Figure 4). At night, there was no visible trend in VSMPE, with green alleys being both warmer and cooler than grey alleys (Figure 4). In TR, green alleys were noticeably cooler than grey alleys at night, however, they were also noticeably warmer than grey alleys during the day (Figure 4).

The rest of the results for the ecosystem service indicator models are presented in Table 3. These results are more complex and varied than the biodiversity support models. In VSMPE, tree abundance was higher in green alleys than grey alleys (global mean = 1 more tree in green alleys

but up to 4 at the high end of the 95% credible interval) and slightly higher than street segments (global mean = 0.7). The average tree size tended to be smaller in green alleys than grey alleys (global mean = -3.9 cm) and much smaller when compared to street segments (global mean = -13.1 cm). Similarly, the mean maximum (or potential) height of trees in green alleys was smaller than that in grey alleys (global mean = -0.73 m) and street segments (global mean = -1.88 m). Finally, the proportion of trees with showy flowers was slightly higher in green alleys when compared to grey alleys (global mean = 7.8 % increase) and was the same as what was found in street segments.

In TR, trends are slightly different (Table 3). Tree abundance was at a similar level although slightly lower in green alleys when compared to grey alleys (global mean = -0.05 trees) and street segments (global mean = -0.07 trees). However, the average tree size was higher in green alleys compared to grey alleys (global mean = 0.66 cm larger). When compared to street segments, average tree size was lower in green alleys (global mean = -2.27 cm smaller), similar to VSMPE. The average maximum height of trees in green alleys was on average higher than in grey alleys (global mean = 1.37 m higher) and street segments (global mean = 1.41 m higher). Finally, the proportion of flowering trees was similar across all infrastructure types, but green alleys had on average slightly higher proportions than both grey alleys (global mean = 2.5 % increase) and street segments (global mean = 5.8 % increase).

2.4 Discussion:

Our hypothesis that green alleys would have higher levels of both biodiversity support and ecosystem services when compared to grey alleys and street segments was only partially supported. Green alleys did provide either similar or higher levels of biodiversity support, i.e., nature for nature, when compared to grey alleys and street segments, except for canopy cover in VSMPE (Montreal). However, ecosystem service indicators, i.e., nature for people, did not follow the same trend. In general, the ecosystem services desired by residents were of similar levels or lower in green alleys compared to grey alleys and street segments, except for tree abundance in Montreal which was higher in green alleys. We also predicted that due to the resident-led program design of green alleys in Montreal, the level of biodiversity support and ecosystem services would be more variable than in Trois-Rivières. For most of the 11 indices, this was not true. Both Montreal and TR had variable levels of biodiversity support and ecosystem service indicators. However, for both temperature regulation and tree abundance, Montreal was more variable than TR, as predicted. It is important to note that our statistical approach only tests for differences within-cities, across-city differences are based on qualitative analysis of overall patterns.

We found that the benefits of small-scale green infrastructure can be context dependent. Though biodiversity support was generally higher in green alleys than grey infrastructure types, canopy cover in Montreal was an exception, with green alleys having lower canopy cover on average than grey alleys and street segments. Initially, this finding may be counterintuitive. Since the green alley program in Montreal prioritizes and funds planting trees (Ville de Montréal 2024), and the presence of large trees was listed as an important ecosystem service indicator by residents (Supplementary Materials A, Table S4), it is reasonable to expect that the establishment

of a green alley may result in an increase in canopy cover. However, significantly increasing canopy cover in an alley is difficult without large scale intervention and changing the function of the alley. Alleys are narrow spaces, averaging approximately 4 m wide, and usually serve a variety of purposes. They are spaces for play and neighbourhood gatherings while also still sometimes used for vehicle access for backyard parking spots and parking for maintenance vehicles and construction equipment (Wolch et al. 2010; Newell et al. 2013; Pham et al. 2022). Due to the design of alleyways, tree planting typically requires the removal of pavement and a reduction of traffic in the alley, which is resource and effort-intensive and can be restricted by city bylaws, participant energy, and desire to get along with other residents (Brazeau-Béliveau and Cloutier 2021). Often, the smaller-scale greening interventions that residents make in green alleys include planter boxes and narrow bands of vegetation along the side of the alley, which may require still require expert support and specialized equipment but do not change car traffic and also do not provide the space required for trees with large canopies (Pham et al. 2022). The presence of car traffic and parking space access were not considered in this study but have been established as important determinants of alley greenness in Montreal (Pham et al. 2022) and should be incorporated as important variables in other studies assessing the capacity of green alleys to provide benefits. Additionally, alley age is most likely tied to canopy cover. Even if green alley programs are planting trees, the green alleys we included may not be old enough to see an increase in canopy cover. Alley age has important implications for tree growth, maintenance, and resident perception (Wolch et al. 2014; Pham et al. 2022). Moving forward, the effect of age should be investigated for a more complete picture.

The hesitation to make large-scale interventions to increase canopy cover in alleyways results in a large proportion of canopy cover in green alleys, and residential areas in general, being provided by trees on private land (Pataki et al. 2013, Hutt-Taylor and Ziter 2022). Given that canopy cover is in large part determined by space availability and decisions made on private land, green alleys having lower levels of canopy may be partially explained by resident motivation. Residents with less access to private green space and associated canopy cover may be more motivated to participate in a green alley program to increase vegetation in the area immediately surrounding their home. By contrast, in Trois-Rivieres the municipality chooses the green alley locations and alleys themselves lack trees, thus the same mechanism does not apply. Future studies that can assess differences in resident perception, motivation, and ecological benefits before and after the development of a green alley instead of comparing different alleys that have already been built may provide an opportunity to gain a more detailed insight into the unexpected levels of canopy cover. Additionally, monitoring how canopy cover and other ecological benefits change across time after the establishment of a green alley would be an important contribution to our understanding of these systems. Canopy and tree cover was mentioned by interviewees in our study as a desirable aspect of green infrastructure, emphasizing the importance of understanding why it may be lower than expected in green alleys and incorporating solutions. Solutions may include providing expert support to residents designing green alleys and using funds specifically designed for greening purposes to increase canopy cover in green alleys moving forward should be a priority (Brazeau-Béliveau and Cloutier 2021, Ville de Québec 2025).

Another context-specific finding from our study was the cooling effect of green alleys. Cooling and shade were mentioned by residents frequently as valuable ecosystem services (Table S4). Southern Quebec reaches high temperatures in the summer, with the urban heat island exacerbating the summer heat levels contributing to heat-related illness and mortality (Boudreault et al. 2024). Given that green alleys are integrated into the urban matrix and have the potential to provide cooling near residences, they can play an important role in combating heat-stress and other heat-related illnesses. We measured temperature in our study cities at different times, with our measurements in TR occurring in late summer, which doesn't allow direct cross-city comparisons of temperature. However, our temperature analyses shows differences in within-city cooling trends in the two cities. In Montreal, green alleys provide a minimal cooling effect of 0.07°C on average during the day and a negligible cooling effect at night at 0.02°C on average, with some alleys showing the potential to cool more (up to 0.3°C). In contrast, green alleys in Trois-Rivières are providing a stronger cooling effect at night than those in Montreal, with a nighttime cooling average of 0.3°C. During the day in TR, green alleys are actually warmer than grey alleys by an average of 0.4°C. These differences are consistent with other studies, which show that open areas of herbaceous vegetation are warmer during the day and cooler at night than areas with higher levels of tree cover, reducing day-night differences (Li et al. 2025). The opposing day-night cooling patterns between the two cities highlights the influence of the differing management strategies across the two cities. Temperature and tree abundance specifically showed higher levels of variation in Montreal, where the green alley program is resident led. Alleys in Montreal have on average 13 trees but can have as few as 0 and up to 85. Similarly, green alleys in Montreal were both warmer and cooler than grey alleys, depending on the specific site. In Trois-Rivières, alleys typically have no trees, with a maximum of 6 and a minimum of 0 (Supplementary Materials C Figure S2). They were also consistently warmer than grey alleys during the day and cooler at night. The differences we found in levels of variation for ecosystem service provision highlight the advantages and disadvantages of the two governance strategies. The resident-led approach used in Montreal allows for a larger-scale proliferation of green infrastructure (Young 2011), while also providing a flexible approach that fully implicates residents in the project and adapts to their needs (Faehnle et al. 2014). However, this approach may not be feasible or advertised to low-income residents, exacerbating inequity (Mason et al. 2019). Long-term stewardship can be an issue in this model (Young 2011), and lack of technical expertise can lead to less efficient design (Brazeau-Béliveau and Cloutier 2021). By contrast, a municipally led program focuses more on ecological issues over resident experience, which can be effective at protecting ecological aspects of the system and implement projects in a more standardized and fair way but can isolate residents and be less effective at adapting to their needs (Faehnle et al. 2014).

A multifaceted approach to green infrastructure management is necessary if we want to provide both biodiversity support and ecosystem services. Our results show that biodiversity support and ecosystem services are distinct, an increase in one does not necessarily align with an increase in the other. However, there are many potential synergies between these two categories that can be managed for (Nassauer 1995). For example, we showed that green alleys in both cities had notably higher levels of native tree species and lower levels of invasive species compared to both grey alleys and sidewalks, which is an important form of biodiversity support.

Invasive and non-native species are a problem in cities, contributing to the decline of native species, overall ecosystem homogenization, and sometimes escaping into habitat outside the city limits (Hardberger et al. 2025). Historically, one issue with establishing native plant species is that they are often deemed less desirable by residents as they don't always have the same aesthetic features of non-natives (Hardberger et al. 2025). However, presence of native species in green alleys in our system indicates that native species may be more acceptable in an alley context. Additionally, the dominance of native trees in green alleys also likely provides more resources for pollinators and birds (Garland and Wells 2020), which were two additional ecosystem services desired by residents. Further, appreciating the odour and presence of flowers and flowering trees was an ecosystem service mentioned by residents as desirable (Supplementary Materials A, Table S4). Planting native flowering trees and shrubs can increase woody plant abundance, provide resources for pollinators and birds, decrease the proportion of invasive species, while increasing the biodiversity of the area (Garland and Wells 2020). This is a success for both biodiversity support and ecosystem services which can be highlighted and encouraged in the future.

We found many other synergies between the ecosystem services that residents desire, and attributes commonly considered part of a healthy functioning ecosystem. For example, the stated desire for large trees and habitat provision by residents are both features that support ecological functioning and biodiversity. Notably, most of our interview participants were highly educated, which may indicate that they have more knowledge about ecosystem functioning and biodiversity, potentially resulting in a biased list of ecosystem services that are unusually synergistic with support for biodiversity (Wojewódzka-Wiewiórska et al. 2022). Engagement with green infrastructure initiatives has a weak correlation with education level in Toronto and Philadelphia, supporting our finding (Conway et al. 2021). Further, level of education is often related to other axes of privilege such as health and race (Steele et al. 2007, James and Parekh 2021, Etindele Sosso et al. 2022), which may further influence how interview participants think about nature and therefore bias our results (Talal et al. 2021, Conway et al. 2021). Repeating more studies that include people with a range of education levels across multiple cities and assessing if the synergistic patterns between ecological benefits and ecosystem services hold would be beneficial to our understanding of this system. There is an abundance of literature that discusses the differences in resident perceptions and preferences between back and front yards, and the ecological implications of said differences (Kurz and Baudains 2012, Ossola et al. 2019b). Expanding that work to alleyways would be an important extension of the literature which could allow for more opportunities to deliver benefits to residents and the urban ecosystem generally.

Notably, many of the stated goals or desires of residents for green alleys can be achieved through pathways that are not tree related. This study focused on the biodiversity support and ecosystem service indicators provided by trees, but there were ecosystem services listed by residents as important – such as overall "greenness", food provisioning, and habitat provisioning for fauna (Table S4)– that would be better captured by assessing non-tree vegetation. We focused on trees as the city of Montreal includes tree planting as a desired outcome of green alleys (Ville de Montréal 2024), trees perform a disproportionate role in ecosystem services such as cooling

(Schwaab et al. 2021), and the presence of trees was highly desired by interviewees (Supplementary Materials A, Table S4). This was a limitation of our research in Trois-Rivieres especially, as the green alleys prioritized permeable pavement and had very few trees.

The framework of ecosystems services itself comes with limitations, including the challenge of translating cultural ecosystem services into measurable metrics (Cheng et al. 2019). With the exception of cooling, we focused on measuring ecosystem service indicators based in ecological metrics. Measuring ecosystem services with more direct, cultural indicators, linked to the perceptions and needs identified by residents would be a powerful extension of this work that would contribute to developing interdisciplinary methods and could improve the management and design of future projects. There is a need for future interdisciplinary research that focuses on measuring the biodiversity support and ecosystem services provided by other types of vegetation in green alleys, such as herbaceous plants, and faunal surveys for pollinators, birds, and other taxa of interest.

Our study is a beginning step in advancing our knowledge on monitoring a poorly understood type of green infrastructure, green alleys. Although there have been some surveys of the biodiversity support and ecosystem services provided by green alleys (Coseo and Larsen 2015, Dade et al. 2024), they are nowhere near as comprehensively studied as other types of green infrastructure such as urban parks or green roofs. Our work was focused on answering fundamental, straightforward green alleys are difficult to study due to their unique form, where vegetation and management can be highly variable even within the same alley and goals for the green alley may vary widely from one to the next (Dade et al. 2024). Our study emphasizes the importance of future work in this field to address the nuances and complexities we touched on in our study. We believe that using approaches that incorporate multiple data types and approaches, such as combining resident interviews and knowledge with ecological fieldwork as we did for this study, can help provide a framework for social-ecological work that results in meaningful indicators and biodiversity studies (van Oudenhoven et al. 2018; Schröter et al. 2021). Extensions of this work that focus on scale would also be highly valuable. At the scale of single alleys, we found a minimal effect of cooling. However, assessing cooling in such a small and varied area is a challenge, and green alleys may have more of an effect on cooling if they are treated as a network, using a mixed approach to promote and assess cooling alongside other benefits at a neighbourhood scale. Using a combination of our knowledge as ecologists, social scientists, and local experts, i.e., residents, we were able to conduct surveys that were relevant for both human and non-human residents of alleys. Using this work, we can continue to build and expand our surveys so that we have a more complete picture of what benefits green alleys are providing in our cities and build better green alleys that serves both other forms of nature and people in the future.

2.5 Conclusion:

Green alleys are an increasingly popular type of green infrastructure in cities, with potential to provide benefits for nature and people. We found that green alleys are indeed capable of providing both biodiversity support and ecosystem services, although they do not always do so and currently provide relatively more biodiversity support. We showed that biodiversity support and ecosystem services are not necessarily provided at the same time, though they can be

synergistic depending on the needs of residents, indicating that small-scale green infrastructure often has context-specific outcomes. Another main finding was that governance of green alleys shapes the amount of variation in biodiversity support and ecosystem services. The community-based management of green alleys in Montreal resulted in higher variation in temperature and tree abundance. The municipal-based "one size fits all" approach of Trois-Rivières resulted in less variation and more nighttime cooling, but also a lower abundance of trees, which were listed as an important provider of ecosystem services by residents. Designing green alleys to meet the needs of both human and non-human residents requires asking people what they need, allowing communities to lead the design and implementation of these green infrastructure projects, and providing technical and expert support to allow communities to reach their goals.

2.6 Tables & Figures

Table 2.1: Summary statistics of the measures of interests across both cities. Standard deviations are presented with means.

Index	**Villeray-Saint Michel-Parc Extension**	**Trois-Rivières**
Number of sites (all types)	100	26
Biodiversity support		
Average canopy cover	33 ± 21 %	18 ± 18 %
Tree species richness	70 total species	22 total species
Number of functional groups (trees)	9/9	5/9
Average proportion of native trees	61 ± 30 % trees native	75 ± 50 % trees native
Average proportion of invasive trees	14 ± 21 % trees invasive	21 ± 42 % trees invasive
Average vegetative complexity	1.40 levels / sampling point	1.31 levels / sampling point
Firefly presence	12/54 sites with fireflies	NA
Ecosystem service indicators		
Average daytime temperature	24.4 ± 3.6°C	20.3 ± 4.9°C
Average nighttime temperature	21.9 ± 2.5°C	16.3 ± 4.1°C
Total tree abundance	1,371 total trees	16 total trees
Average # trees / site	13 ± 13 trees	0 ± 1 tree
Average diameter at breast height (DBH)	19.3 ± 17.2 cm	21.2 ± 17.2 cm
Average potential maximum height	14.0 ± 1.3 m	14.4 ± 2.8 m
Average proportion of flowering trees	22 ± 25 % flowering trees	4 ± 8 % flowering trees

Table 2.2: Model contrasts for biodiversity support models. Model name refers to response variable in the model, city refers to the city where the data was collected, contrast indicates the groups contrasted for each row where 'Green' refers to a green alley, 'Grey' refers to a grey alley, and 'Street segment' refers to street segment class, also referred to as street segment, global mean is the mean difference between the groups after a pairwise contrast was performed on the entire posterior distribution of each group, lower credible interval shows the lower 95% credible interval of the contrast, higher credible interval shows the higher 95% credible interval of the contrast, and units represents the output units of the model/contrast. For each contrast, the global mean value presents the average impact of an intervention where you switch from the state on the right (e.g., grey alley) to the state on the left (e.g., green alley) with the units provided.

Model	City	Contrast	Global Mean	Lower Credible Interval	Higher Credible Interval	Units
Canopy Cover	VSMPE	Green - Grey	-11.8	-19.2	-3.2	% canopy cover
Canopy Cover	VSMPE	Green - Street segment	-18.2	-24.4	-11.6	% canopy cover
Canopy Cover	TR	Green - Grey	0.6	-11.3	11.5	% canopy cover
Canopy Cover	TR	Green - Street segment	7.2	-4.5	20.2	% canopy cover
Firefly Presence/ Absence	VSMPE	Green - Grey	2.5	-13.6	19.3	% chance of firefly presence
Firefly Presence/ Absence	VSMPE	Green - Street segment	4.9	-15.0	23.0	prob. of firefly presence
Tree Species Richness	VSMPE	Green - Grey	0.18	-0.97	1.30	# tree species
Tree Species Richness	VSMPE	Green - Street segment	-0.79	-1.87	0.55	# tree species
Tree Species	TR	Green - Grey	0.00	-0.11	0.10	# tree species

Model	City	Contrast	Global Mean	Lower Credible Interval	Higher Credible Interval	Units
Richness						
Tree Species Richness	TR	Green - Street segment	0.00	-0.14	0.13	# tree species
Functional Tree Diversity	VSMPE	Green - Grey	0.19	-0.27	0.77	# functional groups
Functional Tree Diversity	VSMPE	Green - Street segment	-0.39	-0.88	0.12	# functional groups
Functional Tree Diversity	TR	Green - Grey	0.00	-0.12	0.14	# functional groups
Functional Tree Diversity	TR	Green - Street segment	0.00	-0.19	0.18	# functional groups
Average Vertical Complexity	VSMPE	Green - Grey	0.15	-0.09	0.39	# avg. levels of complexity
Average Vertical Complexity	VSMPE	Green - Street segment	0.31	0.13	0.49	# avg. levels of complexity
Average Vertical Complexity	TR	Green - Grey	0.20	-0.05	0.45	# avg. levels of complexity
Average Vertical Complexity	TR	Green - Street segment	0.31	0.02	0.61	# avg. levels of complexity
Proportion Native	VSMPE	Green - Grey	19.0	9.0	28.5	% native tree species

Model	City	Contrast	Global Mean	Lower Credible Interval	Higher Credible Interval	Units
Tree Species						
Proportion Native Tree Species	VSMPE	Green - Street segment	20.8	15.3	26.9	% native tree species
Proportion Native Tree Species	TR	Green - Grey	4.8	-13.3	23.6	% native tree species
Proportion Native Tree Species	TR	Green - Street segment	20.9	-4.9	47.2	% native tree species
Proportion Invasive Tree Species	VSMPE	Green - Grey	-11.3	-19.7	-3.8	% invasive tree species
Proportion Invasive Tree Species	VSMPE	Green - Street segment	-5.4	-9.6	-1.0	% invasive tree species
Proportion Invasive Tree Species	TR	Green - Grey	-3.9	-19.6	14.5	% invasive tree species
Proportion Invasive Tree Species	TR	Green - Street segment	-17.0	-42.9	7.2	% invasive tree species

Table 2.3: Model contrasts for ecosystem service indicator models. Model name refers to response variable in the model, city refers to the city where the data was collected, contrast indicates the groups contrasted for each row where 'Green' refers to a green alley, 'Grey' refers to a grey alley, and 'Street segment' refers to street segment class, also referred to as street segment, global mean is the mean difference between the groups after a pairwise contrast was performed on the entire posterior distribution of each group, lower credible interval shows the lower 95% credible interval of the contrast, higher credible interval shows the higher 95% credible interval of the contrast, and units represents the output units of the model/contrast. For each contrast, the global mean value presents the average impact of an intervention where you switch from the state on the right (e.g., grey alley) to the state on the left (e.g., green alley) with the units provided.

Model	City	Contrast	Global Mean	Lower Credible Interval	Higher Credible Interval	Units
Tree Abundance	VSMPE	Green - Grey	1.09	-2.75	4.37	# trees
Tree Abundance	VSMPE	Green - Street segment	0.73	-3.65	4.56	# trees
Tree Abundance	TR	Green - Grey	-0.05	-0.18	0.09	# trees
Tree Abundance	TR	Green - Street segment	-0.07	-0.29	0.12	# trees
Mean DBH	VSMPE	Green - Grey	-3.9	-8.9	1.8	mean DBH (cm)
Mean DBH	VSMPE	Green - Street segment	-13.1	-17.5	-8.4	mean DBH (cm)
Mean DBH	TR	Green - Grey	0.7	-14.9	16.7	mean DBH (cm)
Mean DBH	TR	Green - Street segment	-2.3	-22.8	19.2	mean DBH (cm)
Mean Maximum Height	VSMPE	Green - Grey	-0.73	-1.89	0.33	mean max height (m)
Mean	VSMP	Green -	-1.88	-2.86	-0.88	mean max

Model	City	Contrast	Global Mean	Lower Credible Interval	Higher Credible Interval	Units
Maximum Height	E	Street segment				height (m)
Mean Maximum Height	TR	Green - Grey	1.37	-1.16	3.48	mean max height (m)
Mean Maximum Height	TR	Green - Street segment	1.41	-1.86	3.85	mean max height (m)
Proportion Flowering Trees	VSMPE	Green - Grey	7.8	0.0	16.2	% flowering trees
Proportion Flowering Trees	VSMPE	Green - Street segment	0.0	-4.7	5.2	% flowering trees
Proportion Flowering Trees	TR	Green - Grey	2.5	-16.4	20.5	% flowering trees
Proportion Flowering Trees	TR	Green - Street segment	5.8	-17.9	29.5	% flowering trees

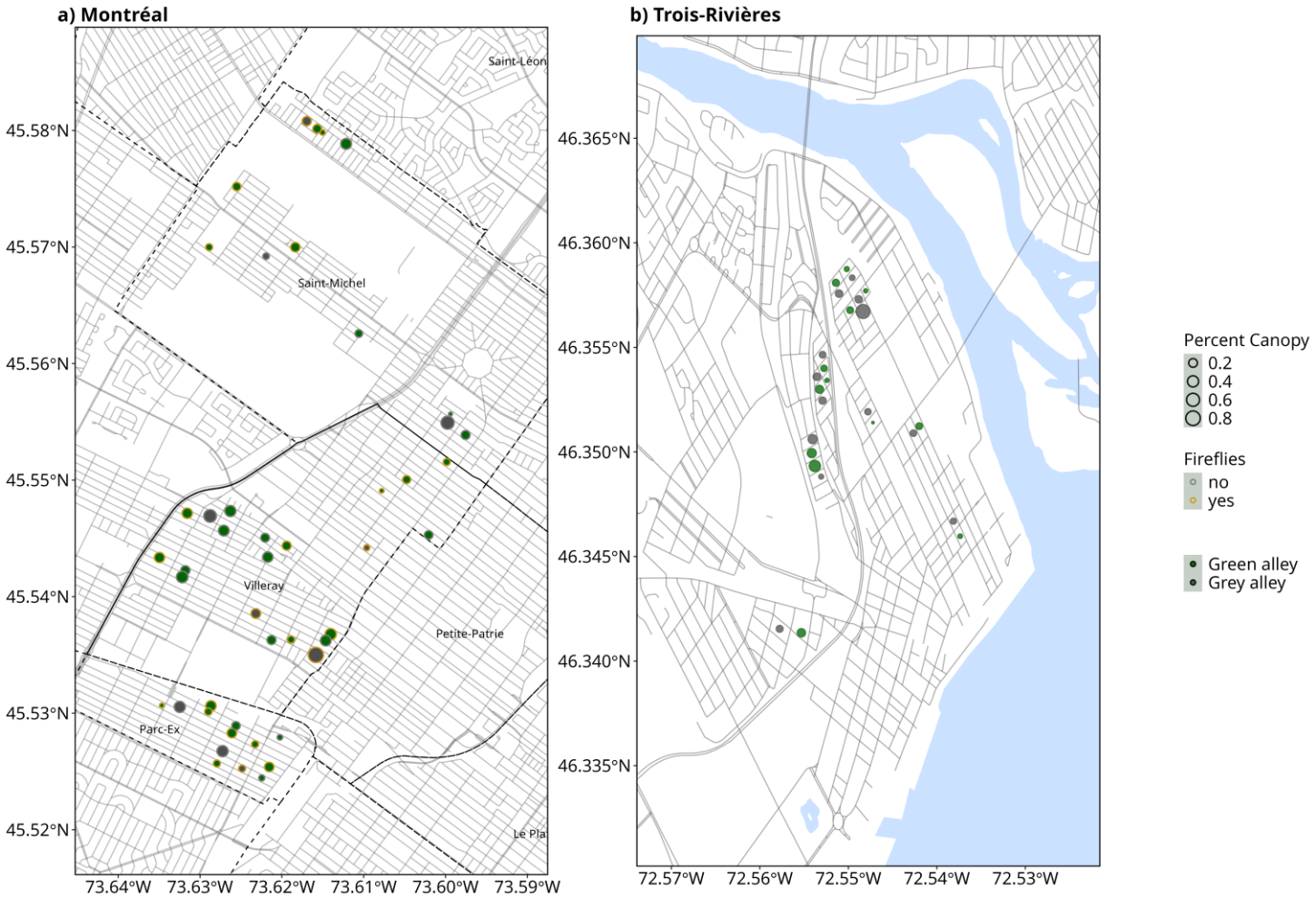


Figure 2.1: Map representing study areas in a) Montréal and b) Trois-Rivières. Each dot represents an alley included in the study, with green dots representing green alleys and grey dots representing grey alleys. A yellow outline on the dot indicates that we surveyed the alley for fireflies (Montréal only). Dot size corresponds to percent canopy cover of the alley. Light grey lines represent roads, black dashed lines represent neighbourhood boundaries. Figure created using sf, ggplot2, and osmdata packages (Padgham et al. 2023, Wickham et al. 2024, Pebesma et al. 2024).

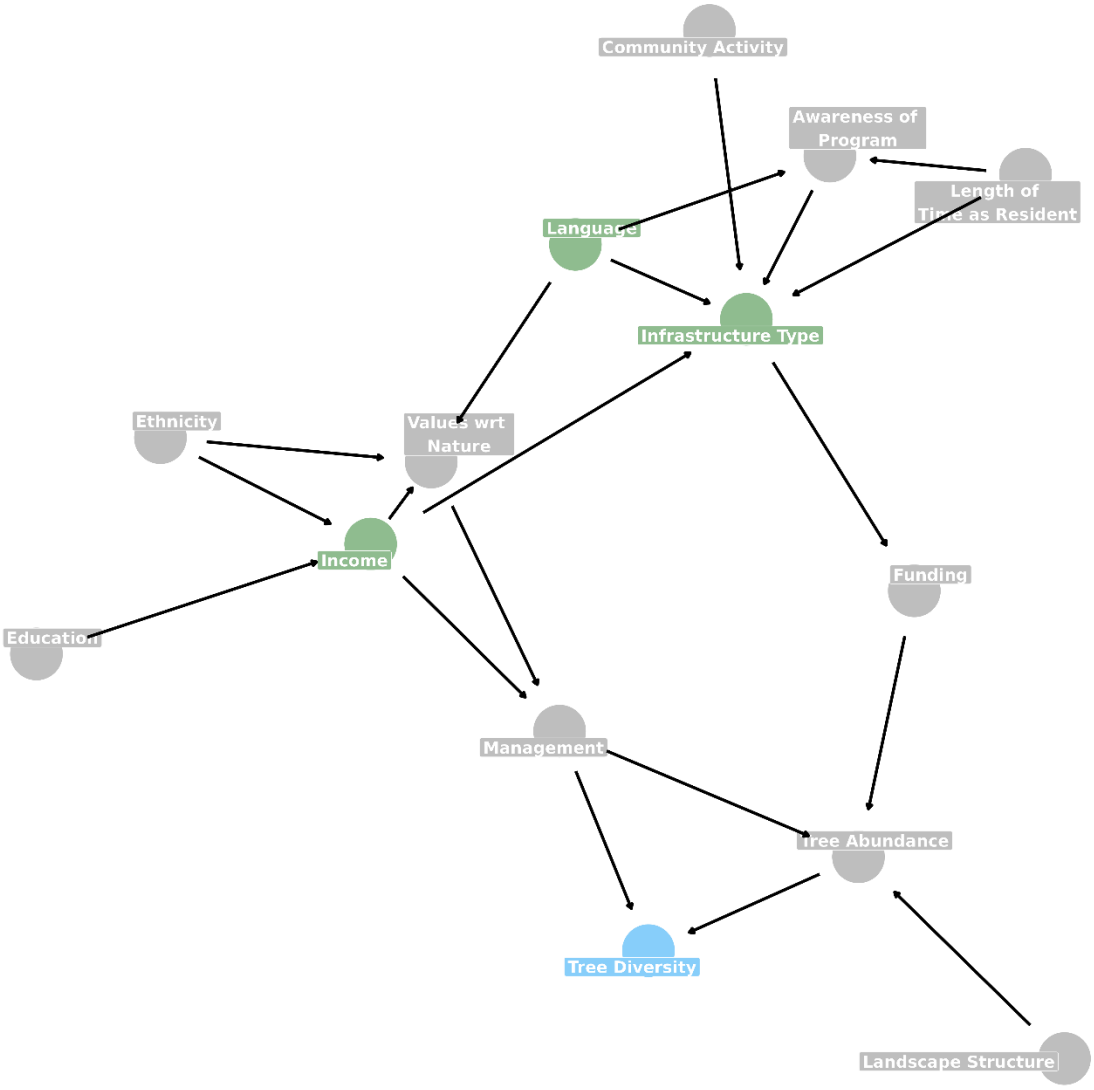


Figure 2.2: Example of a directed acyclic graph (DAG) depicting our hypothesized and assumed causal relationships between variables in our system for Villeray—Saint-Michel—Parc-Extension's resident-led green alley program. The variable highlighted in blue is the outcome variable. Infrastructure type is the variable that we want to test the effect of and is in green. Other variables that are required in the model to deconfound our model, i.e., income and language, are highlighted in green. Figure created using ggdag and ggplot2 (Wickham et al. 2024, Barrett 2024).

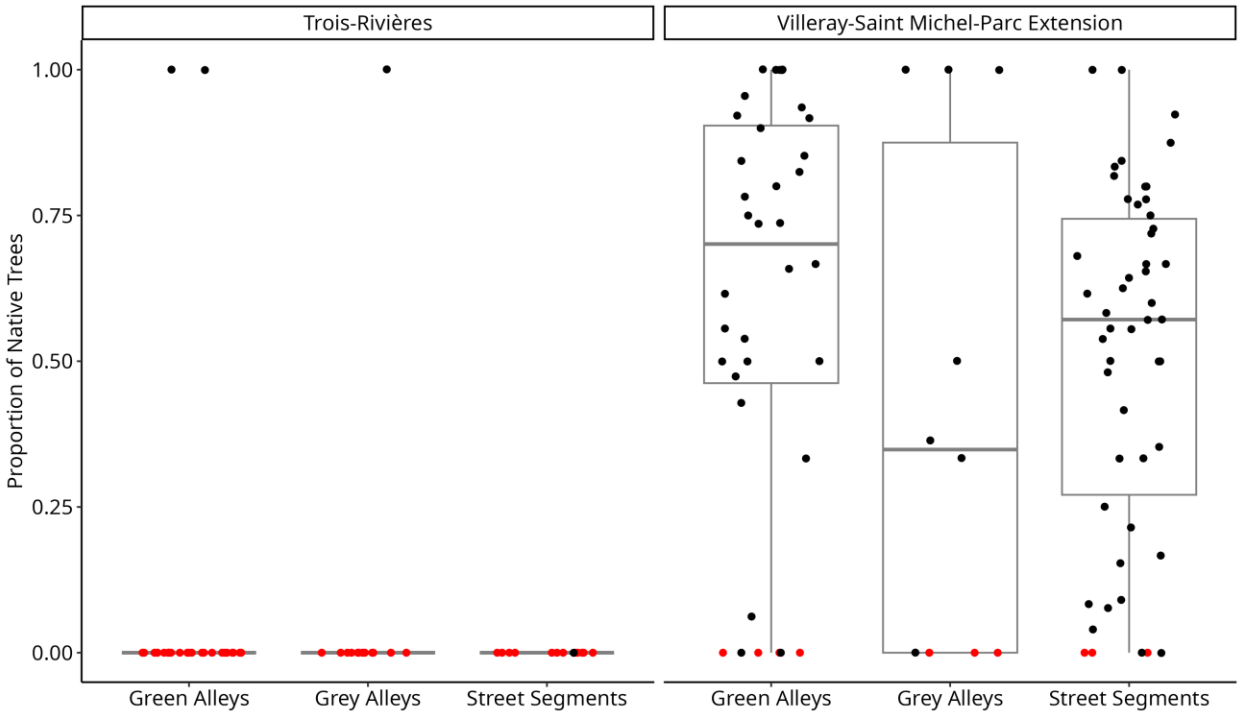


Figure 2.3: Proportion of native trees at each site measured. Boxplots depict the median for each infrastructure type, as well as the 25th and 75th percentiles. Red points indicate sites where there were 0 trees overall. Statistical differences between the infrastructure types for each city can be found in Table 2.

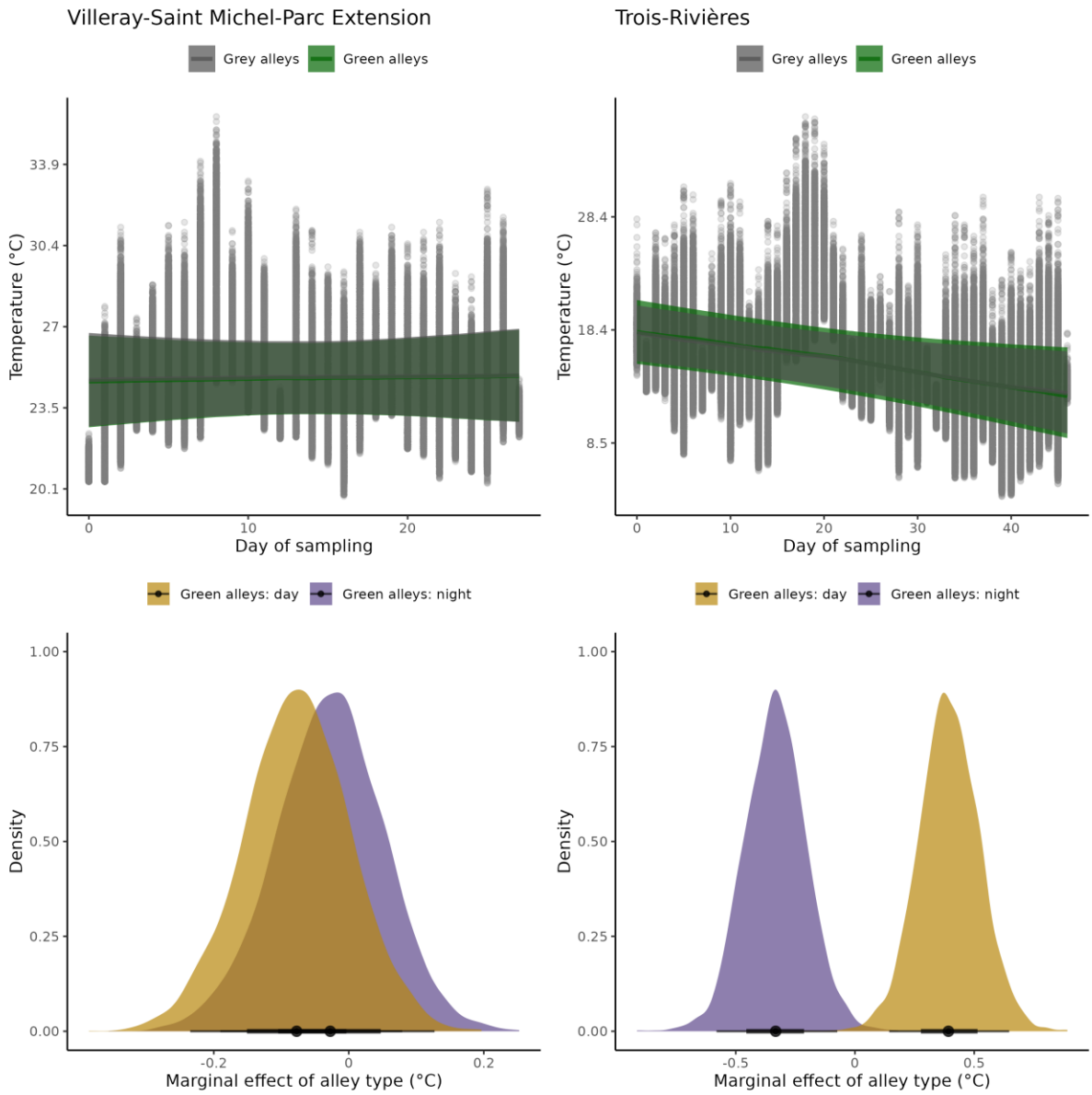


Figure 2.4: Effects of alley type on temperature. The left column presents the results for Villeray-Saint Michel-Parc Extension (VSMPE) and the right column presents the results for Trois-Rivières. The top row is displaying the model's fit between the day of sampling on the x-axis and temperature on the y-axis. Each line indicates a different green infrastructure type, with green displaying green alleys and grey displaying grey alleys. The band surrounding the regression line is the 95% credible interval of the model. Each dot on the graph indicates an individual temperature recording from one of the sites. Temperature was measured from June 28 to July 25 in VSMPE and from August 8 to October 3 in Trois-Rivières. The bottom row presents model contrasts for each city, where pairwise comparisons were performed on the posterior distributions. For each contrast, the black dot represents the global mean value, i.e., the average impact of an intervention on temperature when you switch from a grey alley to a green alley during that time of day. The black lines represent the 95% credible interval, and the coloured area is the posterior distribution of the contrast.

IV. Chapter 3: *Predictors of land-surface temperature and air pollution across Canadian cities are largely scale and city dependent*

Abstract:

Problems of urban heat and air pollution have been increasing in Canadian cities over the past several decades. The distribution and level of temperature and air pollution are directly tied to the structure of cities, including aspects of vegetation, urban form, and sociodemographics. There are currently few studies that investigate patterns of urban heat and air pollution across multiple cities and/or scales in Canada, particularly incorporating elements of vegetation. To address that gap, we use open-source data to predict patterns of temperature and air pollution within and across seven Canadian cities varying in geography and population size. Our goal is to identify the extent to which widely accessible metrics of vegetation, urban form, and sociodemographic variables predict temperature and air pollution. We are also particularly interested in the relative contributions of street trees due to their large contributions to the urban forest and provision of ecosystem services. We implemented random forest modelling and identified the important predictors and their relationships with temperature and air pollution metrics at the street, neighbourhood, and city scales. We found that there are very few generalizable patterns, with most important predictors unique to the response variable and scale. This emphasizes the importance of context dependent management and local expertise for predicting and understanding urban heat and air pollution. However, inequity was an important predictor of temperature and nitrogen dioxide at the city scale. This large-scale trend across Canadian cities indicates that inequity may be a serious problem across our cities and we should take large-scale approaches to dealing with issues of inequity. Additionally, street tree variables appear as important predictors of temperature at the city scale and of temperature and ozone at the neighbourhood scale. At the neighbourhood scale, both ozone and temperature are best predicted by street-tree related variables. These findings indicate that street trees are an important factor when predicting environmental conditions, despite comprising only a small portion of the urban forest. As one of few cross-city and cross-scale studies of its kind in Canada, our findings highlight the need for improved datasets and data accessibility. Our work demonstrates important patterns when predicting land-surface temperature and air pollution across Canadian cities, generating research questions for future investigation, and providing decision-makers in Canada with more information about our cities.

3.1 Introduction:

Across Canada, urban heat is intensifying, with heat waves from coast to coast resulting in thousands of hospitalizations and deaths (BC Coroners 2021, Boudreault et al. 2024). Air pollution is also a serious problem, resulting in the premature deaths of thousands of Canadians each year (Health Canada 2016, HouseFresh 2025). As urban heat and air pollution get worse, cities have been increasingly trying to understand these processes and find solutions due to their serious consequences for urban residents (Zhao et al. 2018, HouseFresh 2025). These issues are caused in part by the design of our cities, where modern Canadian cities have high densities of impervious surfaces and pollutant producing activities, which results in a decrease in the health and well-being of residents (Wu 2014).

Cities are complex ecosystems, with many variables influencing their environmental conditions (Gaston et al. 2013). Three broad categories of variables that impact exposure to both

urban heat and air pollution in cities include the composition and configuration of vegetation (hereafter referred to as “ecological form”), urban form, and resident composition, such as income, race, immigration status, housing, and education (hereafter referred to as "sociodemographics", Schell et al. 2020, Wang et al. 2024a). Many of the best predictors of both temperature and air pollutants are known, because the mechanisms behind urban heat and air pollution are generally understood. Temperature in cities increases with increased impervious surface due to the absorption and reemitting of solar radiation and can be lowered by increasing vegetation cover which blocks solar radiation and cools through transpiration (Stone 2005, Ziter et al. 2019, Richards et al. 2020). Therefore, urban temperature and specifically land surface temperature, can be predicted using daily weather conditions, land cover/use patterns, and the configuration of impervious and vegetative surfaces (Deilami et al. 2018). Vehicle traffic, land use, building configuration, and daily weather conditions are key predictors of CO, NO2, and O3, in cities. CO and NO2 are both produced by combustion engines, though levels can be affected by wind speed which is in turn affected by building and road configuration (Owen et al. 2000, Zhou and Sperling 2001, Mukherjee and Viswanathan 2001, Nigam et al. 2010, Eeftens et al. 2019). Much of ground-level O3 (i.e., ozone) found in cities is produced through chemical reactions between NO2, volatile organic compounds, and sunlight and can be transported long distances by wind (Fusco and Logan 2003, Vingarzan 2004). SO2 is produced by burning fossil fuels and in the Canadian context can be tied to industrial processes and weather conditions (Thi Nguyen and Kim 2006, Akkoyunlu et al. 2010, Environment and Climate Change Canada 2022). The UV aerosol index measures aerosol particles that absorb UV, including potentially dangerous aerosols such as dust and smoke and can also be used to better predict PM2.5 levels (Falah et al. 2023). Predicting these data is dependent on the type of particles captured.

In Canada, types of data required to best predict urban heat and air pollution are not always available or comparable across different cities and/or scales. However, we do know that ecological form, urban form, and resident composition can influence and predict heat and air pollution in some conditions. Additionally, there is increasing interest in using and developing street tree indices that are available across the country via urban tree inventories. We don’t currently know how useful tree inventory data are for many research questions and applications. Therefore, identifying which widely accessible variables are important predictors, and understanding how these predictors may change across cities and scales can help us identify the utility of these data in predictive models in the current context and identify areas for data collection in the future.

Trees and the urban forest are a major part of the ecological form of cities and are widely recognized as potential solutions to issues of urban heat and air pollution (Andersson-Sköld et al. 2015, Kroeger et al. 2018). Cities across North America and the world have invested billions of dollars since the 1980s into urban forestry management plans and tree planting projects, aiming to increase urban canopies and benefits provided by trees (Endreny et al. 2017, Parajuli et al. 2022). In the past decade, Canadian cities across the country have become even more focused on tree planting (Ordóñez Barona et al. 2024), emphasizing the value of these themes in municipal management. Many cities view the urban forest as a main pillar of their strategy to improve the resilience of their cities against climate change, and to improve the quality of life for urban

residents in a variety of ways (Young and McPherson 2013). As part of this trend, there are departments in many Canadian cities dedicated to ecological transition and urban forestry (e.g., City of Toronto 2017, Ville de Montréal 2025). Scientific research in urban forestry has also been increasing alongside these trends since the 1990s (Coleman et al. 2022). However, most studies to date that evaluate the effects of urban green infrastructure focus on describing the effects at a single spatial scale and/or city, with a strong bias towards large cities (Ziter 2016, Kendal et al. 2020). Many of these studies produce measurements at a single local scale and while these studies are highly valuable, we currently lack research that identifies the extent to which effects of the urban forest on issues such as urban heat or air pollution are generalizable across cities and regions (but see Landry et al. 2020, Galle et al. 2021 for multi-city approaches). Given that the urban forest is a key strategy in addressing many of our cities' challenges, identifying if urban forest metrics are useful predictors of urban heat and air pollution is an important step in highlighting gaps that may currently exist in our understanding of the utility of these metrics, the power of modeling, and in urban forest datasets as whole.

Both urban forest composition and structure can impact the levels of urban heat and air pollution in a city (Table 3.1). Trees have a disproportionately large capacity to shape environmental conditions compared to other vegetation types, especially when considering their ability to cool their surroundings and change the level of air pollutants (Schwaab et al. 2021). Tree composition (i.e., species diversity) and structure (i.e., abundance and size) both contribute to cooling the environment through two mechanisms, shade and evapotranspiration (Oke et al. 1997, Livesley et al. 2016, Table 3.1). Similarly, there is evidence that the structure and composition of trees have an impact on air pollution levels through particulate deposition and absorption, though the direction and magnitude of the effect remain uncertain and can change across spatial scales (Table 3.1, Pataki et al. 2021). Street trees specifically are selected and managed by municipal governments to augment the city's canopy cover to provide benefits to residents such as temperature and pollution mitigation (Conway and Vander Vecht 2015). Street trees are only one component of the urban forest (Pataki et al. 2013). However, because they are so well documented and play an important role in urban planning, identifying the relative contribution of street tree related variables to predicting changes in urban heat and air pollution levels across Canadian cities provides information that is valuable for both municipal governments and urban residents.

Urban form, defined here as the composition and structure of roads, buildings, and other man-made structures within a city's borders, has an undeniably large impact on the environmental conditions of a city (Table 3.1). Due to the nature of urban design in North American cities, specifically the predominance of concrete as a building material, built infrastructure typically causes an increase in urban temperature and air pollution (Table 3.1, Stone 2005, Ziter et al. 2019). However, there are trade-offs that occur in these relationships, especially when relating to the urban forest. For example, tall buildings increase impervious cover generating heat, however, they can also provide shade that results in a decrease in daytime temperature, while simultaneously decreasing the cooling efficacy and health of street trees (Table 3.1, Labrecque et al. 1993, Coutts et al. 2016, Yang et al. 2020a, Alonzo et al. 2021). Given that urban form is the foundation of our cities, understanding which aspects of urban form

contribute the most to predicting temperature and air pollution, and understanding their interactions with the contributions of the urban forest will allow us to improve our design and management of predictive models moving forward.

Underlying the structure and composition of both urban form and the ecology of our cities, is the sociodemographic context of our cities (Table 3.1, Schell et al. 2020). Due to historical and ongoing environmental injustice, the structure of our cities reflects the systemic injustice present in our society (Alexander 1992, Ture and Hamilton 1992, Calmore 1997, Powell 2008, Goetz et al. 2020). Across Canada, neighbourhoods with populations dominated by recent immigrants, racialized people, and low-income residents have less vegetation, a lower diversity of trees, higher building and population density, and a higher prevalence of large roads and highways (Tooke et al. 2010, Pham et al. 2013, Landry et al. 2020). Consequently, we also find that neighbourhoods dominated by high-income white people are typically greener, more diverse, and have a lower building and road density (Gerrish and Watkins 2018, Watkins and Gerrish 2018). Environmental injustice across Canada is increasingly well documented (Giang et al. 2022) but much of the urban-focused work to date has been done in cities in the United States where the history of redlining and Jim Crow era urban planning laws has resulted in a very distinct pattern of inequitable environmental conditions (United Church of Christ 1987, Nowak et al. 2022). The relationships between systemic injustice and urban environmental conditions remain less described in Canadian urban areas (Giang et al. 2022). Given these conditions of environmental inequity, revealing predictive patterns and the relative contributions of sociodemographic conditions as related to the prediction of urban heat and air pollution levels in the Canadian context is a key contribution to our cultural understanding of our cities and urban management.

Predicting heat and air pollution is relevant at multiple scales, as heat and air pollution affect people at local, neighbourhood, and landscape levels and consequently, intervention and management occur at many scales (Kumar et al. 2024, Ji et al. 2025). For example, temperature regulation on the street-scale is partially driven by the crown shape of individual trees and thus managing urban heat on a street scale may require specific goals with respect to planting species with specific crown shape and size (Wang et al. 2023a). However, at the neighbourhood scale temperature regulation may be more highly influenced by the density of all the trees in the area and therefore require goals related to overall greenness and abundance of vegetation (Wang et al. 2023a). Municipal governments implement management plans at the neighbourhood and city-wide scales, while also taking direction and funding from provincial and federal policies (Taylor and Bradford 2020). Simultaneously, individual local projects may happen at a street or parcel scale (Taylor and Bradford 2020). To provide appropriate advice and recommendations for future research, we need to understand the contributions of our variables of interest at the scales at which different management interventions occur, including whether these patterns are generalizable across different cities. This means performing studies across spatial scales using comparable data and methods at fine, medium, and large scales, which is not often done.

Here we combine a multi-scale and cross-city approach to identify variables that are important predictors of temperature or air pollution at only one scale or in one city (i.e., unique

predictors) and variables that are important predictors across scales and cities (i.e., general predictors). Our study assesses multiple Canadian cities to provide evidence of key predictor variables for urban temperature and air pollution across Canada, to inform future research, city planning, and management. We ask:

1. What is the relative contribution of street trees to predicting urban heat and air pollution at different scales when compared to urban form and sociodemographics?

2. What are the relationships between important predictors of temperature and air pollution in different cities and across different scales?

To assess the influence of various ecological form, urban form, and sociodemographic variables on urban heat and air pollution levels we frame our results in terms of unique vs general predictors. We expect unique predictors to be specific to individual cities and influence services on a specific spatial scale (i.e., street, neighbourhood, city). For example, the proportion of recent immigrants may not be a good predictor in all cities, as some Canadian cities have much fewer recent immigrants than others (Table A3.1). We define general predictors as processes that influence urban heat or air pollution across cities and scales. For example, we would hypothesize that tree size distribution is a good predictor of temperature, regardless of which city or at what scale we are investigating (Wang et al. 2023a).

3.2 Methods:

3.2.1 Study Areas

We studied seven cities across Canada. Our selected cities varied in population size (500,000 to 2.79 million residents), spanned the geography of the country (approximately 6,000 km), had publicly accessible public tree inventories, and temperate climates (Figure 3.1A, city descriptions in Table A3.1, Figure A3.1). Our selected cities included Halifax, Montreal, Ottawa, Toronto, Winnipeg, Calgary, and Vancouver. These cities are spread across the country from the west coast to the east coast, representing five ecozones including Atlantic Maritime (Halifax), Mixedwood Plains (Montreal, Ottawa, Toronto), Boreal Plains (Winnipeg), Prairies (Calgary), and Pacific Maritime (Vancouver).

Halifax has the lowest population density of included cities, with low building and road density. Overall greenness (i.e., NDVI) is high, though public tree density is lowest of all cities. Residences are dominated by single family homes, and the city has low median incomes, percentage of residents who are recent immigrants, and percentage of residents who are visible minorities. Montreal is the second largest city in terms of population. It has the highest population density at the street level, and residences are dominated by small (i.e., 2-4 story) apartment buildings. It has low overall greenness, with mid-level public tree density. Montreal has low median incomes, with mid-level percentages of recent immigrants, visible minorities, and highly educated people. Ottawa has a very large area and low population density, with high overall greenness. Public tree density and species richness are low. Most residences are single family homes, with some row homes. It has the highest median income of all cities, with low percentages of recent immigrants and visible minorities. Toronto is the city with the highest overall population and population density at the city and neighbourhood levels. Public tree density, diversity, and size are high. The population is highly educated, with a high percentage of

visible minorities and a mid-level median income. Overall, most residents live in large (i.e., > 5 storey) apartment buildings, but many streets are dominated by single family homes. Winnipeg has low population density, with a large majority of residences being single family homes. Overall greenness was mid-level, with public tree density being mid-low and tree diversity the lowest of all cities. Mean tree size is large overall. Median income is low, with the highest percentage of Indigenous residents of any city, a high percentage of recent immigrants, and a low percentage of highly educated residents. Calgary has low population density, high building and road density, and low overall greenness. Public tree diversity and size are both low. Large majority of homes are single family homes. Calgary has the highest median income of all cities and a high percentage of recent immigrants. Vancouver has the smallest city area and mid-level population density. Overall greenness is mid-level, but it has the highest public tree density, diversity, and size. Housing is split across single detached homes, large apartment buildings, and small apartment buildings. It has the highest percentage of highly educated residents and visible minorities, with mid-level median incomes.

3.2.2 Spatial Scales

We evaluated the relationships between predictor variables and urban heat and air pollution at multiples scales for each city. The scales included city, neighbourhood, and street scale. Dissemination area boundaries produced for the 2021 census and street tree inventories produced by each municipality were downloaded for all cities (Table A3.2, Government of Canada 2021, City of Calgary 2025, City of Ottawa 2025, City of Toronto 2025, City of Vancouver 2025a, City of Winnipeg 2025, Halifax Regional Municipality 2025, Ville de Montreal 2025). Street tree data is generally incomplete and not available for entire municipal regions. To address this, we intersected the dissemination areas with the street tree inventories so that only dissemination areas that contained street tree data were included. We then amalgamated all dissemination areas that included street tree data to create the city boundaries that we used in subsequent analyses (Figure 3.1B). We obtained neighbourhood boundaries individually for each city, using municipally produced boundaries that delineate neighbourhoods at the level of management (City of Calgary 2025b, City of Ottawa 2025b, City of Toronto 2025b, City of Vancouver 2025b, City of Winnipeg 2025b, Halifax Regional Municipality 2025b, Ville de Montreal 2025b). We then intersected neighbourhood boundaries with street tree data, keeping neighbourhoods only if they had street tree data present (Figure 3.1C). For the street scale we used the 2024 Road Network File produced by Statistics Canada (Statistics Canada 2024). We first intersected the roads with our city boundaries, then produced a 25 m buffer surrounding each road segment. Finally, we intersected the road segment buffers with street tree data and included only roads that had street trees present in the 25 m buffer (Figure 3.1D).

3.2.3 Urban Heat

We used land surface temperature measured using the Landsat 8 satellite to assess urban heat levels (USGS and NASA 2024). We filtered images to those taken between June 1 and August 31, 2024 to select for dates where heat is highest and vegetation has completed leaf out in our study regions. Following date filtering and after providing our geometries of interest, we used the code and methodology laid out in Ermida et al. (2020) to cloud mask and calculate mean land surface temperature values at each of our spatial scales in Google Earth Engine (Gorelick et al. 2017).

For each date, the land surface temperature of every pixel that had its centroid overlap our area of interest (i.e., each street, neighbourhood, and city) was used to calculate the mean temperature for that area. Because an image may not perfectly overlap our area of interest, i.e., an image only covers 25% of a neighbourhood, we then estimated the coverage of the image for our area of interest (Figure A3.2). We summed the number of pixels used to calculate the mean temperature and then multiplied that by the resolution of the pixel (900 m2, or 30 m x 30 m) to get the approximate area of the pixels. We then divided the area of the pixels by the area of the area of interest, e.g., neighbourhood, to estimate the coverage. We only kept that date's value if the coverage was over 50% of the city's boundary, over 50% of the neighbourhood's boundary, and 100% of the street's boundary.

3.2.4 Air Pollution

We used levels of UV, carbon monoxide (CO), tropospheric nitrogen dioxide (NO_2), ozone (O_3), and sulphur dioxide (SO_2) provided by the Sentinel 5P satellite's TROPOMI instrument to assess urban air pollution levels (European Union et al. 2024a). The UV aerosol index reflects the presence of UV absorbing particulates in the atmosphere, which are related to aerosol plumes caused by dust outbreaks and wildfire smoke (Google Earth Engine 2025). A positive value reflects the presence of these aerosols. Because of the large resolution (3.5 x 7 km2) of this satellite, we only calculated air pollution levels at the city and neighbourhood scales. Following the same process as for land surface temperature, we filtered images to those taken between June 1 and August 31, 2024 with less than 10% cloud cover. We then calculated the mean value of each pollutant for each of our areas of interest. For each date, we then filtered the images based on coverage with the same methodology as we used for land surface temperature. However, coverage of neighbourhoods had to be 100% instead of the 50% cutoff for land surface temperature due to the larger resolution of the images.

3.2.5 Ecological Form Variables

We used street tree inventories published by each individual city to assess our ecological metrics (Table A3.2, Government of Canada 2021, City of Calgary 2025, City of Ottawa 2025, City of Toronto 2025, City of Vancouver 2025a, City of Winnipeg 2025, Halifax Regional Municipality 2025, Ville de Montreal 2025). We then cleaned each dataset so that scientific names matched, typos were corrected, and any trees that were not street trees (i.e., park trees, which are only included in some city inventories) were filtered out of the dataset. For Halifax, Toronto, and Ottawa we had to download supplementary files to convert the species codes provided in the tree inventory to true species names (City of Halifax 2021a, City of Ottawa 2021, City of Toronto 2021). Additionally for Halifax, we downloaded a supplementary file to convert the tree size codes into true DBH (diameter at breast height) values (City of Halifax 2021b). All cultivars were collapsed to the species level and hybrids were considered species.

3.2.5.1 Street Tree Density – We calculated density using basal area and stem density. After calculating the basal area of each tree, we summed the tree basal areas and divided by the area of interest to get the tree density via basal area. We summed all the stems recorded in an area of interest and then divided them by the area of interest to obtain number of stems/km^2.

3.2.5.2 Street Tree Size – We calculated street tree size by taking the average and standard deviation of DBH for all the trees in our area of interest. We only included neighbourhoods that had more than 50 trees within their borders and streets that had more than 1 tree within the 25 m

buffer surrounding the road. For Halifax, where DBH values were presented as codes with value ranges (e.g., 7-15 cm), we randomly sampled values with replacement within the range for each tree that fell within the category.

3.2.5.3 Street Tree Diversity – We calculated street tree diversity using species richness and functional group richness. First, we calculated species richness for each city, neighbourhood, and street using the `specnumber` function in the vegan package (Oksanen et al. 2020). Neighbourhoods were only included if they had over 50 trees and streets were only included if they had over 1 tree.

We then assigned tree species to functional groups using the data and methodology presented in Paquette et al. (2021). We downloaded their publicly available dataset (Belluau et al. 2021) and cross-referenced the four traits they had collected (i.e., seed mass, leaf nitrogen content, wood density, and specific leaf area) with our species list. We then used TRY plant trait database, KEW seed database, and the scientific literature to fill in trait data for any of our species that were not on their list, removing duplicates (Kattge et al. 2020, Society for Ecological Restoration et al. 2023). If a species' trait value was not in the TRY or KEW databases, we conducted a literature search using Web of Science to assess if it was in the literature. When searching the literature, we only included studies if they were primary sources, measured adult trees, and were not experimental data (Paquette et al. 2021). We then estimated trait data for species missing only one or two trait values as outlined in Paquette et al. (2021). For all remaining species, that either had no trait values available or one out of four available, we filled in data with our calculated functional groups where possible. When all species in a genus belonged to a single functional group, we gave unassigned species from that genus the same functional group. For hybrid species, we assigned the functional group of the parents. When these were different and we knew the functional group of both parents, we split individuals evenly and assigned each individual one of the parent's functional groups. We then calculated the Shannon diversity of functional groups in each area of interest.

3.2.6 Urban Form Variables

3.2.6.1 Normalized Difference Building Index (NDBI) & Normalized Difference Vegetation Index (NDVI) – To assess general levels of impervious surface cover and vegetative cover, we calculated mean values of NDBI and NDVI across our areas of interest. NDBI can be considered the overall level of "greyness" of an area, whereas NDVI is the level of "greenness". Since they are calculated using satellite imagery, they are an imperfect metric as it is just one layer of assessment, i.e., grey infrastructure hidden below tree canopies will fail to be considered). However, we did not have access to a detailed impervious or vegetative cover layers at the scales needed. We used 2024 Sentinel-2 imagery (European Union et al. 2024b) filtered to be between June 1, 2024 and August 31, 2024 to calculate both NDBI and NDVI. We filtered images to have less than 10% cloud cover and then calculated the mean value of NDBI and NDVI for each of our areas of interest. We filtered images based on coverage of the area of interest (see Section 3.2.2), coverage of cities and neighbourhoods had to be over 50% and coverage of street segments had to be 100%.

3.2.6.2 Building Cover – We calculated building cover using the building footprint layer published by Microsoft (Table A3.2, Microsoft 2019). We calculated building cover by summing the area occupied by all buildings in our area of interest and subsequently dividing that number by the area of our area of interest.

3.2.6.3 Building Height – To calculate average building height across our area of interest, we used the Microsoft building footprint layer and the High-Resolution Digital Elevation Model dataset published by Natural Resources Canada (Natural Resources Canada 2015, Microsoft 2019). Using Google Earth Engine and the awesome-gee-community-catalog (Gorelick et al. 2017, Roy et al. 2025), we calculated the elevation at the centroid of every building within our area of interest and labelled it building height. We then took the average and standard deviation of building height for all buildings within our area of interest.

3.2.6.4 Road Class – There is no country-wide dataset that outlines roads using polygons. Instead, Statistics Canada published the Road Network File (Table A3.2, Statistics Canada 2024) that delineates roads across the country using line geometries and assigns each one of them a class. We used road class as a proxy for road size, where we classified highways, expressways, primary highways, secondary highways, connectors/ramps, and bridges/tunnels as "highways" and all remaining categories as "roads". We subsequently calculated the proportion of highways and roads by summing the number of road segments in each category and dividing by the total number of road segments in each area of interest to assess road size. We also calculated road density by summing the length of all road segments and dividing it by the area of the area of interest.

3.2.7 Sociodemographic Variables

We selected sociodemographic variables to calculate from the census based on previous work that outlined what factors may be important in Canadian cities (Tooke et al. 2010, Pham et al. 2013, 2017, Landry et al. 2020). For each dissemination area, we calculated the population density, proportion of dwelling types (i.e., single family homes, apartment buildings, semi-detached homes, row houses, duplexes), median income, proportion of residents who are low income, proportion of residents who are recent immigrants, proportion of people who are visible minorities, and the proportion of people who are highly educated (i.e., have a bachelor's degree or higher, Table A3.3.2, Statistics Statistics Canada 2022). We then calculated a weighted mean for each variable for every area of interest, weighted based on the area of the dissemination area that overlapped with the area of interest.

3.2.8 Random Forest Modelling

We used random forests to model our data due to the predictive nature of our questions and the high number of predictive variables of interest. We tested six dependent variables, land surface temperature, carbon monoxide (CO), ozone (O3), sulfur dioxide (SO2), nitrogen dioxide (NO2), and UV aerosols (UV). We built 13 models total: testing all six dependent variables at the city scale, all six dependent variables at the neighbourhood scale, and land surface temperature at the street scale. We didn't test air pollution models at the street scale because the data had too coarse a resolution.

At each scale, we used the same ecological form, urban form, and sociodemographic predictors (outlined in Sections 3.2.4, 3.2.5, 3.2.6). Each predictor was calculated at the scale being tested. At the street scale, the proportion of highways and road density were not included but road class was used. We included latitude and longitude of each area of interest, to address spatial autocorrelation. We also included date of satellite image as a predictor as there are multiple images per area of interest, taken on different days. Areas of interest varied in size (e.g., cities and neighbourhoods were very different sizes), thus we added area as a predictor.

Additionally, we used predictors that are all densities, means, or proportions and thus are not dependent on the size of the area where they are calculated.

We built our random forests using the `rand_forest` function with the ranger engine found in the parsnip package (Kuhn et al. 2025b). To train and test our random forests, we split our data using the `initial_split`, `training`, and `testing` functions in the rsample package (Frick et al. 2025). We created a model recipe where we normalized all numeric predictors using the `step_normalize` and created binary numeric predictors for all categorical predictors using `step_dummy` from the recipes package (Kuhn et al. 2025c). To tune the hyperparameters in our model, number of randomly sampled predictors at each split (mtry) and the minimum number of data points in a node (min_n), we used `tune_grid` function from the tune package (Kuhn et al. 2025a). We used 10 randomly sampled folds of our training data provided by the `vfold_cv` function (Frick et al. 2025) with a 15 point grid to estimate different hyperparameter values. We selected the best model using MAE (mean absolute error) values for both hyperparameters. For the best model, we extracted the variable importance using the corrected impurity importance measure (Nembrini et al. 2018) and the `vip` function from the vip package (Greenwell and Boehmke 2023). For our type of regression model, the variable importance represents the average sum of squared error across all trees when that variable is removed from the model (Berk 2020). For each model, we selected the most important variables and produced accumulated local effect plots (ALEs) for those same variables using the DALEXtra package (Maksymiuk et al. 2023). The most important variables were selected using a qualitative inspection of the variable importance plots (Figure A3.3), where the most important variable and any other variables that were within its range were chosen, i.e. variables that were less than half of its value were excluded. We assessed model performance by comparing R^2 and MAE metrics between training and testing datasets (Table A3.3) and plotting the predicted vs. actual values of our models with training and test data (Figure A3.4). The data and code for all analysis associated with this paper can be found at https://github.com/zule-lab/CrossCityES and https://zenodo.org/records/17186246.

3.3 Results:

We built 13 models to identify patterns in variables that predict air pollution and temperature across cities and scales, which we deem general trends. Here, we present the results from 11 models total: three land-surface temperature models at the city, neighbourhood, and street scales and eight air pollution models, with four different air pollutants tested at the city and neighbourhood scales. We removed both city and neighbourhood scale sulfur dioxide models due to bad model fit (Table A3.3, Figures A3.4d, A3.4k).

3.3.1 Data Summary

All cities, neighbourhoods, and streets had multiple temperature and air pollution satellite images that met our filtering criteria. The land-surface and air pollution satellites pass our study area at different rates, which resulted in a minimum of two images for temperature and 28 for air pollution (Table A3.2). All explanatory variables ranged across scales and cities, a detailed breakdown can be found in the supplementary materials (Table A3.1b, Figure A3.1).

3.3.1.1 Land-surface temperature – Land-surface temperature ranged from 10.2°C to 47.0°C, with a mean of 32.4°C across all scales and cities. City scale temperatures had a mean of 31.9°C, neighbourhood scale 32.5°C, and street scale had a mean of 32.7°C across all cities. Across all

scales, land-surface temperature was predicted to be hottest in Calgary and Toronto. At the city and neighbourhood scales, there was more variation in the predicted temperatures and Calgary was predicted to be several degrees hotter than Toronto (Figures 3.2-3.3). Halifax is consistently one of the coolest cities, though at the city scale Ottawa and Winnipeg are slightly cooler (Figures 3.2-3.3).

3.3.1.2 Air pollution – Different air pollutants had different trends across cities and scales. Carbon monoxide had a mean of 0.04 mol/m2 at the city scale and neighbourhood scales. Nitrogen dioxide had a mean of 3.4x10-5 mol/m2 at the city scale and 3.2x10-5 mol/m2 at the neighbourhood scale. Ozone had a mean of 0.15 mol/m2 at both scales and UV aerosols had a mean of -0.43 m at the city scale and -0.32 m at the neighbourhood scale. Carbon monoxide level varied across cities depending on day of year but was generally highest in Winnipeg and lowest in Calgary and Vancouver at both scales (Figures A3.5a, A3.5e). Nitrogen dioxide was highest in Toronto and lowest in Ottawa and Winnipeg across both scales (Figure A3.5b, A3.5f). The city with the highest values of ozone varied throughout the year, though Ottawa, Montreal, and Winnipeg had consistently high levels across the city and neighbourhood scales (Figure 3.5, Figure A3.5c). Toronto and Calgary both had consistently low levels (Figures 3.5, A3.5c). UV was highest in Winnipeg at the city scale and in Calgary and Winnipeg at the neighbourhood scale (Figures A3.5d, A3.5h). UV aerosols were lowest in Ottawa at the city scale and Halifax at the neighbourhood scale (Figures A3.5d, A3.5h).

3.3.2 General Predictors

We found very few general predictors overall and most of our models were best predicted with day of year only (Tables 3.1, 3.2).

3.3.2.1 Ecological form & temperature – We found greenness and street tree variables were important predictors of temperature at both the city and neighbourhood scales, though the specific variable was scale dependent. At the city scale, NDVI and street tree stem density were both important predictors (Table 3.1). NDVI had a negative relationship with predicted temperature whereas street tree stem density had a positive relationship with predicted temperature (Figure 3.2). At the neighbourhood scale, the most important predictor of land-surface temperature was street tree functional group richness, which had a city-dependent relationship with temperature (Table 3.1, Figure 3.3).

3.3.2.2 Sociodemographics at the city scale – Race and class were important predictors of temperature and nitrogen dioxide at the city scale. These models had race, immigration status, and housing form as important predictors (Tables 3.1 & 3.2). Predicted temperature increased as the proportion of recent immigrants and proportion of visible minorities increased across all cities (Table 3.1, Figure 3.2). Predicted nitrogen dioxide decreased as percent of Indigenous residents, proportion of residences that are moving dwellings (i.e., trailers), and proportion of residences that are single detached homes increased (Table 3.2, Figure 3.4). Both the percentage of moving dwellings and percentage of residents who identify as Indigenous had low averages and skewed distributions across cities. The percentage of moving dwellings remained low across all cities, with a maximum of 2% (Figure 3.4). Most cities had less than 1% of residences as moving dwellings on average, except Halifax which reached an average of 2%. Similarly, all cities except Winnipeg had an average percentage of Indigenous people that was less than 4% of residents, whereas Winnipeg's Indigenous population reached 12% on average (Table A3.1b).

3.3.2.3 Day of year across all models – Day of year was consistently an important predictor, across scales and response variables. It is present as one of the most important predictors in 2/3 temperature models (Table 3.1) and 7/8 air pollution models presented (Table 3.2). However, the effect of day of was dependent on the response variable in question. For example, carbon monoxide levels increased overall as day of year progressed, whereas ozone levels decreased (Figures A3.5a, A3.5d).

3.3.3 Unique Predictors

3.3.3.1 Temperature across scales – Temperature was best predicted by different variables at every scale. The city scale included both ecological form and sociodemographic variables, the neighbourhood scale had only ecological form as an important predictor, and the street scale was predicted best by day of year alone.

3.3.3.2 Temperature across cities – At the neighbourhood scale, the association between functional group richness and predicted temperature was city dependent, where Calgary had a relationship different than the other 6 cities (Figure 3.3, Figure A3.6a). Calgary had a peak in predicted temperature at five functional groups, followed by a sharp decline in predicted temperature at six functional groups. The other 6 cities were the inverse, with a decline in predicted temperature at five functional groups followed by a peak at six functional groups (Figure 3.3, Figure A3.6a). The data for functional group richness across cities is highly skewed. Winnipeg is the only city with neighbourhoods that have functional group richness ranging from 2-6, though there are very few neighbourhoods in Winnipeg that have a functional group richness of 2 (n = 1/207) or 6 (n = 4/207). Calgary is the city with the most even distribution across groups, though it has no neighbourhoods with a functional group richness of 6. By contrast, Toronto and Montreal only have neighbourhoods with 5 or 6 functional groups, all of Ottawa's neighbourhoods have either 4 or 5 functional groups, and all of Halifax's main municipal area has a functional group of 6.

3.3.3.3 Air pollution across pollutants & scales – We found that different pollutants have different predictors and different scales where they are relevant (Table 3.2). All pollutants included day of year as an important predictor. Nitrogen dioxide and ozone were the only two pollutants that had important predictors other than day of year. Nitrogen dioxide included sociodemographic predictors at the city scale, with very low mean levels at the city scale (Table 3.2, Figure 3.4, max possible value = 0.0192). Ozone included ecological form predictors at the neighbourhood scale (Table 3.2), levels of ozone in our study were mid-range (max possible value = 0.3048) but with very little variation across dates (Figure 3.5).

3.3.3.5 Ecological form & ozone – We found that at the neighbourhood scale, ozone was best predicted by several street tree variables and neighbourhood area (Table 3.2). The relationships between ozone and its most important predictors were noisy and largely city-dependent (Figures 3.5, A3.6b). The data was skewed and unbalanced, which resulted in the ALE plots showing the relationships between ozone and the predictors for 3-5 cities, though the partial dependency plot with all cities can be found in the supplementary (Figure A3.6b). Generally, an increase in average tree size and variation in average tree size were associated with an increase in predicted ozone (Figure 3.5). Tree diversity based on tree species and functional groups had mixed relationships, with no clear pattern (Figure 3.5). Tree density was different for each city, where at high stem densities in Halifax, Calgary, Winnipeg, Montreal, and Ottawa there was a positive

relationship with ozone but in Toronto and Vancouver there was a negative relationship (Figures 3.5, A3.6b).

3.4 Discussion:

The goal of this study was to identify patterns in predictors of temperature and air pollution across seven Canadian cities and three spatial scales. We did find some general predictors. For example, ecological form variables were important predictors of temperature at both city and neighbourhood scales, sociodemographic variables were important predictors at the city scale across multiple response variables, and street tree variables specifically were important predictors at the neighbourhood scale across multiple response variables. However, despite these general predictors, our findings were largely non-generalizable across cities, scales, or both, and highlight the importance of local context when predicting temperature and air pollution. This contrasts with our hypothesis that there would be general predictors where a variable would consistently predict an outcome across scales and cities. For example, the important predictors of temperature related to ecological form were different depending on scale, and the effect of street-tree related variables on ozone varied across cities. Our findings indicate that predicting land-surface temperature and air pollution levels in Canadian cities using widely accessible data and metrics must be done in a scale-specific manner.

Despite significant variations in population size, age, and urban form, inequity was an important predictor of temperature and nitrogen dioxide at the city scale across all cities considered in this study. We found that higher temperatures were predicted by higher proportions of recent immigrants and visible minorities. We also found that as the proportion of single detached homes increases, the predicted levels of nitrogen dioxide decrease. The negative relationships between predicted nitrogen dioxide and percentage of Indigenous residents and moving dwellings may initially appear as contrary to the trend of inequity in Canadian cities. However, we believe that this trend is driven by the unbalanced nature of these variables. Winnipeg and Halifax both have low levels of nitrogen dioxide but the highest percentage of Indigenous residents and moving dwellings, whereas other cities have very low, i.e., near zero, values of percentage of Indigenous residents and moving dwellings. Therefore, we believe that this imbalance allows for the negative relationships to be driven by Halifax and Winnipeg and doesn't represent a true cross-city relationship. These relationships may also be capturing a rural-urban gradient, where more suburban and exurban areas have higher proportions of Indigenous residents and moving dwellings and lower levels of nitrogen dioxide. Moving forward, we suggest further studies investigating the causal link between these variables.

The patterns of inequity with respect to recent immigrants, visible minorities, and single detached homes are consistent with other Canadian studies and the broader Luxury Effect, where street tree distribution is negatively associated with recent immigrants and positively associated with higher education levels (Pham et al. 2013), social vulnerability is associated with lower levels of forest resilience and canopy cover (Landry et al. 2020), and high incomes and levels of education are associated with more vegetation (Quinton et al. 2022). All seven cities followed the trends of inequity, raising concerns that should be investigated further regarding the mechanisms behind this relationship. However, all seven cities also include equity as a priority in their forestry, environmental, and/or climate change plans (City of Toronto 2013, City of Ottawa 2017, City of Calgary 2022, Ville de Montréal 2022, City of Winnipeg 2023, City of Halifax 2025, City of Vancouver 2025c), indicating that they are aware of this potential issue and

interested in doing something to change it. Research can help with these goals, assessing how and why environmental equity changes in Canadian cities moving forward.

Another general pattern we found was the presence of ecological form variables as an important predictor of land-surface temperature across city and neighbourhood scales. Our finding is consistent with cities across the word, which have established vegetation as an important predictor of urban temperature (Schwaab et al. 2021, Chen et al. 2022, Zekar et al. 2023). In our study, broad metrics of vegetation such as citywide NDVI and tree density were important predictors of temperature at the larger city scale, whereas at the neighbourhood scale street tree diversity became an important predictor across cities. The appearance of NDVI as an important predictor at a large scale has management implications, as this is a relevant scale of management for all cities and indicates that managing for general "greenness" that includes both trees and other types of vegetation at a city or landscape scale may indeed result in lower temperatures. The importance of NDVI at a broad scale for urban heat has been demonstrated in other cities such as Los Angeles and Chicago (Amaripadath and Sailor 2025), and research has suggested its potential as a useful metric for policy (de la Iglesia Martinez and Labib 2023). Given that NDVI is one of very few comparable datasets that is available globally at high resolutions, its appearance as an important predictor for temperature in our study is encouraging for its continued use in future cross-city comparisons that include a high number of cities that span management jurisdictions, sizes, and climates.

The positive relationship between urban heat and street tree density was the inverse of what we expected. Due to the established cooling effect caused by increased canopy (Ziter et al. 2019, Jung et al. 2021), we expected that as street tree density increased, canopy cover would also increase, and consequently predicted temperatures would decrease. However, in less dense areas of Canadian cities, where land parcels are larger and the planting of street trees becomes correspondingly less dense, there is typically also an increase in trees on private land such as yards (Bacon et al. 2025, Paquette et al. 2025). This decrease in street tree density is therefore associated with an increase in overall greenness and a less dense urban environment, which results in a greater overall canopy cover, and cooler temperatures (Kroft and Ziter 2024). This trade-off between public and private greenspace associated with an increase in population and building cover may explain the unexpected negative relationship between street tree density and temperature in our study. Due to the biases introduced by excluding private trees in urban ecology studies, conducting research that includes both public and private tree inventories is an urgent priority to be able to reduce bias in our analysis and have a fuller picture of the relationships between the urban forest and temperature.

The mixed predictions that we observed between tree functional diversity and temperature at the neighbourhood scale is supported by prior literature, which has also showed mixed results (Chinchilla et al. 2021, Rendon et al. 2024). The impact of tree diversity on cooling is affected by the species composition in question and will therefore always be context dependent (Helletsgruber et al. 2020). We tested the effect of functional diversity using functional groups as described in Paquette et al. (2021). As a relatively new framework that makes functional diversity more accessible, we wanted to test its efficacy in a predictive framework. At the city scale, all cities have all 6 functional groups present in their street tree inventories. It is a useful tool for prediction at the neighbourhood scale, with functional group richness highlighted as the most important predictor in our models. However, the interpretation is difficult as there is not a large gradient across neighbourhoods, with most neighbourhoods

having 5 or 6 functional groups. At the street scale, there is much more variation in number of functional groups which could be useful for other research questions, such as testing the causal links between functional group diversity and the environmental conditions of an area. Moving forward, we recommend this as a useful metric for prediction and causal analyses at fine scales.

We included street tree composition and structure as predictors in our models due to their established mechanistic relationships with temperature and air pollution across scales (Vailshery et al. 2013, He et al. 2024, Wang et al. 2024b). However, in our study street tree variables were only important predictors at the city and neighbourhood scales for temperature and the neighbourhood scale for ozone. At the neighbourhood scale, the relationships between street tree variables and temperature and air pollution were highly complex. The relationship between functional group richness and temperature was city specific. Similarly, ozone was well predicted by street tree density, functional diversity, and size at the neighbourhood scale but all the relationships were city specific. This finding is consistent with literature, which highlights the complex nature of the relationships between tree diversity and temperature (Helletsgruber et al. 2020), and tree diversity, size, and density and ozone levels (Fitzky et al. 2019). Some studies show that street tree plantings are able to decrease ozone levels in cities (Nowak et al. 2000) while others show that depending on the species composition, street trees may increase levels of ozone by producing volatile organic compounds that then react to produce ozone (Chameides et al. 1988). Despite significant investment in green infrastructure as a potential solution to levels of urban heat and air pollution, we were unable to consistently use street tree variables as predictive tools. This highlights the need for further investment in categorizing more of the urban forest and identifying at what scales green infrastructure interventions are most effective.

The ambiguous relationships between tree structure and composition and temperature and air pollution in our study may be attributed to the fact that we included only a small portion of the urban forest, street trees. Private and park trees make up most of the trees in Canadian cities, thus their exclusion from the analysis means we are missing a large part of the picture (Pataki et al. 2013, Avolio et al. 2015). Indeed, the greenest of our study cities often had low street tree density, indicating that street tree variables are only a very small portion of the overall greenness in cities (Table A3.1b). The presence of street tree variables as predictors in any of the models, despite this large portion of missing data, may indicate that trees are in fact very useful tools for regulating the urban microclimate and pollutants, and incorporating other forms of trees into our research would help elucidate more representative relationships between these variables.

In general, air pollution was not well predicted by the variables we included in our models at the scales we used. This was somewhat unexpected, as urban form, sociodemographics, and street trees have all been established as variables that can affect predictors of air pollution levels (Livesley et al. 2016, Yang et al. 2020a, Raaschou-Nielsen et al. 2022). However, we believe this is in part due to the generally high air quality in Canadian cities with respect to the pollutants tested (Canadian Council of Ministers of the Environment 2025). The air pollutant that has the highest levels and exceeds the recommended guidelines most often in Canadian cities is PM2.5, which we could not directly measure in this study due to lack of data availability. Other air pollutants such as nitrogen dioxide and ozone are present in low concentrations and meet annual guidelines for air quality in most of our study cities (Canadian Council of Ministers of the Environment 2025). Further, air pollution is produced by point sources, such as industry (Goldberg et al. 2021, Canadian Council of Ministers of the Environment 2025). Due to the nature of Canada's economy, which is dependent on the

processing of raw materials in processes such as logging and mining, a large portion of pollutant-producing industry is located outside of our major cities and in smaller or medium sized cities throughout the country (Blackbourn and Putnam 1984). Thus, for the pollutants we measured, air pollution levels across our relatively large study cities may not be sufficiently variable for our variables to give strong predictions. Repeating this study with more data from areas and towns that have heavily polluting industries, and thus stronger spatial variability in pollutants, would be an interesting extension and may reveal some of the patterns that have been found in other countries.

Both multi-city and multi-scale studies have been called for as a critical piece of the urban ecology field multiple times (Andersson et al. 2015, Kremer et al. 2016, Ziter 2016, Pickett et al. 2017, Knapp et al. 2021). As a result, many countries have been producing high-quality cross-city studies that evaluate the impact of greening on many different environmental conditions (e.g., Chakraborty et al. 2019, Hu et al. 2023). Canada has not yet matched pace, though there are some examples of excellent cross-city comparisons in Canada that focus their work at a single spatial scale (e.g., Crouse et al. 2017, Landry et al. 2020, Quinton et al. 2022). Currently, the lack of data in Canadian systems is a major barrier to this kind of work. This is beginning to change however, with 2025 being the first year where there is a consolidated, publicly accessible database that contains the urban tree inventories of many Canadian cities and cross-city work has begun to be published as a result (Martin et al. 2025a, 2025b). Most of our urban forest remains undocumented due to the huge proportion of trees located on private land, though there is work expanding our urban tree inventories by documenting private trees in some Canadian cities such as Montreal and Toronto (Yip 2018, Hutt-Taylor and Ziter 2022, Sousa-Silva et al. 2023). City size bias is an issue across urban ecology, where most studies have focused on studying and re-studying large cities while ignoring small cities (Kendal et al. 2020, Masoudi et al. 2025). We contribute to this issue, studying mostly large cities in a country dominated by small and medium sized cities – though our study cities are inclusive of otherwise underrepresented city types such as prairie and central cities. However, very few small cities in Canada have available street tree inventories and/or open-source datasets. Where this data is available, municipalities often don't have the resources to keep it up to date and available in a systematic way. Investing in urban forest management, monitoring, and open data practices across the country would facilitate research in these important and dominant smaller cities.

Canada also lacks national level data such as high-resolution land cover data and finer-scale air temperature and air pollution datasets. Currently, we are often constrained to the use of satellite imagery to complete work related to temperature and air pollution at multiple scales. Satellite imagery is highly valuable but has limitations. For example, land-surface temperature is correlated to daytime air temperature but is mediated by different mechanisms and is limited in temporal and fine-spatial resolution, therefore often leading to different hot and cold spots (Cao et al. 2021, Xiang et al. 2023, Pena Acosta et al. 2023). Thus, land-surface temperature does not always reflect the human experience that we are trying to capture. Satellite air pollution measures have been suggested as best used as a complement to ground-level data due to their total air column measurements and have minimum detection limits (Ialongo et al. 2020, Dubey et al. 2023). Moving forward, addressing these data gaps through government initiatives and academic research contributions is critical if we want to use broad-scale patterns to understand our urban forests, compare across cities, and inform decision making across the country.

Prediction is used in both research and management applications to identify important patterns and manage for potential outcomes. In this study, we used predictive models to identify patterns in how ecological form, urban form, and sociodemographics predict two important environmental determinants of health across cities and scales, temperature and air pollution. We found that in general, the important predictors of temperature and air pollution are scale dependent, indicating that the effects of management may be scale dependent. Day of year was an important predictor in nearly all of our models, showing the high day-to-day variation in temperature and air pollution levels in our cities and suggesting the need for research that considers temporal trends as well as spatial. We found ecological form variables to be important predictors of some determinants of health at both the city and neighbourhood scales, two scales which are highly relevant to the management context. At the city scale, we found broad scale trends of inequity to be important predictors of both temperature and nitrogen dioxide despite citywide forestry plans emphasizing equity. We also found NDVI was an important predictor of city-scale temperature, highlighting its potential use for management and future cross-city studies. At the neighbourhood scale, we found street tree diversity was an important predictor of temperature, and street tree diversity, size, and density as important predictors of ozone levels. Through this work, we also produced a cleaned and published dataset of land-surface temperature, air pollution, ecological form, urban form, and sociodemographic variables across multiple Canadian cities that was not previously available. This work highlights the importance of considering both ecological and anthropogenic drivers across spatio-temporal scales to better understand patterns of urban heat and air pollution.

3.5 Tables & Figures:

Table 3.1: Rationale for the inclusion of variables in our study, with associated references and the data source where we obtained the data for our study. Links to individual data sources can be found in the supplementary (Table S3.2).

Ecosystem Service	**Indicator**	**Rationale**		**Data Source**
Temperature regulation	Land surface temperature (°C)	Heatwaves in Canadian cities can have tragic consequences. In British Columbia, during the summer of 2021, 569 people lost their lives due to heat-related causes, primarily in the greater Vancouver area (BC Coroners 2021).		2024 Landsat 8 imagery (30x30m)
Air pollution mitigation	UV aerosol index, CO, O_3, SO_2, and NO_2 levels	The Canadian government estimates that over 15,000 Canadians die prematurely from air pollution every year (Health Canada 2016). Most of Canada's population lives in areas where nitrogen dioxide quantities require improvement through active management (Canadian Council of Ministers of the Environment 2025).		2024 Sentinel-5P imagery (3.5x7km^2)
Factor	**Measure**	**Temperature Rationale**	**Air Pollution Rationale**	
Tree biodiversity (*Ecological form*)	Street tree species richness, street tree functional group richness	Species and functional group richness of trees can decrease cooling in the short-term because of the incorporation of species that are less suited to provide cooling (Kremer et al. 2016, Ziter 2016, Thompson et al. 2021). Long-term, species and functional group richness maintain a higher level of cooling via an increase in forest resilience (Pinho et al. 2021, Paquette et al. 2021).	Species and functional group richness of trees have a complex and inconsistent relationship with air pollution (Han et al. 2020). Trees with long leaf-out periods can reduce air pollution by interception of particles by leaves (Nowak et al. 2006, Yang et al. 2020b). However, some species of trees produce volatile organic compounds which leads to higher levels of ozone (O_3), increasing air pollution (Chameides et al. 1988).	Municipal tree inventories
Tree size distribution *(Ecological form*)	DBH distribution of street tree community	Tree size distribution determines the shade provision and transpiration rate of the tree, both of which decrease daytime temperature (Rötzer et al. 2019, Alonzo et al. 2021).	Tree size changes rates of air pollution removal (Samson et al. 2017) but the relationship is species dependent (Grote et al. 2016, Livesley et al. 2016, Roman et al. 2021a).	Municipal tree inventories
Tree density	Basal area of street	Due to the increase in shading,	Tree density can locally increase air	Municipal tree

(*Ecological form*)	trees	transpiration, and biomass, an increase in tree density decreases daytime temperature (Shahidan 2015, Tsoka et al. 2021).	pollution depending on the crown and leaf structure, which can potentially reduce airflow, increasing air pollution (Salmond et al. 2013, Grote et al. 2016). Tree density can also increases leaf area leading to higher deposition rates, decreasing air pollution (Nowak et al. 2006, Samson et al. 2017).	inventories
Vegetative cover (*Ecological form)*	Normalized difference vegetation index (NDVI)	All vegetation contributes to reducing temperatures, through transpiration (Richards et al. 2020). NDVI of an area has been shown to decrease urban temperature, though the effect varies depending on climatic zone (Mackey et al. 2012, Wang et al. 2022, Aghazadeh et al. 2023).	Higher NDVI decreases several different air pollutants and improves air quality (Zhou et al. 2021, Sheng et al. 2023).	2024 Sentinel-2 imagery (10x10m)
Road size (*Urban form*)	National road class	Wider roads decrease street tree cover in Montréal (Pham et al. 2017) while simultaneously increasing impervious cover. We expect increased road width to increase daytime temperature. Road width can also interact with building height, creating a canyon type effect, where narrow roads with taller buildings produce more shade and cooler daytime temperatures (Jamei et al. 2016).	Road width increases vehicle traffic (Krishnamurthy and Thamizh Arasan 2014), which increases air pollution levels (Pant and Harrison 2013).	2024 Statistics Canada Road Network
Impervious surface cover (*Urban form*)	Normalized difference building index (NDBI)	Impervious surfaces cause increases in temperature due to absorbed and re-emitted solar radiation (Stone 2005, Lee and French 2009, Ziter et al. 2019).	Impervious surfaces increase air pollution through an increase in the production of ozone (Stone 2005) and sometimes decreasing wind levels and trapping other air pollutants (Lee and French 2009, Han et al. 2020).	2024 Sentinel-2 imagery (10 m)
Building cover (*Urban*	Area covered by	Increased building cover increases	Increased building cover can create	2019 Microsoft

form)	buildings (km^2) / total area (km^2)	urban temperatures by increasing the area covered by impervious surfaces and by reducing air flow, trapping heat (Yang et al. 2020b, Kroft and Ziter 2024).	canyons that reduce airflow and wind, increasing air pollutant levels (Lee and French 2009, Han et al. 2020).	building footprints
Building height distribution (*Urban form*)	Building height (m) distribution of a study area	Increasing building height increases impervious surface, therefore increasing temperature (Ziter et al. 2019). However, the increase in building height also produces shade, which can decrease daytime temperature (Alonzo et al. 2021).	Increasing building height reduces air flow and generally increases air pollution levels (Yang et al. 2020b).	2015-2022 Natural Resources Canada High-Resolution Digital Elevation Model (1mx1m)
Class/income (*Sociodemographics*)	% of population low income after tax, median income after tax	Household income determines the type of housing individuals are able to live in as well as the vegetation cover, tree diversity, and road size that you live near in Canadian cities, all of which impact temperature and air pollution levels (Pham et al. 2017, Schell et al. 2020, Landry et al. 2020).		2021 Statistics Canada Census
Race/ethnicity (*Sociodemographics*)	# recent immigrants (2016-2021), visible minority population	Due to systemic inequity, the proportion of recent immigrants and visible minorities in Canada causes a change in tree cover, dwelling type, and road size, in turn impacting temperature and air pollution levels (Pham et al. 2017, Schell et al. 2020, Landry et al. 2020).		2021 Statistics Canada Census
Housing type (*Sociodemographics*)	Count of each household type in study area	Dwelling type in Canadian cities causes differences in vegetation cover, building cover, and building height, all of which in turn impact temperature and air pollution levels (Pham et al. 2013, 2017). Dwelling type is an important indicator of generational wealth and privilege that captures social inequity (McKee 2012).		2021 Statistics Canada Census

Table 3.2: Variable importance metrics for the most important variables in the temperature models.

Model	Scale	Variable	Corrected Impurity	Relationship
Temperature	City	NDVI	14.47	negative
Temperature	City	Recent Immigrants (%)	13.58	positive
Temperature	City	NDBI	12.55	positive
Temperature	City	Visible Minorities (%)	12.52	positive
Temperature	City	Tree Stem Density (stems/m^2)	12.37	positive
Temperature	City	Day of Year	11.18	positive
Temperature	Neighbourhood	Functional Group Richness	1.02×10^5	mixed
Temperature	Street	Day of Year	1.06×10^4	positive

Table 3.3: Variable importance values using a corrected impurity calculation for the most important variables in air pollution models.

Model	Scale	Variable	Corrected Impurity	Relationship
Carbon Monoxide	City	Day of Year	0.02	positive
Carbon Monoxide	Neighbourhood	Day of Year	2.15	positive
Nitrogen Dioxide	City	Indigenous People (%)	1.40×10^{-8}	negative
Nitrogen Dioxide	City	Moving Dwellings (%)	1.37×10^{-8}	negative
Nitrogen Dioxide	City	Single Detached Homes (%)	1.35×10^{-8}	negative
Nitrogen Dioxide	City	Day of Year	1.11×10^{-8}	mixed
Nitrogen Dioxide	Neighbourhood	Latitude	1.63×10^{-6}	mixed
Nitrogen Dioxide	Neighbourhood	Day of Year	1.20×10^{-6}	mixed
Ozone	City	Day of Year	0.01	negative
Ozone	Neighbourhood	Mean DBH (cm)	1.67×10^{3}	mixed
Ozone	Neighbourhood	Standard Deviation DBH (cm)	1.18×10^{3}	mixed
Ozone	Neighbourhood	Shannon	1.04×10^{3}	mixed
Ozone	Neighbourhood	Species Richness	848.48	mixed
Ozone	Neighbourhood	Functional Group Shannon	768.82	mixed
Ozone	Neighbourhood	Tree Stem Density (stems/km^2)	653.03	mixed
Ozone	Neighbourhood	Neighbourhood Area (m^2)	481.95	mixed
UV Aerosols	City	Day of Year	13.45	positive
UV Aerosols	Neighbourhood	Day of Year	1.05×10^{4}	positive

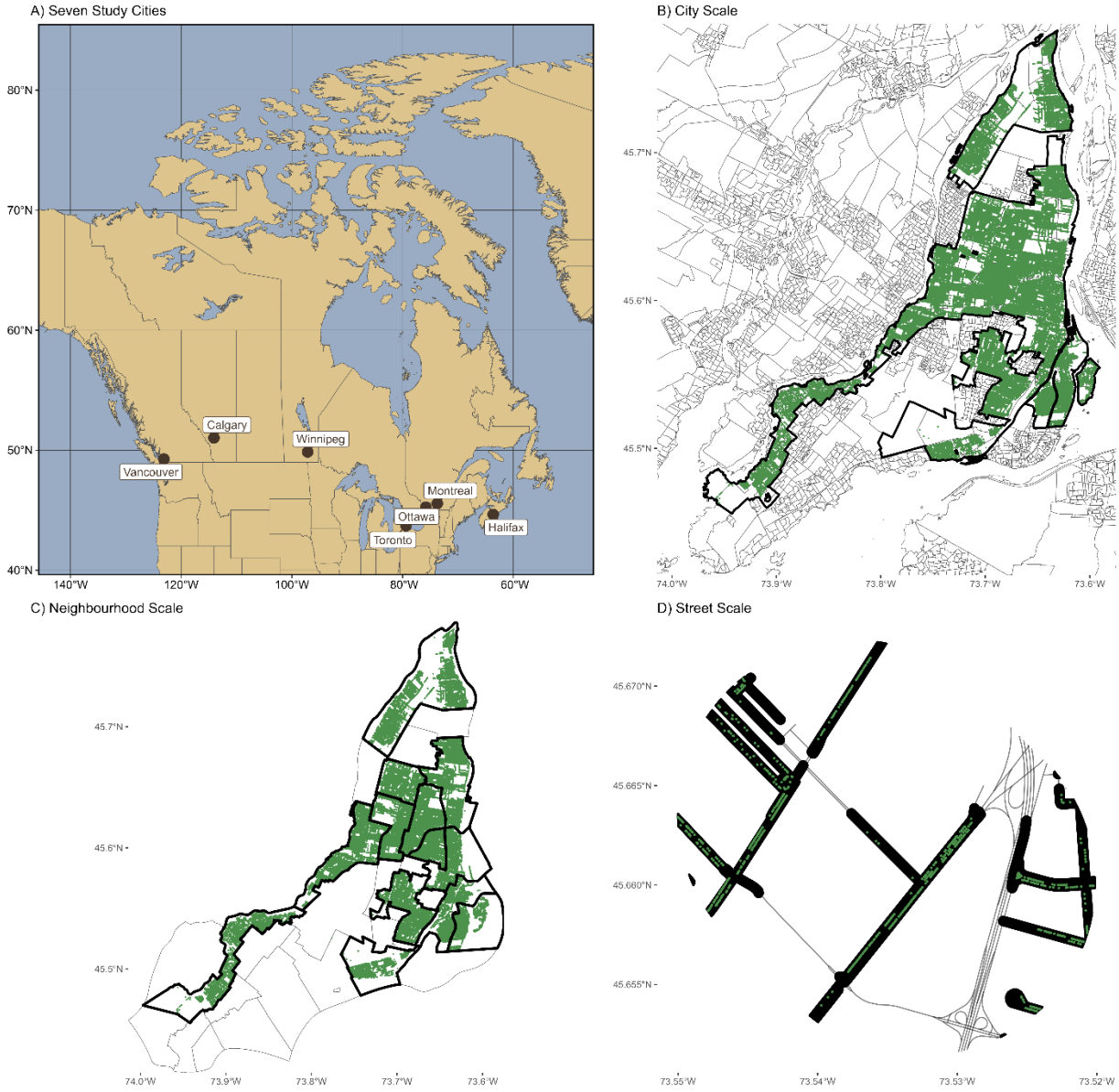


Figure 3.1: A) Distribution of seven study cities across Canada. B) Example of the creation of the "city boundaries" for the city of Montreal. Dissemination areas were downloaded for the larger census metropolitan area (grey). Those dissemination areas that had public street tree inventory data (green) were included and amalgamated to make a city boundary outline (black). C) Example of the selection of the neighbourhoods for the city of Montreal. Neighbourhood boundaries (black) were provided by individual municipalities and intersected with the public street tree inventory (green) to include only those neighbourhoods that had public street tree data present. D) Example of street selection for a subset of Montreal. Streets that had public street tree inventory data (green) present within a 25 m buffer surrounding the street were included (black). Trees that did not have street tree data present within 25 m were excluded (grey). Plot was made with sf and ggplot2 packages (Wickham et al. 2024, Pebesma et al. 2024).

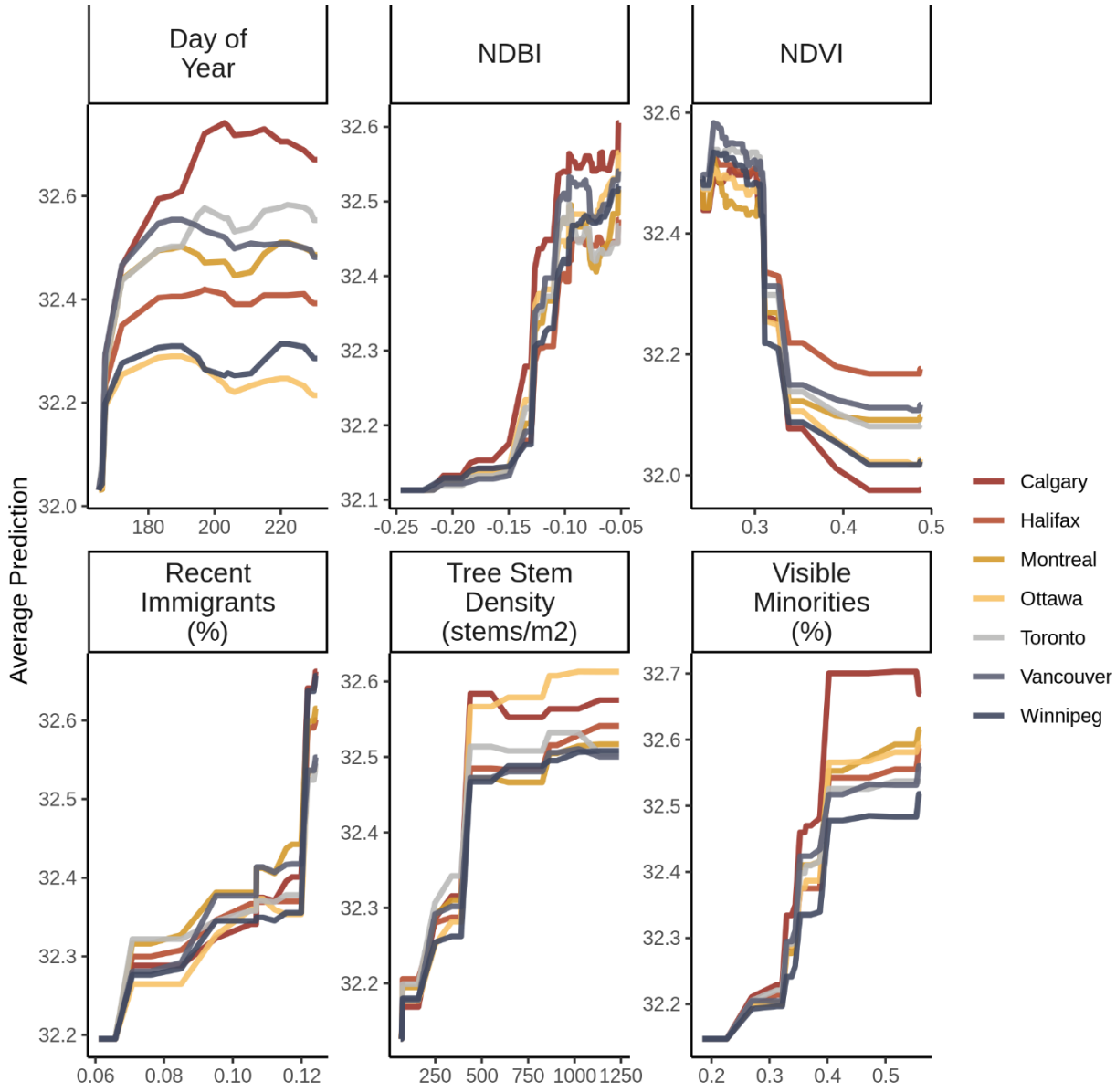


Figure 3.2: Accumulated local effects plot depicting the relationships between the most important predictive variables and average predicted mean temperature at the city scale. Predicted temperature value is the predicted temperature calculated from the difference between two neighbouring values.

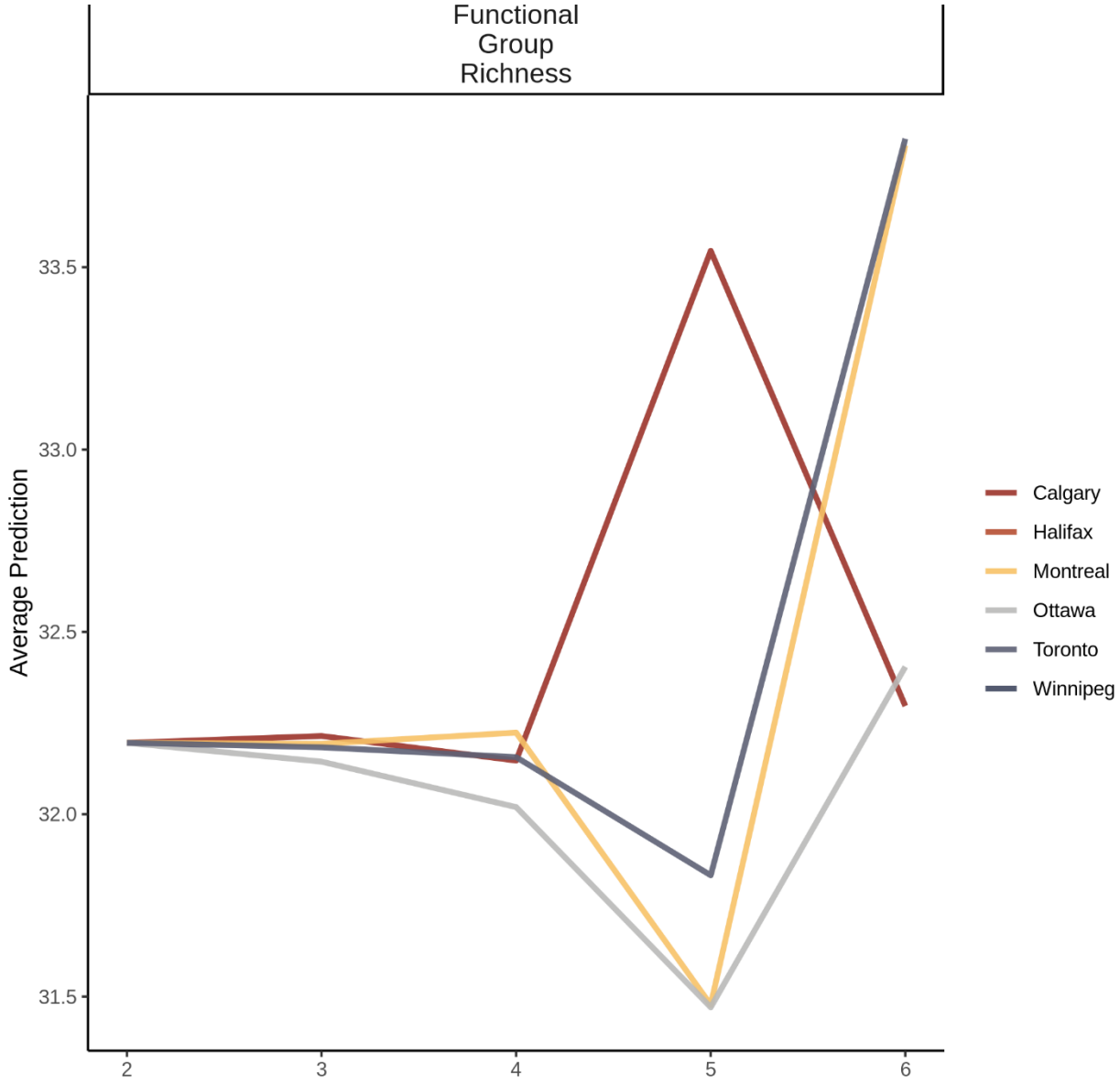


Figure 3.3: Accumulated local effects plot depicting the relationships between the most important predictive variables and average predicted mean temperature at the neighbourhood scale. Some cities, i.e., Halifax, Winnipeg, and Vancouver, were dropped from the plot due to not enough data points in each category but they follow the same trends as Toronto, Ottawa, and Montreal when plotted using a partial dependency plot (Fig A3.6a). Predicted temperature value is the predicted temperature calculated from the difference between two neighbouring values.

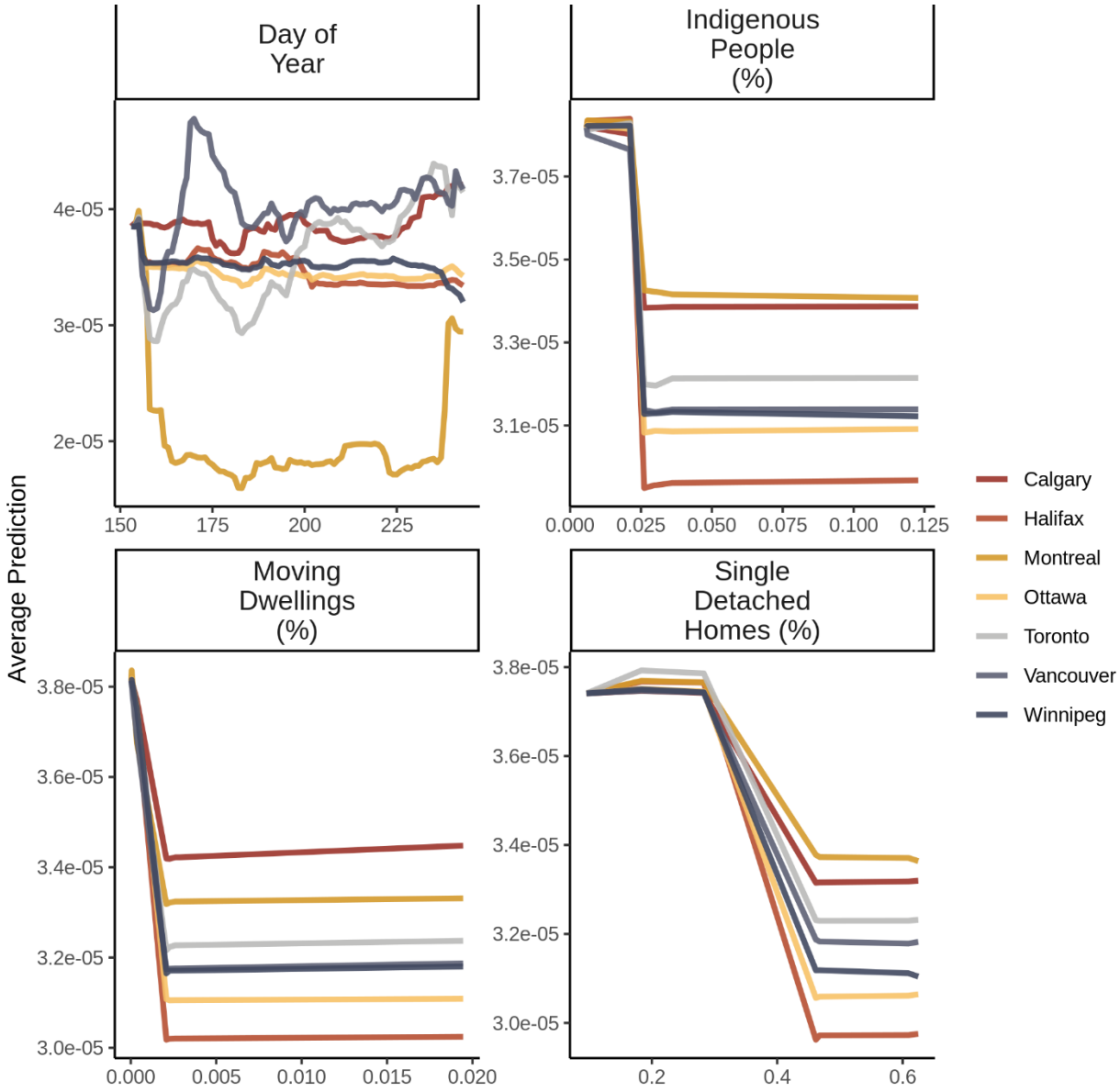


Figure 3.4: Accumulated local effects plot depicting the relationships between the most important predictive variables and average predicted nitrogen dioxide levels at the city scale. Predicted nitrogen dioxide value is the predicted nitrogen dioxide calculated from the difference between two neighbouring values.

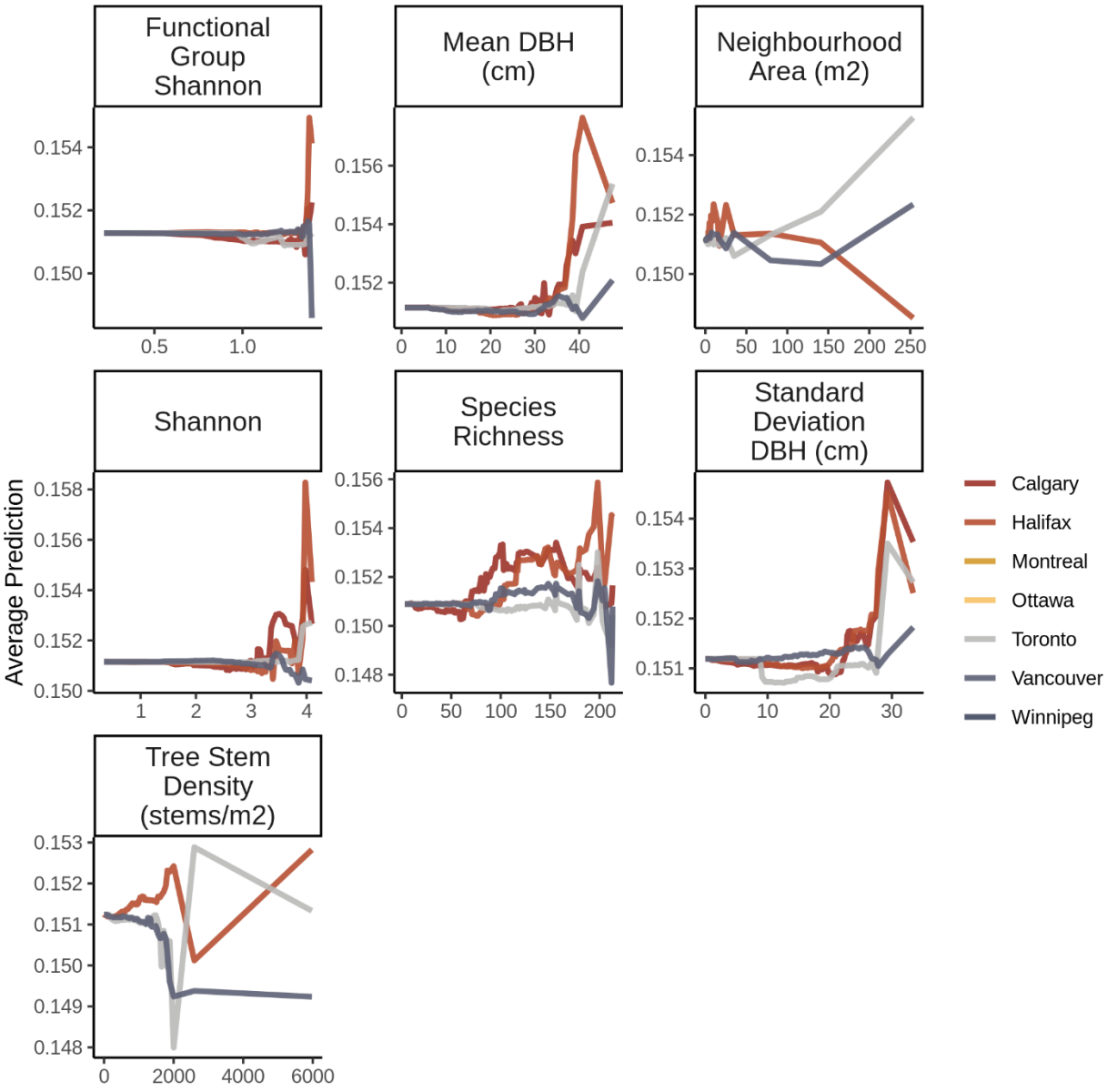


Figure 3.5: Relationships between the most important predictive variables and the predicted mean ozone levels at the neighbourhood scale. Some cities, i.e., Montreal, Ottawa, and Winnipeg, were dropped from the plot due to not enough data points in each category but are shown in the supplementary using a partial dependency plot (Fig A3.6b). Predicted ozone value is the predicted ozone calculated from the difference between two neighbouring values.

V. General Conclusion:

Thesis Objectives & Results:

In Chapter 1, I established similarities in daytime cooling provided by parks across historical conditions, likely resulting from contemporary policies that emphasize tree planting and diversity in parks. However, I simultaneously found differences in capacity for nighttime cooling, whereby parks located in areas that were industrial immediately prior to park development have a lower capacity to cool during the night. The difference in nighttime cooling effect of previously industrial parks is most likely due to landscape-scale processes, which result in a stronger overall heat island effect in these areas and highlights the limitations of greenspace management in delivering ecosystem services without broader landscape changes. This chapter also suggested the presence of systemic inequity in residents' access to nighttime cooling, as the neighbourhoods surrounding previously industrial sites had lower median incomes and higher population densities. This chapter presents both evidence of ongoing inequity based on historical conditions and evidence that contemporary management can help to overcome these issues, highlighting the importance of both long-term (i.e., decadal), and short-term (i.e., daily) temporal considerations in urban ecology.

In Chapter 2, I demonstrated that green alleys have the potential to provide more benefits than traditional, "grey" alleys, but currently lack consistency. Having conducted field measurements in two Quebec cities, we provided evidence that the establishment of a green alley leads to an increase in biodiversity support across different management regimes but does not always increase provision of the ecosystem services most desired by residents. By combining traditional ecological sampling with semi-structured interviews to answer our research question, this chapter highlights the potential to – and importance of – bringing in residents' perspectives when conducting research that attempts to quantify the benefits of nature. As green alleys are an understudied form of green infrastructure, the findings of this chapter also contribute to both knowledge and methodological gaps in urban ecology research.

Chapter 3 showed the importance of scale when predicting land-surface temperature and air pollution across Canadian cities, with the most important predictors of both changing across scales. Day of year was the most consistent important predictor of these two processes, indicating that land-surface temperature and air pollution had high variation at all scales across Canadian cities in the summer of 2024. We found that at the city scale, inequity was an important predictor of temperature and nitrogen dioxide across all seven cities, indicating that our findings of distributional inequity from Chapter 1 are not unique to Montreal. Predicted temperature was negatively associated with the percent of recent immigrants and the percent of visible minorities in a city. Predicted nitrogen dioxide was positively associated with the percent of single-family homes. The large-scale patterns of inequity as important predictors of both temperature and nitrogen dioxide across cities with extremely different sizes, demographics, and environmental conditions indicates that this is a trend that should be investigated further. Ecological form appeared as an important predictor at both the city and neighbourhood scales for temperature and ozone. The presence of ecological form variables as important predictors at city and neighbourhood scales is a finding that highlights the value of urban forestry metrics in predictive

models. The appearance of street tree variables such as functional group richness and mean size as predictors of temperature and ozone at broad scales emphasizes the importance of trees and vegetation in the urban environment. This chapter contributes to filling the gap of multi-city, multi-scale studies in Canadian urban ecology, while simultaneously highlighting the need for more high-resolution, publicly accessible datasets across the country to improve the quality of this type of study moving forward.

The overarching objective of my thesis was to identify causes and predictors of the benefits of nature within and across cities. Addressing my overall objectives across these three chapters provides insight into how the capacity for nature's benefits varies across multiple spatial and temporal scales, functions, and green infrastructure types.

Scale:

Throughout my thesis, my work added evidence to the idea that scale, both spatial and temporal, is of critical importance when discussing nature's benefits in an urban context. It is well established that cities are highly heterogeneous (Cadenasso and Pickett 2008, Gaston et al. 2013, Des Roches et al. 2021), and my work supports this claim. Local context was key to interpreting my results and providing management suggestions in every chapter. In Chapter 1, variation in cooling was high both within and among individual parks, indicating the importance of spatial scale. Additionally, historical conditions caused changes in current nighttime conditions, emphasizing the relevance of temporal scale at both historical and diurnal scales. Maximizing the cooling potential of a park relies on varied management of the forest structure and adaptation of management to the specific park in question. In Chapter 2, there were differences in the magnitude and type of benefits provided across cities. The differences in management approaches across the two cities caused changes in local results. At the within-city scale, the resident-led management style in Villeray-Sant Michel-Parc Extension, where management techniques were specific to each individual alley, meant that benefits also differed among alleys. Finally, in Chapter 3, I expanded from two cities to seven and showed that the most important variables in predicting temperature and air pollution levels are different across street, neighbourhood, and city scales. Temperature was best predicted by large-scale processes such as NDVI, street tree density, and socioeconomic conditions at the city scale. At the neighbourhood scale however, tree diversity became the most important predictor. Fine-scale temperature and air pollutants showed the importance of temporal scale, as they had high day-to-day variation and subsequently did not have many important predictor variables other than day of year in our study.

Together, my results suggest that management of our urban greenspaces and green infrastructure would benefit from being scale specific. Throughout my work, there are some more generalizable patterns. For example, the positive relationship between tree density and daytime cooling Chapter 1 is common across parks and historical conditions and the large-scale trends of inequity at the city scale in Chapter 3 hold across cities. However, for the most part, local context is critical, and solutions that improve capacity for ecosystem services at a street scale or for an individual green infrastructure project may not be the solutions that work at a neighbourhood or city scale. My thesis adds evidence demonstrating the importance of intentionally selecting spatial and temporal scales, which is relevant for urban ecology but also

for the field of urban political ecology. Urban political ecology is a field that seeks to understand the current socioeconomic conditions of cities, through investigating the social processes and dynamics of cities (Zimmer 2010). Scale is a key concept in the field, as the scale of interest for both ecological and social processes can affect the dynamics of power and control in cities and is inherently related to the social struggles faced by residents (Swyngedouw and Heynen 2003). My work can contribute to the understanding of multi-scale processes, contributing to the urban political ecology field. Further research investigating how different interventions, policies, and conditions impact the capacity for green infrastructure to provide benefits in cities must be done at multiple scales. We must assess the effects of management strategies across spatial and temporal scales, including both establishment of a project and long-term maintenance.

Multifunctionality:

My thesis measures the capacity of several different ecosystem services, or benefits of nature, and biodiversity support provided by urban nature. In many studies, there is a trade-off between depth and breadth when assessing ecosystem services. Studying a single ecosystem service allows for greater detail and complexity, though inherently narrows the focus and conclusions about urban nature. Chapter 1 focuses on one ecosystem service, temperature regulation. It is my only chapter that assesses only one ecosystem service. Reducing impacts of the urban heat island effect is a major challenge in Canadian cities (Jandaghian and Akbari 2021, Boudreault et al. 2024) and a highly complex phenomenon (Mokhtari et al. 2022, Benaomar and Outzourhit 2024). As such, understanding the mechanisms of temperature regulation in cities often requires the in-depth, detailed analysis afforded by studies with evaluating only one ecosystem service. However, urban green infrastructure serves many roles (van Leeuwen et al. 2010). We expect our parks, green alleys, and other types of green infrastructure to be spaces that provide a myriad of benefits (Jabbar et al. 2022). For example, a public park may be designed and used for temperature regulation, flood control, access to nature, and as a space for social connection and recreation (Shi and Woolley 2014, Lafrenz 2022). Given the varied expectations we have for our green spaces, assessing green infrastructure's capacity to provide multiple ecosystem services is highly relevant for researchers and decision-makers making recommendations and/or decisions aimed to optimize the delivery of ecosystem services.

In addition to expanding from a single city to multiple, I expanded my single service approach from Chapter 1 in both my subsequent chapters. In Chapter 2, I assessed multiple ecosystem services as well as multiple forms of biodiversity support provided by green alleys. I measured ecosystem services and biodiversity support because increasingly, municipalities and residents are prioritizing benefits for nature, such as biodiversity support and ecosystem functioning, in addition to ecosystem services (Newell et al. 2013, Kremen and Merenlender 2018). The literature has established that providing both benefits for nature and benefits for people can be in conflict and decisions may result in trade-offs (Nassauer 1993, Larson et al. 2020, Lis et al. 2022). Conducting interviews highlighted that residents design and use their green alleys to obtain multiple ecosystem services, which span cultural, regulating, and provisioning categories. We also found that green alleys are adapted for providing biodiversity support. In our system, the desired ecosystem services and ecological benefits were often in

harmony, suggesting that it is possible to have a synergistic relationship between humans and nature in our green infrastructure projects.

In Chapter 3, I assessed two ecosystem service proxies while using a multi-scale approach that is both within and across cities. By assessing the extent to which natural elements of cities predicted both temperature and air pollution (i.e., provided multiple ecosystem services), we were able to identify potential generalities across scales and cities, providing an opportunity to highlight potential synergies and trade-offs between services. Our results suggest that predictors of temperature and air pollution in Canadian cities are largely different with respect to the variables we used. This suggests that ecosystem services should be considered simultaneously, as there are potential trade-offs when attempting to design urban spaces that reduce both land-surface temperature and air pollution. While a predictive study can't identify causal relationships between variables, our study is among the first to compare predictors of ecological form, urban form, and sociodemographics across multiple Canadian cities at multiple spatial scales, and can be used to generate hypotheses and highlight areas of future study based on patterns that emerge.

Including multiple ecosystem services in Chapters 2 and 3 allowed us to identify when different management strategies may be able to provide multiple ecosystem services and therefore resist making recommendations that may increase capacity of a single ecosystem service at the detriment of others. For example, increasing the number of fruit trees in green alleys would increase the presence of flowers, which was identified as an important ecosystem service by residents. However, due to the small stature of fruit trees, they may not regulate temperature or increase overall "greenness" as much as a different type of tree. Thus, based on local context we would recommend planting fruit trees in green alleys though mixed with other species and types of trees so as to not decrease other types of ecosystem services. Given that the many demands on urban nature are continuing to increase (Grima et al. 2020, Jevtic et al. 2022), understanding synergies and trade-offs between multiple ecosystem services, biodiversity support, and resident needs is necessary. Moving forward, studies should prioritize integrating the effects of different variables, interventions or preferences on multiple ecosystem services to be able to plan for future distribution of urban nature and its benefits.

Green infrastructure types:

There is a need for many types of green infrastructure to improve our quality of life, as different types of green infrastructure provide different types of benefits (Evans et al. 2022). My first chapter studied the cooling effect of parks, which is one of the most studied green infrastructure types in urban ecology (Ying et al. 2022). Although well studied, my work provided evidence that historical conditions of parks – largely ignored in contemporary urban ecology studies – do matter with respect to cooling, a highly valued ecosystem service. Additionally, I found that the forest structure and composition of parks is dependent both on current day management and historical conditions. Finally, I established that tree density causes cooling differences, which has implications for management in our system. My work emphasizes the importance of the historical aspects of this type of green infrastructure for future work and provides evidence that

can inform management decisions for this critically important type of urban green infrastructure in our cities.

Like public parks, street trees are a type of green infrastructure that has been extensively studied in urban ecology (Chatzimentor et al. 2020, Ying et al. 2022). In Chapter 3, I use publicly available street tree inventories to do a cross-city cross-scale study of air temperature and air pollution, which would not be possible in Canada with another type of green infrastructure. My work suggests that there is a link between street tree size, diversity, and density and land-surface temperature and ozone levels at neighbourhood and city scales. The predictive link between these variables suggests that further research should be done across Canadian cities to test causal relationships between street trees and temperature and air pollution, thereby providing an opportunity for targeted management strategies. The centralized management nature of publicly owned street trees means that it is easier, though not simple, to implement policies based on scientific research. Also, street tree management programs often have specific goals outlined by the city, including tree planting to increase ecosystem services such as temperature regulation and increasing biodiversity (Ordóñez Barona et al. 2024). Given that street trees are a large proportion of the urban forest and are managed on a municipal scale, providing direction for future research and potential management recommendations for this green infrastructure type on a large scale can be meaningful and an efficient way to increase ecosystem services across a city.

In contrast to public parks and street trees, green alleys are a relatively understudied form of green infrastructure. Alleys are very different spaces from other, more commonly studied types of green infrastructure and require more work on how to best assess their capacity to provide nature's benefits (Dade et al. 2024). My work in Chapter 2 adds to a growing body of literature that establishes green alleys as a viable space to provide both ecosystem services and biodiversity support in densely built areas of our cities, where access to nature and its benefits is often most lacking. The green alleys in our studies provide multiple ecosystem services and forms of biodiversity support at higher levels than traditional alleys. I also show that biodiversity support and ecosystem services desired by residents can be synergistic and that with expert support that is maintained over time, residents and cities can build green alleys that meaningfully improve quality of life. Future work should continue to assess the benefits of green alleys, as we don't yet know all the benefits we are able to cultivate in green alleys and what design strategies would maximize these benefits.

Management implications:

In Chapter 1, I show that there is a density-size trade-off in parks where large trees are often isolated and dense trees are often small. Because of this trade-off, tree density is the main driver of cooling but has a positive relationship with daytime cooling and a negative relationship with nighttime cooling. These findings suggest that in the situation where large, dense trees are not maintainable, it is preferable to plant smaller, denser trees if daytime cooling is the goal. However, denser stands of smaller trees have the potential to trap heat at night and so balancing dense treed areas with more open areas with large trees that allow heat to escape may facilitate both daytime and nighttime cooling. This approach is consistent with the "savannah approach" which suggest a diverse composition and configuration of vegetation to allow for both daytime

and nighttime cooling (Kraemer and Kabisch 2022). In this chapter I also highlight that in previously industrial areas residents are being underserved with respect to nighttime temperature, which is a particularly concerning management issue as excessive heat is most dangerous to human health at night (Iungman et al. 2023). One of the ways to combat this issue is to increase the amount of vegetation in these areas, especially as they have higher population densities than areas surrounding parks developed on previously agricultural or previously forested land. However, these interventions need to be coupled with housing policies that resist the processes of gentrification and promote community-led design (Goossens et al. 2020, Parish 2020, Triguero-Mas et al. 2021). Otherwise, greening efforts can result in both psychological and physical displacement of the communities that new green spaces are intending to serve (Anguelovski 2016, Sax et al. 2022). We present evidence on this issue, where across all parks, there are lower rates of recent immigrants and visible minorities than we would expect given the Montreal average in the immediately surrounding area. Intentional and community-led management of all areas is needed to preserve the residents' sense of place and access to housing while simultaneously addressing the inequitable nighttime urban heat with green infrastructure.

Our Chapter 2 results suggest that allowing a municipality to manage green alleys to achieve ecosystem services and biodiversity support may be a good option due to their technical expertise. However, in Trois-Rivieres this approach did not leave room for adapting the green alleys to the needs and wants of residents, and in this instance, it focused on only a single ecosystem service, i.e., stormwater management, to the detriment of others. In Villeray-Saint Michel-Parc Extension, the biodiversity support and ecosystem services were extremely variable across green alleys. The resident-led aspect of this approach meant that residents often felt very attached to their alley, the process of alley transformation increased residents' sense of community, and in some cases the green alley was specifically designed to the needs of the residents. However, the maintenance of green alleys over time and the expertise required to design green alleys to truly meet the needs of residents were both shortfalls of the current resident-led management system. In both cities, integrating the expertise of municipal employees and/or local researchers and practitioners to help residents design their green alleys would help to address these issues (Brazeau-Béliveau and Cloutier 2021). Many residents wanted ecosystem services that were aligned with both the city's environmental priorities and biodiversity support but lacked the expertise to design a green alley that delivered those aspects. Experts working with residents to design their green alleys may preserve the benefits of both top-down and bottom-up approaches by providing the expertise needed to actualize the visions of residents. Additionally, ongoing maintenance funding must be available for these projects to be successful, as many residents do not have access to the disposable income required to maintain green alley projects after establishment, thereby decreasing the biodiversity support and ecosystem services provided over time.

Given the predictive approach to Chapter 3, it is difficult to translate our results into direct management recommendations. However, our work generates several hypotheses for future studies that would have management implications. My study identifies inequity as an important predictor for both temperature and air pollution across 7 Canadian cities. Environmental inequity has been established as part of Canadian cities (Pham et al. 2012, Landry

et al. 2020, Martin et al. 2025b). My study predicting this trend across cities that include relatively understudied city types such as prairie cities highlights the need for work that establishes causal links between these variables and finding areas where the trend does not hold. I have published the datasets and code associated with my analysis, which provide a valuable resource for future cross-city urban ecology research in Canadian cities. Additionally, the presence of ecological form variables as important predictors of both land-surface temperature and ozone across Canadian cities at broad scales indicates the importance of our urban forest. Finally, the complex relationships between ozone and street tree size, density, and diversity and between land-surface temperature and functional group richness indicate that there are some effects of trees on temperature and air pollution that are species specific. This requires an understanding of the local context to manage for, as species composition is a highly local issue. We recommend the continued investigation of relationships between ecological form and temperature and air pollution across Canadian cities with the newly released Open Urban Forests project, which would facilitate management recommendations that could impact cities across the country (Canadian Institute of Forestry 2025).

Future directions:

In Chapter 1, my conclusions stimulated several interesting future research questions. Due to the variation in cooling within individual parks, looking at the relationships between historical legacies, park layout, and cooling capacity would be an interesting future study. Further, I was unable to test the causal relationship between historical socioeconomic conditions and current cooling capacity due to a lack of data. To do so, I would have needed the demographic composition of the neighbourhoods surrounding the parks during the time of their establishment. These data are available for some of the study parks thanks to the Canadian census, but for many of the older parks these data were not accessible. This link is a critical piece of the puzzle in determining the legacies of inequity in our cities and would be an excellent contribution to the field in Montreal or otherwise. Finally, expanding this study to include the effects of historical land-use on other ecosystem services, especially cultural ecosystem services, would allow us to plan and manage our cities for more equitable service distribution in the future.

The main limitation of Chapter 2 was the sole focus on trees as supports for biodiversity support and ecosystem services. Green alleys are often designed around herbaceous vegetation, and moving forward expanding on our study to include the biodiversity support and ecosystem services provided by other vegetation types is a promising next step. Further, explicitly testing the areas of trade-offs and synergies between biodiversity support and ecosystem services would allow better design and management of green spaces. Finally, further assessing capacity for cultural and provisioning ecosystem services in green alleys is a natural extension of our work, as many of the ecosystem services mentioned by residents in our study fell within those categories.

My third chapter highlighted that there are many future directions left to tackle with respect to multi-city studies in Canada. As data increasingly becomes available, integrating park tree and private tree databases into cross-city studies to have a more complete picture of the urban forest is an exciting extension of this work. However, Canada suffers from a lack of data

availability. It is difficult to access high-quality, relevant data for many Canadian cities, which makes multi-city studies challenging. For example, most Canadian cities do not publish high-resolution data on land-cover or impervious surface cover and these data are not available nationally, even though they are extremely useful in multi-city studies. Additionally, given that most cities in Canada are small to medium sized (Government of Canada and Statistics Canada 2022), continuing this work to find similar patterns in smaller cities is highly relevant for management recommendations in the Canadian context. Expanding this work to include other ecosystem services and find hotspots across different contexts could also help to find large-scale patterns that benefit urban greening in Canadian cities.

My work also inevitably led me to many cross-cutting questions and research directions that I could not address during my PhD. One theme that consistently appeared as integral to effective management and success of urban greening was community-led projects (Crowley et al. 2021). Building relationships and collaborating with communities to conduct research is difficult and can lead to research outcomes that are different from those typically produced in the traditional academic routes (Minkler 2005). However, the purpose of green infrastructure is to improve the quality of life and environment for urban residents, whether that is through improved stormwater management or an improved connection to nature (Grabowski et al. 2022). To provide management recommendations that achieve that goal, it is necessary to integrate the needs and wants of the communities one is trying to serve (Semenza et al. 2007, Sax et al. 2022). Thus, moving forward, more research and greening projects grounded in the bottom-up desires of residents and community is necessary.

Throughout my work my relationship with the framework of ecosystem services has evolved. In my introduction, there is a strong emphasis on ecosystem services. However, as my work continues through my thesis, I find myself shifting to more generic “benefits” language. The framework of ecosystem services, like any framework, has its weaknesses (Díaz et al. 2015, Chan et al. 2025). Notably, it overrepresents an instrumental value system in our scientific research and policy (IPBES 2022). We are currently missing both relational and intrinsic value systems in our scientific evidence and resulting policy, as ecosystem services are designed to highlight benefits that are unidirectional, i.e., benefits that go from nature to people (IPBES 2022). To me, this weakness makes it difficult to use ecosystem services to do urban ecology, which is a space filled with many value systems and especially relational values. Adjusting our research approach from the framework of ecosystem services to include relational and intrinsic values will make our scientific literature and policy more robust and will better represent the systems that we are trying to study. There has been some work moving in this direction in recent years, namely the nature’s contributions to people (Díaz et al. 2015) and nature with people (Reyers and Bennett 2025) frameworks. Moving forward, I believe that using frameworks alternative to ecosystem services such as the nature with people framework will allow urban ecologists to more accurately assess the value of nature to people and thus manage our cities to be places where people connect with nature more and the benefits of nature are delivered more equitably.

Conclusion:

Urban ecosystems are expanding and provide most the world's people with opportunities to experience nature, providing connection to people who are increasingly disconnected from natural processes (Beery et al. 2023). Urban ecologists are in an extremely lucky position, we are contributing to a field that is highly relevant, dynamic, and working towards a more interdisciplinary, just, and engaged paradigm (Byrne 2022, Frantzeskaki et al. 2024). Change in urban systems has the potential to affect millions of people and be a key driver of climate adaptation (Egerer et al. 2021). The future of urban ecology is hopeful, full of opportunities to do better, and will be driven by the communities that are affected the most.

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VII. Appendices

Appendix 1: *Chapter 1 Supplementary Materials*

Table A1.1: Historical data sources used to reconstruct history of park sites to extract previous land-cover type and age of park.

Title	Organization	Data Type	Date	Link
D1900-1 : Parcs - Administration	Archives de Montréal	Historical documentation	[18-]-[19-]	https://archivesdemontreal.ica-atom.org/d1900-1-parcs-administration-18-19
D1901-18-1 : Parcs et terrains de jeux : Parc Baldwin - Historique.	Archives de Montréal	Historical documentation	[18-]-[19-]	https://archivesdemontreal.ica-atom.org/d1901-18-1-parcs-et-terrains-de-jeux-parc-baldwin-historique-18-19
D1901-38-30-3 : Parcs et terrains de jeux : Parc La Fontaine - Historique - Documents.	Archives de Montréal	Historical documentation	[18-]-[19-]	https://archivesdemontreal.ica-atom.org/d1901-38-30-3-parcs-et-terrains-de-jeux-parc-la-fontaine-historique-documents-18-19
D1925-2 : Parcs - Jardin botanique : Historique.	Archives de Montréal	Historical documentation	[18-]-[19-]	https://archivesdemontreal.ica-atom.org/d1925-2-parcs-jardin-botanique-historique-19
D1925-3 : Parcs -	Archives de Montréal	Historical documentation	[19-]	https://archivesdemontreal.ica-

Jardin botanique : Construction.				atom.org/d1925-3-parcs-jardin-botanique-construction-19
D3040-12-A : Ile Bizard : Général.	Archives de Montréal	Historical documentation	[19-]	https://archivesdemontreal.ica-atom.org/d3040-12-a-ile-bizard-general-19
D3050-23-19 : Ville - Pierrefonds : Parcs.	Archives de Montréal	Historical documentation	[19-]	https://archivesdemontreal.ica-atom.org/d3050-23-19-ville-pierrefonds-parcs-19
D1900-A-4 : Parcs et terrains de jeux - Répertoire alphabétique : Général.	Archives de Montréal	Historical documentation	Après 1957	https://archivesdemontreal.ica-atom.org/d1900-a-4-parcs-et-terrains-de-jeux-repertoire-alphabetique-general-apres-1957
D1900-A-4 : Parcs et terrains de jeux - Répertoire alphabétique : Général.	Archives de Montréal	Historical documentation	Avant 1958	https://archivesdemontreal.ica-atom.org/d1900-a-4-parcs-et-terrains-de-jeux-repertoire-alphabetique-general-avant-1958
D1901-17-1 : Parcs et terrains de jeux - Île Sainte-Hélène :	Archives de Montréal	Historical documentation	Avant 1961	https://archivesdemontreal.ica-atom.org/d1901-17-1-parcs-et-terrains-de-jeux-ile-sainte-helene-historique-avant-1961

Historique.				
D1900-A-1 : Parcs et terrains de jeux : Général.	Archives de Montréal	Historical documentation	Après 1971	https://archivesdemontreal.ica-atom.org/d1900-a-4-parcs-et-terrains-de-jeux-repertoire-alphabetique-general-avant-1958
D1900-A-1 : Parcs et terrains de jeux : Général.	Archives de Montréal	Historical documentation	Avant 1972	https://archivesdemontreal.ica-atom.org/d1900-a-1-parcs-et-terrains-de-jeux-general-avant-1972
Photothèque 1930-2003	Division de la géomatique	Satellite imagery	1930-2003	https://www.arcgis.com/apps/webappviewer/index.html?id=b4d43eb1a247498c85034ef1d47bd98b
Carte de localisation des anciennes carrières et des dépôts de surface de la Ville de Montréal	Division Soutien Technique, Infrastructures, CESM	Historical documentation, spatial data	2023	https://www.arcgis.com/apps/webappviewer/index.html?id=eddfe22f7ef54982a6545e8eb3c86a9a
Angrignon	Personal website	Historical documentation		https://www.angrignon.ca/gene/indexg1.html
Analyse de la valeur patrimoniale de la	Arrondissement Pierrefonds-Roxboro	Historical documentation	2008	http://ville.montreal.qc.ca/pls/portal/docs/PAGE/CONS_PAT_MTL_FR/MEDIA/DOCUMENTS/MAIS

Maison Jacques Richer dit Louveteau				ON_JACQUES_RICHER_DIT_LOUVETEAU_JANVIER_2008.PDF
Le parc Thomas-Chapais	WWF	Historical documentation	2016	https://wwf.ca/wp-content/uploads/2016/11/Thomas-Chapais_Caract%C3%A9ristiques_%C3%A9cologiques.pdf
Historique de Tétreaultvill	Comité citoyen du parc Thomas-Chapais	Historical documentation		https://comitecitoyenduparcthomas-chapais.ca/historique/
Le Douglas: une longue histoire d'excellence	Douglas Research Centre	Historical documentation		https://douglas.research.mcgill.ca/fr/historique/
Le boisé de Saint Sulpice	Blog	Historical documentation	2020	https://floraurbana2.blogspot.com/2020/06/le-boise-de-saint-sulpice.html
Ancien Dépotoir du Boisé de l'Heritage	Gestion des Lieux Contaminés	Historical documentation	1987	https://drive.google.com/file/u/1/d/133JOw0GVkMOqn6vJgWIZVT55Sc44_cJn/view?usp=embed_facebook
Ancien Dépotoir Beaubien	Gestion des Lieux Contaminés	Historical documentation	1991	https://drive.google.com/file/u/1/d/133JOw0GVkMOqn6vJgWIZVT55Sc44_cJn/view?usp=embed_facebook
Extrémité Sud et Sud-Ouest de	Gestion des Lieux Contaminés	Historical documentation	1991	https://drive.google.com/file/u/1/d/133JOw0GVkMOqn6vJgWIZVT55Sc44_cJn/

l'Ile-des-Soeurs				view?usp=embed_facebook
Commission de toponymie	Gouvernement du Québec	Historical documentation	2023	https://toponymie.gouv.qc.ca/ct/
Maison Saint-Gabriel	Grand répertoire du patrimoine bati de Montréal	Historical documentation	2012	http://patrimoine.ville.montreal.qc.ca/inventaire/fiche_zone.php?affichage=fiche&civique=&voie=0&est_ouest=&appellation=&arrondissement=9&protection=0&batiment=oui&zone=oui&lignes=25&type_requete=simple&id=1176
Ancien Dépotoir du Parc Lafond	Group d'étude et de restauration des lieux d'élimination des déchets dangereux	Historical documentation		https://drive.google.com/file/d/1egb2BQx4WXT0hOkVuG8fG3BIX-BPaGbY/view
Détection de biogaz au Parc Baldwin	Ville de Montréal	Historical map	1992	https://drive.google.com/file/u/1/d/1HkSGrBr4q5Q9qL1U4lNMLaCZb4sGQV5L/view?usp=embed_facebook
Parc-nature de l'Anse-à-l'Orme	Laboratoire d'histoire et de patrimoine de Montréal	Historical documentation		https://chronomontreal.uqam.ca/chronologie/2154-parc-nature-de-l-anse-a-l-orme
Parc-nature du Bois-de-Liesse	Laboratoire d'histoire et de patrimoine de Montréal	Historical documentation		https://montreal.ca/toponymie/toponymes/parc-regional-du-bois-de-liesse
History of Centennial Hall and				

Memorial Park	Personal report	Historical documentation	2013	https://www.shbbhs.ca/j3/images/RAngelContest/Works/2013Centennial%20Hall%20and%20Memorial%20Park,%20Isabelle.pdf
Fritz Farm Planning Committee, N&V, Sep 1980	Town Hall report	Historical documentation	1980	http://home.linuxfocus.org/~guido/book-a-history-of-the-town-of-baie-d-urfe/then-and-now/2020-08-09_1734-088-nv-sep-1980-fritz-park-planing.html
Le Domaine Saint-Sulpice, un quartier en partage	Société D'Histoire d'Ahuntsic-Cartierville	Historical documentation	2015	https://www.lashac.com/panneaux-historiques.html
Adrien-D. Archambault	Société Historique de Montréal	Historical documentation	2020	https://www.societehistoriquedemontreal.org/notre-histoire/liste-des-presidents-depuis-la-fondation/adrien-d-archambault/
Parcours riverain	Ville de Montréal	Historical documentation, spatial data	2023	https://donnees.montreal.ca/dataset/parcours-riverain
Répertoire historique des toponymes	Ville de Montréal	Historical documentation	2023	https://montreal.ca/toponymie/
Le parc Frédéric-Back : une	Ville de Montréal	Historical documentation	2023	https://montreal.ca/articles/le-parc-frederic-back-une-metamorphose-

métamorphose unique				unique-18997

Table A1.2: Park names, ID, legacies (i.e., past land use(s)), the municipalities parks are found in, and if they are in the City of Montreal, their borough, the year they were established, the number of temperature sensors deployed in each park, and the number of temperature sensors retrieved at the end of the season. An ID that begins with CON indicates a control sensor, found in a parking lot at least 500 m away from the associated park(s). Benny park had all three sensors stolen and was thus removed from the temperature analysis.

Park	Park ID	Legacy(ies)	Municipality	Borough	Year Established	Sensors deployed	Sensors Retrieved
Adrien-D-Archambault	IND1	Industrial	Montreal	Verdun	2002	3	3
Angrignon	FOR1, AGR1	Forested, Agricultural	Montreal	Le Sud-Ouest	1927	6	5
Arborétum du Jardin botanique	IND7	Industrial	Montreal	Rosemont-La Petite-Patrie	1936	3	3
Arthur-Therrien	IND2	Industrial	Montreal	Verdun	~ 1964	3	3
Baldwin	IND3	Industrial	Montreal	Le Plateau-Mont Royal	1909	3	3
Benny	AGR7	Agricultural	Montreal	Notre-Dame-de-Grâce	1965	3	0
Boisé-du-Saint-Sulpice	FOR4	Forested	Montreal	Ahuntsic-Cartierville	1990	3	3
Bois-de-Liesse	FOR2	Forested	Montreal	Pierrefonds-Roxboro / Saint-Laurent	1987	3	3
Bois-de-Saraguay	FOR3	Forested	Montreal	Ahuntsic-Cartierville	1987	3	3

Cap-Saint-Jacques	FOR5, AGR2	Forested, Agricultural	Montreal	Pierrefonds-Roxboro	1985	6	6
Centennial Hall	AGR8	Agricultural	Beaconsfield		1945	3	3
Coulée-Grou	FOR6	Forested	Montreal	Rivière-des-Prairie-Pointe-aux-Trembles	1988	3	3
Félix-Leclerc	IND5	Industrial	Montreal	Mercier-Hochelaga-Maisonneuve	1990	3	2
Frédéric-Back	IND6	Industrial	Montreal	Vileray-Saint Michel-Parc Extension	2016	3	2
Fritz	AGR9	Agricultural	Baie-d'Urfe		1979	3	3
Île-Bizard	FOR7, AGR3	Forested, Agricultural	Montreal	L'Île-Bizard–Sainte-Geneviève	1991	6	6
Jean-Drapeau	FOR8	Forested	Montreal	Ville-Marie	1908	3	3
L'Anse-à-L'Orme	FOR9, AGR4	Forested, Agricultural	Montreal	Pierrefonds-Roxboro / Saint-Laurent	1987	6	6
Lafond	IND8	Industrial	Montreal	Rosemont-La Petite-Patrie	1952-1955	3	3
Lafontaine	AGR5	Agricultural	Montreal	Le Plateau-Mont-	1901	3	1

				Royal			
Lalancette	IND9	Industrial	Montreal	Mercier-Hochelaga-Maisonneuve	1922	3	1
Marguerite-Bourgeoys	AGR6	Agricultural	Montreal	Le Sud-Ouest	1913	3	3
Père-Marquette	IND11	Industrial	Montreal	Rosemont-La Petite-Patrie	1953	3	3
Pointe-Aux-Prairies	IND12, FOR10, AGR11	Industrial, Forested, Agricultural	Montreal	Rivière-des-Prairies-Pointe-aux-Trembles	1992	8	7
Promenade-Bellerive	IND13	Industrial	Montreal	Mercier-Hochelaga-Maisonneuve	1978	3	2
Saint-Gabriel	AGR10	Agricultural	Montreal	Le Sud-Ouest	1887	2	1
Thomas-Chapais	FOR11	Forested	Montreal	Mercier-Hochelaga-Maisonneuve	1960	3	1
Coulée-Grou + Pointe-Aux-Prairies	CON-PaP-CG	Control	Montreal	Rivière-des-Prairies-Pointe-aux-Trembles		1	1
Promenade-Bellerive	CON-P-B	Control				1	1

Félix-Leclerc	CON-F-L	Control				1	1
Frédéric-Back + Boisé-du-Saint-Sulpice	CON-FB-SS	Control				1	1
Arborétum du Jardin botanique + Lafond + Lalancette	CON-LAL-LAF-JAR	Control				1	1
Lafontaine + Baldwin + Jean-Drapeau	CON-LAF-BAL	Control				1	0 (supplemented sensor)
Père-Marquette	CON-P-M	Control				1	1
Marguerite-Bourgeoys + Saint-Gabriel	CON-MB-SG	Control				1	1
Adrien-D-Archambault	CON-ADA	Control				1	1
Arthur-Therrien	CON-AT	Control				1	1
Angrignon	CON-ANG	Control				1	1
Benny	CON-BEN	Control				1	1
Bois-de-Liesse	CON-BDL	Control				1	1
Bois-de-Saraguay	CON-BDS	Control				1	1

Île-Bizard	CON-IB	Control				1	1
Centennial Hall	CON-CENTENNIAL	Control				1	1
Fritz	CON-Fritz	Control				1	1
Cap-Saint-Jacques + L'Anse-à-L'Orme	CON-LALO-CSJ	Control				1	1

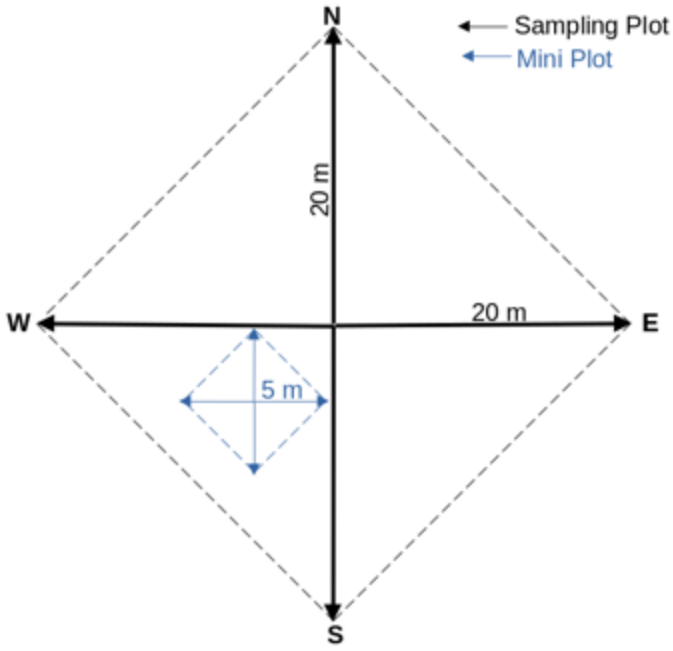


Figure A1.1: Sampling plot configuration. Mini-plot was located in the most representative part of the larger plot, as decided in the field. Mini-Plot Information: due to the nature of the permits we received, most of the "full plot" sampling of trees < 5 cm was done in typical urban parks (n = 11/14 parks). These parks are characterized by large grassy lawns, with a low density of very large deciduous trees. There are sometimes new plantings which results in small trees, but very few of them. For many of these plots, there were no trees < 5 cm even when the "full plot" is used. We switched to the mini plot method when we started sampling "nature parks", where there is a more natural forest ecosystem. In these systems, we could find hundreds of trees < 5 cm, even within our mini plot. Thus, the full plots are very similar or identical to what the mini plots would look like in the majority of cases, as they either have 0 or 1 trees < 5 cm.



Figure A1.2: Example sensor setup. Sensor is a CredoSense CSL-T0.5 temperature logger located within a 3-D printed shield and hung with an informational flyer containing the contact information of the lead author. Photo taken by Isabella C Richmond.

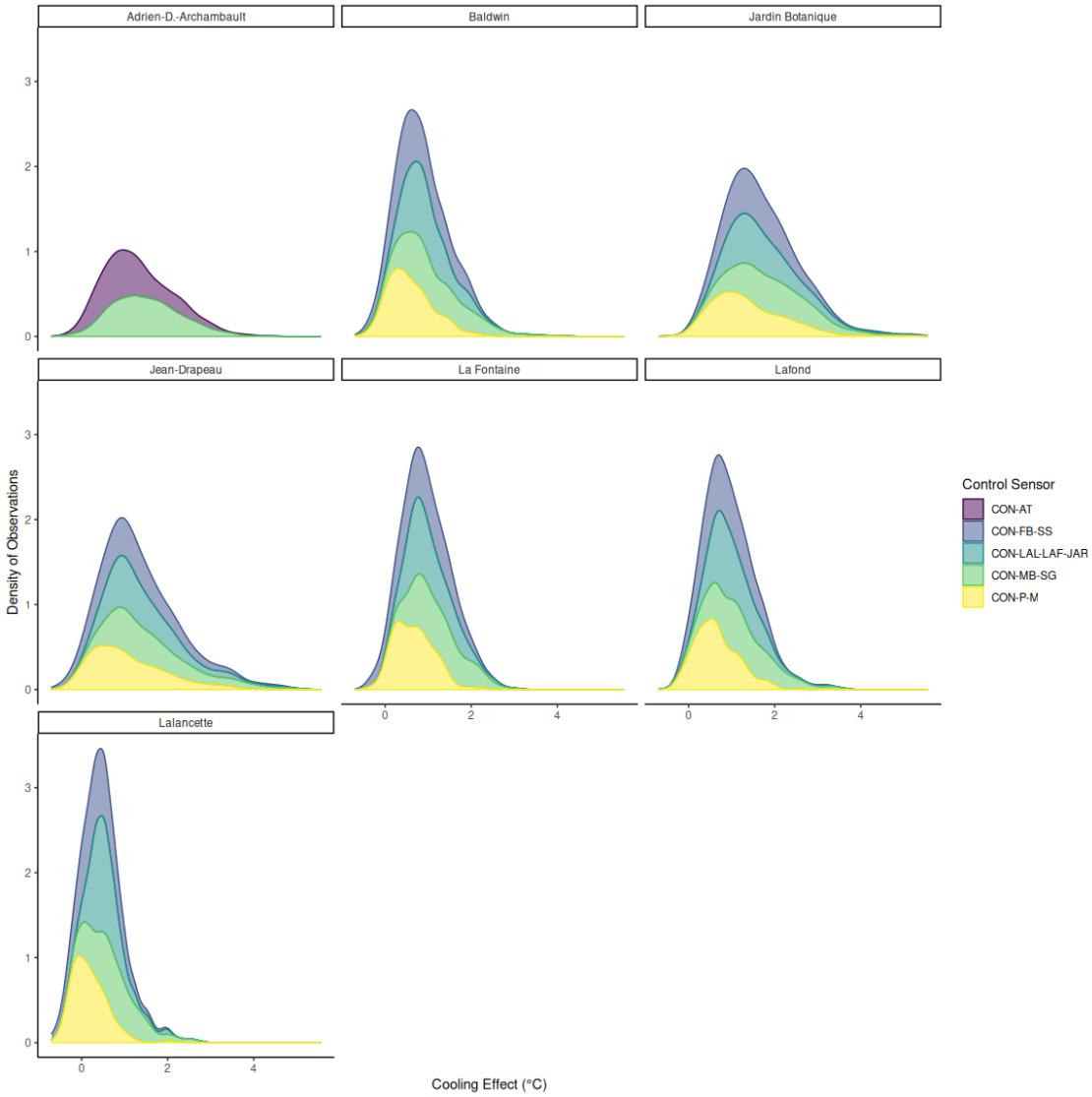


Figure A1.3: Sensitivity analysis showing the cooling effect across all dates for each park where the control sensor was replaced due to missing data. Plots were made with the remaining control sensors closest to the park in question. CON-LAL-LAF-JAR indicates the control sensor that we used from another, similar study.

Figure A1.4: Below are the math stats notations for all models run in our paper.

Total Effect of Past Land-Use on Cooling Effect:

$$Cooling_i \sim Normal(\mu_i, \sigma)$$
$$\mu_i \sim \alpha_{Park[i]} + \alpha_{Plot[i]} + \gamma_{PLU[i]} + \gamma_{tod[i]} + \beta_{PLU} tod + \beta_{PLU[i]} + \beta_{tod[i]} + \beta_{age} age_i$$
$$\alpha_{Park[j]} \sim Normal\left(\acute{\alpha}, \sigma_{\alpha_{Park}}\right)$$
$$\alpha_{Plot[j]} \sim Normal\left(0, \sigma_{\alpha_{Plot}}\right)$$
$$\gamma_j \sim Normal(0,0.5)$$
$$\beta_j \sim Normal(0,0.5)$$
$$\acute{\alpha} \sim Normal(0,0.5)$$
$$\sigma_{\alpha_{Park}} \sim Half - Normal(0,0.2)$$
$$\sigma_{\alpha_{Plot}} \sim Half - Normal(0,0.2)$$
$$\sigma \sim Exponential(1)$$

- α and γ both represent intercepts, α is used for random effects and γ for fixed interaction effects
- $Cooling_i$ is the centered and scaled cooling effect in each plot in degrees Celsuis
- $Park_i$ is the park that each plot is in
- $Plot_i$ is the plot that each measurement is in
- PLU_i is the past land use category that each measurement is in (i.e., agricultural, forested, industrial)
- d_i is the time of day category that each measurement is in (i.e., daytime, nighttime)
- age_i is the centered and scaled age of the park that each measurement is in

Direct Effect of Past Land-Use on Forest Composition:

Large Tree Density

$$DensL_i \sim Normal(\mu_i, \sigma)$$
$$\mu_i = \alpha + \beta_1 forested_{[i]} + \beta_2 industrial_{[i]}$$
$$\alpha \sim Normal(0,0.5)$$
$$\beta_j \sim Normal(0,0.5)$$
$$\sigma \sim Exponential(1)$$

Where:

- $DensL_i$ is the centered and scaled basal area of large trees in each plot
- forested is the factor level from PastLandUse that indicates previously forested parks. Previously agricultural parks are the default level, absorbed into the intercept.
- industrial is the factor level from PastLandUse that indicates previously forested parks. Previously agricultural parks are the default level, absorbed into the intercept.

Small Tree Density

$$log(DensS_i) \sim Normal(\mu_i, \sigma)$$
$$\mu_i = \alpha + \beta_1 forested_{[i]} + \beta_2 industrial_{[i]}$$
$$\alpha \sim Normal(0,0.5)$$
$$\beta_j \sim Normal(0,0.5)$$
$$\sigma \sim Exponential(1)$$

- $log(DensS_i)$ is the centered and scaled density of small trees in each plot. Logged for model fit.
- forested is the factor level from PastLandUse that indicates previously forested parks. Previously agricultural parks are the default level, absorbed into the intercept.
- industrial is the factor level from PastLandUse that indicates previously forested parks. Previously agricultural parks are the default level, absorbed into the intercept.

Large Tree Size

$$L_i \sim Normal(\mu_i, \sigma) \mu_i = \alpha + \beta_1 forested_{[i]} + \beta_2 industrial_{[i]} \alpha \sim Normal(-1,0.5) \beta_j \sim Normal(0,0.5) \sigma \sim Exponential(1)$$

- L_i is the centered and scaled median size of large trees in each plot.
- forested is the factor level from PastLandUse that indicates previously forested parks. Previously agricultural parks are the default level, absorbed into the intercept.
- industrial is the factor level from PastLandUse that indicates previously forested parks. Previously agricultural parks are the default level, absorbed into the intercept.

Small Tree Size

$$S_i \sim Normal(\mu_i, \sigma) \mu_i = \alpha + \beta_1 forested_{[i]} + \beta_2 industrial_{[i]} \alpha \sim Normal(1,0.5) \beta_j \sim Normal(0,0.5) \sigma \sim Exponential(1)$$

- S_i is the centered and scaled median size of small trees in each plot.
- forested is the factor level from PastLandUse that indicates previously forested parks. Previously agricultural parks are the default level, absorbed into the intercept.
- industrial is the factor level from PastLandUse that indicates previously forested parks. Previously agricultural parks are the default level, absorbed into the intercept.

Large Tree Species Richness

$$SRL_i \sim Normal(\mu_i, \sigma)$$
$$\mu_i = \alpha + \beta_1 forested_{[i]} + \beta_2 industrial_{[i]}$$
$$\alpha \sim Normal(2,1)$$
$$\beta_j \sim Normal(0,0.5)$$
$$\sigma \sim Exponential(1)$$

- SRL_i is the centered and scaled species richness of large trees in each plot.
- forested is the factor level from PastLandUse that indicates previously forested parks. Previously agricultural parks are the default level, absorbed into the intercept.
- industrial is the factor level from PastLandUse that indicates previously forested parks. Previously agricultural parks are the default level, absorbed into the intercept.

Direct Effect of Forest Composition on Cooling Effect

$$Cooling_i \sim Normal(\mu_i, \sigma)$$
$$\mu_i \sim \alpha_{Park[i]} + \alpha_{Plot[i]} + \gamma_{tod[i]} + \beta_{tod[i]} DensityL_i + \beta_{tod[i]} DensityS_i + \beta_{tod[i]} L_i + \beta_{tod[i]} S_i + \beta_{tod[i]} SRL_i + \beta_{DensityL} DensityL_i + \beta_{DensityS} DensityS_i + \beta_{SizeL} L_i + \beta_{SizeS} S_i + \beta_{SRL} SRL_i \alpha_{Park[j]} \sim Normal(\acute{\alpha}, \sigma_{\alpha_{Park}}) \alpha_{Plot[j]} \sim Normal(0, \sigma_{\alpha_{Plot}}) \gamma_j \sim Normal(0,0.5) \beta_j \sim Normal(0,0.5) \acute{\alpha} \sim Normal(0,0.5) \sigma_{\alpha_{Park}} \sim Half - Normal(0,0.2) \sigma_{\alpha_{Plot}} \sim Half - Normal(0,0.2) \sigma \sim Exponential(1)$$

- α and γ both represent intercepts, α is used for random effects and γ for fixed interaction effecst
- $Cooling_i$ is the centered and scaled cooling effect in each plot in degrees Celsuis
- $Park_i$ is the park that each plot is in
- $Plot_i$ is the plot that each measurement is in
- PLU_i is the past land use category that each measurement is in (i.e., agricultural, forested, industrial)
- d_i is the time of day category that each measurement is in (i.e., daytime, nighttime)
- age_i is the centered and scaled age of the park that each measurement is in

Figure A1.5: Prior Predictive Checks

Prior predictive checks are used to ensure that the values selected for priors for our models allow a biologically reasonable range of values. For models with fixed effects fit to the model (models 1 and 5), we simulate predictive draws for prior only models and visualize the slope/intercept of the values. We then do a "posterior predictive check" but with the prior only model, to see if the data is captured in the priors. For models with only random effects, we only use the posterior predictive check.

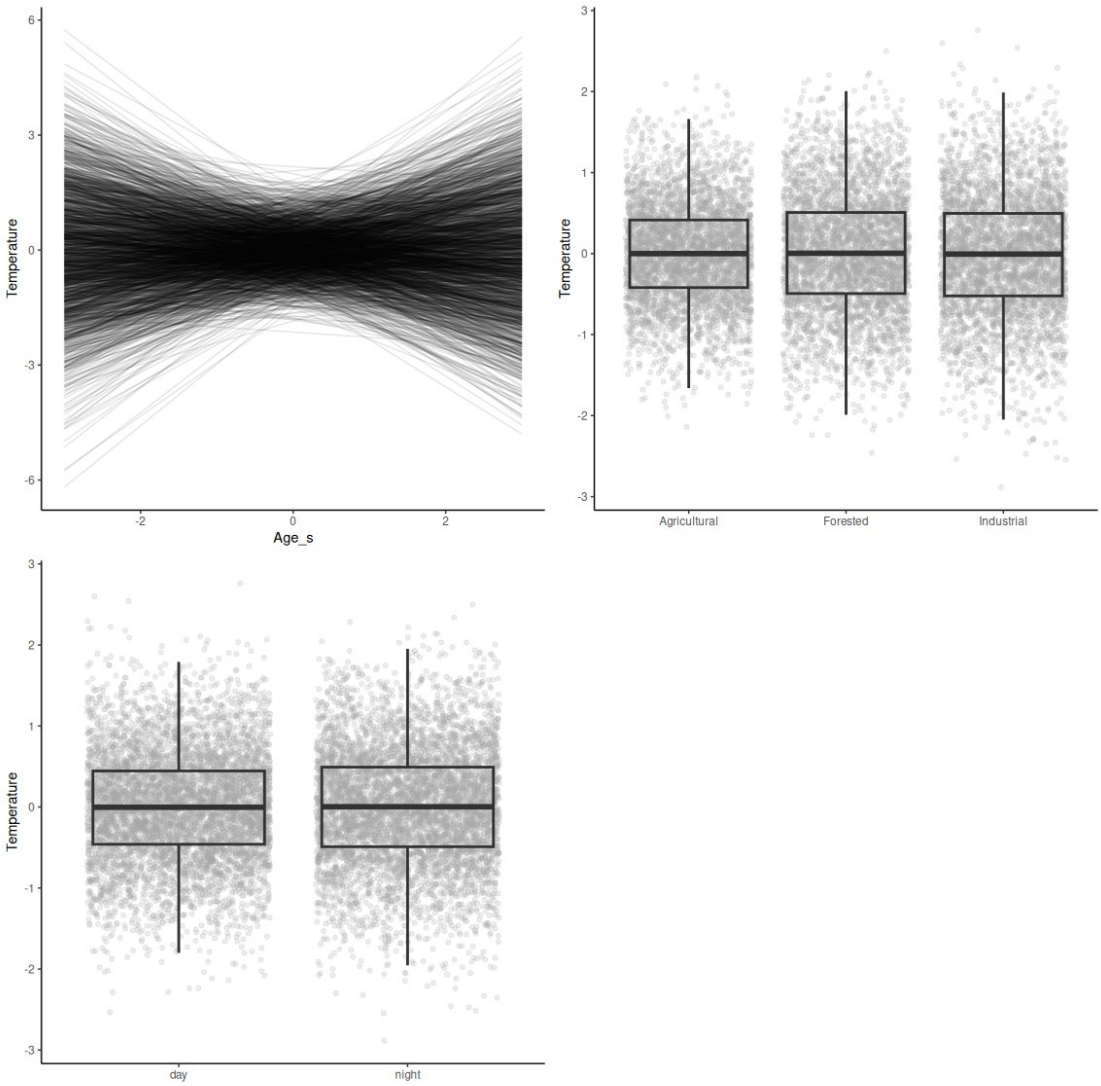


Figure A1.5a: Model 1 - Total Effect of Past Land-Use on Temperature

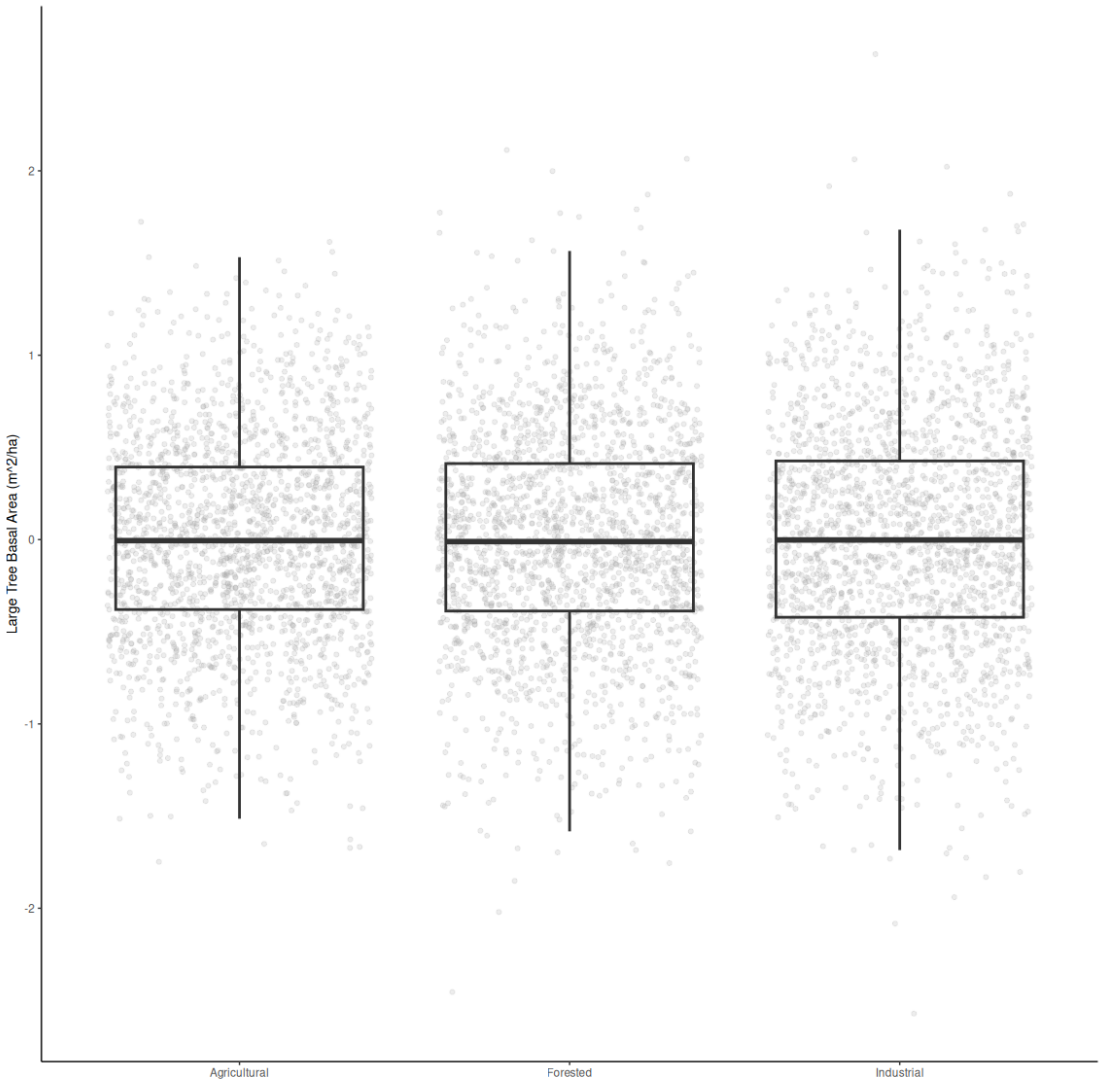


Figure A1.5b: Model 2a - Direct Effect of Past Land-Use on Large Tree (>= 5 cm DBH) Basal Area

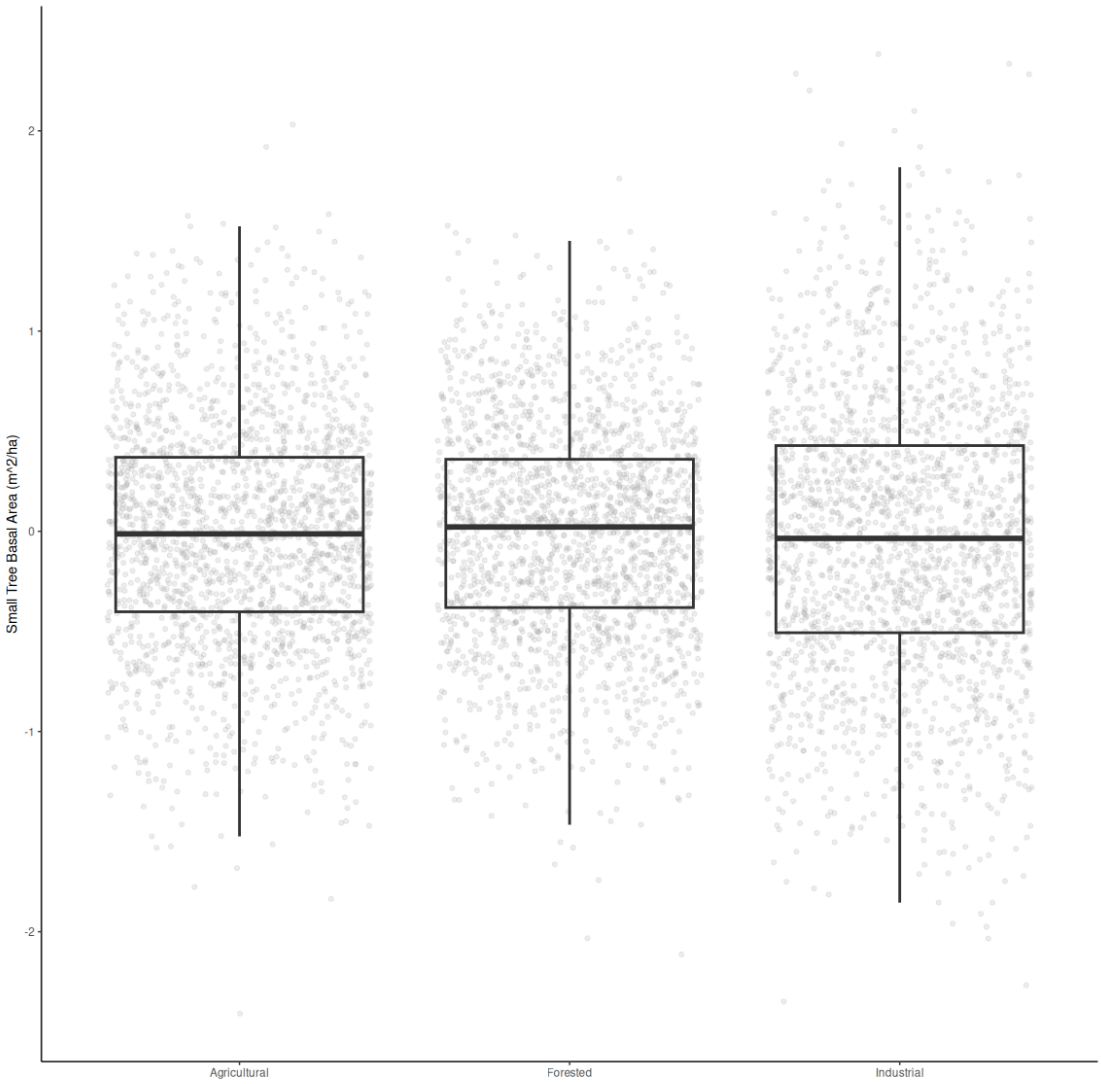


Figure A1.5c: Model 2b - Direct Effect of Past Land-Use on Small Tree (< 5 cm DBH) Density

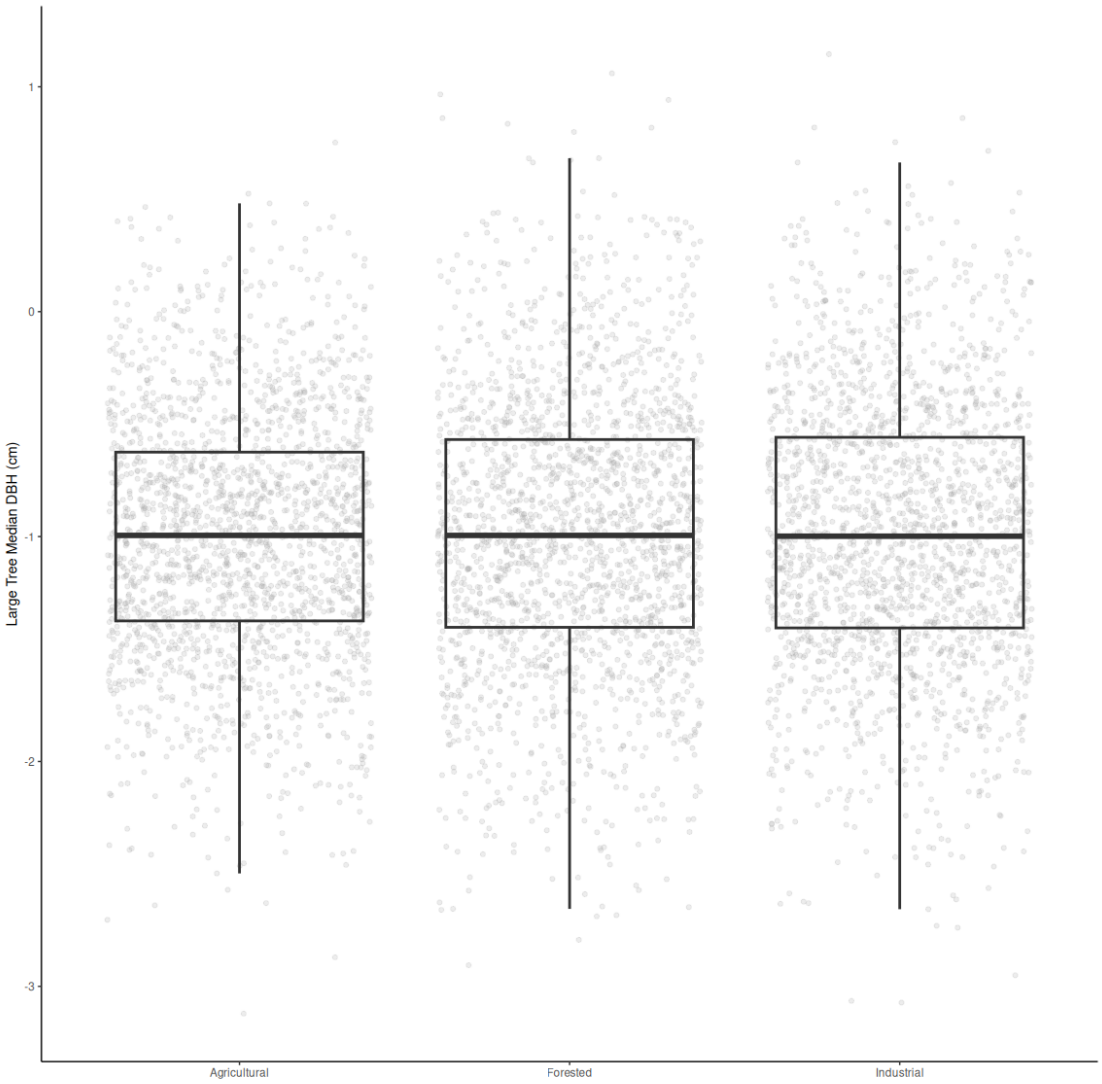


Figure A1.5d: Model 3a - Direct Effect of Past Land-Use on Large Tree (>= 5 cm DBH) Size

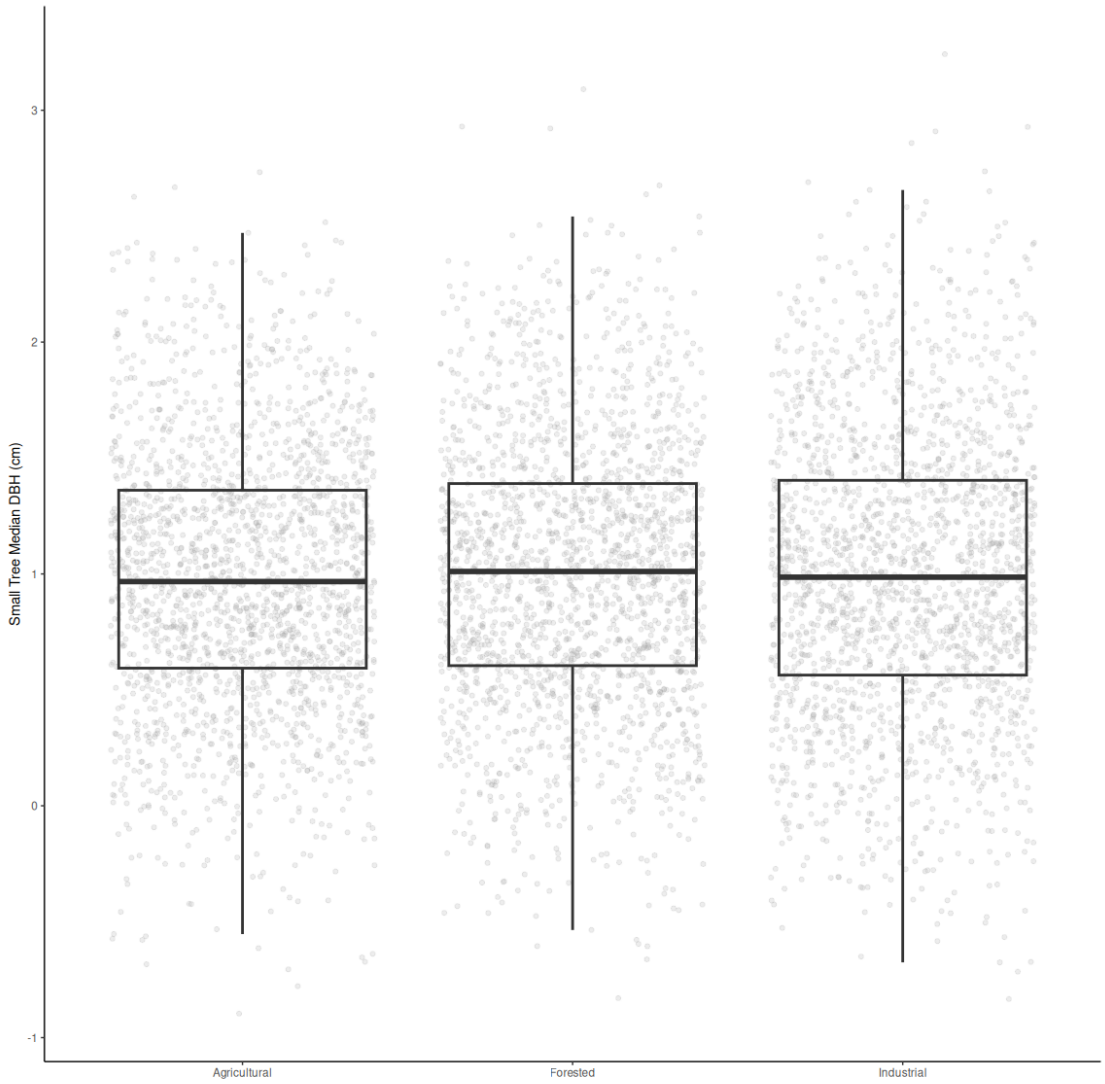


Figure A1.5e: Model 3b - Direct Effect of Past Land-Use on Small Tree (< 5 cm DBH) Size

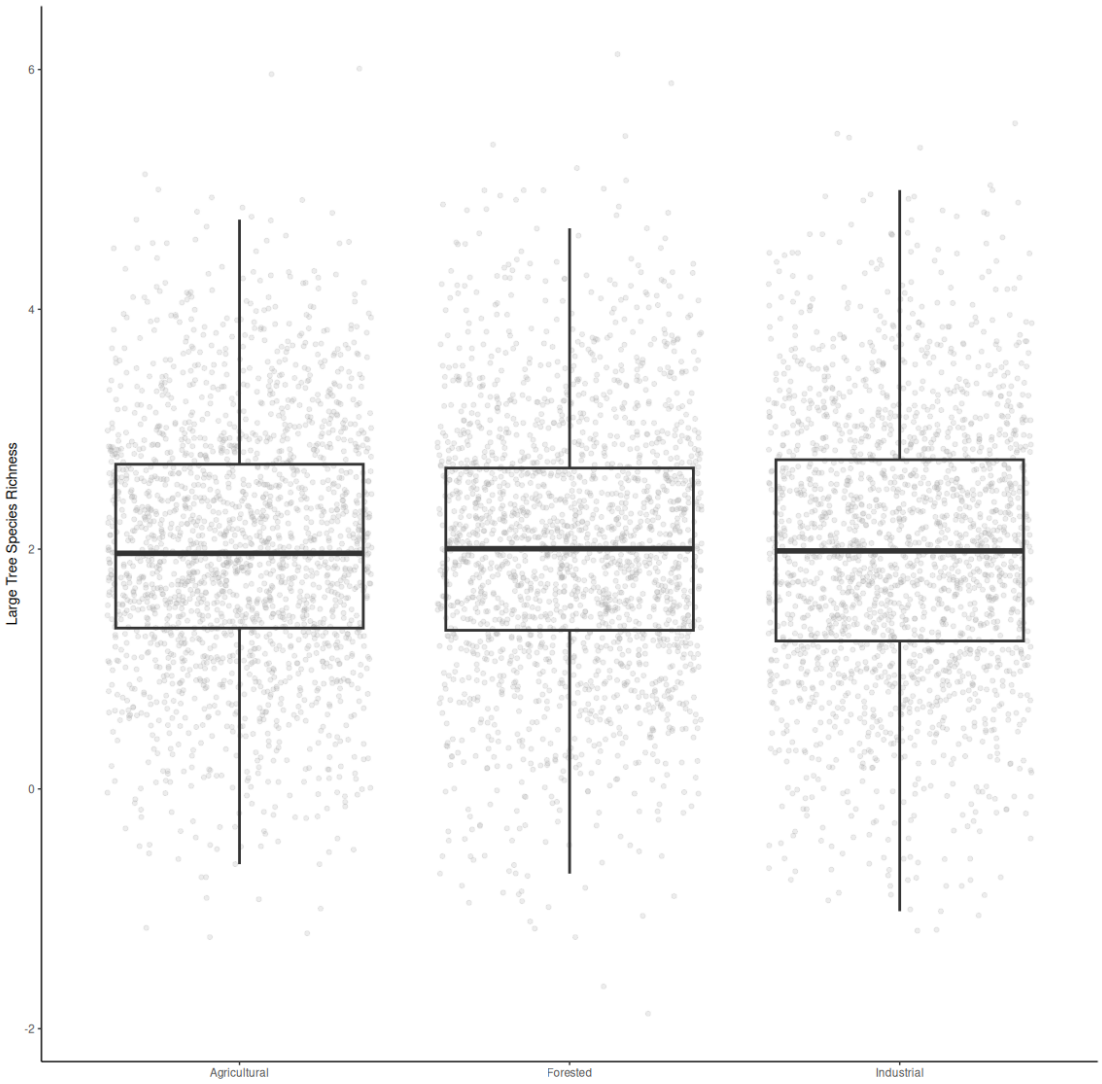


Figure A1.5f: Model 4 - Direct Effect of Past Land-Use on Large Tree (>= 5 cm DBH) Species Richness

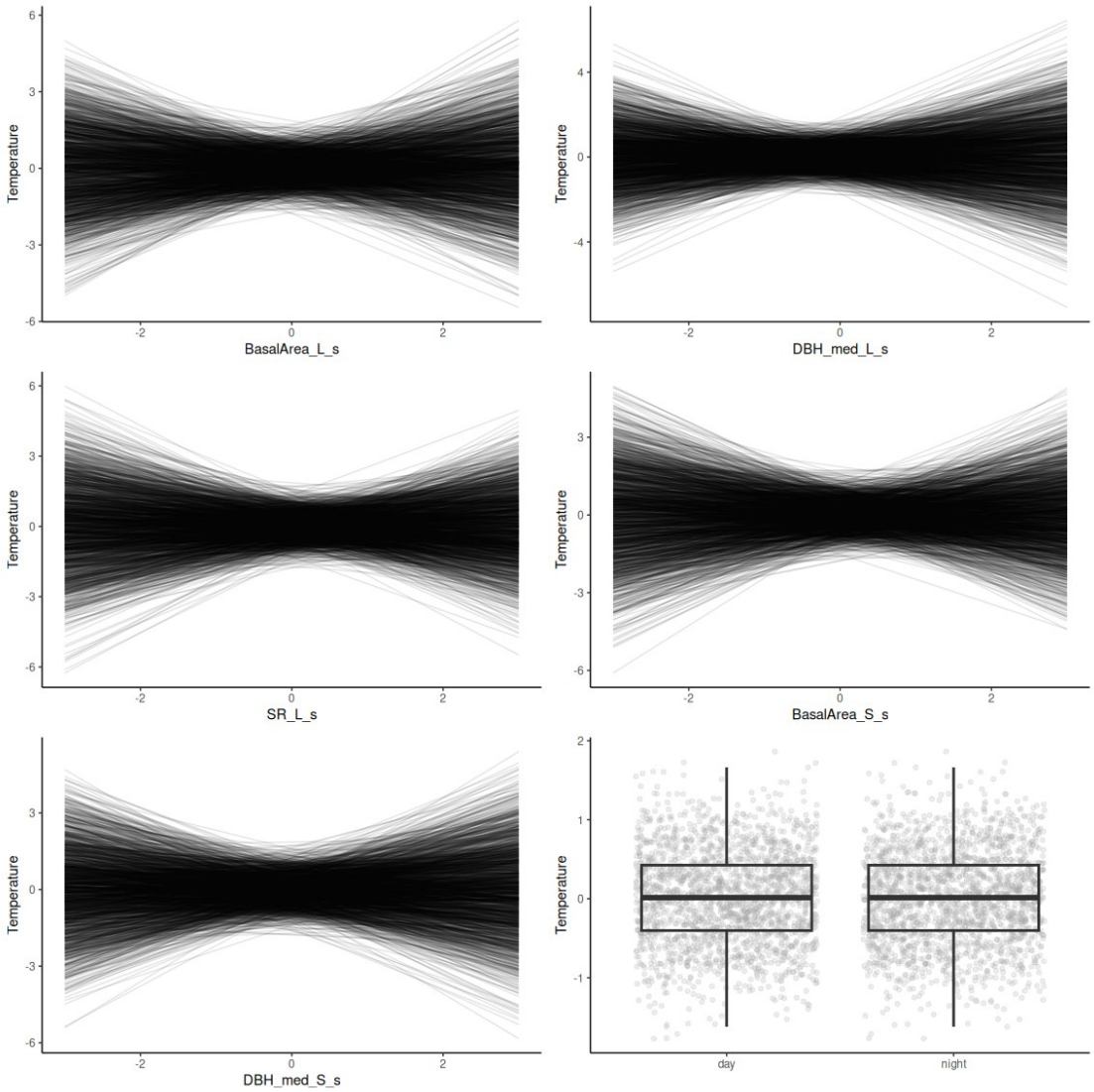
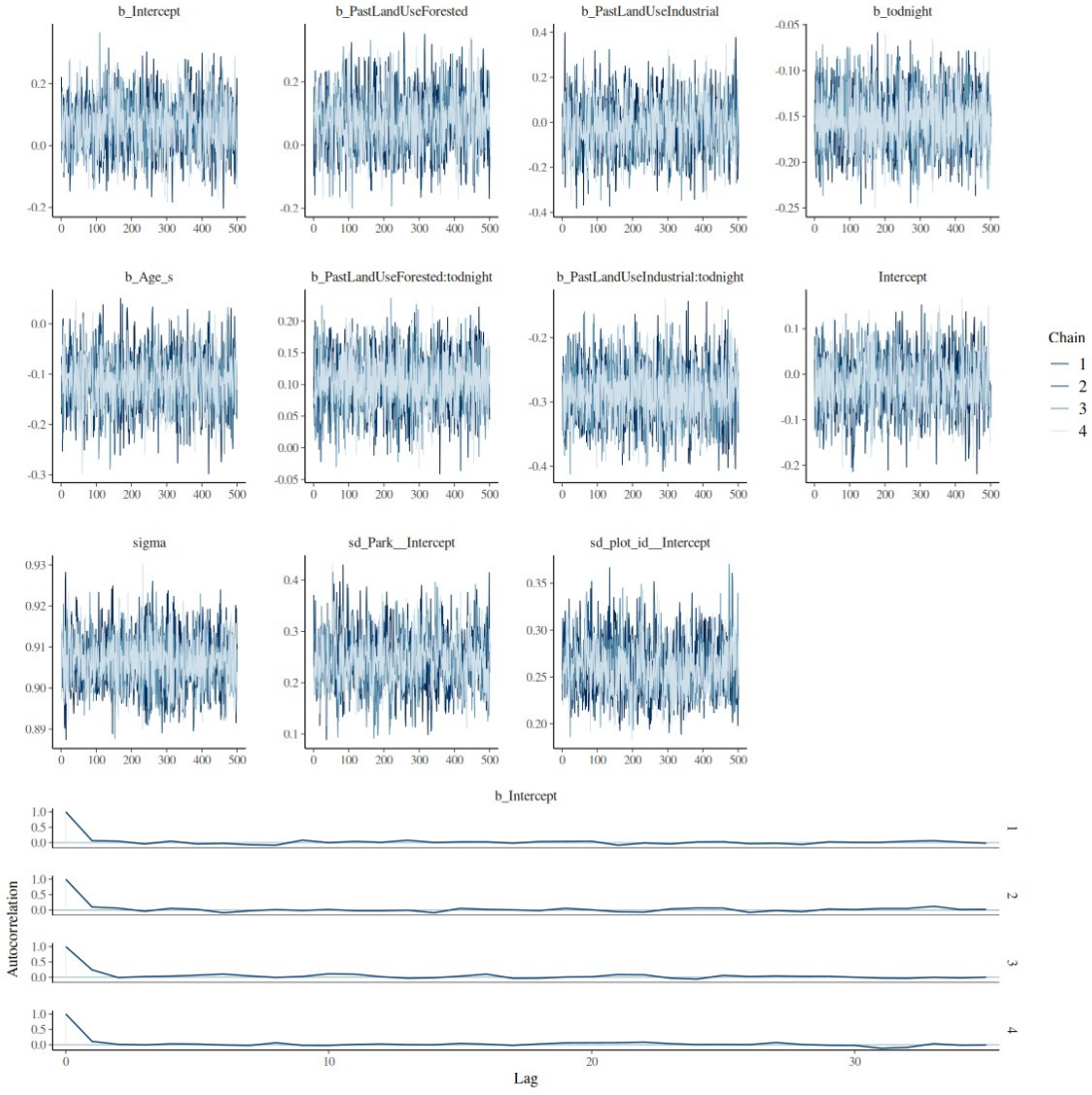


Figure A1.5g: Model 5 - Direct Effect of Forest Composition on Temperature

Figure A1.6: Model Diagnostic Plots

These model diagnostic plots assess whether the chains of our models are converged and well mixed, and if the model is well specified and has an adequate fit.

The first plot of the series shows trace plots for each of our parameters, where we want to see stationary and well-mixed chains. The second plot shows an autocorrelation plot by chain and parameter. We want our autocorrelation to quickly drop to zero with increasing lag. Thirdly, the Rhat plot monitors whether a chain has converged to the equilibrium distribution, if all chains are at equilibrium Rhat will be one. If chains have not converged, Rhat will be greater than 1. The fourth plot is the ratio between effective sample size (Neff) and total sample size (N).Because the draws within a Markov chain are not independent if there is autocorrelation, the effective sample size, neff, is usually smaller than the total sample size, N. The larger the ratio, the better. Finally, we have the posterior predictive check where we want the black line to be within/close to the blue lines, to indicate that our model is adequately generative.



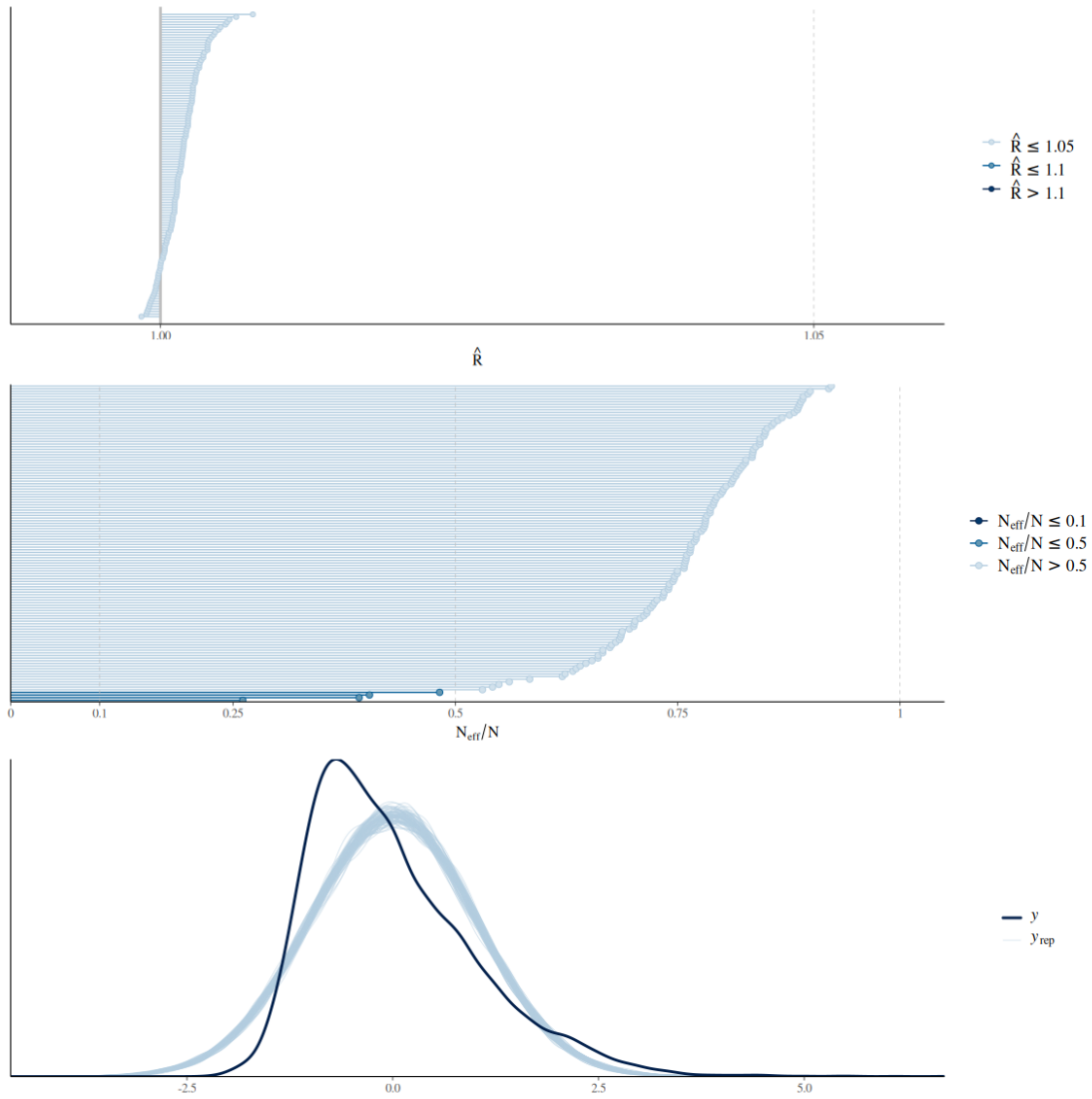
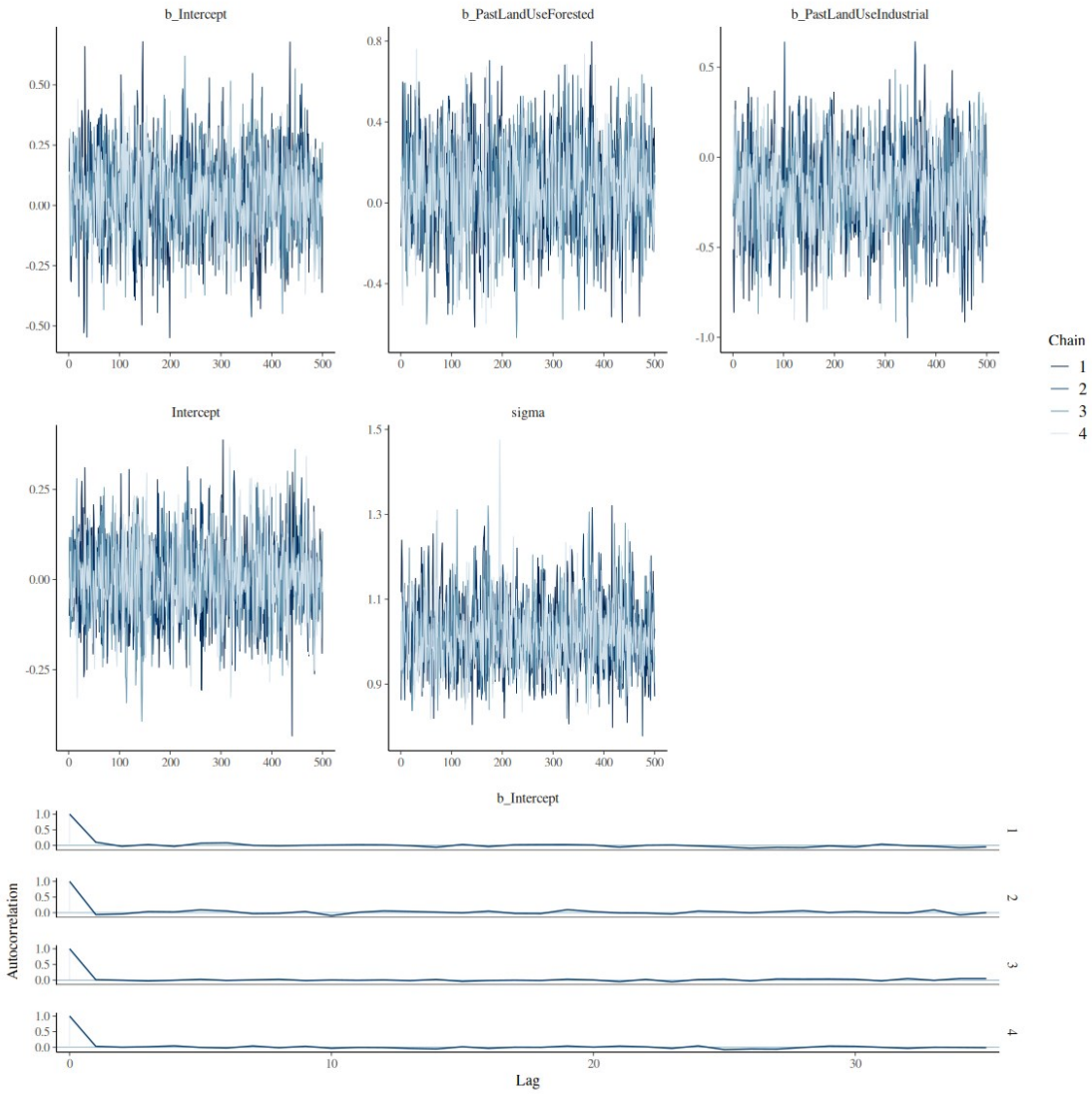


Figure A1.6a: Model 1 - Total Effect of Past Land-Use on Temperature


b_Intercept
b_PastLandUseForested
b_PastLandUseIndustrial
Intercept
sigma
Chain
1
2
3
4
b_Intercept
Autocorrelation
Lag

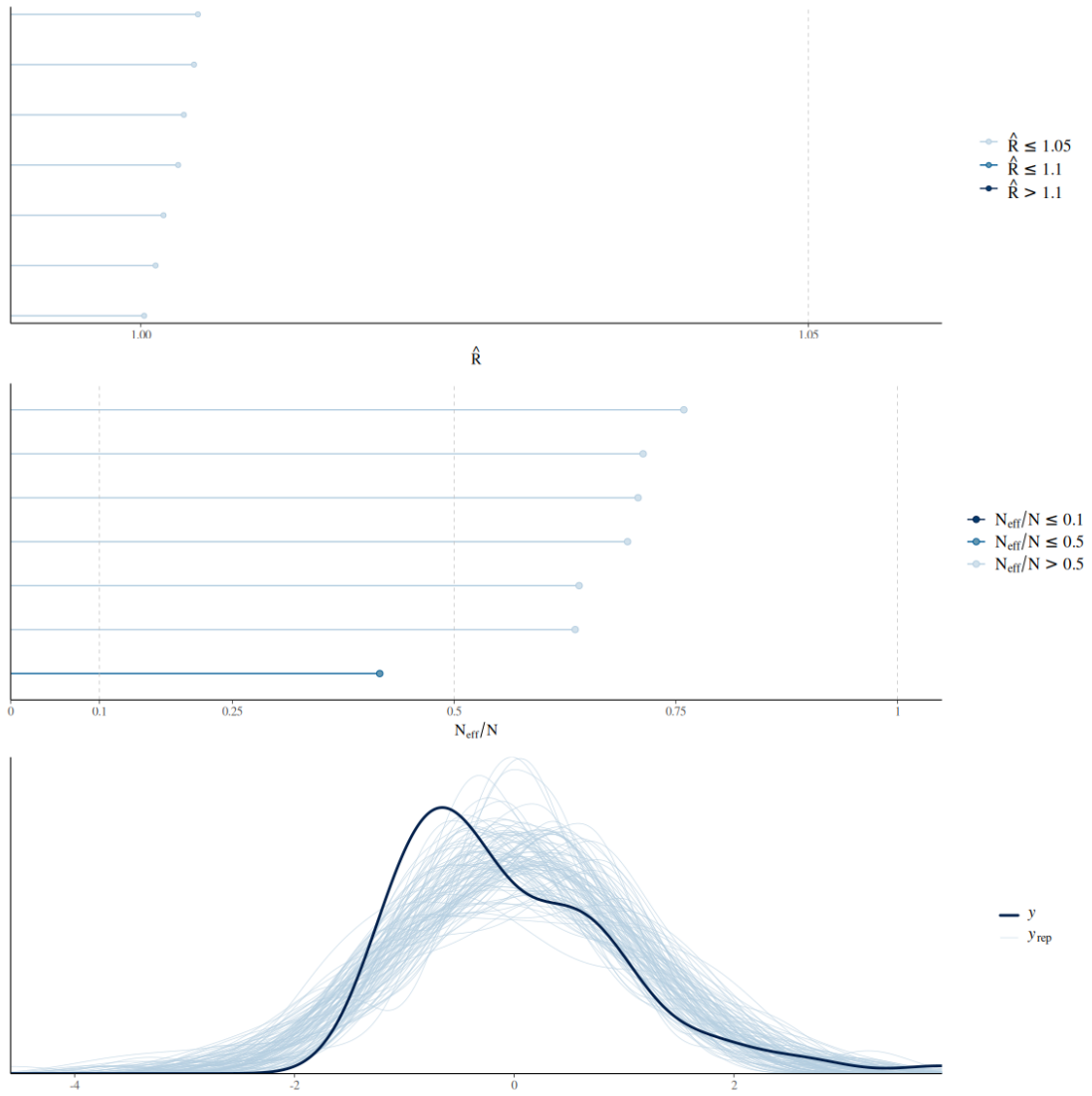
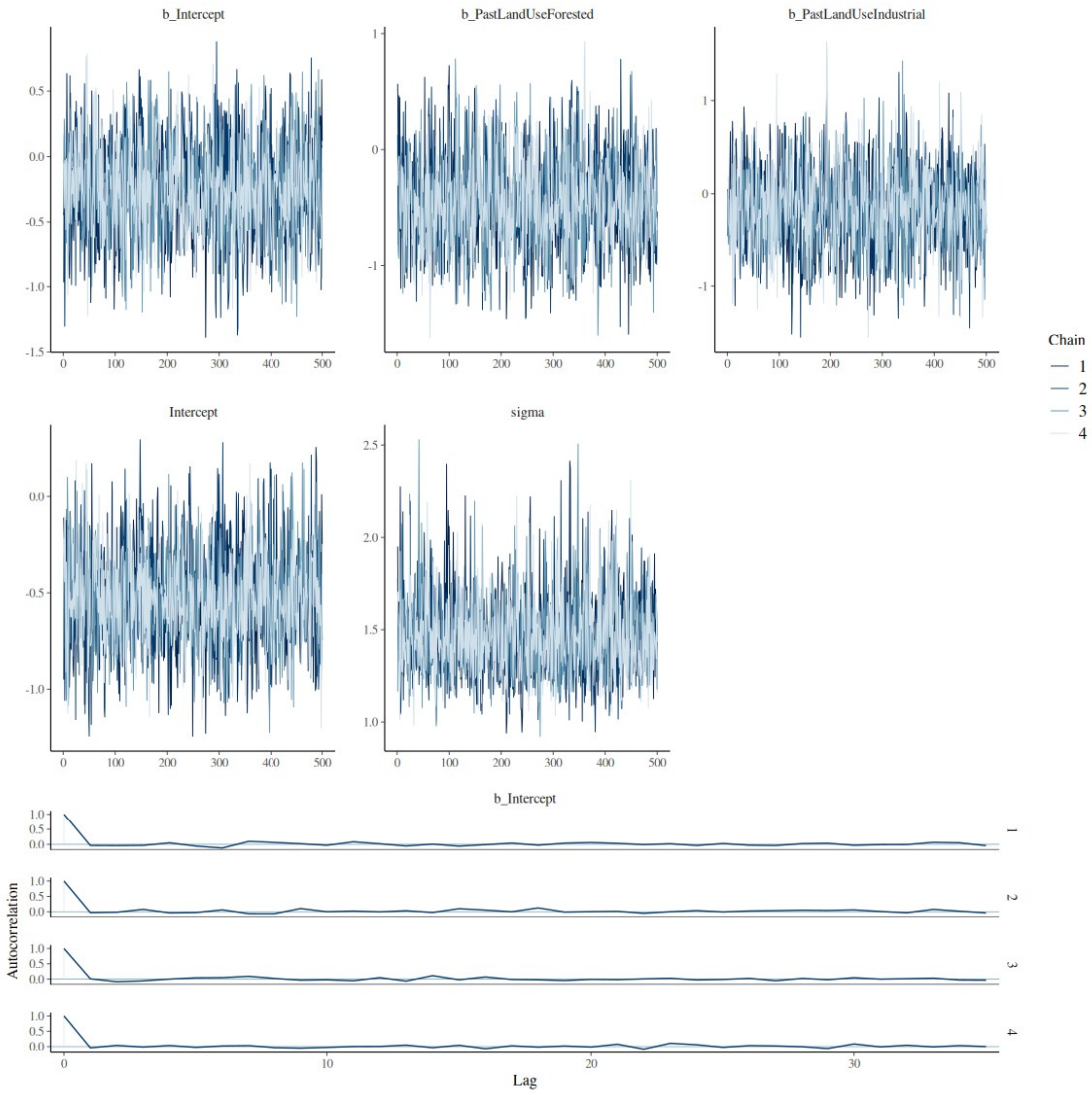


Figure A1.6b: Model 2a - Direct Effect of Past Land-Use on Large Tree (>= 5 cm DBH) Density


b_Intercept
b_PastLandUseForested
b_PastLandUseIndustrial
Intercept
sigma
Chain
1
2
3
4
b_Intercept
Autocorrelation
Lag

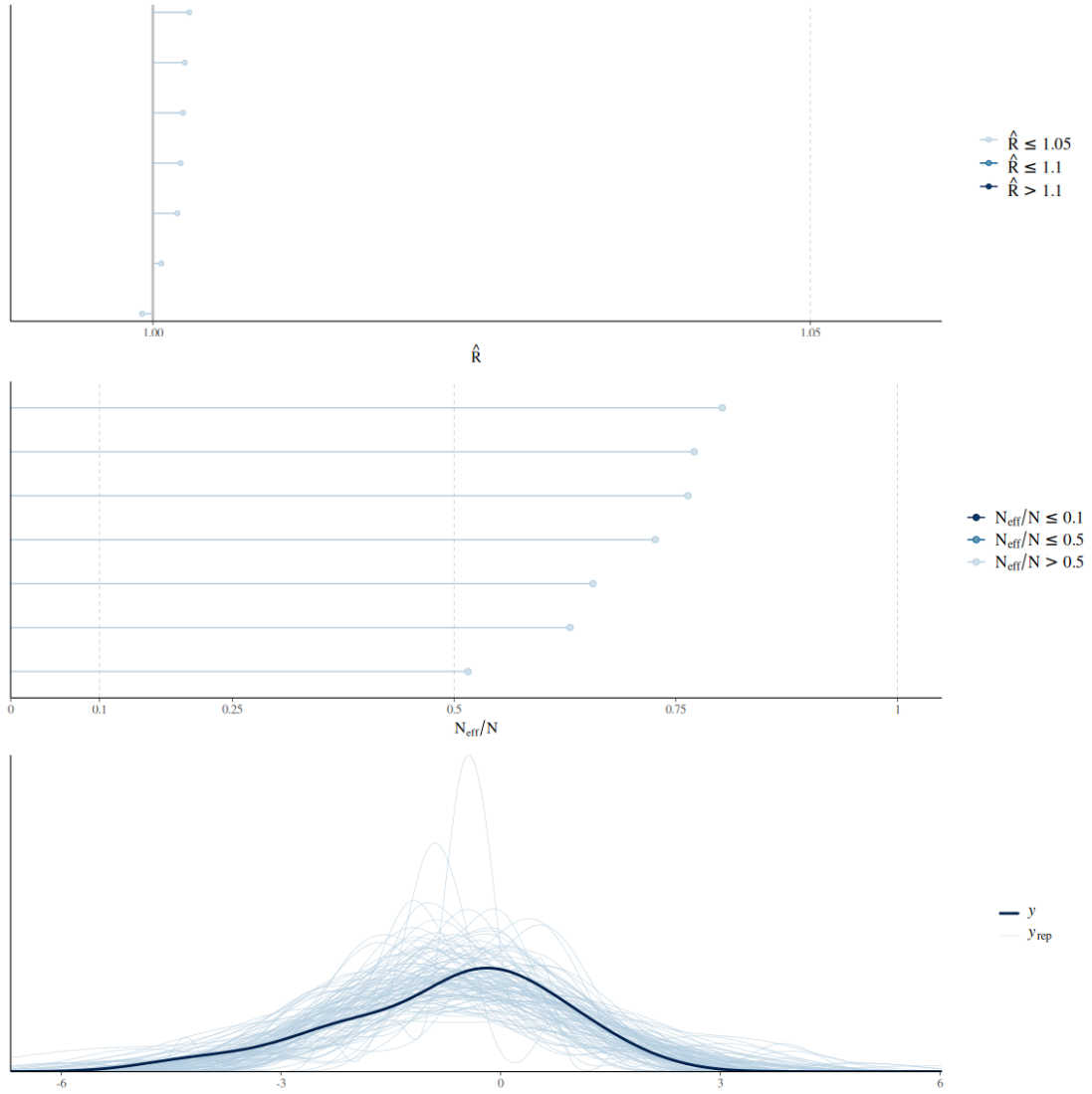
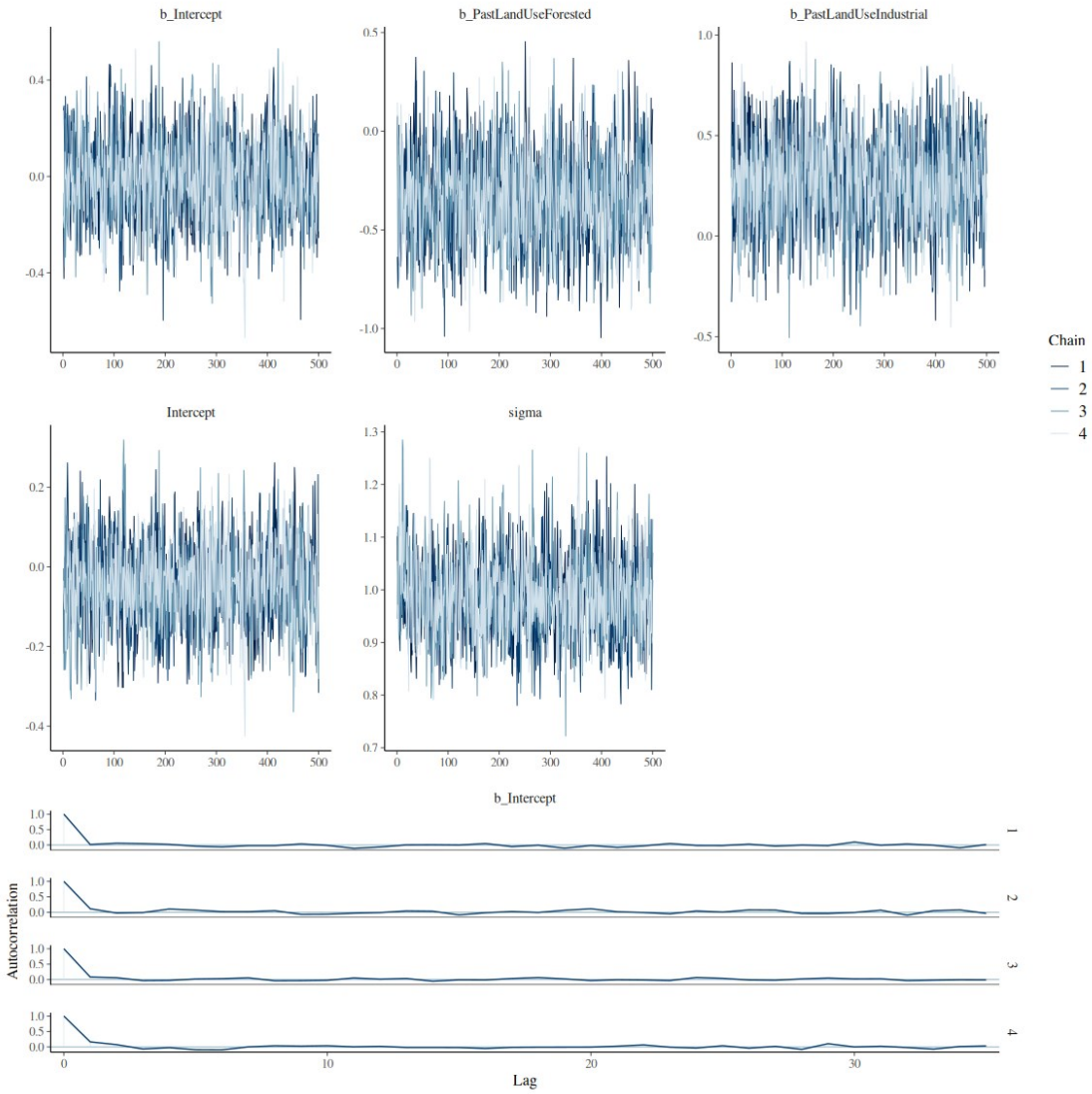


Figure A1.6c: Model 2b - Direct Effect of Past Land-Use on Small Tree (< 5 cm DBH) Density


b_Intercept
b_PastLandUseForested
b_PastLandUseIndustrial
Intercept
sigma
Chain
1
2
3
4
b_Intercept
Autocorrelation
Lag

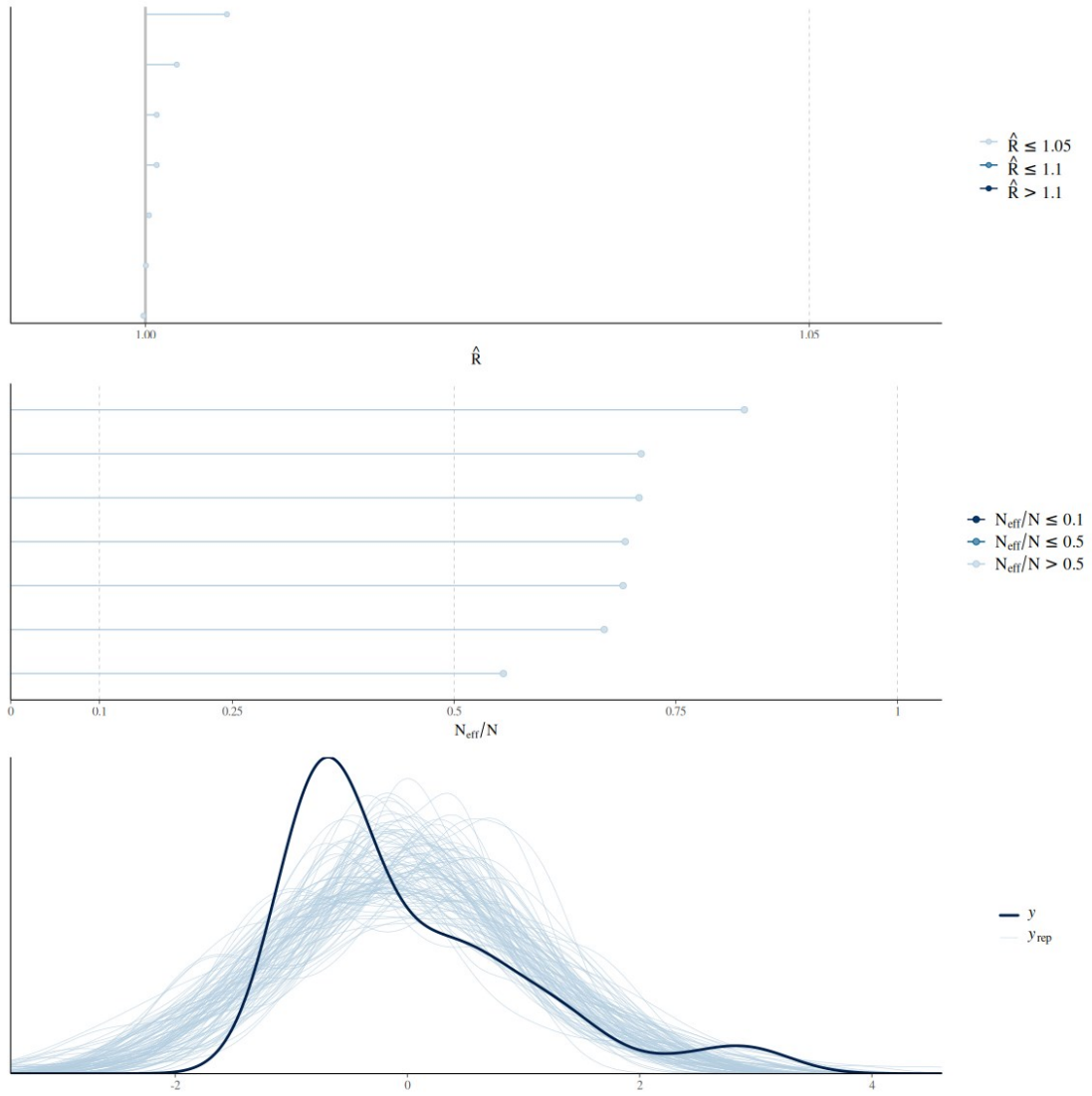
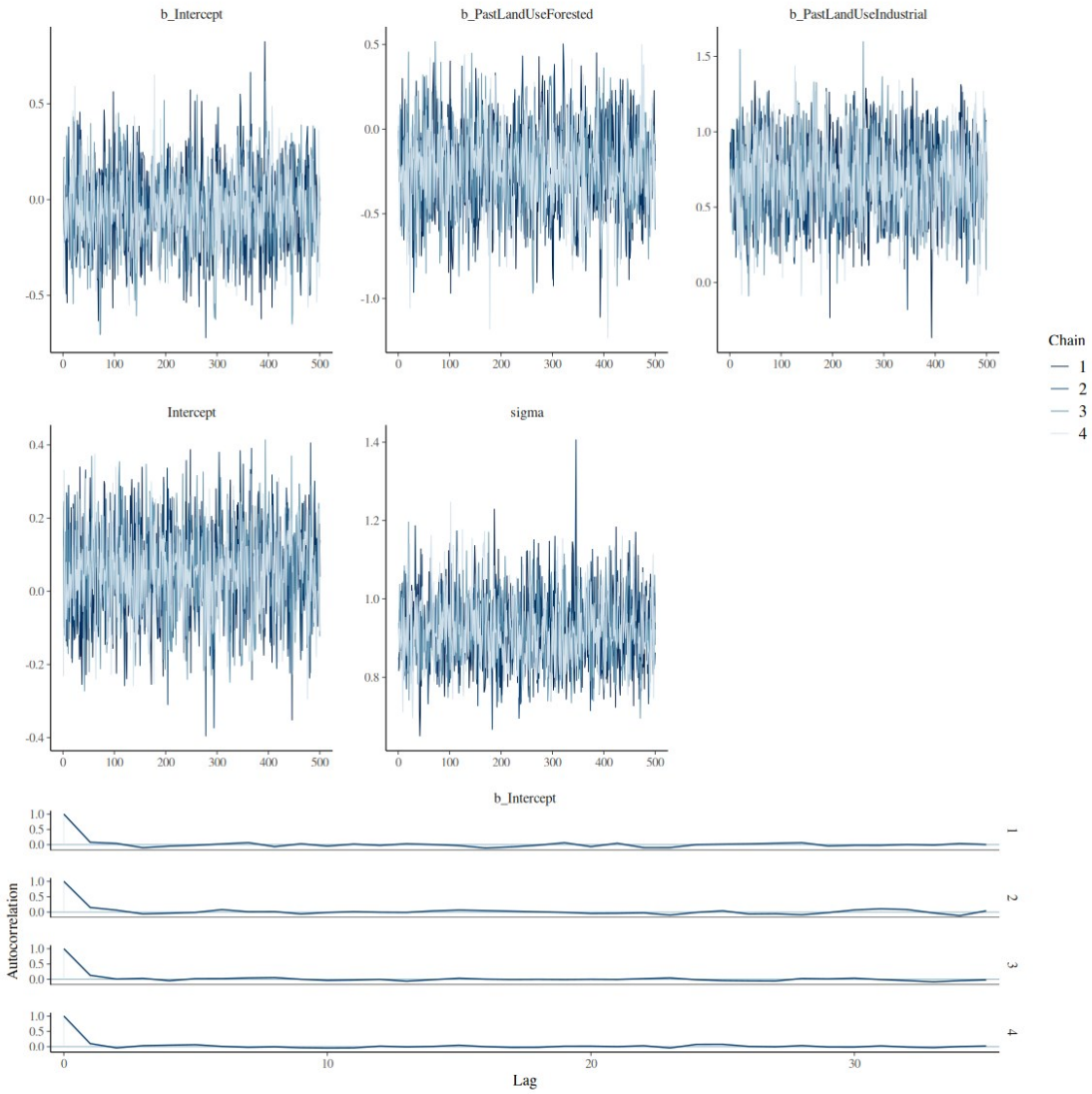


Figure A1.6d: Model 3a - Direct Effect of Past Land-Use on Large Tree (>= 5 cm DBH) Size


b_Intercept
b_PastLandUseForested
b_PastLandUseIndustrial
Intercept
sigma
Chain
1
2
3
4
b_Intercept
Autocorrelation
Lag

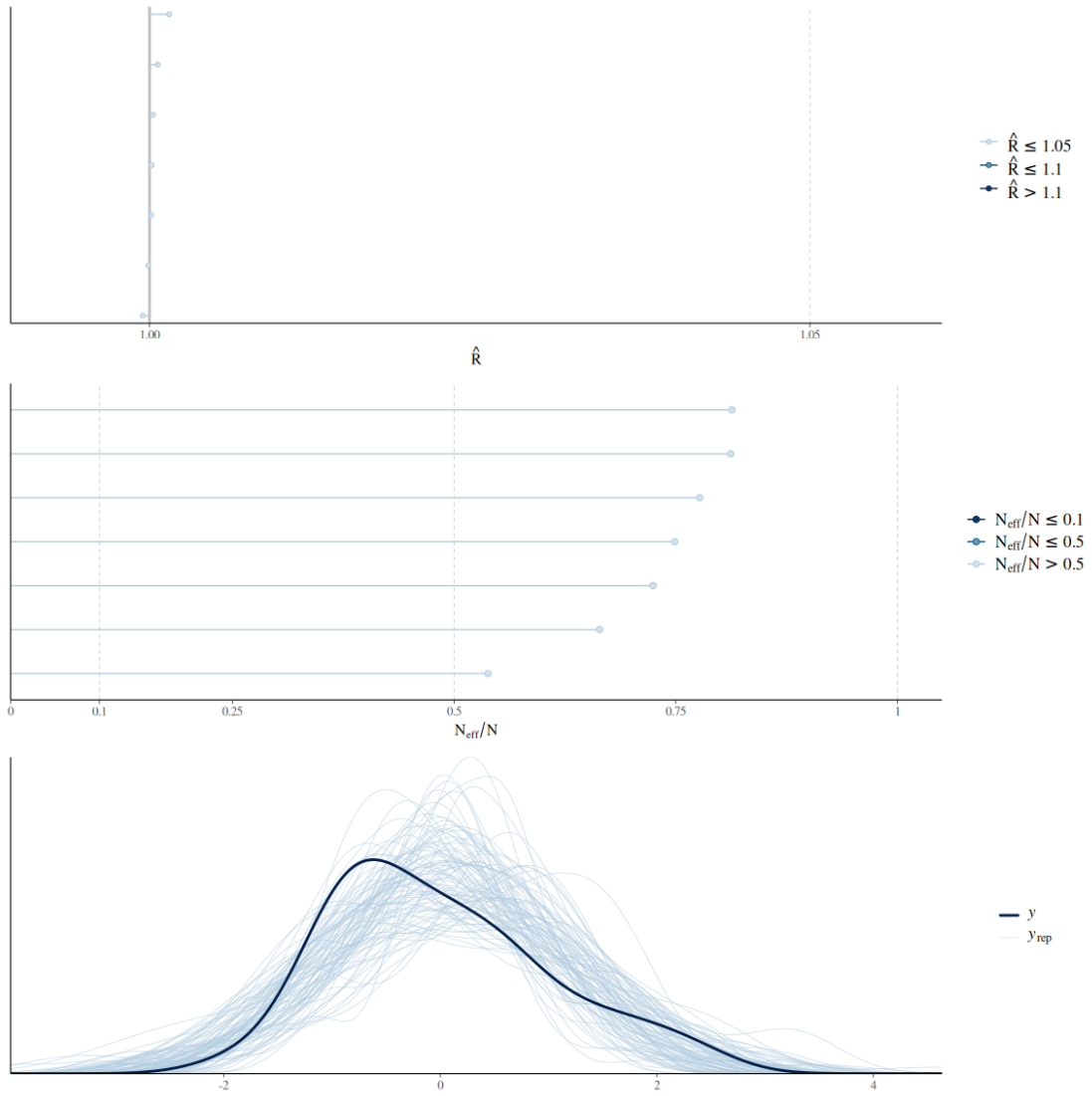
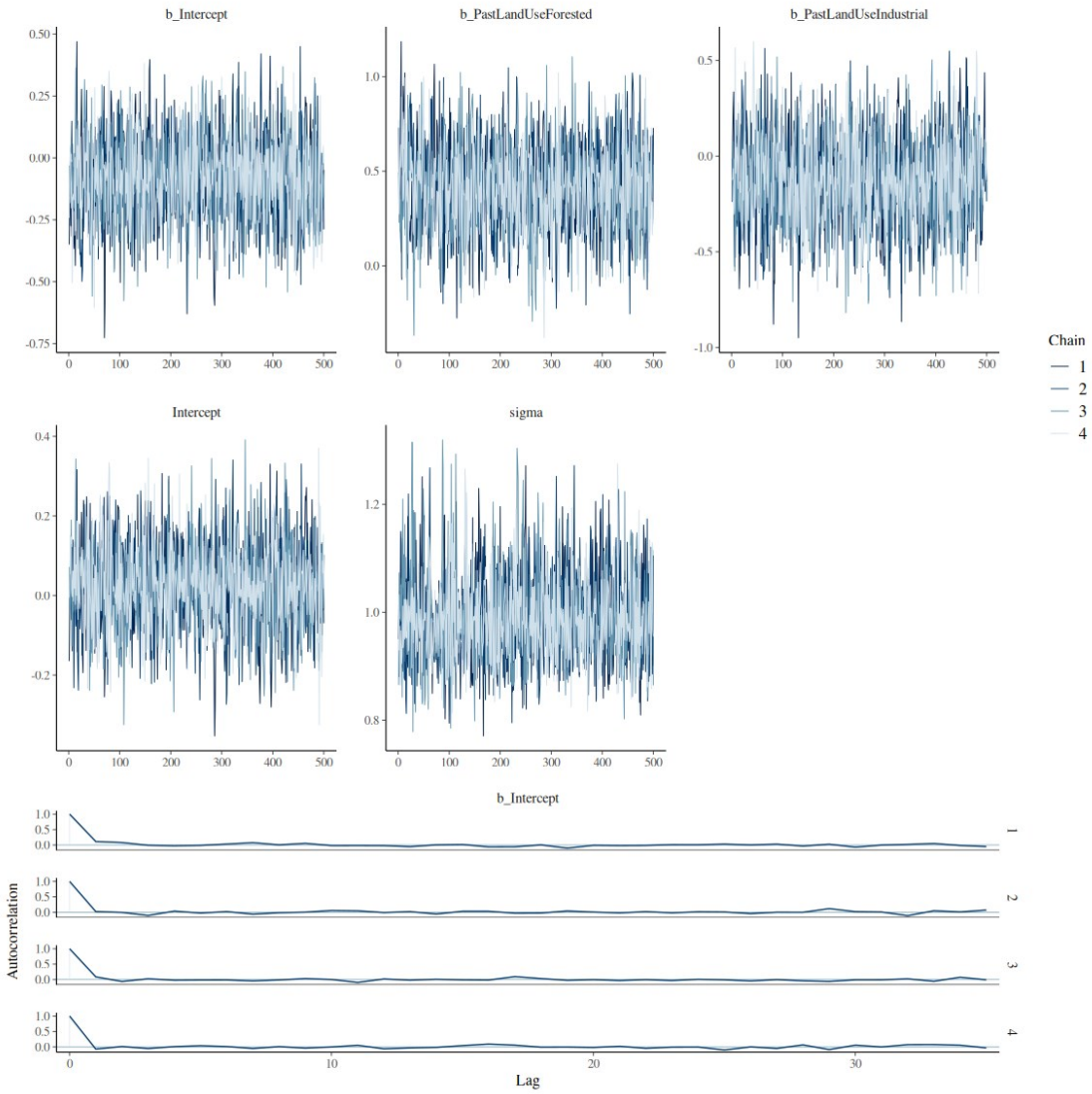


Figure A1.6e: Model 3b - Direct Effect of Past Land-Use on Small Tree (< 5 cm DBH) Size


b_Intercept
b_PastLandUseForested
b_PastLandUseIndustrial
Intercept
sigma
Chain
1
2
3
4
b_Intercept
Autocorrelation
Lag

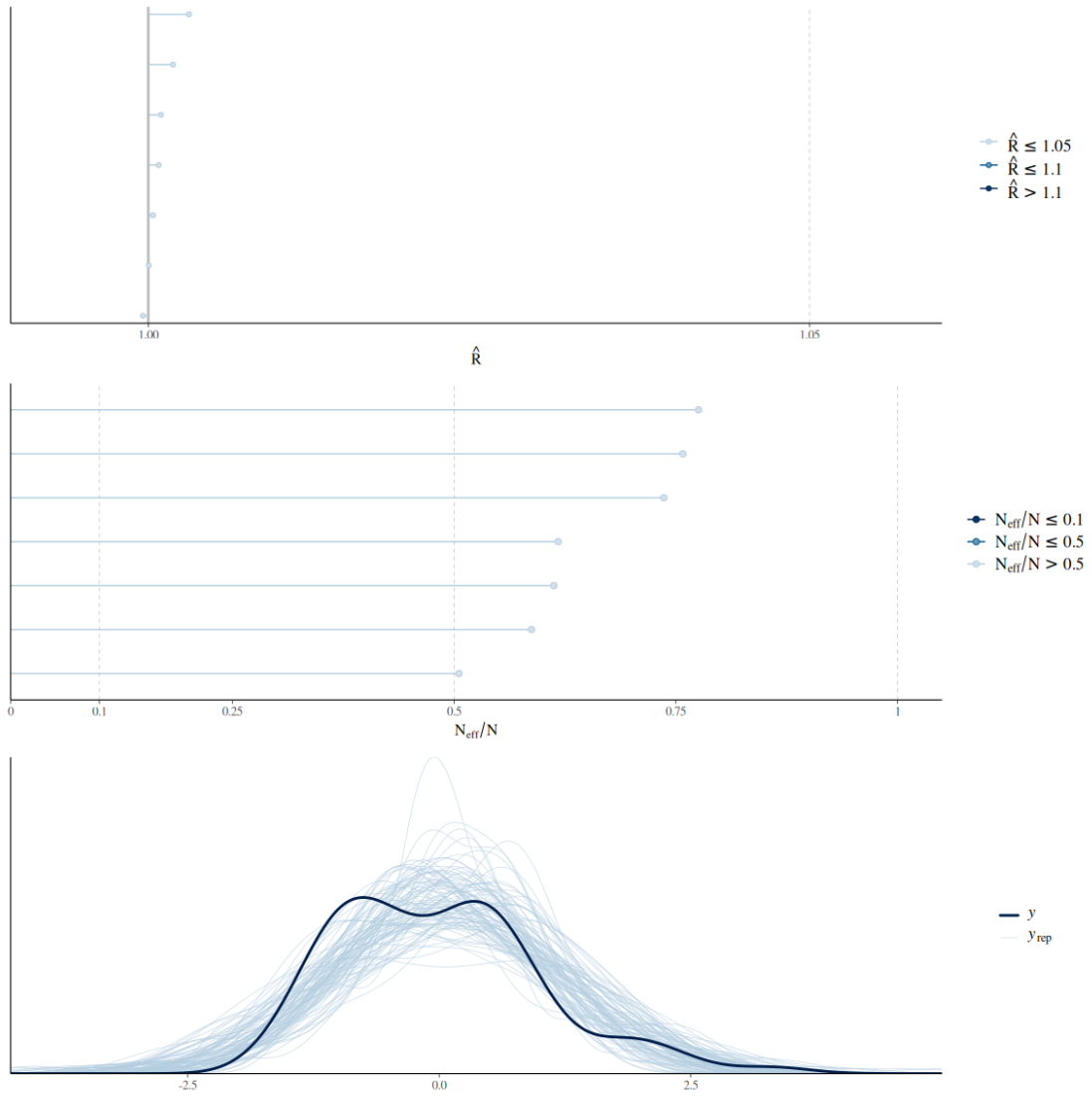
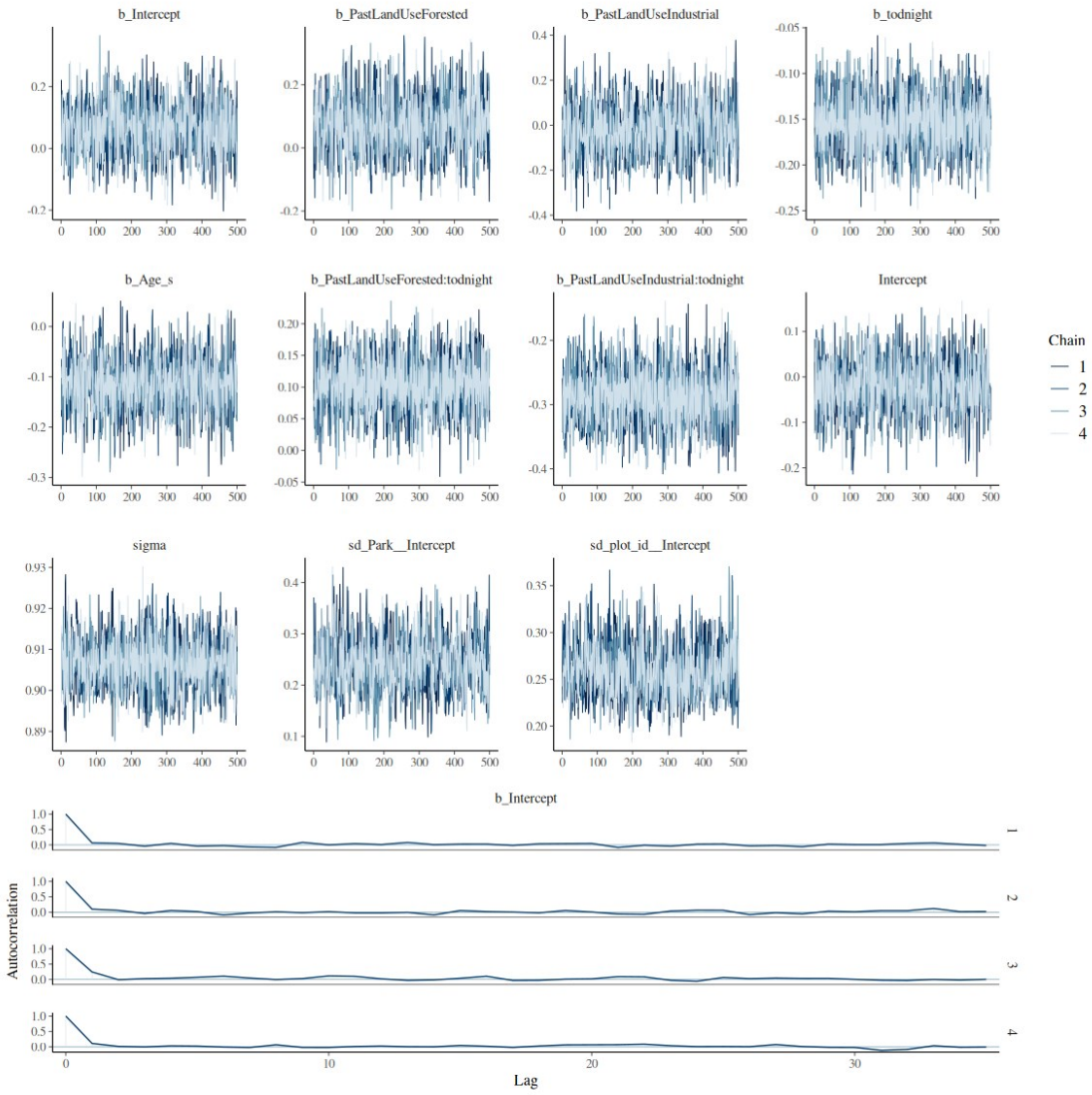


Figure A1.6f: Model 4 - Direct Effect of Past Land-Use on Large Tree (>= 5 cm DBH) Species Richness


b_Intercept
b_PastLandUseForested
b_PastLandUseIndustrial
b_todnight
b_Age_s
b_PastLandUseForested:todnight
b_PastLandUseIndustrial:todnight
Intercept
sigma
sd_Park__Intercept
sd_plot_id__Intercept
Chain
1
2
3
4
b_Intercept
Autocorrelation
Lag

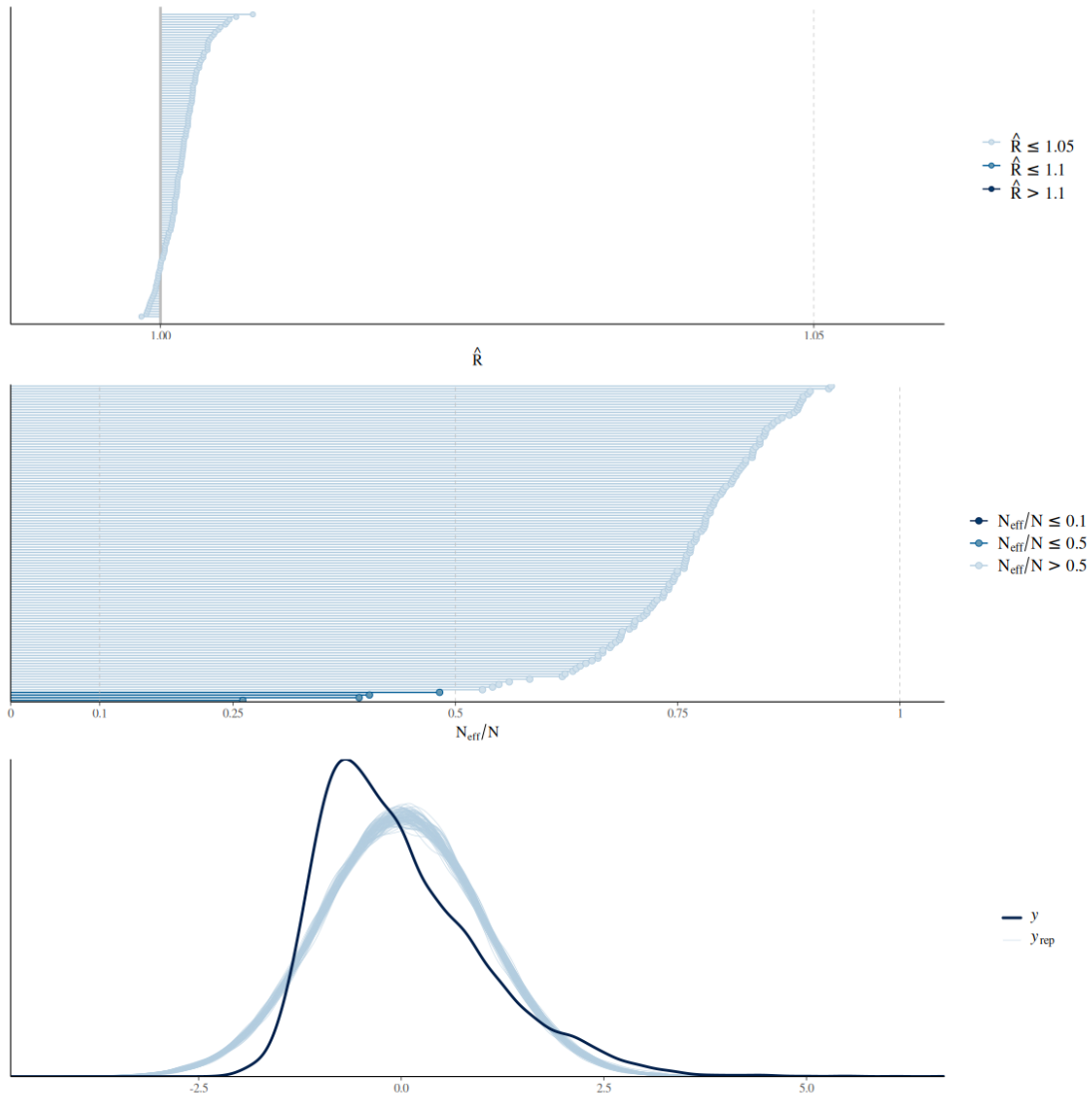


Figure A1.6g: Model 5 - Direct Effect of Forest Composition on Temperature

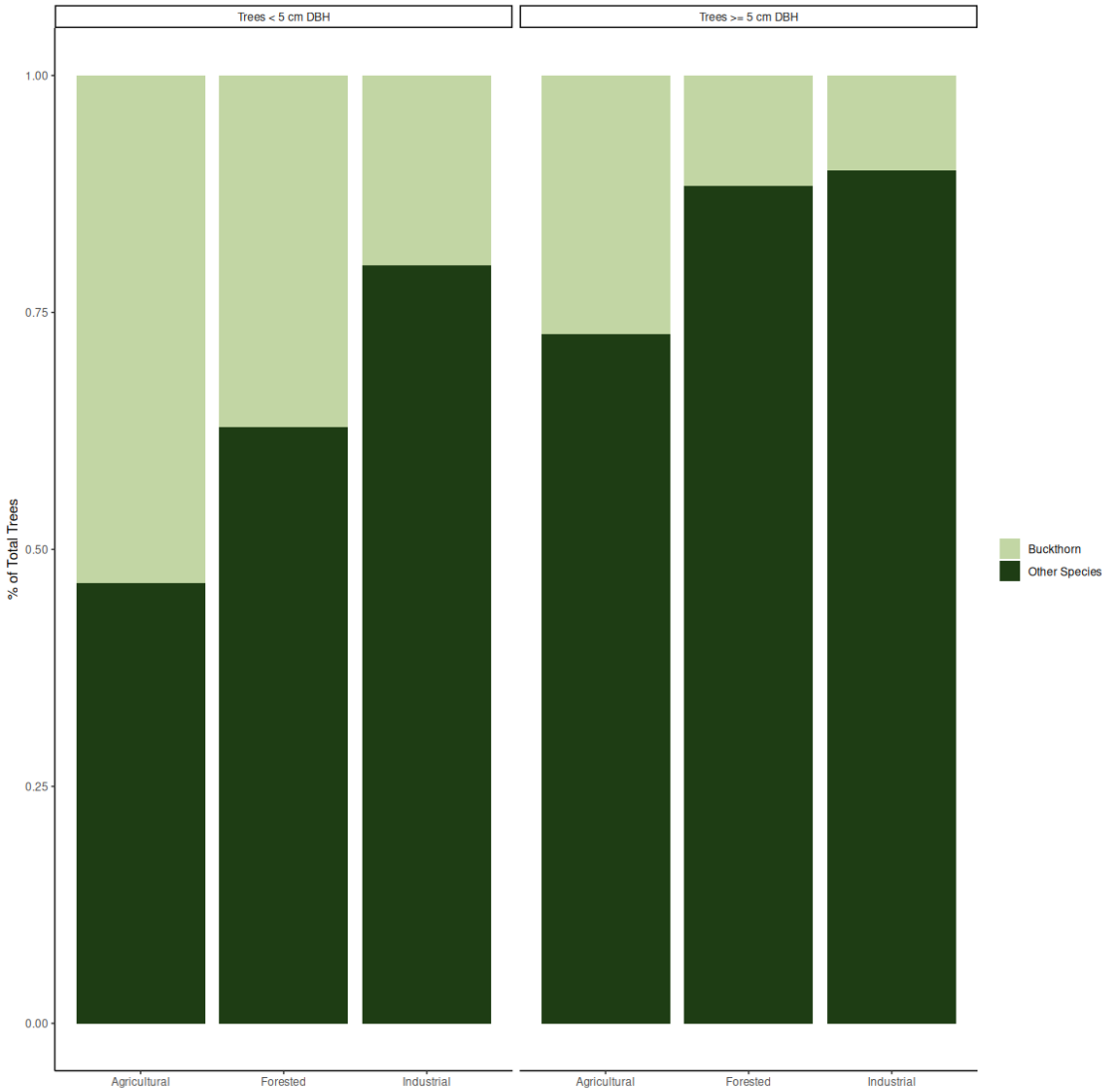


Figure A1.7: Proportion of common buckthorn (*Rhamnus cathartica*) across past land-use types for trees < 5 cm DBH and trees >= 5 cm DBH. Proportions were calculated across all plots and parks. All other species observed were pooled for the "Other Species" category.

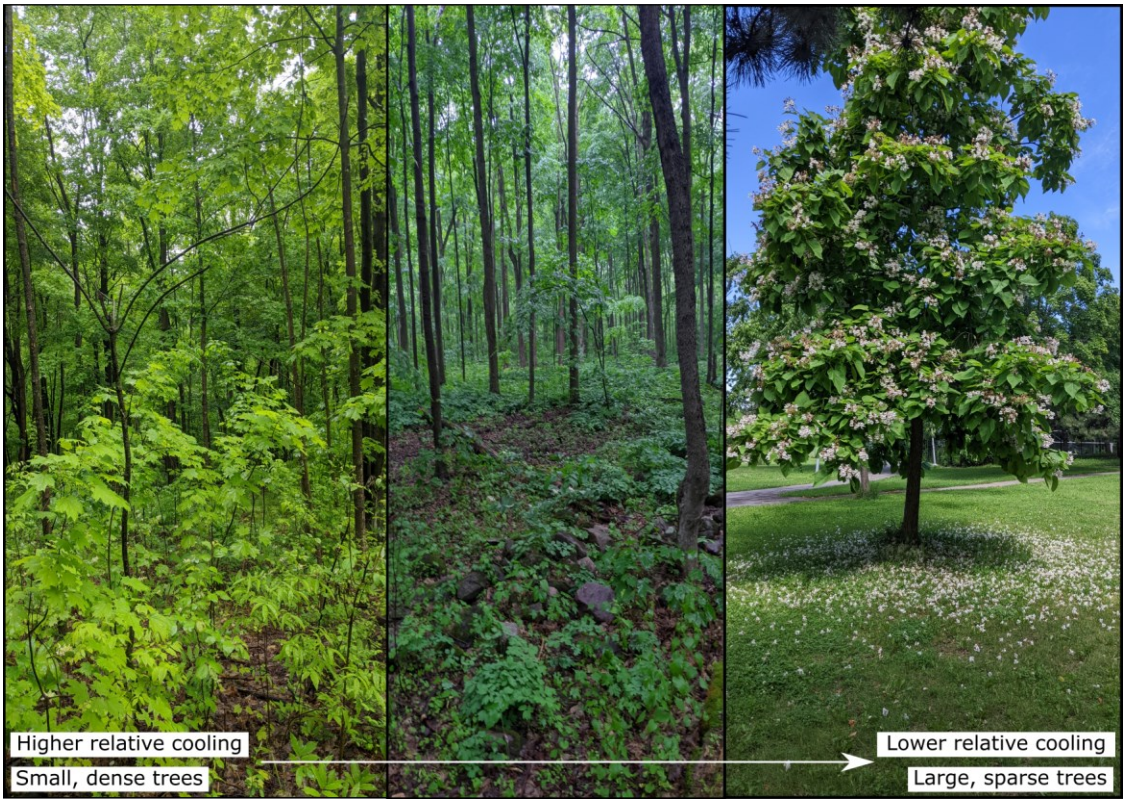


Figure A1.8: Examples of the trade-off that happens in urban parks, moving from areas with small, dense trees (often in previously forested or agricultural "nature" parks) to large, sparse trees (often found in more traditional "urban" parks). Photos taken by Isabella C Richmond.

Appendix 2: *Chapter 2 Supplementary Materials*

Section 2A: Tables

Table A2.1: Site characteristics. Infrastructure ID is the unique ID assigned to each individual site, where CON indicates a grey alley, RV indicates a green alley, and SS indicates a street segment. Parallel street names one of the parallel streets to each alley, and for street segments it indicates the street segment that was sampled for each alley. City is where the sampling occurred, VSMPE = Villeray-Saint Michel-Parc Extension and TR = Trois-Rivières. Infrastructure type indicates the site type, with three potential options, green alley, grey alley, and street segment. Percent canopy indicates the percent canopy of the site in decimal form. Firefly presence is a binomial variable, where 1 indicates that fireflies were found, 0 indicates no fireflies were found, and a blank indicates that the site was not sampled for fireflies. Number of points is the number of points where vegetative complexity was sampled (i.e., number of 10 m intervals).

Infrastructure ID	Parallel Street	City	Infrastructure Type	Percent Canopy	Firefly Presence	Number of Points
CON-SS-TR-10	Ste Angèle	TR	street segment	0.39		17
CON-SS-VSMPE-1	d'Outremont	VSMPE	street segment	0.06	0	15
CON-SS-VSMPE-2	d'Outremont	VSMPE	street segment	0.35		31
CON-SS-VSMPE-3	de l'Epée	VSMPE	street segment	0.53		25
CON-SS-VSMPE-4	51e	VSMPE	street segment	0.12	0	9
CON-SS-VSMPE-5	9e	VSMPE	street segment	0.41		52

Infrastructure ID	Parallel Street	City	Infrastructure Type	Percent Canopy	Firefly Presence	Number of Points
CON-SS-VSMPE-6	2e	VSMPE	street segment	0.61		21
CON-SS-VSMPE-7	Casgrain	VSMPE	street segment	0.54	0	17
CON-SS-VSMPE-8	Chambord	VSMPE	street segment	0.65	1	15
CON-SS-VSMPE-9	de Chateaubriand	VSMPE	street segment	0.61		17
CON-TR-10	Ste Angèle	TR	grey alley	0.12		21
CON-VSMPE-1	d'Outremont	VSMPE	grey alley	0.10	0	20
CON-VSMPE-2	d'Outremont	VSMPE	grey alley	0.39		37
CON-VSMPE-3	de l'Epée	VSMPE	grey alley	0.38		26
CON-VSMPE-5	9e	VSMPE	grey alley	0.08		47
CON-VSMPE-6	2e	VSMPE	grey alley	0.60		24
CON-VSMPE-	Casgrain	VSMPE	grey alley	0.90	0	21

Infrastructure ID	Parallel Street	City	Infrastructure Type	Percent Canopy	Firefly Presence	Number of Points
7						
CON-VSMPE-9	de Chateaubriand	VSMPE	grey alley	0.54		17
RV-SS-TR-11	Gingras	TR	green alley	0.37		6
RV-TR-10	St Paul	TR	green alley	0.13		21
RV-VSMPE-10	Durocher	VSMPE	green alley	0.25	0	28
RV-VSMPE-11	2e	VSMPE	green alley	0.07		24
RV-VSMPE-12	Louis-Hébert	VSMPE	green alley	0.19		28
RV-VSMPE-13	13e	VSMPE	green alley	0.21	0	23
RV-VSMPE-14	1re	VSMPE	green alley	0.17		6
RV-VSMPE-15	6e	VSMPE	green alley	0.21		25
RV-VSMPE-16	9e	VSMPE	green alley	0.31	0	27
RV-VSMPE-17	2e	VSMPE	green alley	0.15		26
RV-VSMPE-	47e	VSMPE	green	0.38		9

Infrastructure ID	Parallel Street	City	Infrastructure Type	Percent Canopy	Firefly Presence	Number of Points
18			alley			
RV-VSMPE-19	Bressani	VSMPE	green alley	0.31		35
RV-VSMPE-2	Durocher	VSMPE	green alley	0.04	1	26
RV-VSMPE-20	48e	VSMPE	green alley	0.11	0	9
RV-VSMPE-21	44e	VSMPE	green alley	0.30	0	11
RV-VSMPE-22	des Belges	VSMPE	green alley	0.40	0	18
RV-VSMPE-23	Drolet	VSMPE	green alley	0.24	0	25
RV-VSMPE-24	Papineau	VSMPE	green alley	0.24		31
RV-VSMPE-25	St Andre	VSMPE	green alley	0.30	0	17
RV-VSMPE-26	Boyer	VSMPE	green alley	0.50	0	25
RV-VSMPE-28	Drolet	VSMPE	green alley	0.11		30
RV-VSMPE-29	de Lorimier	VSMPE	green alley	0.40	1	26

Infrastructure ID	Parallel Street	City	Infrastructure Type	Percent Canopy	Firefly Presence	Number of Points
RV-VSMPE-3	de l'Epée	VSMPE	green alley	0.32	1	16
RV-VSMPE-30	St Andre	VSMPE	green alley	0.04	0	13
RV-VSMPE-31	de Chateaubriand	VSMPE	green alley	0.04	0	10
RV-VSMPE-32	de Normanville	VSMPE	green alley	0.13	0	25
RV-VSMPE-33	Drolet	VSMPE	green alley	0.10		24
RV-VSMPE-34	Casgrain	VSMPE	green alley	0.06		26
RV-VSMPE-36	de Gaspé	VSMPE	green alley	0.19	0	25
RV-VSMPE-37	Casgrain	VSMPE	green alley	0.35		7
RV-VSMPE-38	Chabot	VSMPE	green alley	0.35		25
RV-VSMPE-39	Henri-Julien	VSMPE	green alley	0.31	0	21
RV-VSMPE-4	Stuart	VSMPE	green alley	0.35		34
RV-	des	VSMPE	green	0.12	0	25

Infrastructure ID	Parallel Street	City	Infrastructure Type	Percent Canopy	Firefly Presence	Number of Points
VSMPE-40	Belges		alley			
RV-VSMPE-6	de l'Epée	VSMPE	green alley	0.10	1	33
RV-VSMPE-7	d'Outremont	VSMPE	green alley	0.18		29
RV-VSMPE-8	Durocher	VSMPE	green alley	0.10	0	32
RV-VSMPE-9	Bloomfield	VSMPE	green alley	0.06	1	35
SS-VSMPE-1	de l'Epée	VSMPE	street segment	0.70		24
SS-VSMPE-10	Durocher	VSMPE	street segment	0.19	0	23
SS-VSMPE-11	2e	VSMPE	street segment	0.42		20
SS-VSMPE-12	Louis-Hébert	VSMPE	street segment	0.59		20
SS-VSMPE-13	13e	VSMPE	street segment	0.16	0	14
SS-VSMPE-14	1re	VSMPE	street segment	0.62		6
SS-VSMPE-	6e	VSMPE	street segment	0.49		26

Infrastructure ID	Parallel Street	City	Infrastructure Type	Percent Canopy	Firefly Presence	Number of Points
15						
SS-VSMPE-16	9e	VSMPE	street segment	0.10	0	27
SS-VSMPE-18	47e	VSMPE	street segment	0.35		17
SS-VSMPE-19	Bressani	VSMPE	street segment	0.39		33
SS-VSMPE-2	Durocher	VSMPE	street segment	0.16	0	26
SS-VSMPE-20	48e	VSMPE	street segment	0.01	1	9
SS-VSMPE-22	des Belges	VSMPE	street segment	0.66	0	18
SS-VSMPE-23	Drolet	VSMPE	street segment	0.58	0	25
SS-VSMPE-24	Papineau	VSMPE	street segment	0.53		26
SS-VSMPE-25	St Andre	VSMPE	street segment	0.48	0	18
SS-VSMPE-26	Boyer	VSMPE	street segment	0.59	0	21
SS-VSMPE-27	Saint Dominique	VSMPE	street segment	0.36		23

Infrastructure ID	Parallel Street	City	Infrastructure Type	Percent Canopy	Firefly Presence	Number of Points
SS-VSMPE-28	Drolet	VSMPE	street segment	0.55		27
SS-VSMPE-29	de Lorimier	VSMPE	street segment	0.22	0	20
SS-VSMPE-3	de l'Epée	VSMPE	street segment	0.30	0	14
SS-VSMPE-30	St Andre	VSMPE	street segment	0.66	1	18
SS-VSMPE-31	de Chateaubriand	VSMPE	street segment	0.62	0	7
SS-VSMPE-32	de Normanville	VSMPE	street segment	0.86	0	16
SS-VSMPE-33	Drolet	VSMPE	street segment	0.57		22
SS-VSMPE-34	Casgrain	VSMPE	street segment	0.63		25
SS-VSMPE-35	de Gaspé	VSMPE	street segment	0.43	1	8
SS-VSMPE-36	de Gaspé	VSMPE	street segment	0.74	0	25
SS-VSMPE-37	Casgrain	VSMPE	street segment	0.66		7
SS-	Chabot	VSMPE	street	0.56		26

Infrastructure ID	Parallel Street	City	Infrastructure Type	Percent Canopy	Firefly Presence	Number of Points
VSMPE-38			segment			
SS-VSMPE-39	Henri-Julien	VSMPE	street segment	0.51	0	21
SS-VSMPE-4	Stuart	VSMPE	street segment	0.31		31
SS-VSMPE-40	des Belges	VSMPE	street segment	0.55	0	22
SS-VSMPE-5	Hutchison	VSMPE	street segment	0.19		31
SS-VSMPE-6	de l'Epée	VSMPE	street segment	0.31	0	30
SS-VSMPE-7	d'Outremont	VSMPE	street segment	0.03		26
SS-VSMPE-8	Durocher	VSMPE	street segment	0.19	0	31
SS-VSMPE-9	Bloomfield	VSMPE	street segment	0.33	0	28
CON-TR-1	Saint-Louis	TR	grey alley	0.06		7
CON-TR-11	Ste Angèle	TR	grey alley	0.10		9
CON-TR-12	Williams	TR	grey alley	0.16		8
CON-	Amherst	TR	grey	0.18		4

Infrastructure ID	Parallel Street	City	Infrastructure Type	Percent Canopy	Firefly Presence	Number of Points
TR-13			alley			
CON-TR-2	Saint-Louis	TR	grey alley	0.30		7
CON-TR-3	Dumoulin	TR	grey alley	0.15		26
CON-TR-4	Gingras	TR	grey alley	0.85		10
CON-TR-5	Cloutier	TR	grey alley	0.11		16
CON-TR-6	Jutras	TR	grey alley	0.08		14
CON-TR-7	Jutras	TR	grey alley	0.17		14
CON-TR-8	Honoré Mercier	TR	grey alley	0.16		13
CON-TR-9	Montcalm	TR	grey alley	0.13		12
CON-VSMPE-10	Henri-Julien	VSMPE	grey alley	0.26	1	25
CON-VSMPE-4	51e	VSMPE	grey alley	0.22	0	9
CON-VSMPE-8	Chambord	VSMPE	grey alley	0.07	0	15
RV-TR-1	Avenue 4	TR	green alley	0.50		18
RV-TR-11	Gingras	TR	green alley	0.04		6
RV-TR-12	Williams	TR	green alley	0.13		11

Infrastructure ID	Parallel Street	City	Infrastructure Type	Percent Canopy	Firefly Presence	Number of Points
RV-TR-13	Wolfe	TR	green alley	0.11		9
RV-TR-2	Avenue 5	TR	green alley	0.29		18
RV-TR-3	Amherst	TR	green alley	0.04		6
RV-TR-4	Honoré Mercier	TR	green alley	0.21		10
RV-TR-5	Brébeuf	TR	green alley	0.24		17
RV-TR-6	Godbout	TR	green alley	0.06		11
RV-TR-7	Godbout	TR	green alley	0.15		12
RV-TR-8	Mgr Cooke	TR	green alley	0.03		16
RV-TR-9	Ste Cécile	TR	green alley	0.05		10
RV-VSMPE-1	de l'Epée	VSMPE	green alley	0.21		32
RV-VSMPE-27	Saint Dominique	VSMPE	green alley	0.43		15
RV-VSMPE-35	de Gaspé	VSMPE	green alley	0.17	1	7
RV-VSMPE-5	Hutchison	VSMPE	green alley	0.22		41
CON-SS-TR-1	Saint-Louis	TR	street segment	0.46		7

Infrastructure ID	Parallel Street	City	Infrastructure Type	Percent Canopy	Firefly Presence	Number of Points
CON-SS-TR-11	Ste Angèle	TR	street segment	0.10		9
CON-SS-TR-12	Williams	TR	street segment	0.03		9
CON-SS-TR-13	Amherst	TR	street segment	0.01		8
CON-SS-TR-2	Saint-Louis	TR	street segment	0.29		6
CON-SS-TR-3	Dumoulin	TR	street segment	0.10		17
CON-SS-TR-4	Gingras	TR	street segment	0.00		11
CON-SS-TR-5	Cloutier	TR	street segment	0.00		12
CON-SS-TR-6	Jutras	TR	street segment	0.03		14
CON-SS-TR-7	Jutras	TR	street segment	0.00		18
CON-SS-TR-8	Honoré Mercier	TR	street segment	0.08		12
CON-SS-TR-9	Montcalm	TR	street segment	0.00		15
CON-SS-VSMPE-10	Henri-Julien	VSMPE	street segment	0.50	1	25
RV-SS-TR-1	Avenue 4	TR	green alley	0.42		14
RV-SS-	St Paul	TR	green	0.32		14

Infrastructure ID	Parallel Street	City	Infrastructure Type	Percent Canopy	Firefly Presence	Number of Points
TR-10			alley			
RV-SS-TR-12	Williams	TR	green alley	0.00		9
RV-SS-TR-13	Wolfe	TR	green alley	0.20		9
RV-SS-TR-2	Avenue 5	TR	green alley	0.34		14
RV-SS-TR-3	Amherst	TR	green alley	0.63		6
RV-SS-TR-4	Honoré Mercier	TR	green alley	0.00		12
RV-SS-TR-5	Brébeuf	TR	green alley	0.33		16
RV-SS-TR-6	Godbout	TR	green alley	0.06		12
RV-SS-TR-7	Godbout	TR	green alley	0.02		13
RV-SS-TR-8	Mgr Cooke	TR	green alley	0.46		12
RV-SS-TR-9	Ste Cécile	TR	green alley	0.00		11
SS-VSMPE-17	2e	VSMPE	street segment	0.01		24
SS-VSMPE-21	44e	VSMPE	street segment	0.00	0	9

Table A2.2: Tree species characteristics for species found in this study. Species represents binomial nomenclature for the species, max height represents the maximum height (in metres) for the species, flowers indicate if the species has showy or non-showy flowers when in bloom, native is a binomial category that indicates if the species is native to the St Lawrence Lowlands ecoregion (1 = yes, 0 = no), invasive is a binomial category that indicates if the species is invasive to the region (1 = yes, 0 = no), functional group represents the functional group assigned by Paquette et al. for that species (Paquette et al., 2021, Praise for diversity: A functional approach to reduce risks in urban forests). Blank cells indicate that we could not find the information for that species.

Species	Max Height (m)	Flowers	Native_SLL	Invasive	Functional Group
Abies concolor	15.2	not showy	0	0	1A
Acer freemanii	15.0	not showy	1	0	2A
Acer miyabei	13.5	not showy	0	0	
Acer negundo	12.0	not showy	0	0	2B
Acer nigrum	22.9	not showy	0	0	2A
Acer platanoides	13.5	not showy	0	1	2B
Acer platanoides 'Columnare'	18.2	not showy	0	1	2B
Acer rubrum	15.0	showy	1	0	2A
Acer saccharinum	18.0	not showy	1	0	2A
Acer saccharum	20.5	not showy	1	0	2A
Acer tataricum	5.5	not showy	0	1	
Aesculus glabra	9.0	showy	0	0	4B
Aesculus hippocastanum	19.0	showy	0	0	4B

Species	Max Height (m)	Flowers	Native_SLL	Invasive	Functional Group
Amelanchier arborea	6.5	showy	1	0	2B
Catalpa speciosa	15.0	showy	0	0	2B
Celtis occidentalis	15.0	not showy	1	0	2A
Cercidiphyllum japonicum	15.0	not showy	0	0	5
Dead sp.					
Fagus grandifolia	18.0	not showy	1	0	2A
Fraxinus americana	19.5	not showy	1	0	2A
Fraxinus pennsylvanica	16.5	not showy	1	0	2A
Ginkgo biloba	19.5	not showy	0	0	1B
Gleditsia triacanthos	15.0	not showy	0	0	2A
Gymnocladus dioicus	20.5	not showy	0	0	4A
Juglans cinerea	15.0	not showy	1	0	4B
Larix decidua	22.0	not showy	0	0	1B
Larix sp.	22.0	not showy	0	0	1B
Lonicera sp.	3.4	showy	0	0	
Maackia amurensis	7.5	showy	0	0	3B
Magnolia sp.	7.6	showy	0	0	2B

Species	Max Height (m)	Flowers	Native_SLL	Invasive	Functional Group
Malus baccata	8.5	showy	0	0	3A
Morus alba	12.0	not showy	0	0	3A
Ostrya virginiana	10.0	showy	1	0	2A
Phellodendron amurense	11.5	not showy	0	0	2B
Picea abies	15.0	not showy	0	0	1A
Picea glauca	15.0	not showy	1	0	1A
Picea pungens	13.5	not showy	0	0	1A
Pinus resinosa	19.5	not showy	1	0	1A
Pinus strobus	19.5	not showy	1	0	1A
Populus canadensis	40.0	not showy	0	0	5
Populus deltoides	26.5	not showy	1	0	5
Populus grandidentata	21.3	not showy	1	0	5
Prunus cerasus	9.0	showy	0	0	3
Prunus pensylvanica	10.7	showy	1	0	2B
Prunus virginiana	8.5	showy	1	0	2B
Pyrus domestica	8.3	showy	0	0	3A
Quercus alba	19.5	not showy	1	0	4A

Species	Max Height (m)	Flowers	Native_SLL	Invasive	Functional Group
Quercus bicolor	16.5	not showy	1	0	4A
Quercus macrocarpa	22.5	not showy	1	0	4A
Quercus robur 'Fastiagata'	16.8	not showy	0	0	4A
Quercus rubra	20.5	not showy	1	0	4A
Rhamnus catharticus	6.5	not showy	0	1	2A
Rhus typhina	6.5	not showy	1	0	2B
Robinia pseudoacacia	12.0	showy	0	0	3B
Rosa woodsii	2.0	showy	0	0	
Salix discolor	2.9	showy	1	0	
Saraca indica	10.0	showy	0	0	
Sorbus alnifolia	15.2	showy	0	0	3A
Sorbus aucuparia	9.0	showy	0	0	3A
Syringa reticulata	7.5	showy	0	0	3A
Syringa vulgaris	3.5	showy	0	0	3A
Thuja occidentalis	15.0	not showy	1	0	1A
Tilia americana	21.0	showy	1	0	2B
Tilia cordata	19.5	showy	0	0	2B
Ulmus	24.1	not showy			
Ulmus	18.2	not	0	0	

Species	Max Height (m)	Flowers	Native_SLL	Invasive	Functional Group
'Homestead'		showy			
Ulmus 'Morton Glossy'	18.0	not showy	0	0	3A
Ulmus 'New Horizon'	18.0	not showy	0	0	3A
Ulmus americana	21.0	not showy	1	0	2B
Ulmus crassifolia	21.3	not showy	0	0	
Ulmus davidiana 'Discovery'	24.3	not showy	0	0	3A
Ulmus davidiana 'Prospector'	24.3	not showy	0	0	3A
Ulmus frontier	12.2	not showy	0	0	
Ulmus hollandica	18.2	not showy	0	0	
Ulmus parvifolia	13.7	not showy	0	0	3A
Ulmus pumila	18.0	not showy	0	1	3A
Unknown sp.					

Table A2.3: Data displaying the composition of interviewees across different categories. Count indicates the number of interviewees who belonged to that category, and Percent indicates the percentage of interviewees who belonged to that category.

Variable	Levels	Count	Percent
Age	20-29	7	2
Age	30-39	6	1
Age	40-49	3	1
Age	50-59	7	2
Age	60-69	5	1
Age	70-79	0	0
Age	80+	1	0
Gender	Man	10	2
Gender	Woman	19	5
Gender	Other	1	0
Country of Origin	Canada/QC	16	4
Country of Origin	France	4	1
Country of Origin	China	1	0
Country of Origin	Ukraine	1	0
Country of Origin	Ghana	1	0
Country of Origin	Morocco	1	0
Country of Origin	Switzerland	2	0
Country of Origin	Ireland	1	0
Country of Origin	Colombia	1	0
Country of Origin	Iran	1	0
Years in QC	Née au Québec	16	4
Years in QC	Immi 0-4 ans	4	1
Years in QC	Immi 5-9 ans	3	1

Variable	Levels	Count	Percent
Years in QC	Immi 10-14 ans	1	0
Years in QC	Immi 15-19 ans	0	0
Years in QC	Immi 20 ans +	6	1
Household Size	1 person	14	3
Household Size	2 people	10	2
Household Size	3 people	5	1
Household Size	4 people	1	0
Number of Kids	0 kids	18	4
Number of Kids	1 kid	9	2
Number of Kids	2 kids	2	0
Number of Kids	3 kids	1	0
Education Level	Universitaire	23	6
Education Level	Collégial	5	1
Education Level	Secondaire	2	0
Employment Status	Student	7	2
Employment Status	Retired	4	1
Employment Status	Full-time	16	4
Employment Status	Unemployed	1	0
Employment Status	Self-employed	2	0
Annual Salary	-19 999$	4	1
Annual Salary	20 000$-29 999$	4	1
Annual Salary	30 000$-39 999$	2	0
Annual Salary	40 000$-49 999$	0	0
Annual Salary	50 000$-59 999$	5	1
Annual Salary	60 000$-69 999$	1	0
Annual Salary	70 000$-79 999$	2	0

Variable	Levels	Count	Percent
Annual Salary	80 000$-89 999$	0	0
Annual Salary	90 000$-99 999$	0	0
Annual Salary	100 000$ +	9	2
Car	Yes	14	3
Car	No	16	4
Housing Type	Apartment	18	4
Housing Type	Single family home	8	2
Housing Type	Condo	3	1
Housing Type	Coop	1	0
Alley Knowledge	Know the alleys	9	2
Alley Knowledge	Don't know the alleys	20	5
Alley Knowledge	Know one alley	1	0
City	Montréal	16	4
City	Trois-Rivières	14	3
Montreal Neighbourhood	Villeray	12	3
Montreal Neighbourhood	Parc-Extension	3	1
Montreal Neighbourhood	Saint-Michel	1	0
TR Neighbourhood	Sainte-Cécile	4	1
TR Neighbourhood	Saint-Patrick	5	1
TR Neighbourhood	Vieux Trois-Rivières	2	0
TR Neighbourhood	Saint-Sacrement	3	1

Table A2.4: Data showing the number of mentions that each ecosystem service received in the interviews. Ecosystem service category categorizes each ecosystem service using the four categories proposed in the Millenium Ecosystem Assessment (2005). Total mentions refers to the total number of times an ecosystem service was mentioned, regardless of if the same person brought it up multiple times. Number of people mentioned refers to the total number of people who mentioned that ecosystem service, without incorporating how many times they mentioned it. A darker colour depicts a higher number of mentions.

Ecosystem Service	Ecosystem Service Category	Total Mentions	Number of People Mentioned
Cultural and aesthetic values of greening	Cultural	66	26
Temperature regulation	Regulating	59	25
Cultural value of trees	Cultural	58	20
Aesthetic value of flowers	Cultural	52	17
Supporting wildlife	Supporting/Cultural	48	18
Provisioning of food from plants	Provisioning	40	17
Cultural value of vegetation management	Cultural	38	15
Presence of biodiversity	Supporting	33	14
Cultural value of large trees	Cultural	31	20
Cultural value of wild plants	Cultural	27	13
Aesthetic value of vines	Cultural	23	12
Cultural experience of odours	Cultural	19	12
Cultural value of vegetation maintenance	Cultural	18	14
Aesthetic value of colours	Cultural	13	8
Stormwater management	Regulating	10	7
Presence of native species	Supporting	8	4
Permeable surface management	Regulating	3	2
Air quality regulation	Regulating	2	2
Production of allergens	Provisioning/Cultural	1	1

Section 2B: Methodological Details

Canopy Cover

We calculated percent canopy cover of all green alleys, grey alleys, and street segments using publicly available LiDAR data collected in 2020 at a spatial resolution of 1 m (Institut National de Santé Publique du Québec and Gouvernement du Québec, 2022). For street segments, we calculated the canopy cover of sidewalks using the same dataset. Sidewalk boundaries were extracted from an open dataset for VSMPE (Ville de Montréal, 2024) and hand-drawn for TR using QGIS 3.16.8 (QGIS Development Team, 2020).

Tree Diversity

Tree diversity was assessed in two ways. First, we calculated the species richness of each alley and street segment by counting the number of unique tree species. We identified the species of each individual in the field (Farrar, 1995; Little, 1980). If a tree species could not be identified in the field, it was marked as unknown (n = 1/1,469). If a tree was dead, it was still recorded but was removed from the diversity calculations (n = 7/1,469). We recorded a total of 75 species (Table S2).

The second diversity metric was functional diversity. Using the original dataset and methodology from Paquette et al. (2021), we assigned a functional group to each of the tree species present in our dataset (Belluau et al., 2021, Table S2). The database published online did not have a functional group assignment for 15 of our species (20%, predominantly cultivars), thus those species were removed from the functional diversity calculations. If a cultivar or hybrid was not present in the database, but both parent species were and they shared the same functional group, we assigned the functional group of the parent species to the cultivar. We then summed how many functional groups each alley or street segment contained.

Proportion of Invasives/Natives

To assess the proportion of invasive and native species at each study site, we assigned a status of native or invasive to each of our study species (Padvaiskas et al., subm, Philp, 2024, Table S2). A species' native range was evaluated using the St. Lawrence Lowlands ecoregion. The St. Lawrence Lowlands ecoregion surrounds the St. Lawrence River ranging from Quebec City south through Montreal and just beyond Ottawa (Minister of Industry, 2010). If the native range of a species fell within a region we deemed it native to that region (Canadian Wildlife Federation, 2024; Dirr and Warren, 2019; Fryer, 2018; Government of Canada, 2013; The Morton Arboretum, 2022; Tree Canada, 2024; United States Department of Agriculture and Natural Resources Conservation Service, 2024; Woody Invasives of the Great Lakes Collaborative, 2019).

We categorized invasive species based on sources within the Eastern Temperate Forest ecoregion (The Morton Arboretum, 2022; Woody Invasives of the Great Lakes Collaborative, 2019). This is a larger ecoregion which runs west to east from Ontario to Nova Scotia and north to south from Southern Canada to Florida, USA (bplant.org, 2024). Any cultivar of a parent species that was considered invasive was also recorded as invasive. Hybrids with an invasive parent were noted

as invasive only if the invasive traits persisted in the hybrid (Dirr and Warren, 2019). Once each species was assigned a status, we calculated the proportion of stems at each site that were native and invasive.

Vegetative Complexity

We measured vegetative complexity by walking through each study site and stopping every 10 m. At each stop, we assessed which of the 5 following vegetative layers were present: ground cover, herbaceous vegetation, wall vegetation, shrubs, or canopy. If the presence of one of the layers was less than 1% of the area, it was ignored (e.g., one dandelion does not indicate the presence of an herbaceous vegetation layer). We define wall vegetation as vines and crawling vegetation that live on fences or walls. Average vegetative complexity of alleys and street segments was calculated by summing the total number of layers counted and then dividing by the number of points measured.

Firefly Presence

To assess the habitat quality of our study alleys, we selected a subset of alleys in VSMPE and performed a presence/absence survey of fireflies (Family: Lampyridae). Fireflies are known bioindicators in cities, as they require leaf litter, access to water, and low levels of light pollution (Firefly Atlas et al., 2023; Picchi et al., 2013). We selected the 28 green alleys with the highest canopy cover and most vegetative complexity for our subset, the five grey alleys with the least canopy cover and vegetative complexity as our controls, and the associated street segment for all 34 alleys surveyed. We sampled in groups of three between dusk and early nightfall, between 9:00 and 11:30 pm. Each person surveyed a section of the alley for five minutes and watched for the presence of fireflies. When a firefly was seen, the sampler recorded its presence. After 5 minutes, each person rotated spots and repeated the survey in the next segment. We did this three times for each alley. We did not sample in the rain, when firefly flight does not occur (Firefly Atlas et al., 2023; Picchi et al., 2013). If the presence of a firefly was noted in any of the surveys, the alley was assigned as having fireflies present.

DBH

We assessed the presence of large trees in two ways, we calculated the mean observed tree DBH and the mean potential height for each study site. To calculate mean observed DBH, we evaluated tree size by identifying and measuring the diameter at breast height (DBH) of every tree (defined as a woody plant > 2 m tall) found in the alley. If a tree had a split stem with the split above or near DBH, we measured the DBH at the narrowest part of the stem below the fork. If the split occurred below DBH but above 6” from the ground, we measured each stem individually and calculated DBH by taking the square root of the sum of all squared stem DBHs. If the split occurred below 6” from the ground, we counted the stems as separate individuals (Magarik et al., 2020). We then took the average DBH of all the trees in an alley or street segment.

Interview Questions

Sociodemographic data:

Age

Gender

Ethnocultural group

Time since arriving in Quebec

Household composition

Number of kids / their ages

Level of education

Employment status

Annual revenue bracket

Housing type

Car ownership

The neighbourhood:

What represents the neighbourhood for you? What characterizes it? What do you value in the neighbourhood? (or what would you be ready to invest in?)

What are the boundaries of your neighbourhood?

What is here in terms of public green space management?

According to you, what are the objectives and intended benefits of these developments for the riverside community? Are they being achieved?

What are the downsides of the developments for the riverside community?

What do you like the most or the least about these green spaces?

How do these spaces improve the neighbourhood (social, road and urban safety, mobility, health)

According to you, what does the city do to ensure the management, quality of development, and the management of these spaces? Are they doing enough?

The neighbourhood, green spaces, and changes:

What has changed in your neighbourhood in the last years (green infrastructure, management of the neighbourhood, demographics, social composition, etc.)?

When do you remember the changes starting?

Who makes the changes and for what reasons?

Has there been citizen mobilization?

Who has changed their activities since the changes?

How have the neighbourhood relationships changed (residential, institutional)?

Do you make any links between the management of green spaces and the changes in the neighbourhood?

The walk starts:

Discuss what attracts your attention here?

Discuss how you feel here?

Discuss what activities you do here?

Discuss the interventions/management/equipment (anthropogenic elements)

Discuss the richness, diversity, cohabitation, and conditions of the space?

Before concluding:

Which green spaces do you like the most and the least? Why?

Which green spaces should be improved? Why?

When comparing the spaces we visited, does your perception of the spaces change?

After the visit, what do you think is different (or similar) between green spaces and non-green spaces? What do the green spaces you visit have in common?

How do these spaces relate to other green spaces in the city/nature in the city? What do these green spaces have in common with other green spaces in the city?

Do you have other comments to share with us?

Section 2C: Figures

Figure A2.1: Directed acyclic graphs (DAGs).

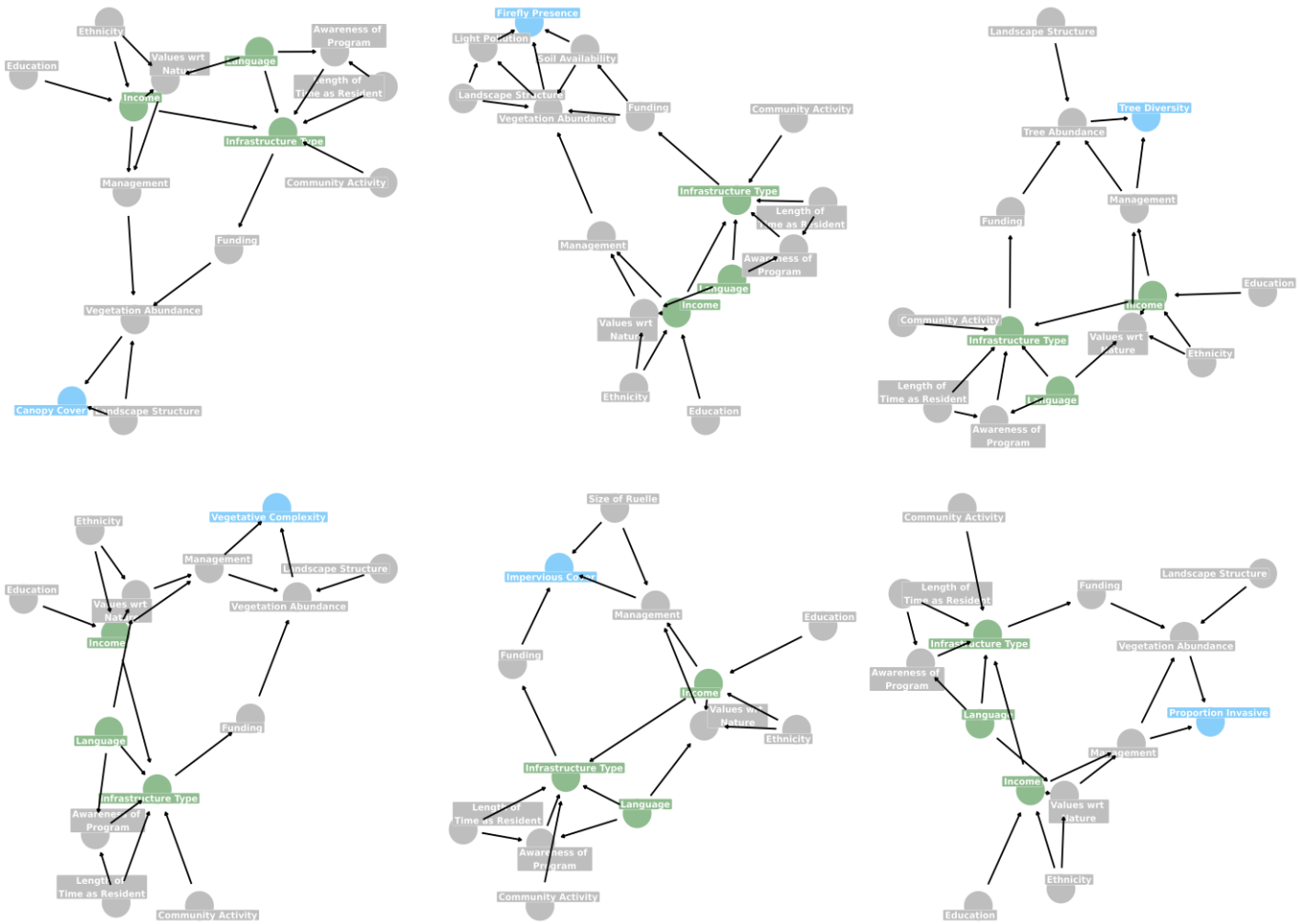


Figure A2.1a: DAGs that indicate the system assumptions for biodiversity support indices measured in this study. Blue indicates the response variable of interest, green indicates the variable of interest and all variables adjusted for.

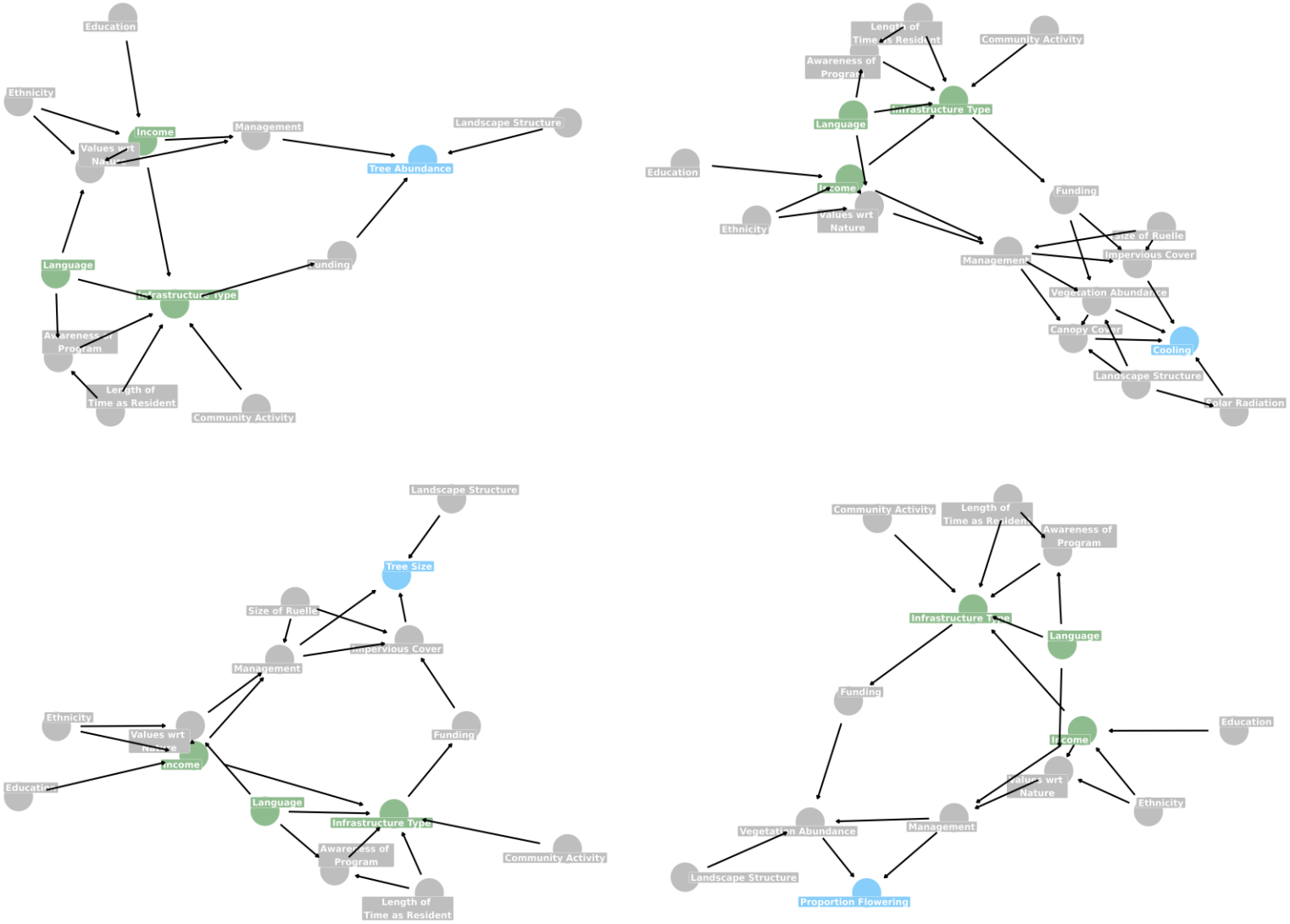


Figure A2.1b: DAGs that indicate the system assumptions for ecosystem service indices measured in this study. Blue indicates the response variable of interest, green indicates the variable of interest and all variables adjusted for.



Figure A2.2: Examples of typical green alleys in Trois-Rivières and Villeray-Saint Michel-Parc Extension. Photos were taken by Isabella C Richmond in the summer of 2023.

Section 2D: Equations

Below are the mathstats formulas for each of the models included in the paper.

Canopy Cover

1. VSMPE

$$
\begin{gathered}
Canopy_i \sim Normal(\mu_i, \sigma) \\
\mu_i = \alpha_{Qsocio[i]} + \beta_{type[i]} + \beta_{medinc} medinc_i + \beta_{french} french_i + \beta_{english} english_i + \beta_{none} none_i \\
\beta_j \sim Normal(0, 0.3) \\
\alpha_j \sim Normal(\bar{\alpha}, \sigma_\alpha) \\
\bar{\alpha} \sim Normal(0, 0.5) \\
\sigma_\alpha \sim Half-Normal(0, 0.2) \\
\sigma \sim Exponential(1)
\end{gathered}
$$

Terms:

`Canopy` is the centered and scaled percent canopy cover of each site

`type` is the type of infrastructure (i.e., green alley, grey alley, street segment)

`medinc` is the centered and scaled median income of the dissemination area surrounding the site

`french` is the centered and scaled percent of residents in the dissemination area surrounding the site that speak french

`english` is the centered and scaled percent of residents in the dissemination area surrounding the site that speak english

`none` is the centered and scaled percent of residents in the dissemination area surrounding the site that do not speak french or english

2. TR

$$
\begin{gathered}
Canopy \sim Normal(\mu_i, \sigma) \\
\mu_i = \alpha + \beta_1 green_{[i]} + \beta_2 street_{[i]} \\
\alpha \sim Normal(0, 0.7) \\
\beta_j \sim Normal(0, 0.7) \\
\sigma \sim Exponential(1)
\end{gathered}
$$

Terms:

`Canopy` is the centered and scaled percent canopy cover of each site

`green` is the factor level from `type` that indicates green alleys. Grey alleys are the default level, absorbed into the intercept.

`street` is the factor level from `type` that indicates street segments. Grey alleys are the default level, absorbed into the intercept.

Species Richness

3. VSMPE

$$SpeciesRichness_i \sim Gamma - Poisson(\lambda_i, \phi)$$
$$log(\lambda_i) = \alpha_{Qsocio[i]} + \beta_{type[i]} + \beta_{medinc} medinc_i + \beta_{french} french_i + \beta_{english} english_i + \beta_{none} none_i$$
$$\beta_j \sim Normal(0, 0.2)$$
$$\alpha_j \sim Normal(\bar{\alpha}, \sigma_\alpha)$$
$$\bar{\alpha} \sim Normal(0, 0.5)$$
$$\sigma_\alpha \sim Half - Normal(0, 0.1)$$
$$\phi \sim Inverse - Gamma(0.4, 0.3)$$

Terms:

`Species Richness` is number of unique tree species found at each site

`Q socio` is the neighbourhood of the site (i.e., Villeray, Saint-Michel, or Parc Extension)

`type` is the type of infrastructure (i.e., green alley, grey alley, or street segment)

`medinc` is the centered and scaled median income of the dissemination area surrounding the site

`french` is the centered and scaled percent of residents in the dissemination area surrounding the site that speak french

`english` is the centered and scaled percent of residents in the dissemination area surrounding the site that speak english

`none` is the centered and scaled percent of residents in the dissemination area surrounding the site that do not speak french or english

4. TR

$$SpeciesRichness_i \sim Poisson(\lambda_i)$$
$$log(\lambda_i) = \alpha + \beta_1 green * [i] + \beta_2 street_{[i]}$$
$$\alpha \sim Normal(0, 0.5)$$
$$\beta_j \sim Normal(0, 0.2)$$

Terms:

`Canopy` is the centered and scaled percent canopy cover of each site

`green` is the factor level from `type` that indicates green alleys. Grey alleys are the default level, absorbed into the intercept.

`street` is the factor level from `type` that indicates street segments. Grey alleys are the default level, absorbed into the intercept.

Functional Diversity

5. VSMPE

$$FunctionalGroups_i \sim Binomial(9, p_i)$$
$$logit(p_i) = \alpha_{Qsocio[i]} + \beta_{type[i]} + \beta_{medinc} medinc_i + \beta_{french} french_i + \beta_{english} english_i + \beta_{none} none_i$$
$$\beta_j \sim Normal(0, 0.2)$$
$$\alpha_j \sim Normal(\bar{\alpha}, \sigma\alpha)$$
$$\bar{\alpha} \sim Normal(0, 0.5)$$
$$\sigma\alpha \sim Half-Normal(0, 0.1)$$

Terms:

`Functional Groups` is number of unique functional groups found at each site

`Q socio` is the neighbourhood of the site (i.e., Villeray, Saint-Michel, or Parc Extension)

`type` is the type of infrastructure (i.e., green alley, grey alley, or street segment)

`medinc` is the centered and scaled median income of the dissemination area surrounding the site

`french` is the centered and scaled percent of residents in the dissemination area surrounding the site that speak french

`english` is the centered and scaled percent of residents in the dissemination area surrounding the site that speak english

`none` is the centered and scaled percent of residents in the dissemination area surrounding the site that do not speak french or english

6. TR

$$FunctionalGroups_i \sim Binomial(9, p_i)$$
$$logit(p_i) = \alpha + \beta_1 green_{[i]} + *\beta_2 street_{[i]}$$
$$\alpha \sim Normal(0, 0.5)$$
$$\beta_j \sim Normal(0, 0.2)$$

Terms:

`Functional Groups` is number of unique functional groups found at each site

`green` is the factor level from `type` that indicates green alleys. Grey alleys are the default level, absorbed into the intercept.

`street` is the factor level from `type` that indicates street segments. Grey alleys are the default level, absorbed into the intercept.

Proportion of Native Species

7. VSMPE

$$
\begin{gathered}
ProportionNative_i \sim Binomial(N_i, p_i) \\
logit(p_i) = \alpha_{Qsocio[i]} + \beta_{type[i]} + \beta_{medinc} medinc_i + \beta_{french} french_i + \beta_{english} english_i + \beta nonenone_i \\
\beta_j \sim Normal(0, 0.5) \\
\alpha_j \sim Normal(\bar{\alpha}, \sigma\alpha) \\
\bar{\alpha} \sim Normal(0, 1.5) \\
\sigma_\alpha \sim Half-Normal(0, 0.2)
\end{gathered}
$$

Terms:

`N` is the total number of trees found at each site

`Proportion Native` is number of native trees found at each site

`Q socio` is the neighbourhood of the site (i.e., Villeray, Saint-Michel, or Parc Extension)

`type` is the type of infrastructure (i.e., green alley, grey alley, or street segment)

`medinc` is the centered and scaled median income of the dissemination area surrounding the site

`french` is the centered and scaled percent of residents in the dissemination area surrounding the site that speak french

`english` is the centered and scaled percent of residents in the dissemination area surrounding the site that speak english

`none` is the centered and scaled percent of residents in the dissemination area surrounding the site that do not speak french or english

8. TR

$$
\begin{gathered}
ProportionNative_i \sim Binomial(N_i, p_i) \\
logit(p_i) = \alpha + \beta_1 green_{[i]} + \beta_2 street_{[i]} \\
\alpha \sim Normal(0, 1.5) \\
\beta_j \sim Normal(0, 0.5)
\end{gathered}
$$

`N` is the total number of trees found at each site

`Proportion Native` is number of native trees found at each site

`green` is the factor level from `type` that indicates green alleys. Grey alleys are the default level, absorbed into the intercept.

`street` is the factor level from `type` that indicates street segments. Grey alleys are the default level, absorbed into the intercept.

Proportion of Invasive Species

9. VSMPE

$$ProportionInvasive_i \sim Binomial(N_i, p_i)$$
$$logit(p_i) = \alpha_{Qsocio[i]} + \beta_{type[i]} + \beta_{medinc} medinc_i + \beta french french_i + \beta_{english} english_i + \beta_{none} none_i$$
$$\beta_j \sim Normal(0, 0.5)$$
$$\alpha_j \sim Normal(\bar{\alpha}, \sigma\alpha)$$
$$\bar{\alpha} \sim Normal(-1.4, 0.5)$$
$$\sigma_\alpha \sim Half - Normal(0, 0.2)$$

Terms:

`N` is the total number of trees found at each site

`Proportion Invasive` is number of invasive trees found at each site

`Q socio` is the neighbourhood of the site (i.e., Villeray, Saint-Michel, or Parc Extension)

`type` is the type of infrastructure (i.e., green alley, grey alley, or street segment)

`medinc` is the centered and scaled median income of the dissemination area surrounding the site - `french` is the centered and scaled percent of residents in the dissemination area surrounding the site that speak french

`english` is the centered and scaled percent of residents in the dissemination area surrounding the site that speak english

`none` is the centered and scaled percent of residents in the dissemination area surrounding the site that do not speak french or english

10. TR

$$ProportionInvasive_i \sim Binomial(N_i, p_i)$$
$$logit(p_i) = \alpha + \beta_1 green_{[i]} + \beta_2 street_{[i]}$$
$$\alpha \sim Normal(0, 1.5)$$
$$\beta_j \sim Normal(0, 0.5)$$

Terms:

`N` is the total number of trees found at each site

`Proportion Invasive` is number of invasive trees found at each site

`green` is the factor level from `type` that indicates green alleys. Grey alleys are the default level, absorbed into the intercept.

`street` is the factor level from `type` that indicates street segments. Grey alleys are the default level, absorbed into the intercept.

Vegetative Complexity

11. VSMPE

$$
\begin{gathered}
Complexity_i \sim Normal(\mu_i, \sigma) \\
\mu_i = \alpha_{Qsocio[i]} + \beta_{type[i]} + \beta_{medinc} medinc_i + \beta_{french} french_i + \beta_{english} english_i + \beta_{none} none_i \\
\beta_j \sim Normal(0, 0.5) \\
\alpha_j \sim Normal(\bar{\alpha}, \sigma_\alpha) \\
\bar{\alpha} \sim Normal(0, 0.5) \\
\sigma_\alpha \sim Half-Normal(0, 0.2) \\
\sigma \sim Exponential(1)
\end{gathered}
$$

Terms:

`Complexity` is the centered and scaled average vegetative complexity of each site

`type` is the type of infrastructure (i.e., green alley, grey alley, street segment)

`medinc` is the centered and scaled median income of the dissemination area surrounding the site

`french` is the centered and scaled percent of residents in the dissemination area surrounding the site that speak french

`english` is the centered and scaled percent of residents in the dissemination area surrounding the site that speak english

`none` is the centered and scaled percent of residents in the dissemination area surrounding the site that do not speak french or english

12. TR

$$
\begin{gathered}
Complexity_i \sim Normal(\mu_i, \sigma) \\
\mu_i = \alpha + \beta_1 green_{[i]} + \beta_2 street_{[i]} \\
\alpha \sim Normal(0, 0.5) \\
\beta_j \sim Normal(0, 0.5)
\end{gathered}
$$

Terms:

`Complexity` is the centered and scaled average vegetative complexity of each site

`green` is the factor level from `type` that indicates green alleys. Grey alleys are the default level, absorbed into the intercept.

`street` is the factor level from `type` that indicates street segments. Grey alleys are the default level, absorbed into the intercept.

Firefly Presence

13. VSMPE

$$
\begin{gathered}
FireflyPresence_i \sim Bernoulli(p_i) \\
logit(p_i) = \alpha_{Qsocio[i]} + \beta_{type[i]} + \beta_{medinc} medinc_i + \beta_{french} french_i + \beta_{english} english_i + \beta_{none} none_i \\
\beta_j \sim Normal(0, 0.5) \\
\alpha_j \sim Normal(\bar{\alpha}, \sigma\alpha) \\
\bar{\alpha} \sim Normal(-1.4, 0.5) \\
\sigma_\alpha \sim Half-Normal(0, 0.2)
\end{gathered}
$$

Terms:

`Firefly Presence` is binary success of observing a firefly at a site (1 = presence, 0 = absence)

`Q socio` is the neighbourhood of the site (i.e., Villeray, Saint-Michel, or Parc Extension)

`type` is the type of infrastructure (i.e., green alley, grey alley, or street segment)

`medinc` is the centered and scaled median income of the dissemination area surrounding the site

`french` is the centered and scaled percent of residents in the dissemination area surrounding the site that speak french

`english` is the centered and scaled percent of residents in the dissemination area surrounding the site that speak english

`none` is the centered and scaled percent of residents in the dissemination area surrounding the site that do not speak french or english

Temperature

14. VSMPE

$$
\begin{gathered}
Temperature_i \sim Normal(\mu_i, \sigma) \\
\mu_i = \alpha_{date[i]} + \alpha_{Qsocio[i]} + \alpha_{ID[i]} + \gamma type[i] + \gamma_{tod[i]} + \gamma_{doy[i]} + \\
\beta_{type} tod + \beta_{tod} doy + \beta_{doy} type + \beta_{type[i]} + \beta_{tod[i]} + \beta_{doy} doy_i + \\
\beta_{medinc} medinc_i + \beta_{french} french_i + \beta_{english} english_i + \beta_{none} none_i \\
\alpha_{date[j]} \sim Normal(\bar{\alpha}, \sigma_{\alpha_{date}}) \\
\alpha_{Qsocio[j]} \sim Normal(0, \sigma_{\alpha_{Qsocio}}) \\
\alpha_{ID[j]} \sim Normal(0, \sigma_{\alpha_{ID}}) \\
\gamma_j \sim Normal(0, 1) \\
\beta_j \sim Normal(0, 0.5) \\
\bar{\alpha} \sim Normal(0, 1) \\
\sigma_{\alpha_{date}} \sim Exponential(1) \\
\sigma_{\alpha_{Qsocio}} \sim Exponential(1) \\
\sigma_{\alpha_{ID}} \sim Exponential(1) \\
\sigma \sim Exponential(1)
\end{gathered}
$$

Terms:

α and γ both represent intercepts, α is used for random effects and γ for fixed interaction effecst

`Temperature` is the centered and scaled temperature measurement in degrees Celsius

`date` is the calendar date represented as a character with a different level for each day

`Q socio` is the neighbourhood of the site (i.e., Villeray, Saint-Michel, or Parc Extension)

`ID` is the individual identifier for each infrastructure (e.g., VSMPE-RV-1)

`type` is the type of infrastructure (i.e., green alley, grey alley, or street segment)

`tod` is the time of day of each measurement, split into two categories; day (after sunrise/before sunset) and night (after sunset/before sunrise)

`doy` is the numeric and continuous value representing day of year, which has been subtracted by the first day of sampling so that it starts at 0

`medinc` is the centered and scaled median income of the dissemination area surrounding the site

`french` is the centered and scaled percent of residents in the dissemination area surrounding the site that speak french

`english` is the centered and scaled percent of residents in the dissemination area surrounding the site that speak english

`none` is the centered and scaled percent of residents in the dissemination area surrounding the site that do not speak french or english

15. TR

$$
\begin{gathered}
Temperature_i \sim Normal(\mu_i, \sigma) \\
\mu_i = \alpha_{date[i]} + \alpha_{ID[i]} + \gamma_{type[i]} + \gamma_{tod[i]} + \gamma_{doy[i]} + \\
\beta_{type} tod + \beta_{tod} doy + \beta_{doy} type + \beta_{type[i]} + \beta_{tod[i]} + \beta_{doy} doy_i \\
\alpha_{date[j]} \sim Normal(\bar{\alpha}, \sigma_{\alpha_{date}}) \\
\alpha_{Qsocio[j]} \sim Normal(0, \sigma_{\alpha_{Qsocio}}) \\
\alpha_{ID[j]} \sim Normal(0, \sigma_{\alpha_{ID}}) \\
\gamma_j \sim Normal(0, 1) \\
\beta_j \sim Normal(0, 0.5) \\
\bar{\alpha} \sim Normal(0, 1) \\
\sigma \alpha date \sim Exponential(1) \\
\sigma_{\alpha_{Qsocio}} \sim Exponential(1) \\
\sigma_{\alpha_{ID}} \sim Exponential(1) \\
\sigma \sim Exponential(1)
\end{gathered}
$$

Terms:

α and γ both represent intercepts, α is used for random effects and γ for fixed interaction effects

`Temperature` is the centered and scaled temperature measurement in degrees Celsius

`date` is the calendar date represented as a character with a different level for each day

`ID` is the individual identifier for each infrastructure (e.g., VSMPE-RV-1)

`type` is the type of infrastructure (i.e., green alley, grey alley, or street segment)

`tod` is the time of day of each measurement, split into two categories; day (after sunrise/before sunset) and night (after sunset/before sunrise)

`doy` is the numeric and continuous value representing day of year, which has been subtracted by the first day of sampling so that it starts at 0

Tree Abundance

16. VSMPE

$$TreeAbundance_i \sim Gamma - Poisson(\lambda_i, \phi)$$
$$log(\lambda_i) = \alpha_{Qsocio[i]} + \beta_{type[i]} + \beta_{medinc} medinc_i + \beta_{french} french_i + \beta_{english} english_i + \beta_{none} none_i$$
$$\beta_j \sim Normal(0, 0.2)$$
$$\alpha_j \sim Normal(\bar{\alpha}, \sigma_\alpha)$$
$$\bar{\alpha} \sim Normal(0, 0.5)$$
$$\sigma_\alpha \sim Half - Normal(0, 0.1)$$
$$\phi \sim Inverse - Gamma(0.4, 0.3)$$

Terms:

`Tree Abundance` is number of individual trees found at a site

`Q socio` is the neighbourhood of the site (i.e., Villeray, Saint-Michel, or Parc Extension)

`type` is the type of infrastructure (i.e., green alley, grey alley, or street segment)

`medinc` is the centered and scaled median income of the dissemination area surrounding the site

`french` is the centered and scaled percent of residents in the dissemination area surrounding the site that speak french

`english` is the centered and scaled percent of residents in the dissemination area surrounding the site that speak english

`none` is the centered and scaled percent of residents in the dissemination area surrounding the site that do not speak french or english

17. TR

$$TreeAbundance_i \sim Poisson(\lambda_i)$$
$$log(\lambda_i) = \alpha + \beta_1 green_{[i]} + \beta_2 street_{[i]}$$
$$\alpha \sim Normal(0, 0.5)$$
$$\beta_j \sim Normal(0, 0.2)$$

Terms:

`Tree Abundance` is number of individual trees found at a site

`green` is the factor level from `type` that indicates green alleys. Grey alleys are the default level, absorbed into the intercept.

`street` is the factor level from `type` that indicates street segments. Grey alleys are the default level, absorbed into the intercept.

Tree Size (Diameter at Breast Height)

18. VSMPE

$$DBH_i \sim Normal(\mu_i, \sigma)$$
$$\mu_i = \alpha_{Qsocio[i]} + \beta_{type[i]} + \beta_{medinc} medinc_i + \beta_{french} french_i + \beta_{english} english_i + \beta_{none} none_i$$
$$\beta_j \sim Normal(0, 0.3)$$
$$\alpha_j \sim Normal(\bar{\alpha}, \sigma_\alpha)$$
$$\bar{\alpha} \sim Normal(0, 0.5)$$
$$\sigma_\alpha \sim Half-Normal(0, 0.2)$$
$$\sigma \sim Exponential(1)$$

Terms:

`DBH` is the centered and scaled mean diameter at breast height (DBH) of trees at each site

`type` is the type of infrastructure (i.e., green alley, grey alley, street segment)

`medinc` is the centered and scaled median income of the dissemination area surrounding the site

`french` is the centered and scaled percent of residents in the dissemination area surrounding the site that speak french

`english` is the centered and scaled percent of residents in the dissemination area surrounding the site that speak english

`none` is the centered and scaled percent of residents in the dissemination area surrounding the site that do not speak french or english

19. TR

$$DBH_i \sim Normal(\mu_i, \sigma)$$
$$\mu_i = \alpha + \beta_1 green_{[i]} + \beta_2 street_{[i]}$$
$$\alpha \sim Normal(0, 0.7)$$
$$\beta_j \sim Normal(0, 0.7)$$
$$\sigma \sim Exponential(1)$$

Terms:

`DBH` is the centered and scaled mean diameter at breast height (DBH) of trees at each site

`green` is the factor level from `type` that indicates green alleys. Grey alleys are the default level, absorbed into the intercept.

`street` is the factor level from `type` that indicates street segments. Grey alleys are the default level, absorbed into the intercept.

Tree Size (Potential Maximum Height)

20. VSMPE

$$MaxHeight_i \sim Normal(\mu_i, \sigma)$$
$$\mu_i = \alpha_{Qsocio[i]} + \beta_{type[i]} + \beta_{medinc} medinc_i + \beta_{french} french_i + \beta_{english} english_i + \beta_{none} none_i$$
$$\beta_j \sim Normal(0, 0.3)$$
$$\alpha_j \sim Normal(\bar{\alpha}, \sigma_\alpha)$$
$$\bar{\alpha} \sim Normal(0, 0.5)$$
$$\sigma_\alpha \sim Half-Normal(0, 0.2)$$
$$\sigma \sim Exponential(1)$$

Terms:

`Max Height` is the centered and scaled mean maximum (potential) height of trees at each site

`type` is the type of infrastructure (i.e., green alley, grey alley, street segment)

`medinc` is the centered and scaled median income of the dissemination area surrounding the site

`french` is the centered and scaled percent of residents in the dissemination area surrounding the site that speak french

`english` is the centered and scaled percent of residents in the dissemination area surrounding the site that speak english

`none` is the centered and scaled percent of residents in the dissemination area surrounding the site that do not speak french or english

21. TR

$$MaxHeight_i \sim Normal(\mu_i, \sigma)$$
$$\mu_i = \alpha + \beta_1 green_{[i]} + \beta_2 street_{[i]}$$
$$\alpha \sim Normal(0, 0.7)$$
$$\beta_j \sim Normal(0, 0.7)$$
$$\sigma \sim Exponential(1)$$

Terms:

`Max Height` is the centered and scaled mean maximum (potential) height of trees at each site

`green` is the factor level from `type` that indicates green alleys. Grey alleys are the default level, absorbed into the intercept.

`street` is the factor level from `type` that indicates street segments. Grey alleys are the default level, absorbed into the intercept.

Proportion of Trees with Showy Flowers

22. VSMPE

$$
\begin{gathered}
ProportionShowy_i \sim Binomial(N_i, p_i) \\
logit(p_i) = \alpha_{Qsocio[i]} + \beta_{type[i]} + \beta_{medinc} medinc_i + \beta_{french} french_i + \beta_{english} english_i + \beta_{none} none_i \\
\beta_j \sim Normal(0, 0.5) \\
\alpha_j \sim Normal(\bar{\alpha}, \sigma_\alpha) \\
\bar{\alpha} \sim Normal(0, 0.5) \\
\sigma_\alpha \sim Half-Normal(0, 0.2)
\end{gathered}
$$

Terms:

`N` is the total number of trees found at each site

`Proportion Showy` is number of trees with showy flowers found at each site

`Q socio` is the neighbourhood of the site (i.e., Villeray, Saint-Michel, or Parc Extension)

`type` is the type of infrastructure (i.e., green alley, grey alley, or street segment)

`medinc` is the centered and scaled median income of the dissemination area surrounding the site

`french` is the centered and scaled percent of residents in the dissemination area surrounding the site that speak french

`english` is the centered and scaled percent of residents in the dissemination area surrounding the site that speak english

`none` is the centered and scaled percent of residents in the dissemination area surrounding the site that do not speak french or english

23. TR

$$
\begin{gathered}
ProportionShowy_i \sim Binomial(N_i, p_i) \\
logit(p_i) = \alpha + \beta_1 green_{[i]} + \beta_2 street_{[i]} \\
\alpha \sim Normal(0, 0.5) \\
\beta_j \sim Normal(0, 0.5)
\end{gathered}
$$

Terms:

`N` is the total number of trees found at each site

`Proportion Showy` is number of trees with showy flowers found at each site

`green` is the factor level from `type` that indicates green alleys. Grey alleys are the default level, absorbed into the intercept.

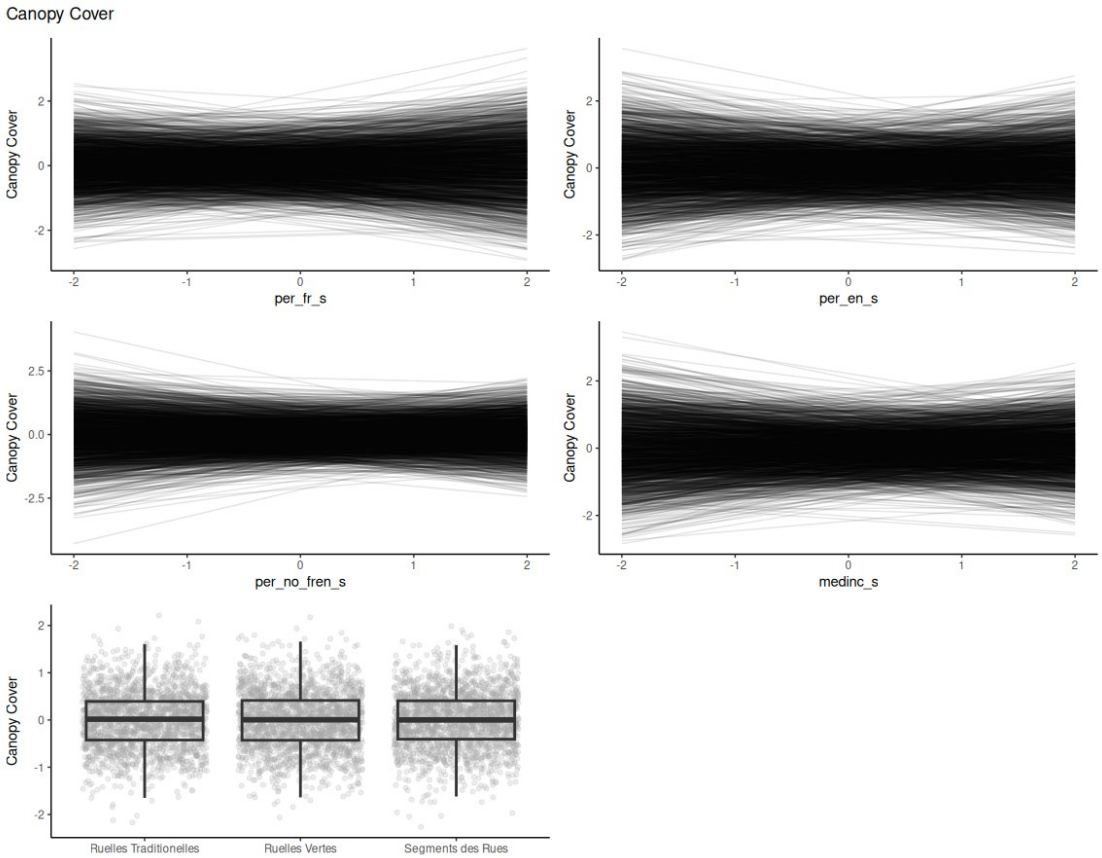
`street` is the factor level from `type` that indicates street segments. Grey alleys are the default level, absorbed into the intercept.

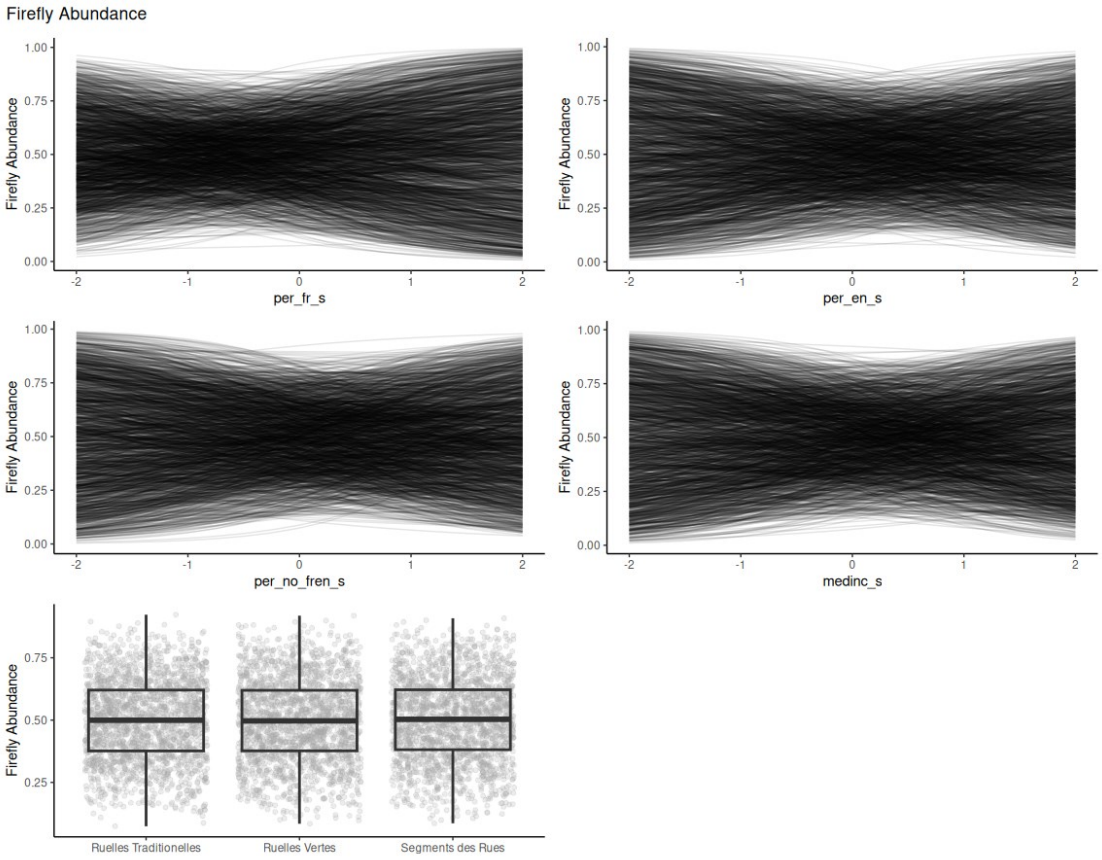
Section 2E: Prior Predictive Checks

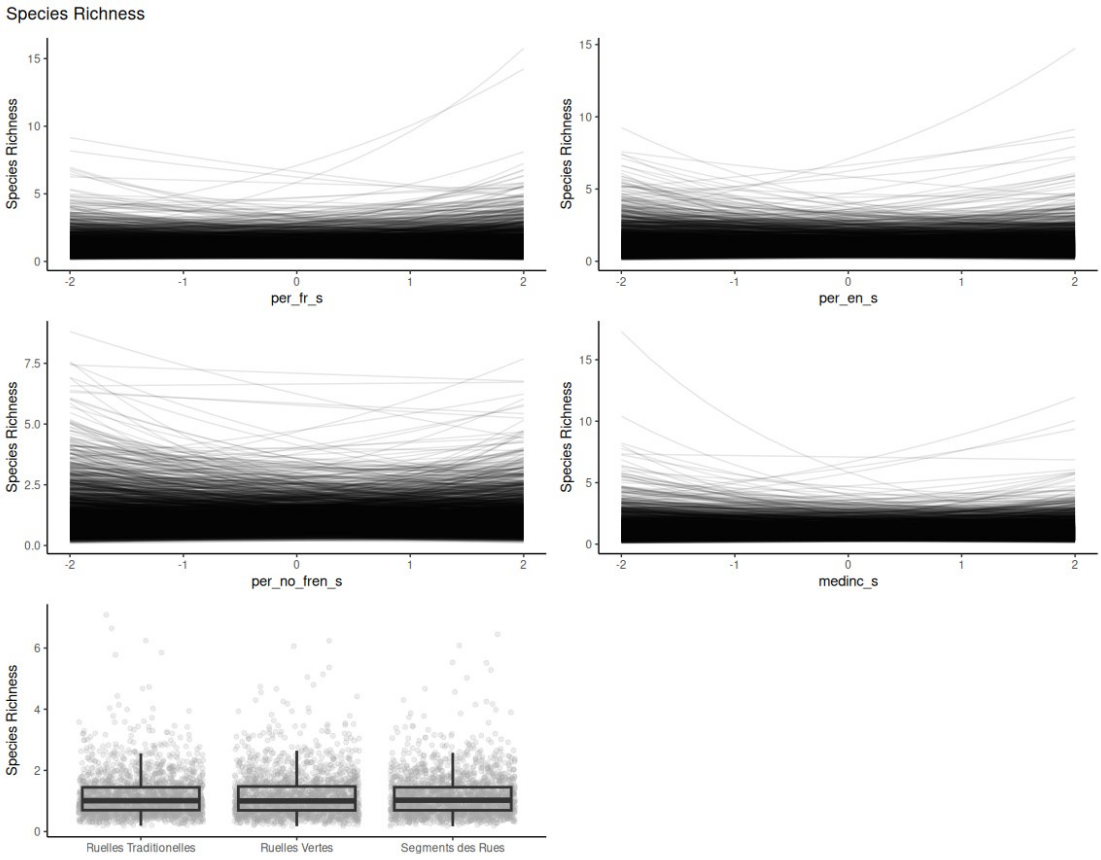
Prior predictive checks are used to ensure that the values selected for priors for our models allow a biologically reasonable range of values. For numeric predictor variables, we simulate predictive draws for prior only models and visualize the slope/intercept of the values. We then do a "posterior predictive check" but with the prior only model, to see if the data is captured in the priors. Note that all data is scaled and centered in these data.

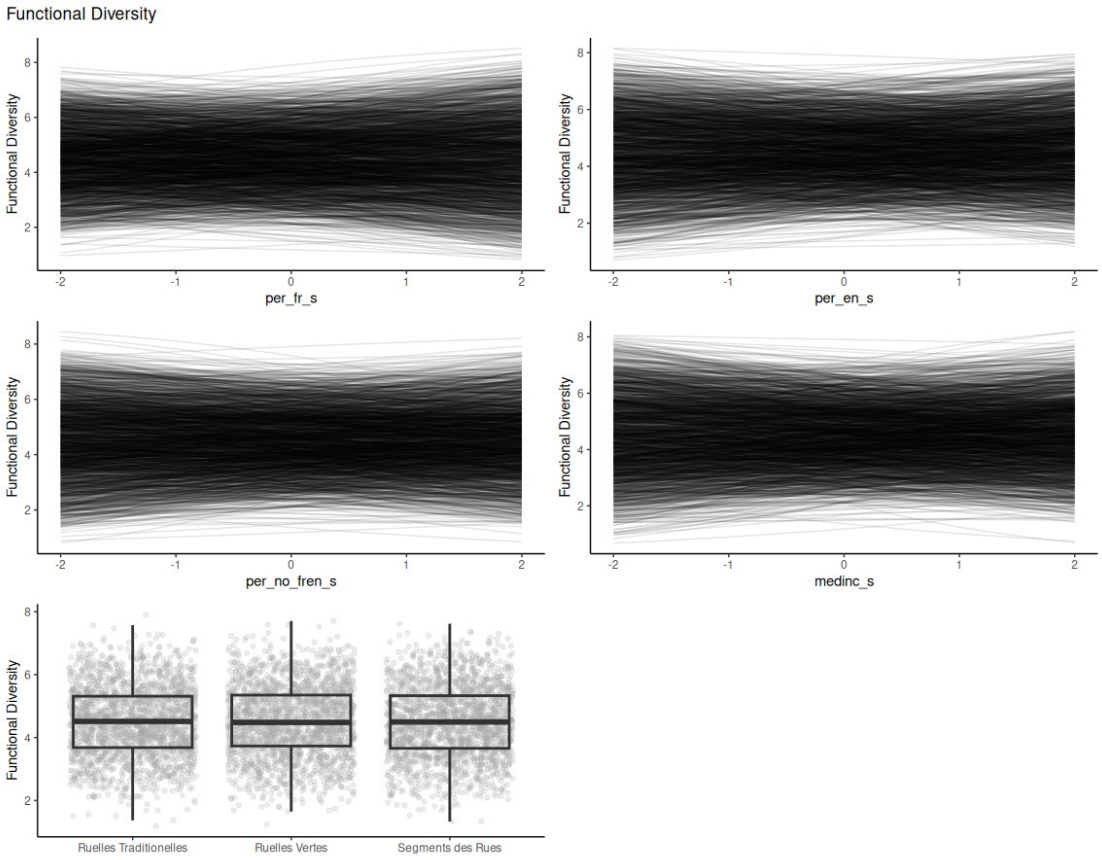
For Trois-Rivieres, there is only a categorical predictor variable. Therefore, only the posterior predictive check is presented.

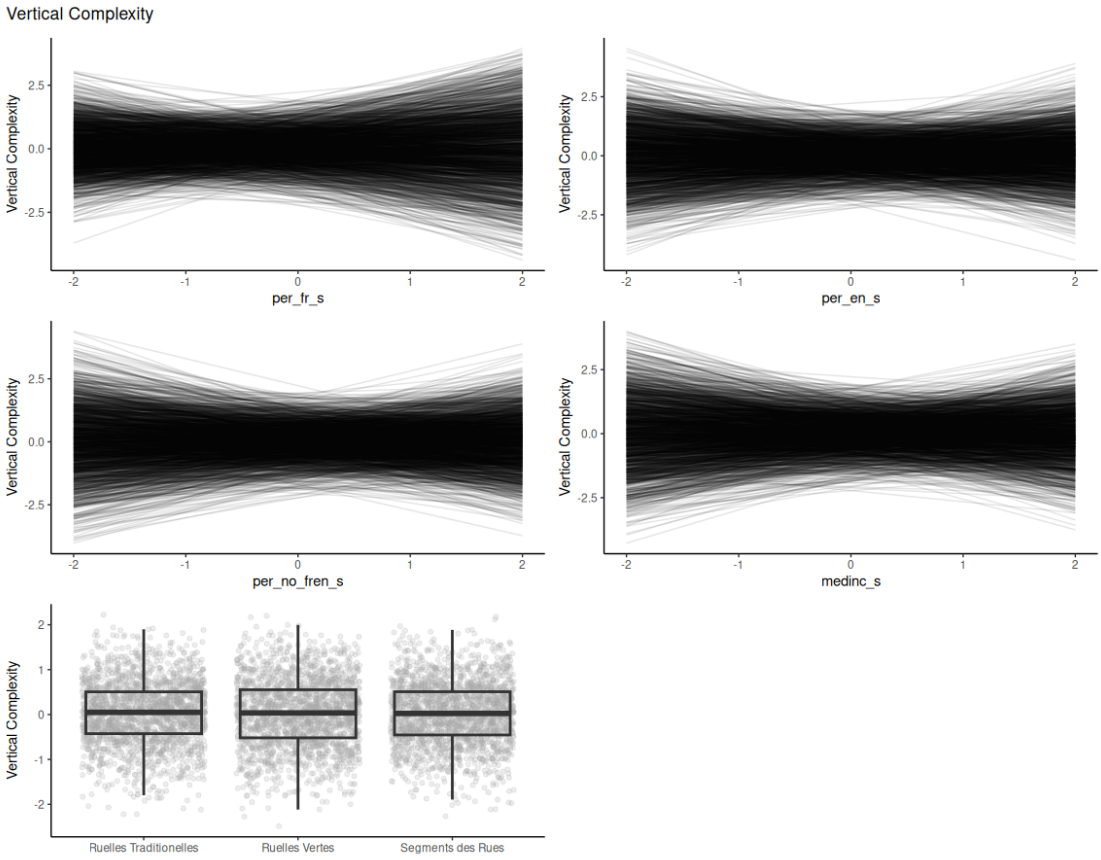
Villeray-Saint Michel-Parc Extension



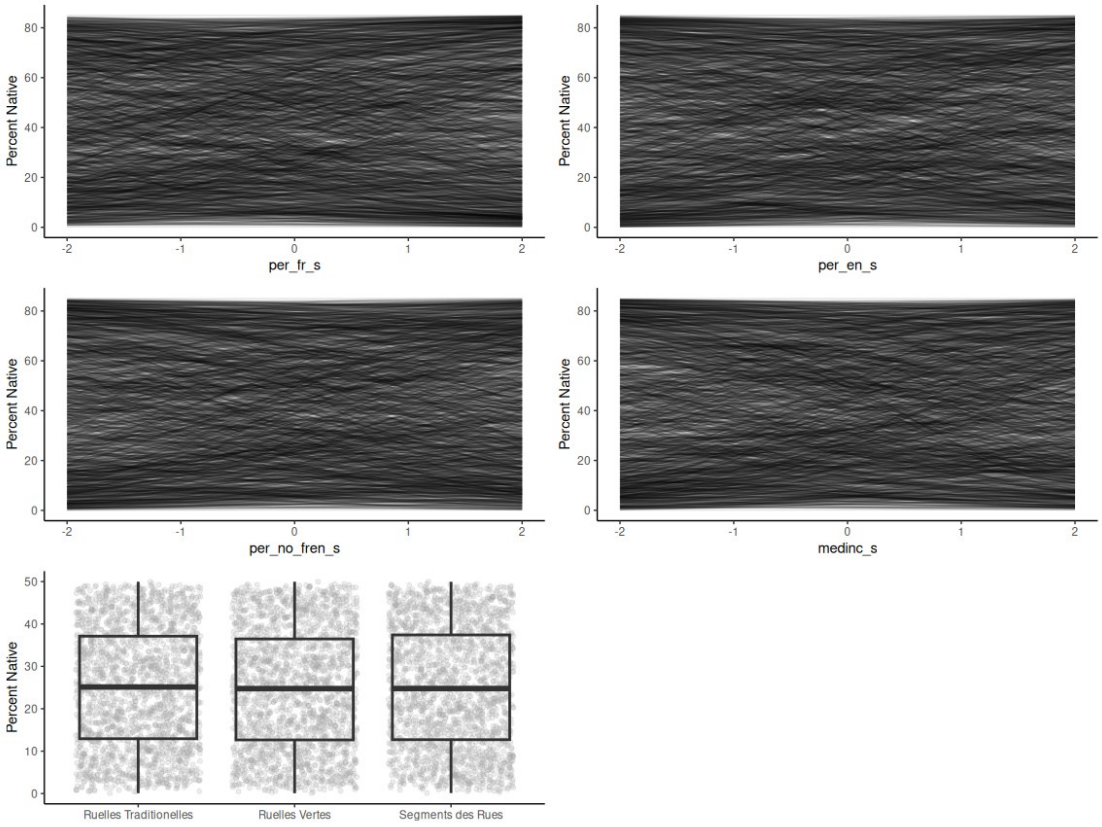

Firefly Abundance
Firefly Abundance
per_fr_s
per_en_s
per_no_fren_s
medinc_s
Ruelles Traditionelles
Ruelles Vertes
Segments des Rues

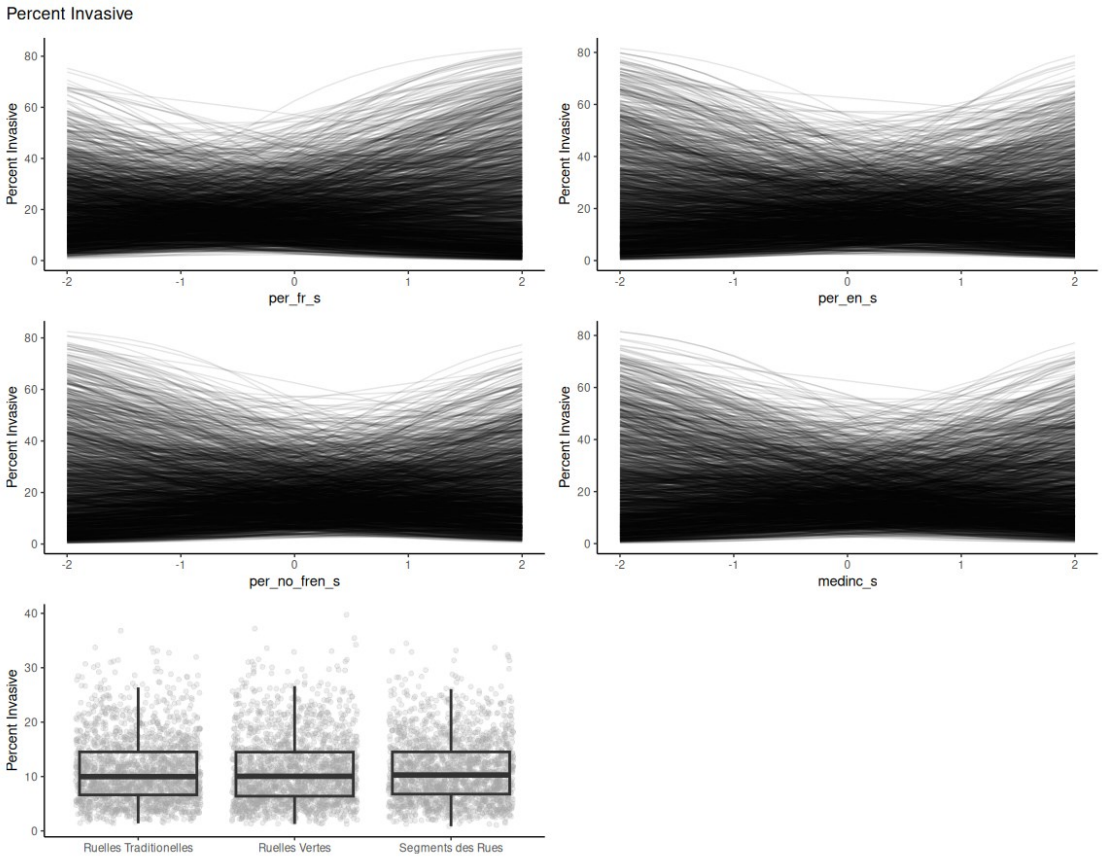

Species Richness
Species Richness
per_fr_s
Species Richness
per_en_s
Species Richness
per_no_fren_s
Species Richness
medinc_s
Species Richness
Ruelles Traditionelles
Ruelles Vertes
Segments des Rues

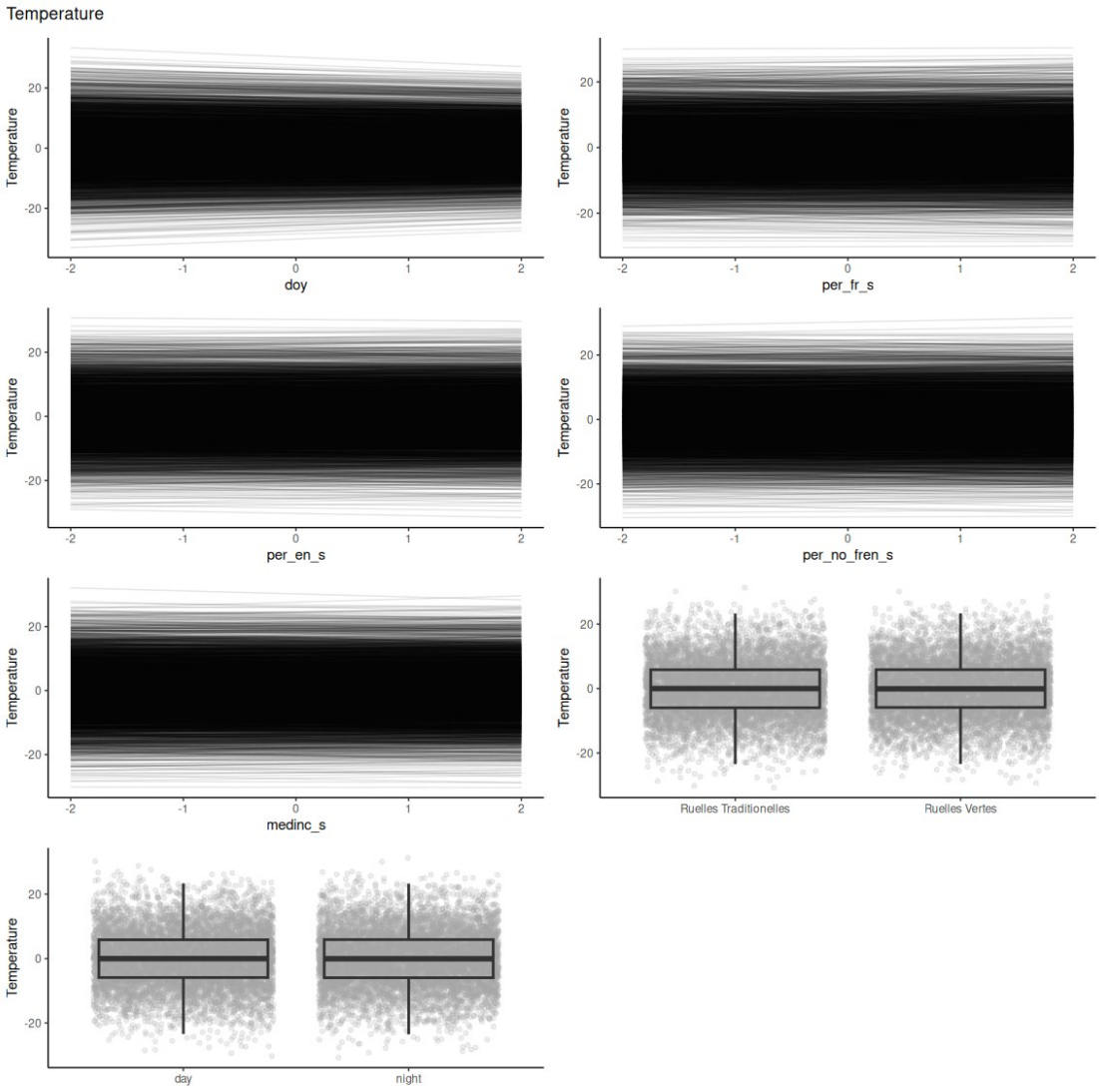

Functional Diversity
Functional Diversity
per_fr_s
Functional Diversity
per_en_s
Functional Diversity
per_no_fren_s
Functional Diversity
medinc_s
Functional Diversity
Ruelles Traditionelles
Ruelles Vertes
Segments des Rues

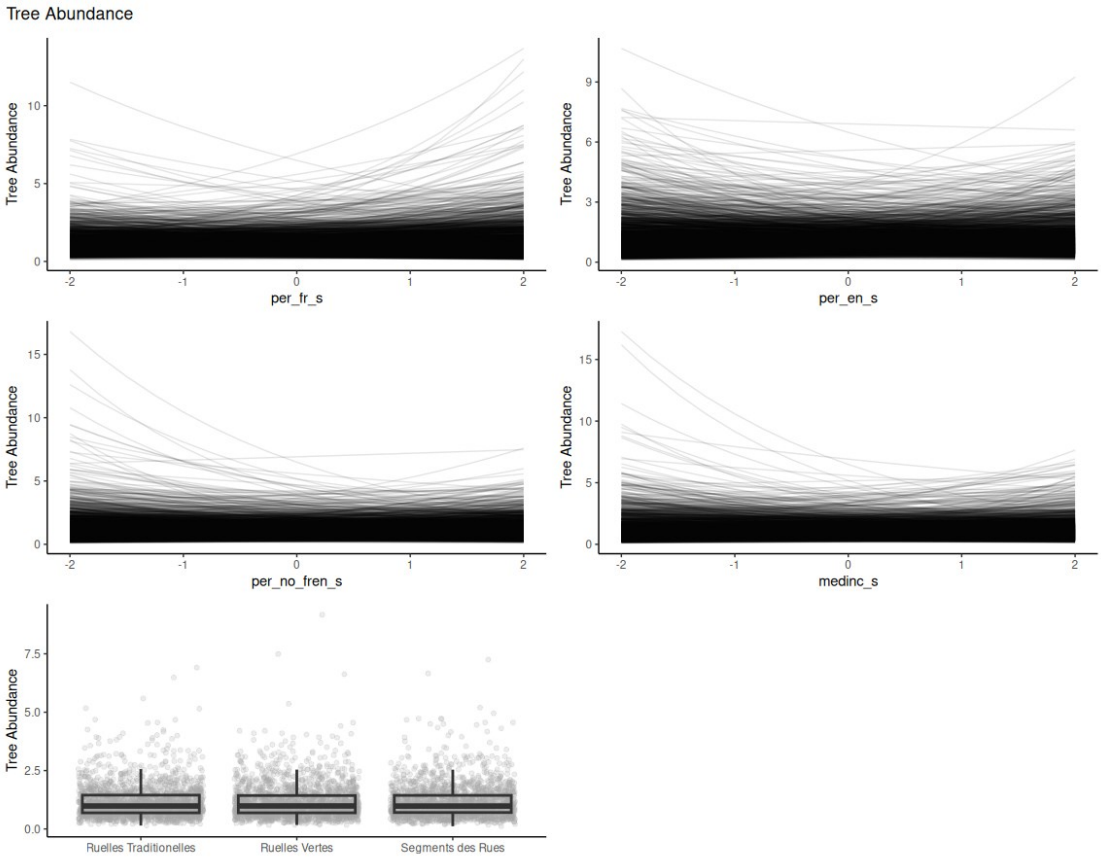

Vertical Complexity
Vertical Complexity
per_fr_s
Vertical Complexity
per_en_s
Vertical Complexity
per_no_fren_s
Vertical Complexity
medinc_s
Vertical Complexity
Ruelles Traditionelles
Ruelles Vertes
Segments des Rues

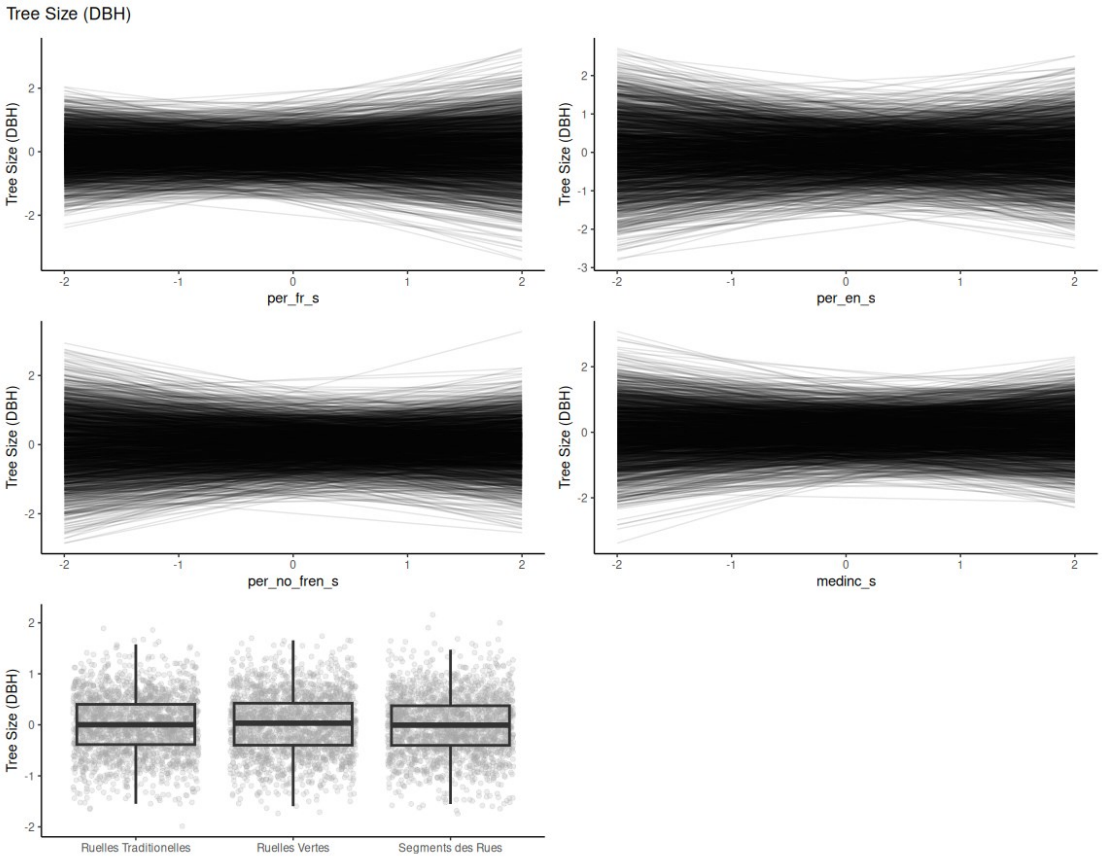
Percent Native

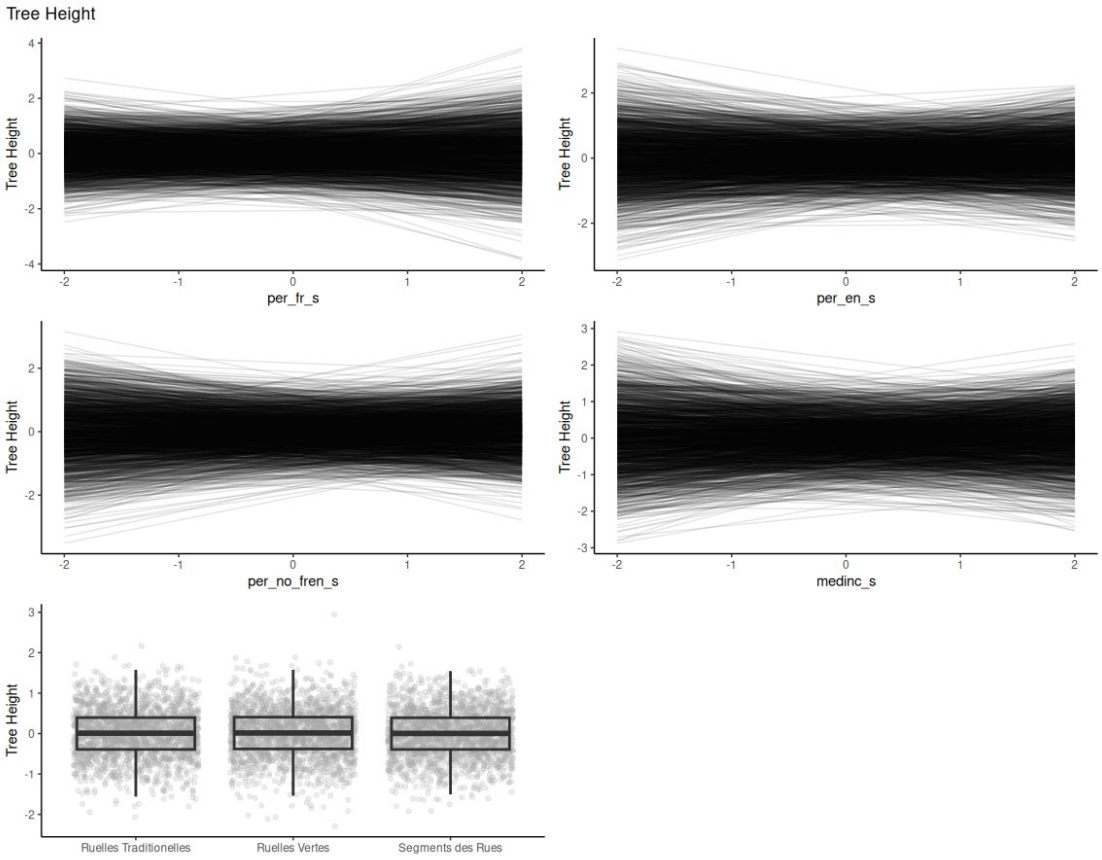


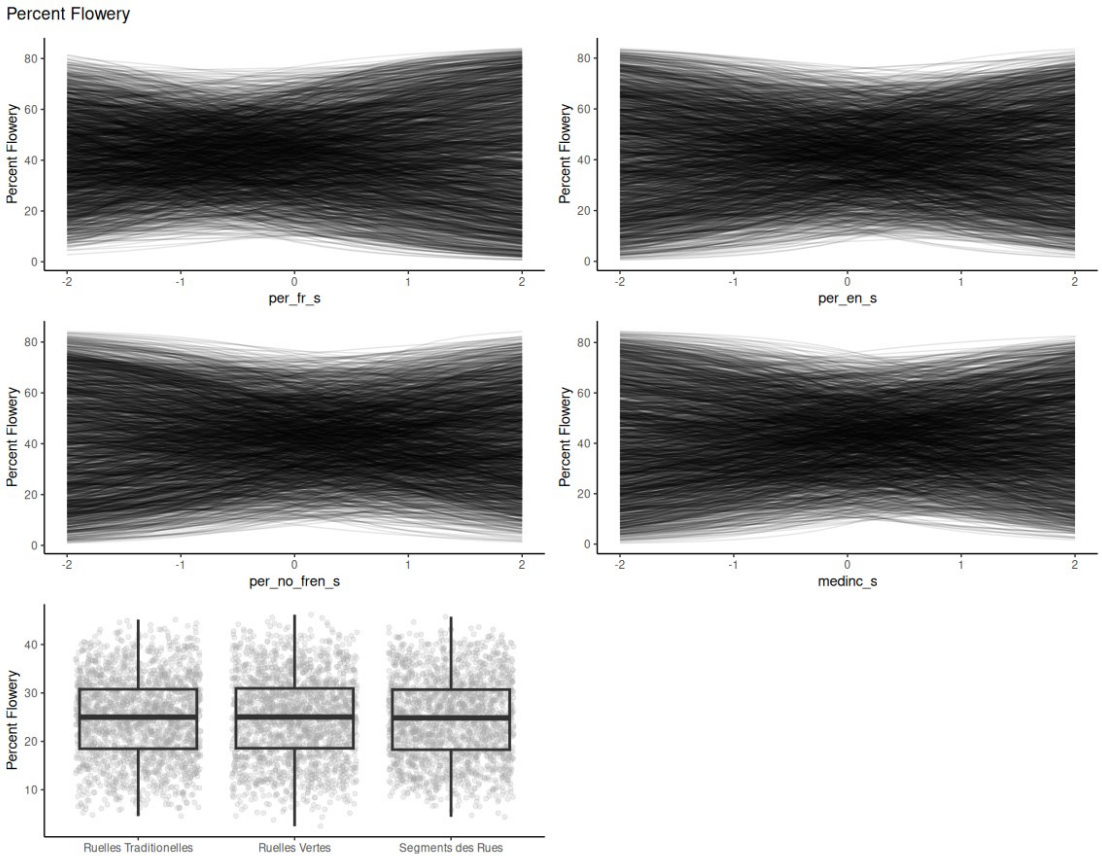

Percent Invasive
Percent Invasive
per_fr_s
Percent Invasive
per_en_s
Percent Invasive
per_no_fren_s
Percent Invasive
medinc_s
Percent Invasive
Ruelles Traditionelles
Ruelles Vertes
Segments des Rues


Temperature
Temperature
20
0
-20
-2
-1
0
1
2
doy
per_fr_s
per_en_s
per_no_fren_s
medinc_s
Ruelles Traditionelles
Ruelles Vertes
day
night

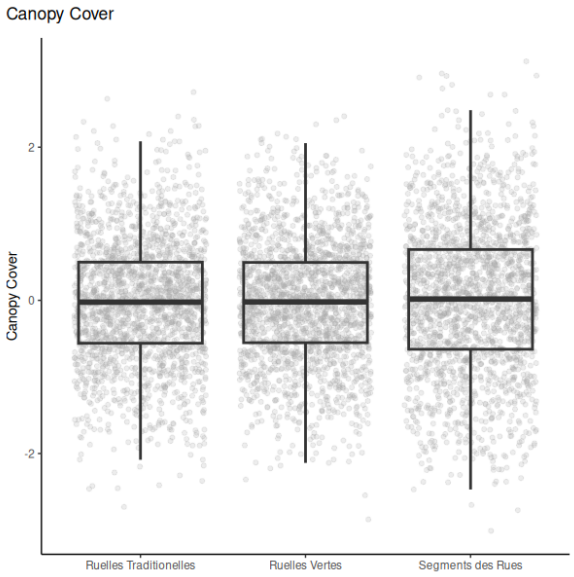

Tree Abundance
Tree Abundance
per_fr_s
Tree Abundance
per_en_s
Tree Abundance
per_no_fren_s
Tree Abundance
medinc_s
Tree Abundance
Ruelles Traditionelles
Ruelles Vertes
Segments des Rues

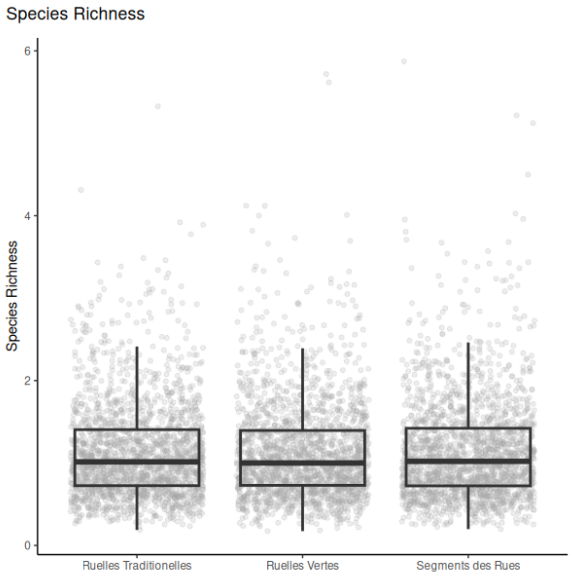

Tree Size (DBH)
Tree Size (DBH)
per_fr_s
Tree Size (DBH)
per_en_s
Tree Size (DBH)
per_no_fren_s
Tree Size (DBH)
medinc_s
Tree Size (DBH)
Ruelles Traditionelles
Ruelles Vertes
Segments des Rues

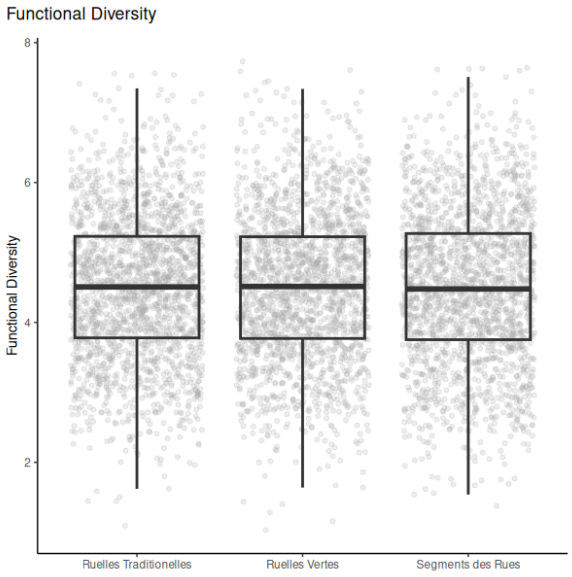

Tree Height
Tree Height
per_fr_s
Tree Height
per_en_s
Tree Height
per_no_fren_s
Tree Height
medinc_s
Tree Height
Ruelles Traditionelles
Ruelles Vertes
Segments des Rues

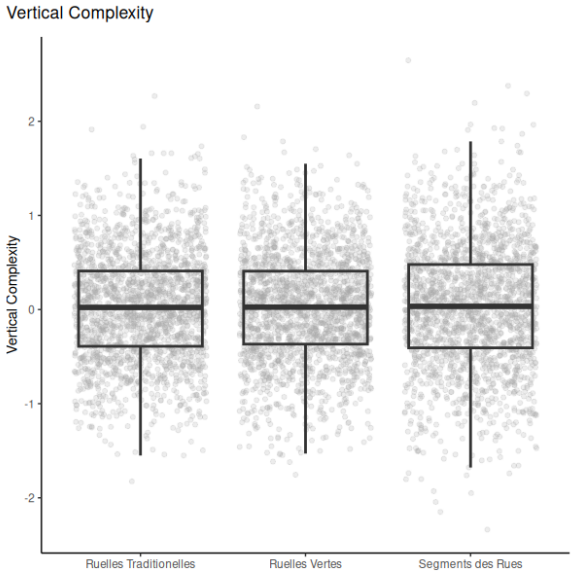

Percent Flowery
Percent Flowery
per_fr_s
Percent Flowery
per_en_s
Percent Flowery
per_no_fren_s
Percent Flowery
medinc_s
Percent Flowery
Ruelles Traditionelles
Ruelles Vertes
Segments des Rues

Trois-Rivieres

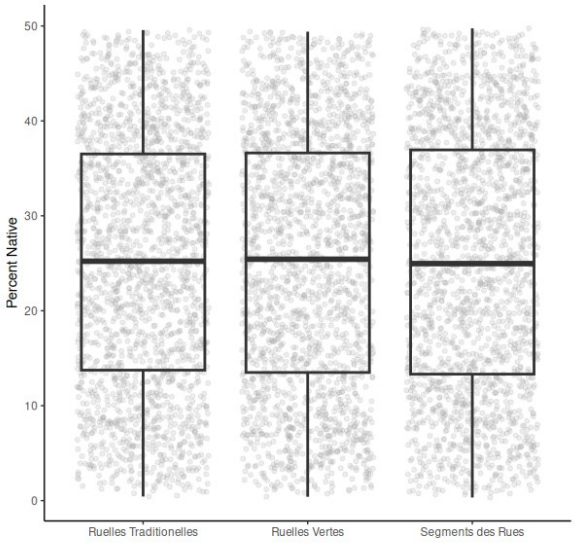




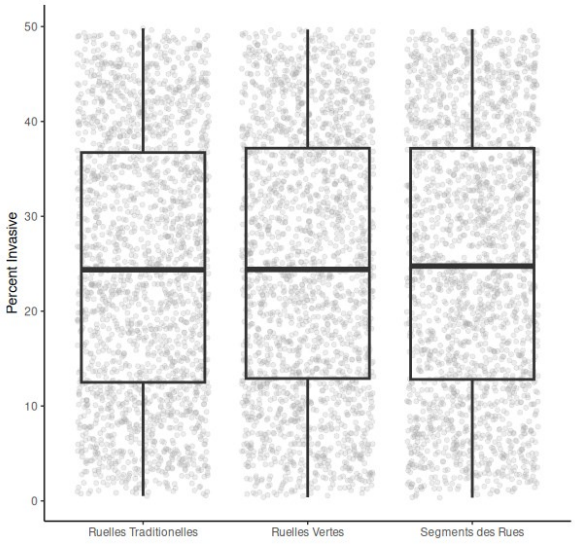

Functional Diversity
Functional Diversity
8
6
4
2
Ruelles Traditionelles
Ruelles Vertes
Segments des Rues

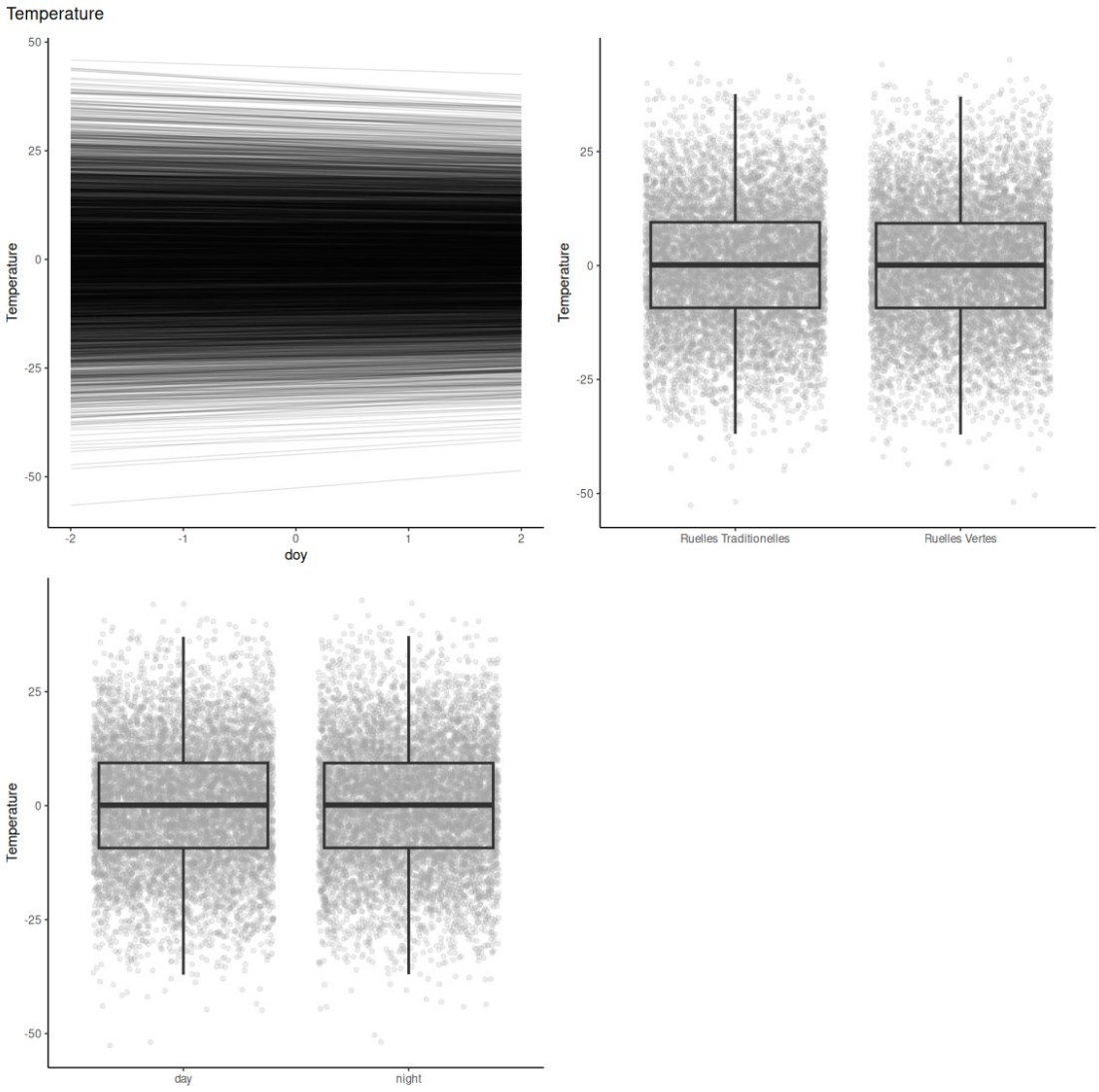

Vertical Complexity
Vertical Complexity
2
1
0
-1
-2
Ruelles Traditionelles
Ruelles Vertes
Segments des Rues

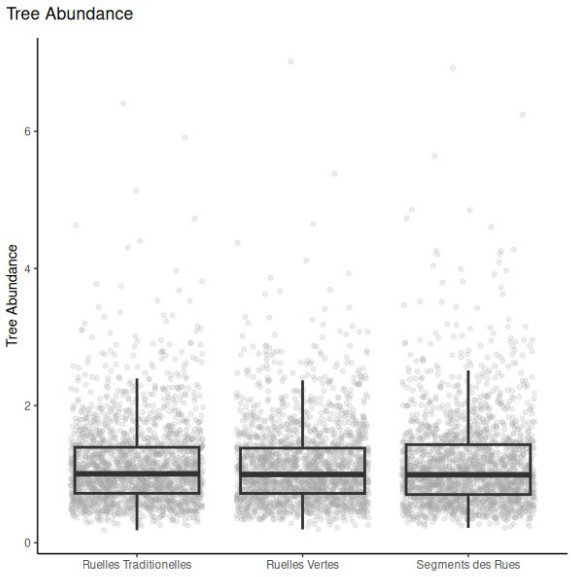
Percent Native

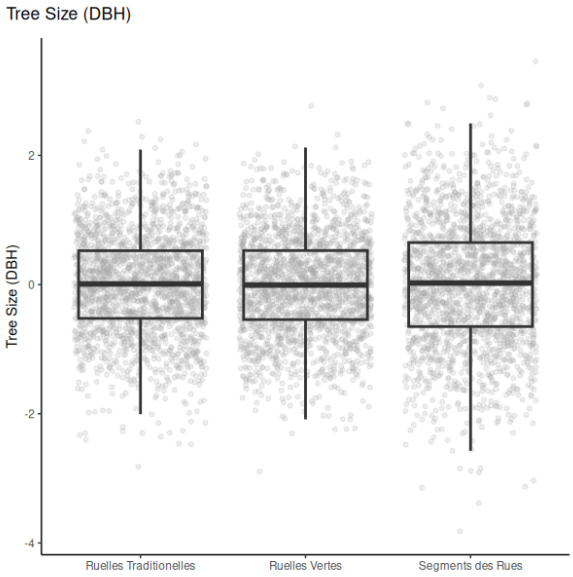


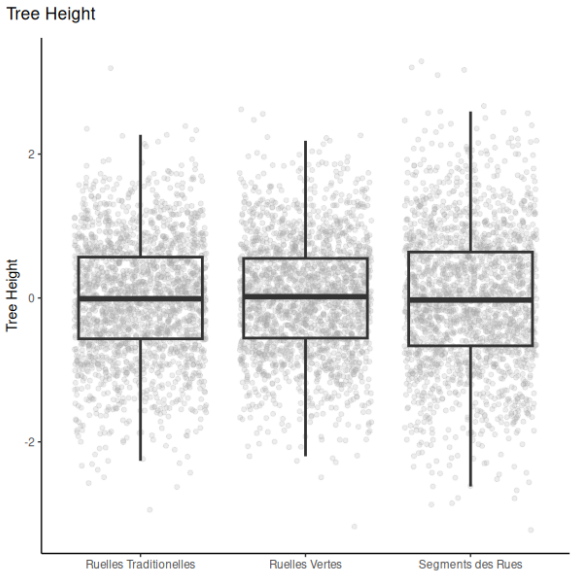
Percent Invasive

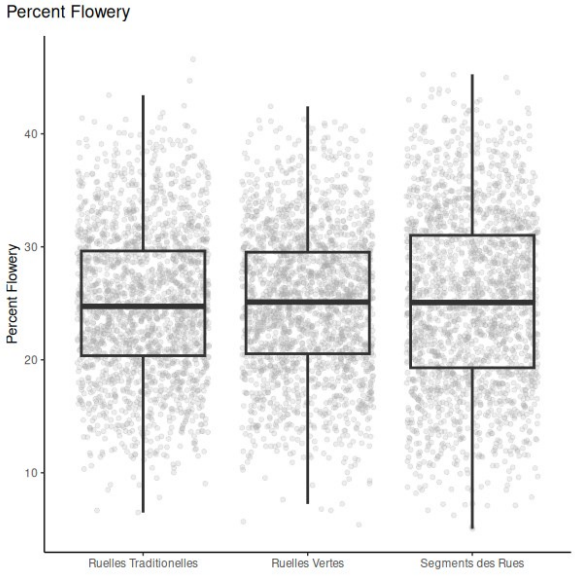



Temperature
Temperature
doy
Temperature
Ruelles Traditionelles
Ruelles Vertes
Temperature
day
night


Tree Abundance
Tree Abundance
6
4
2
0
Ruelles Traditionelles
Ruelles Vertes
Segments des Rues


Tree Size (DBH)
Tree Size (DBH)
2
0
-2
-4
Ruelles Traditionelles
Ruelles Vertes
Segments des Rues


Tree Height
Tree Height
2
0
-2
Ruelles Traditionelles
Ruelles Vertes
Segments des Rues

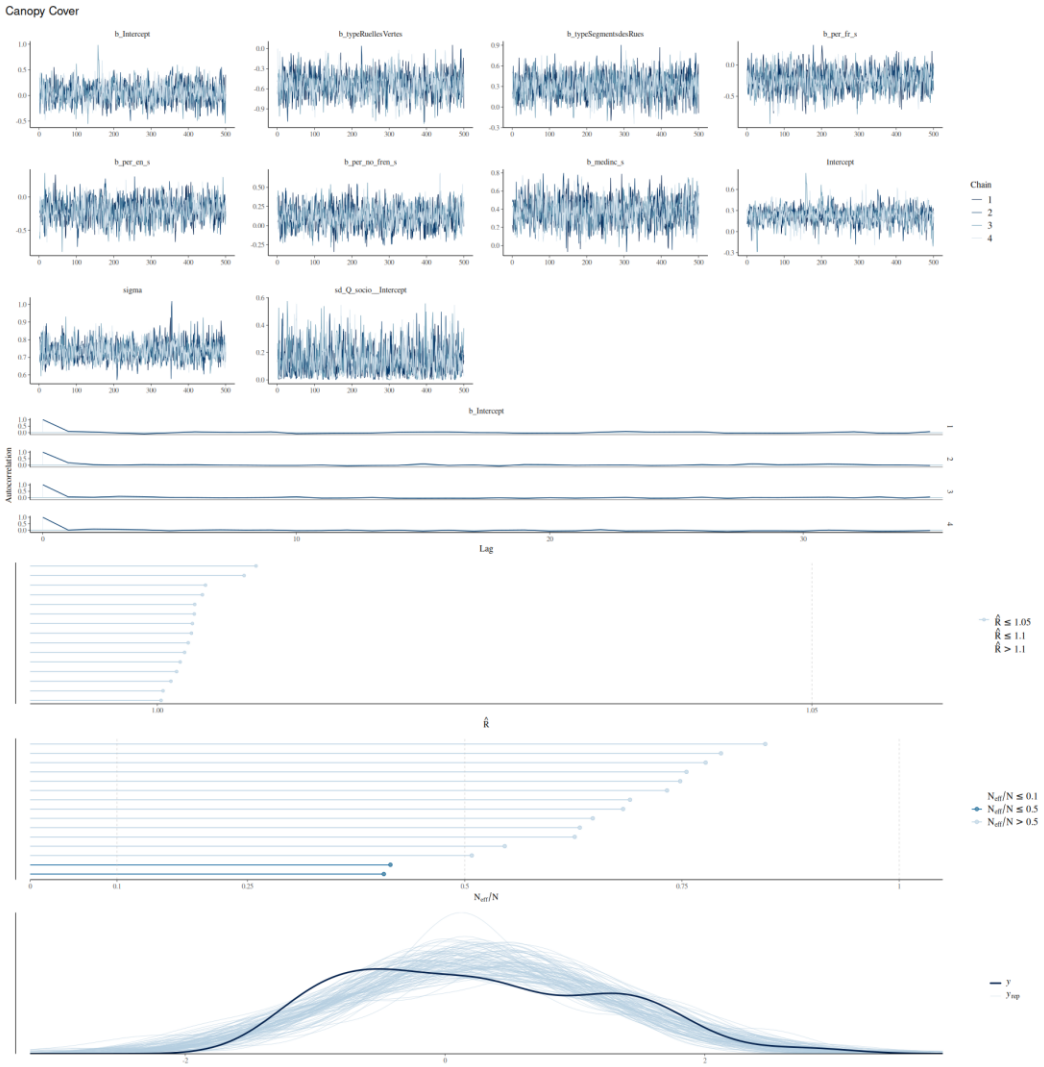

Percent Flowery
Percent Flowery
40
30
20
10
Ruelles Traditionelles
Ruelles Vertes
Segments des Rues

Section 2F: Model Diagnostics

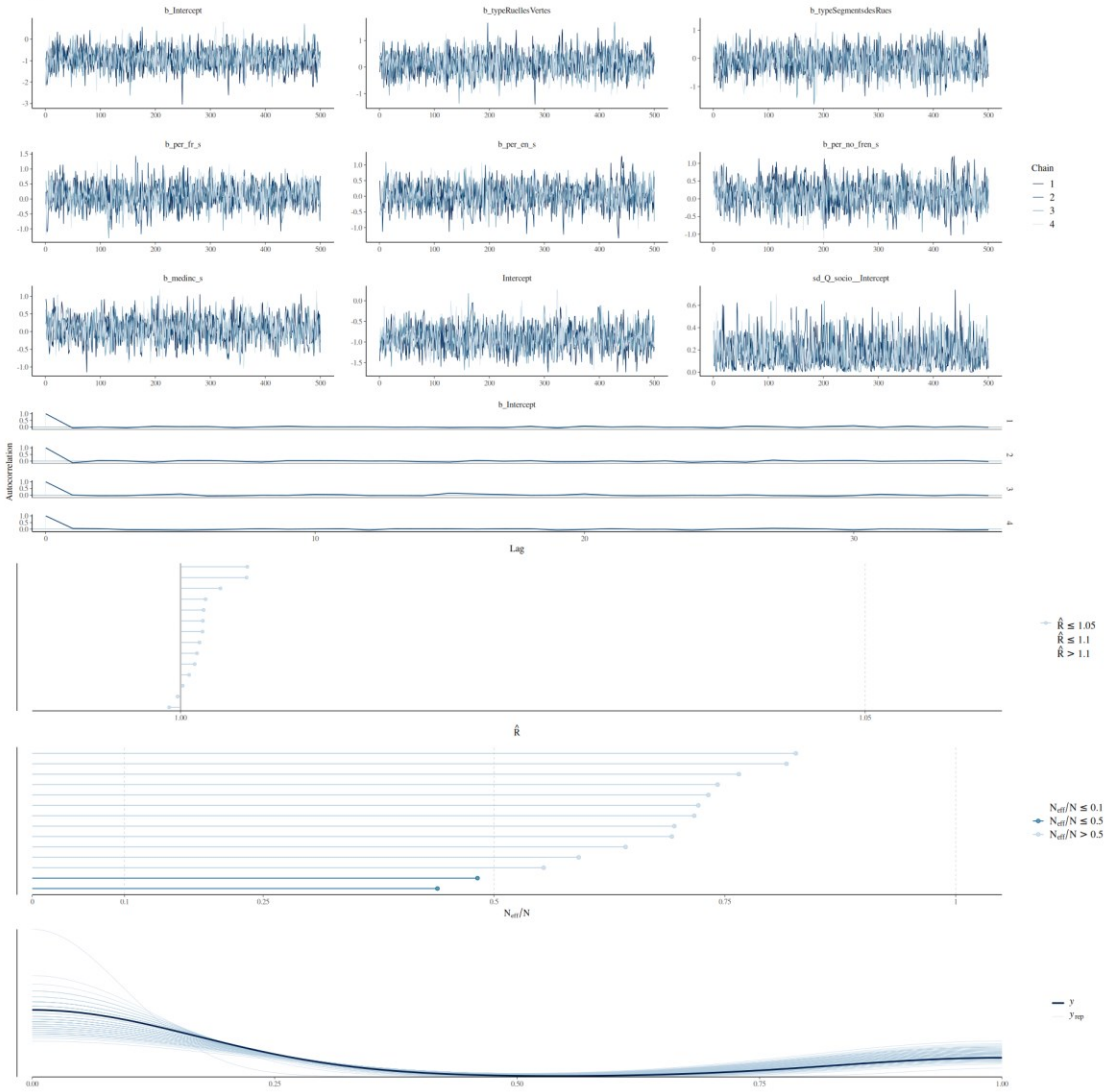
These model diagnostic plots assess whether the chains of our models are converged and well mixed, and if the model is well specified and has an adequate fit.

The first plot of the series shows trace plots for each of our parameters, where we want to see stationary and well-mixed chains. The second plot shows an autocorrelation plot by chain and parameter. We want our autocorrelation to quickly drop to zero with increasing lag. Thirdly, the Rhat plot monitors whether a chain has converged to the equilibrium distribution, if all chains are at equilibrium Rhat will be one. If chains have not converged, Rhat will be greater than 1. The fourth plot is the ratio between effective sample size (Neff) and total sample size (N).Because the draws within a Markov chain are not independent if there is autocorrelation, the effective sample size, neff, is usually smaller than the total sample size, N. The larger the ratio, the better. Finally, we have the posterior predictive check where we want the black line to be within/close to the blue lines, to indicate that our model is adequately generative.

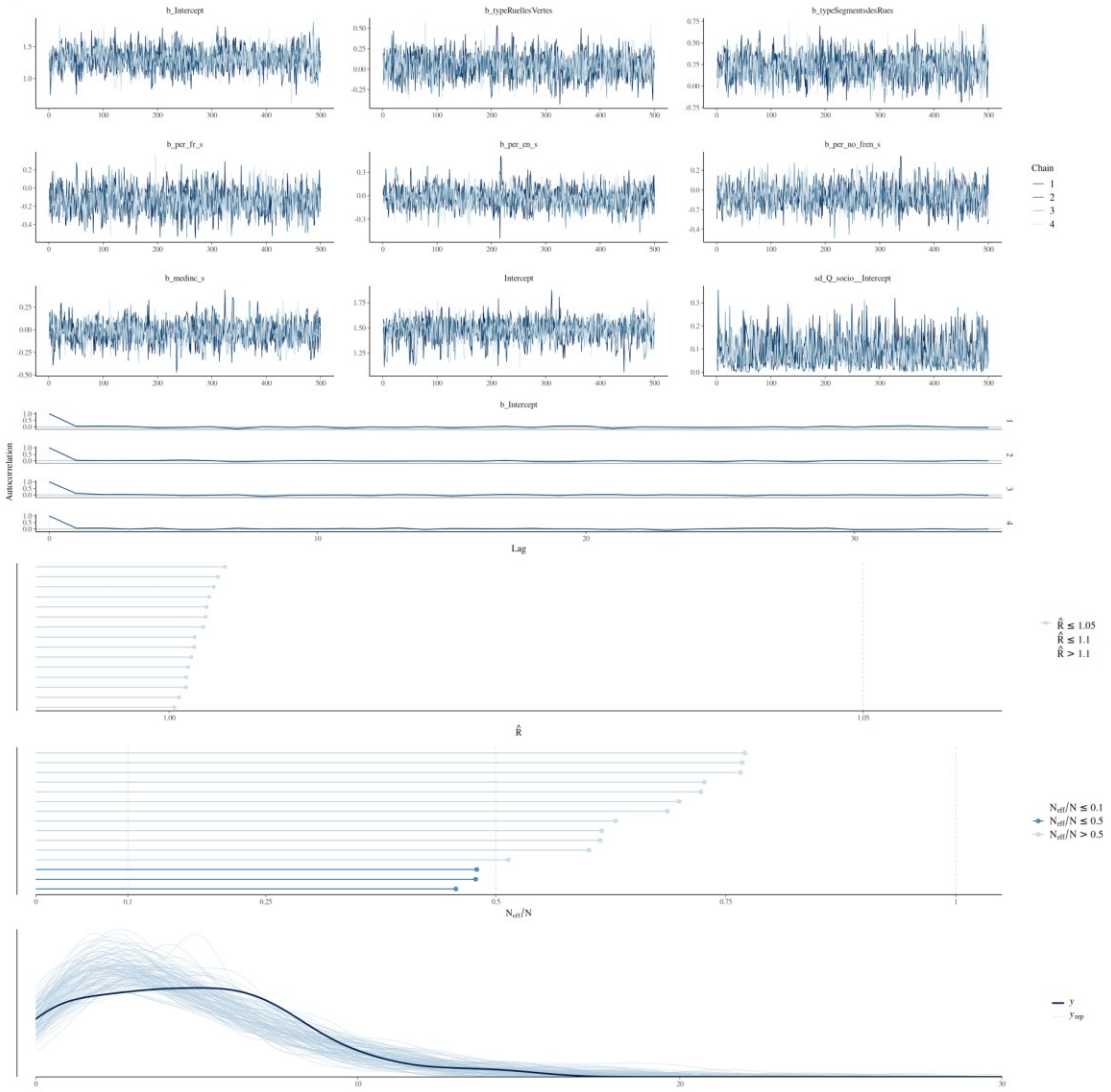
Villeray-Saint Michel-Parc Extension



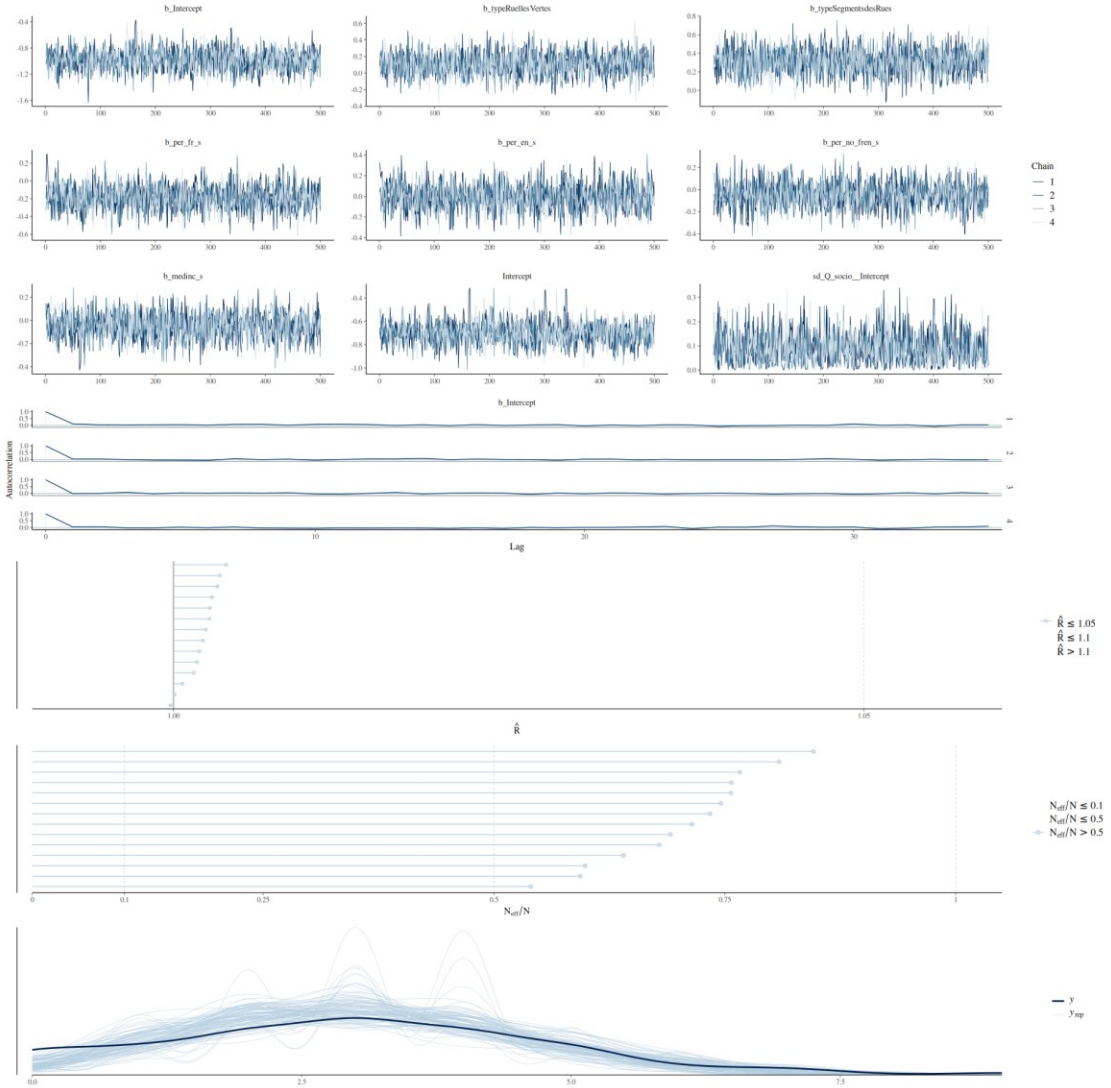
Firefly Abundance



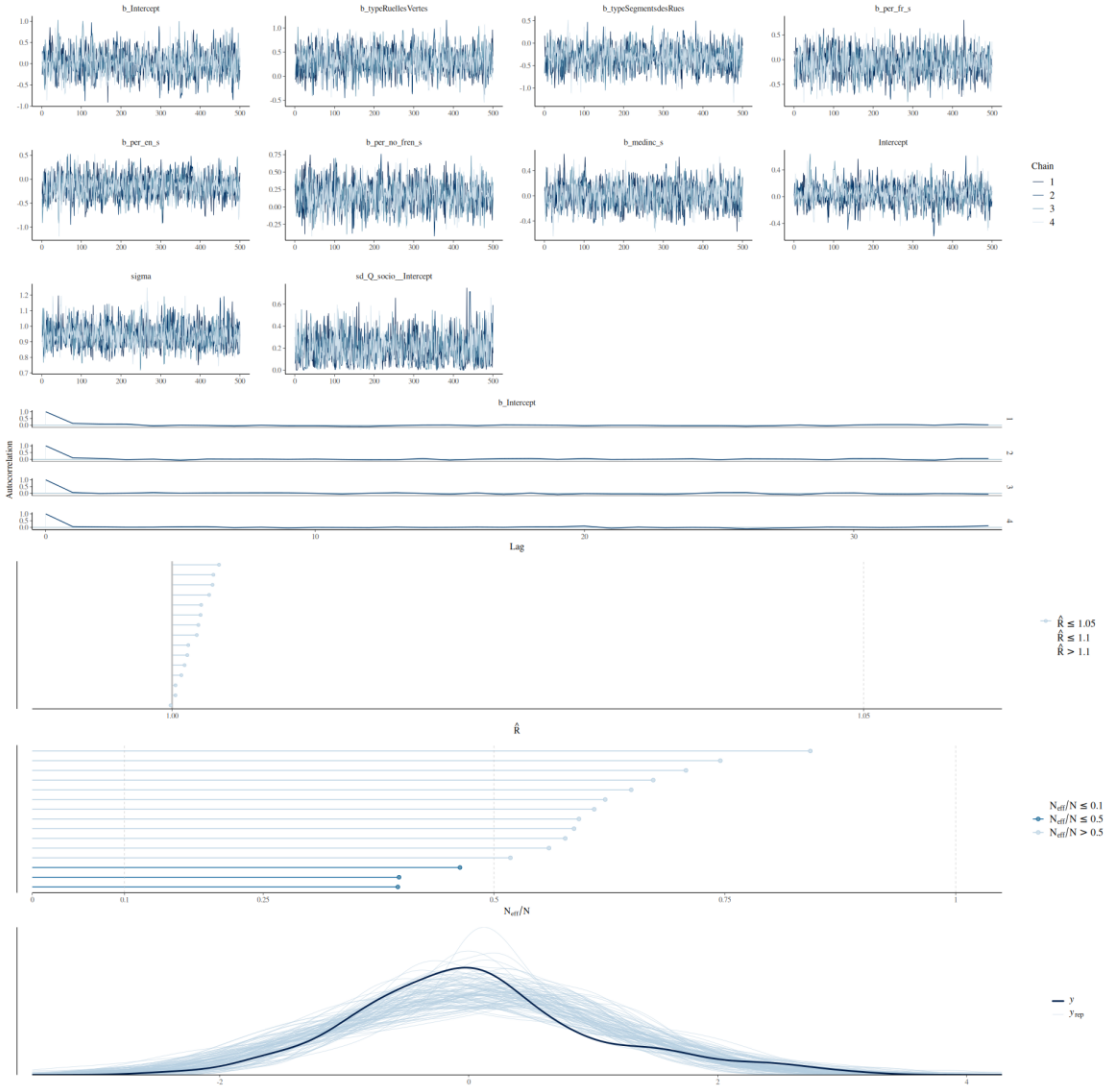
Species Richness

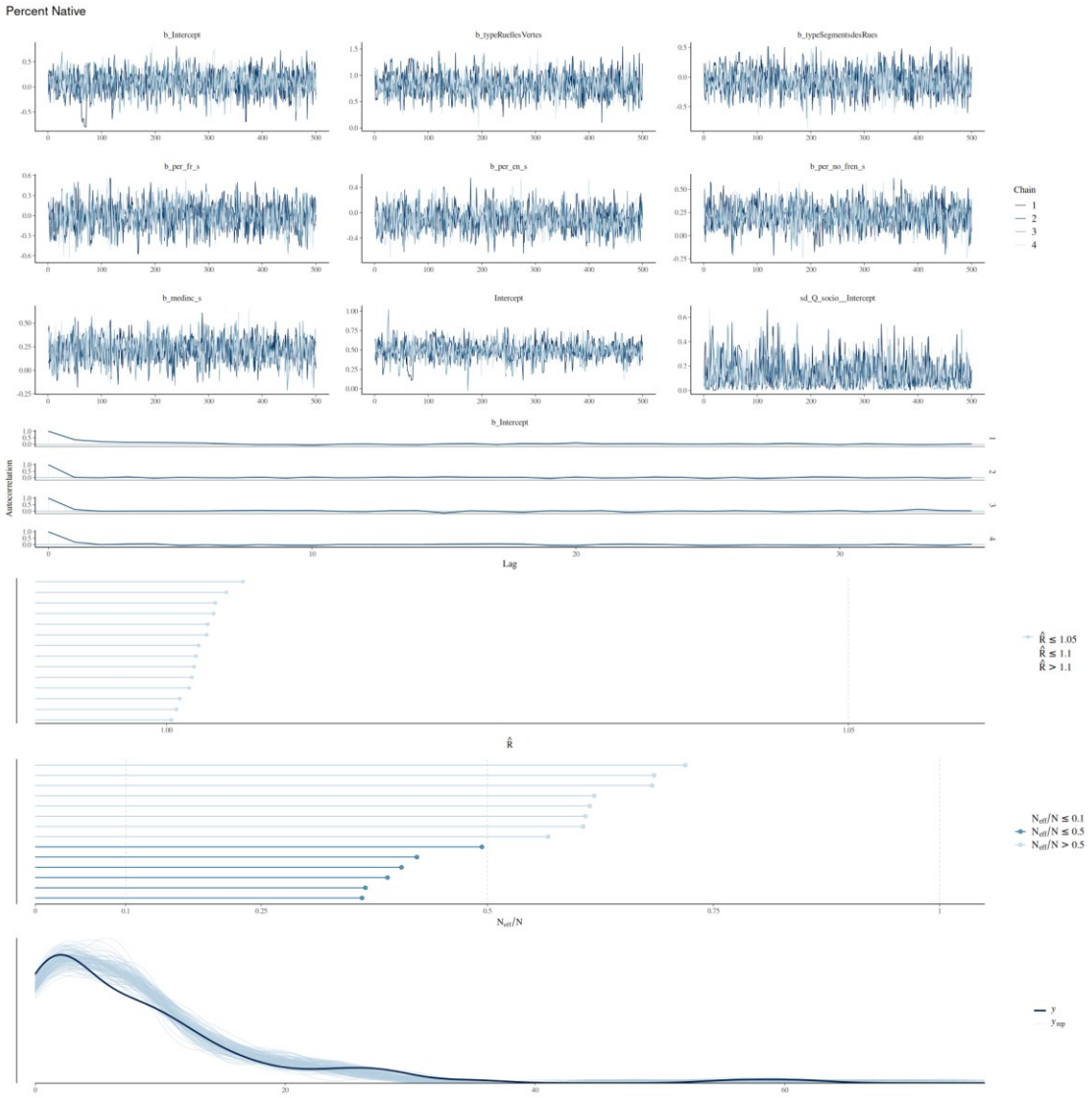


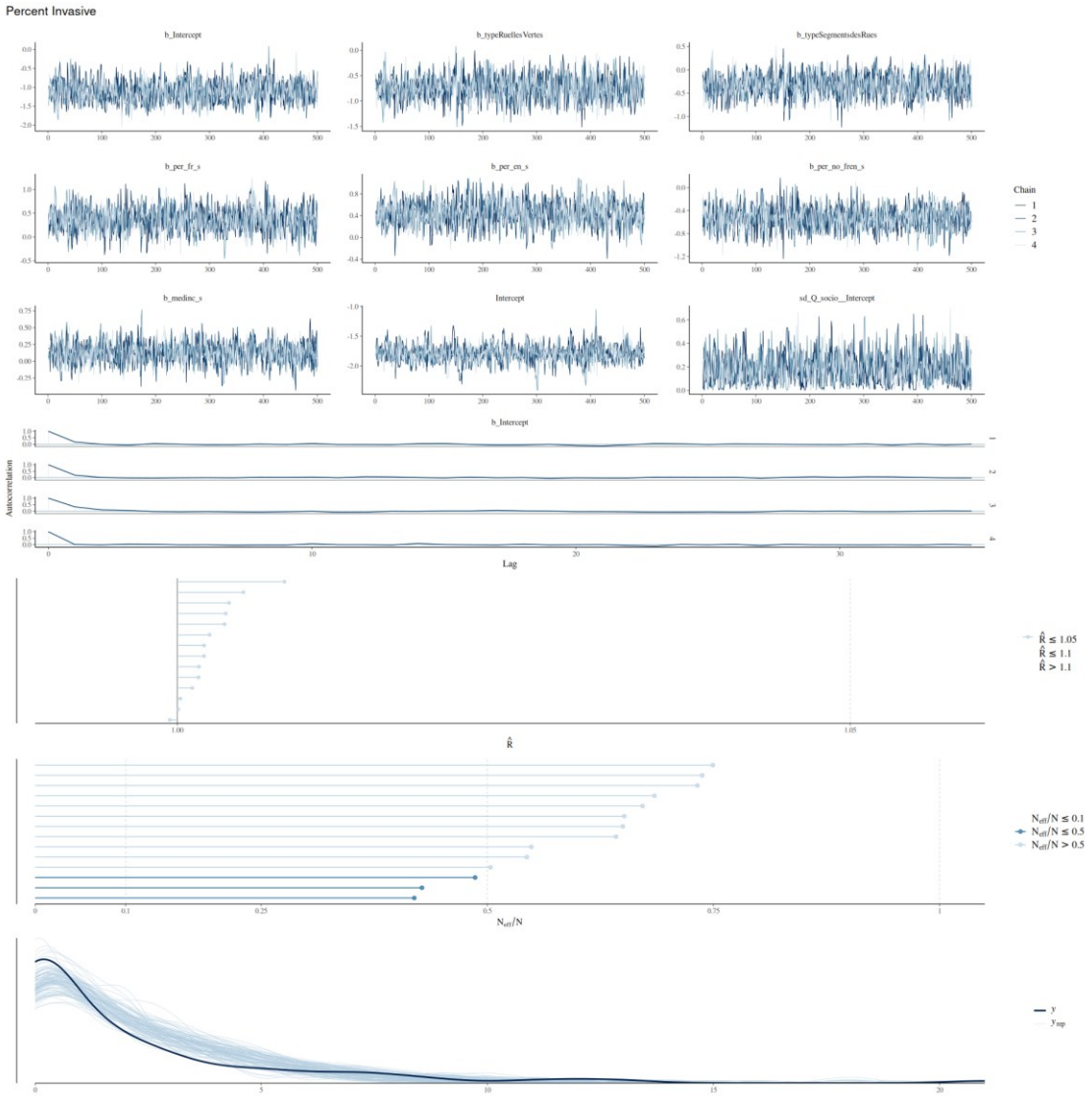
Functional Diversity

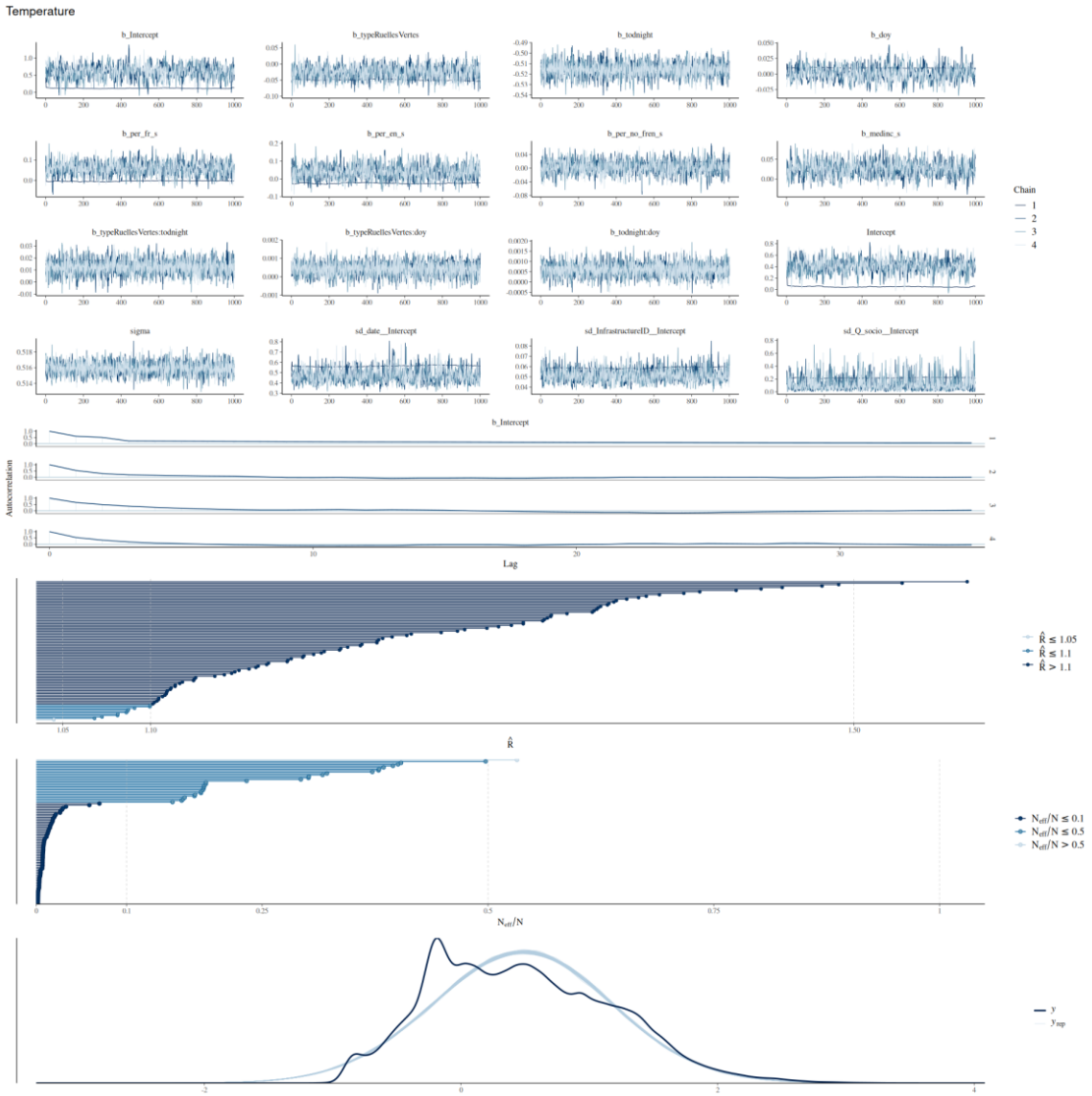


Vertical Complexity

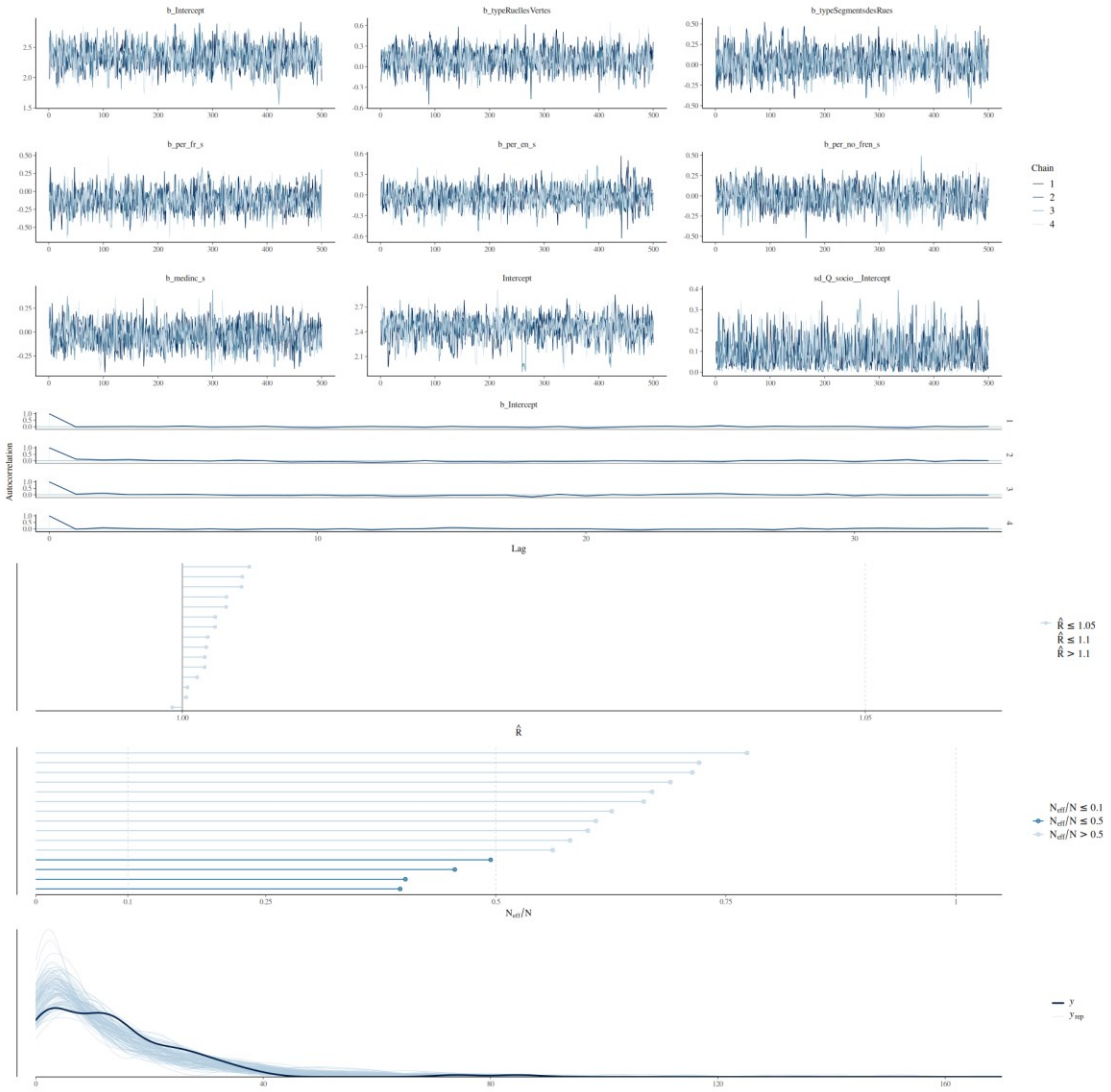



Percent Native
b_Intercept
b_typeRuellesVertes
b_typeSegmentsdesRues
b_per_fr_s
b_per_en_s
b_per_no_fren_s
b_medinc_s
Intercept
sd_Q_socio__Intercept
Chain
1
2
3
4
b_Intercept
Autocorrelation
Lag
$\hat{R} \leq 1.05$
$\hat{R} \leq 1.1$
$\hat{R} > 1.1$
$\hat{R}$
$N_{eff}/N \leq 0.1$
$N_{eff}/N \leq 0.5$
$N_{eff}/N > 0.5$
N_{eff}/N
y
y_{rep}

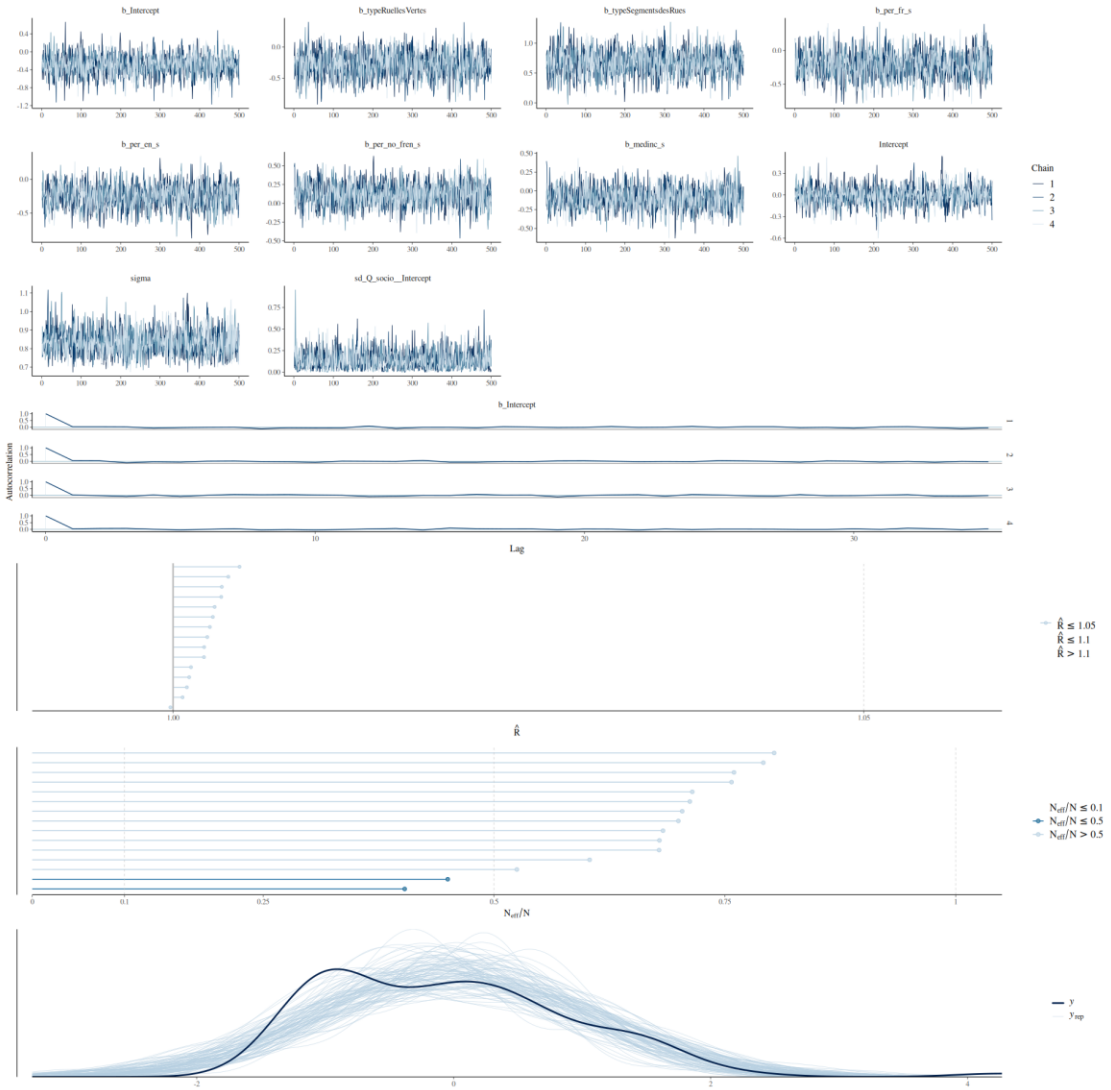

Percent Invasive
b_Intercept
b_typeRuellesVertes
b_typeSegmentsdesRues
b_per_fr_s
b_per_en_s
b_per_no_fren_s
b_medinc_s
Intercept
sd_Q_socio__Intercept
Chain
1
2
3
4
b_Intercept
Autocorrelation
Lag
$\hat{R} \leq 1.05$
$\hat{R} \leq 1.1$
$\hat{R} > 1.1$
$\hat{R}$
$N_{eff}/N \leq 0.1$
$N_{eff}/N \leq 0.5$
$N_{eff}/N > 0.5$
N_{eff}/N
y
y_{rep}

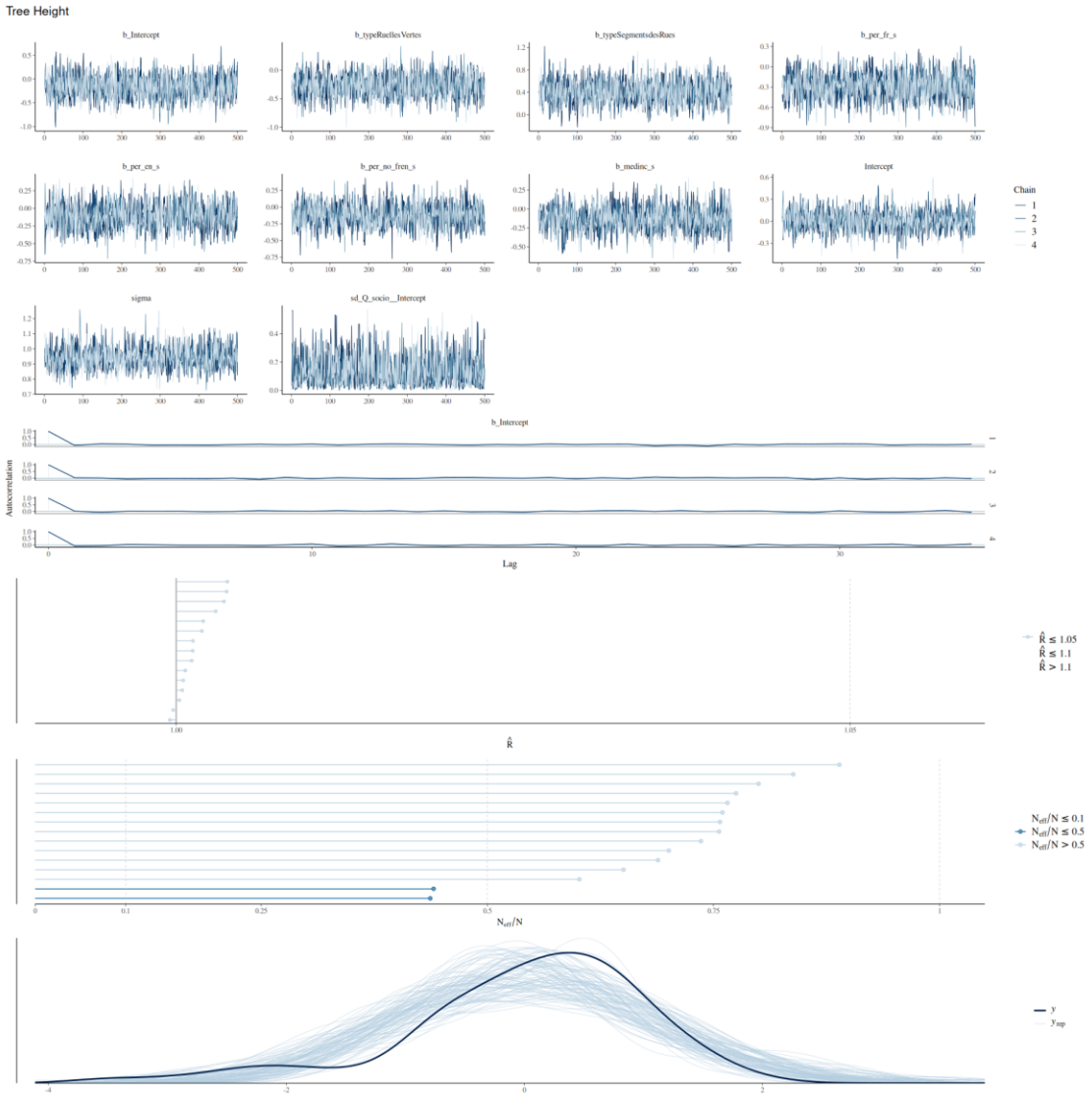

Temperature
b_Intercept
b_typeRuellesVertes
b_todnight
b_doy
b_per_fr_s
b_per_en_s
b_per_no_fren_s
b_medinc_s
b_typeRuellesVertes:todnight
b_typeRuellesVertes:doy
b_todnight:doy
Intercept
sigma
sd_date__Intercept
sd_InfrastructureID__Intercept
sd_Q_socio__Intercept
Chain
1
2
3
4
b_Intercept
Autocorrelation
Lag
$\hat{R} \leq 1.05$
$\hat{R} \leq 1.1$
$\hat{R} > 1.1$
$\hat{R}$
$N_{eff}/N \leq 0.1$
$N_{eff}/N \leq 0.5$
$N_{eff}/N > 0.5$
N_{eff}/N
y
y_{rep}

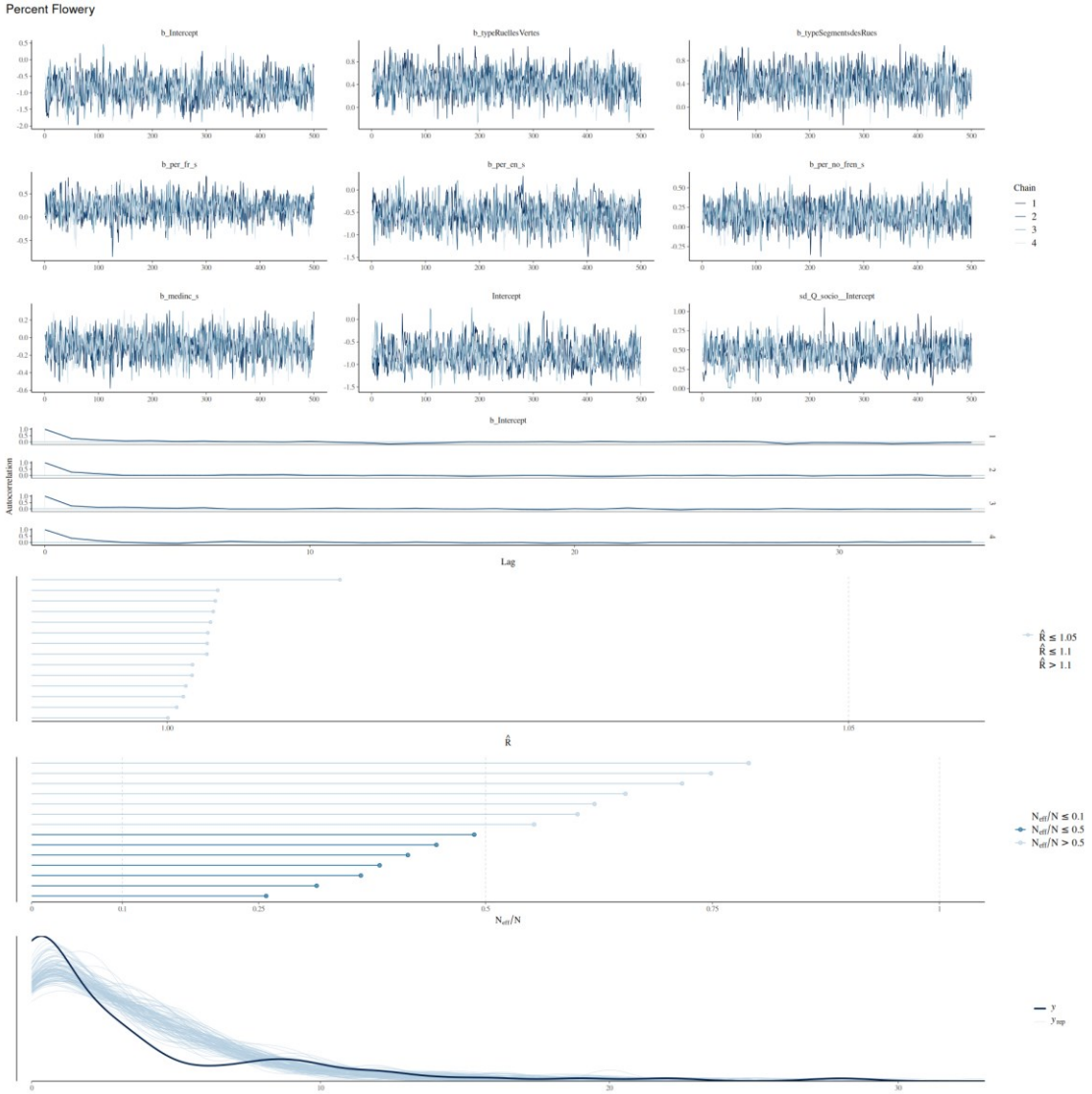
Tree Abundance



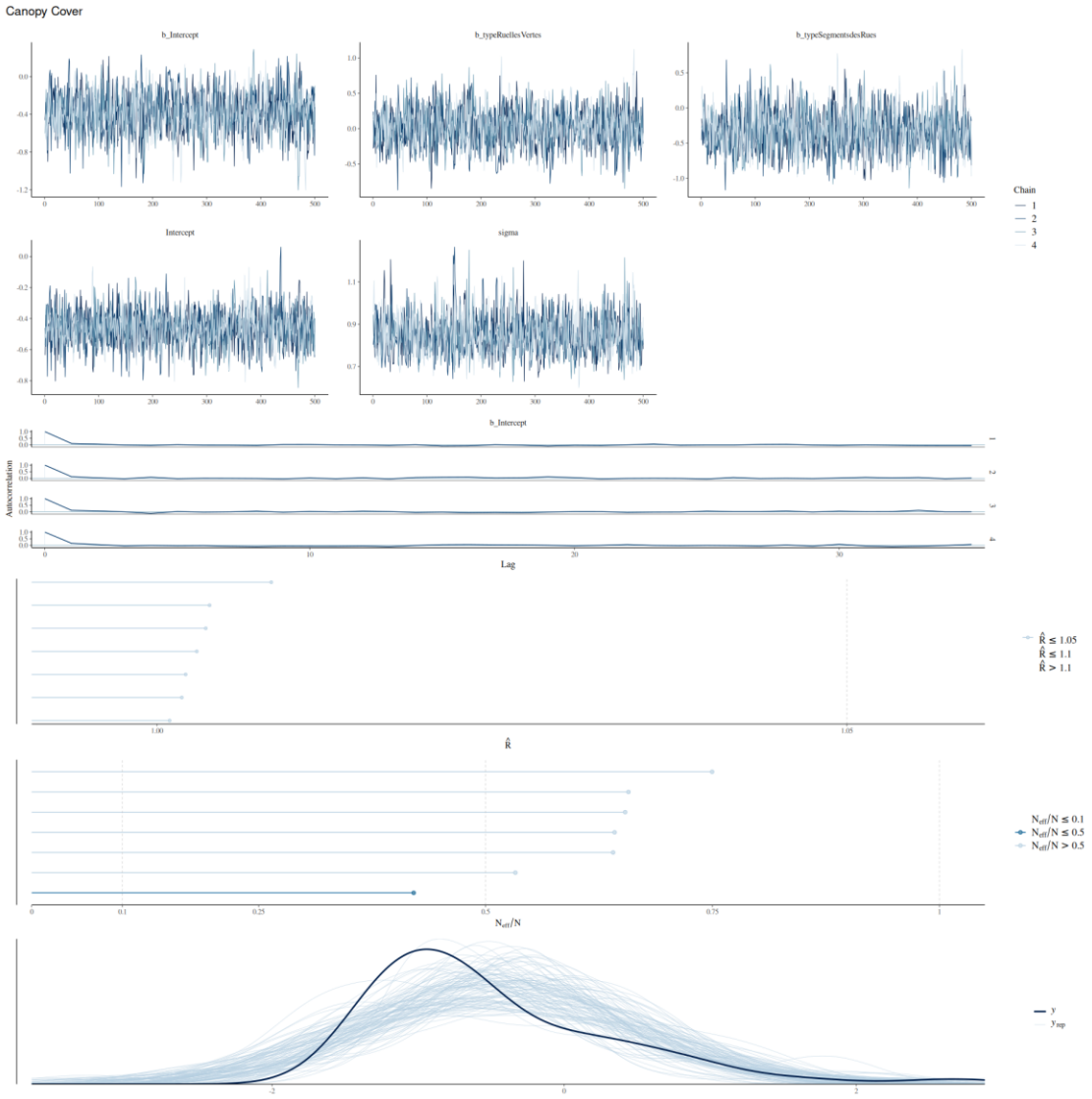
Tree Size (DBH)



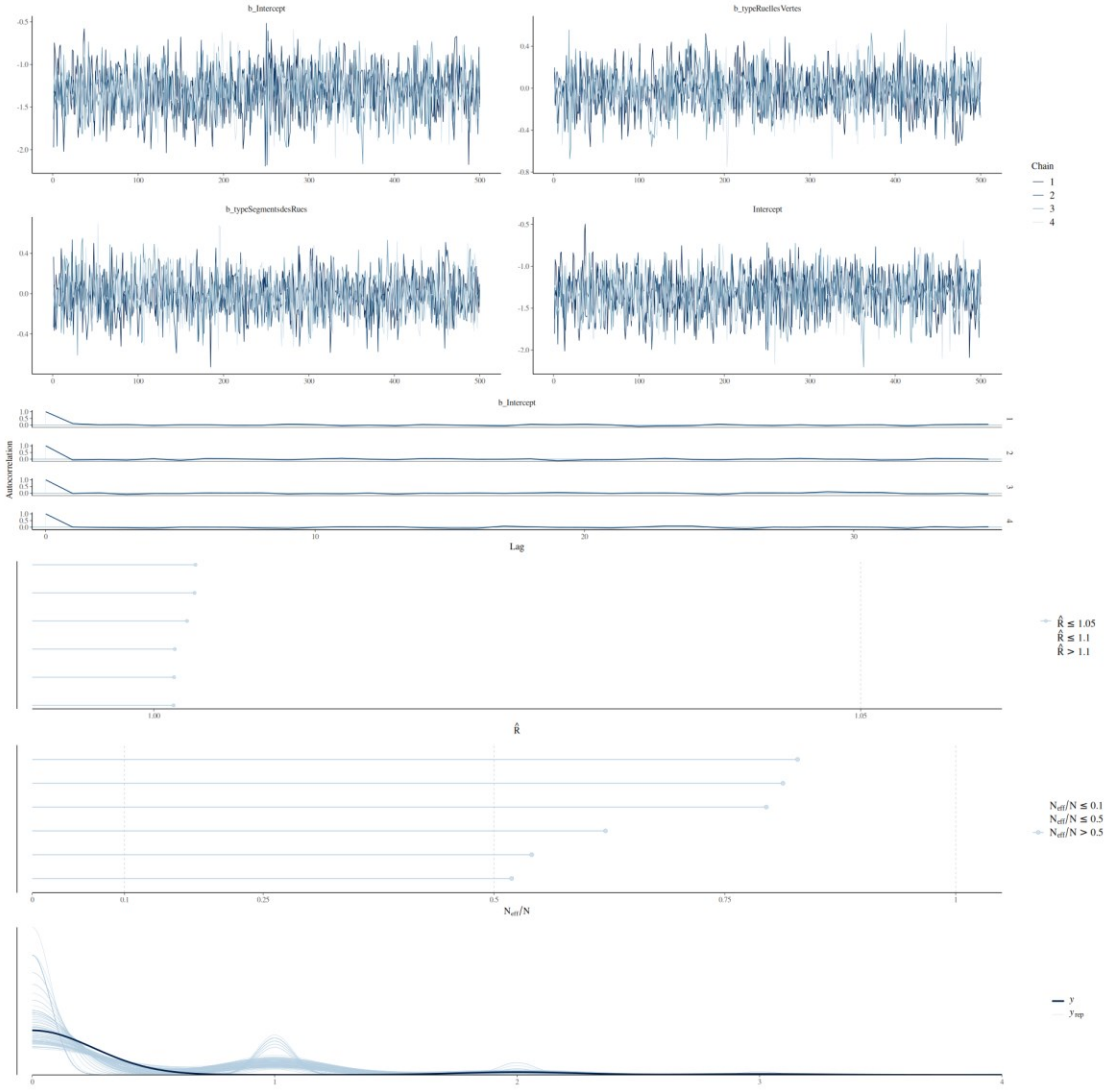

Tree Height
b_Intercept
b_typeRuellesVertes
b_typeSegmentsdesRues
b_per_fr_s
b_per_en_s
b_per_no_fren_s
b_medinc_s
Intercept
sigma
sd_Q_socio__Intercept
Chain
1
2
3
4
b_Intercept
Autocorrelation
Lag
$\hat{R} \leq 1.05$
$\hat{R} \leq 1.1$
$\hat{R} > 1.1$
$\hat{R}$
$N_{eff}/N \leq 0.1$
$N_{eff}/N \leq 0.5$
$N_{eff}/N > 0.5$
N_{eff}/N
y
y_{rep}


Percent Flowery
b_Intercept
b_typeRuellesVertes
b_typeSegmentsdesRues
b_per_fr_s
b_per_en_s
b_per_no_fren_s
b_medinc_s
Intercept
sd_Q_socio__Intercept
Chain
1
2
3
4
b_Intercept
Autocorrelation
Lag
$\hat{R} \leq 1.05$
$\hat{R} \leq 1.1$
$\hat{R} > 1.1$
$\hat{R}$
$N_{eff}/N \leq 0.1$
$N_{eff}/N \leq 0.5$
$N_{eff}/N > 0.5$
N_{eff}/N
y
y_{rep}

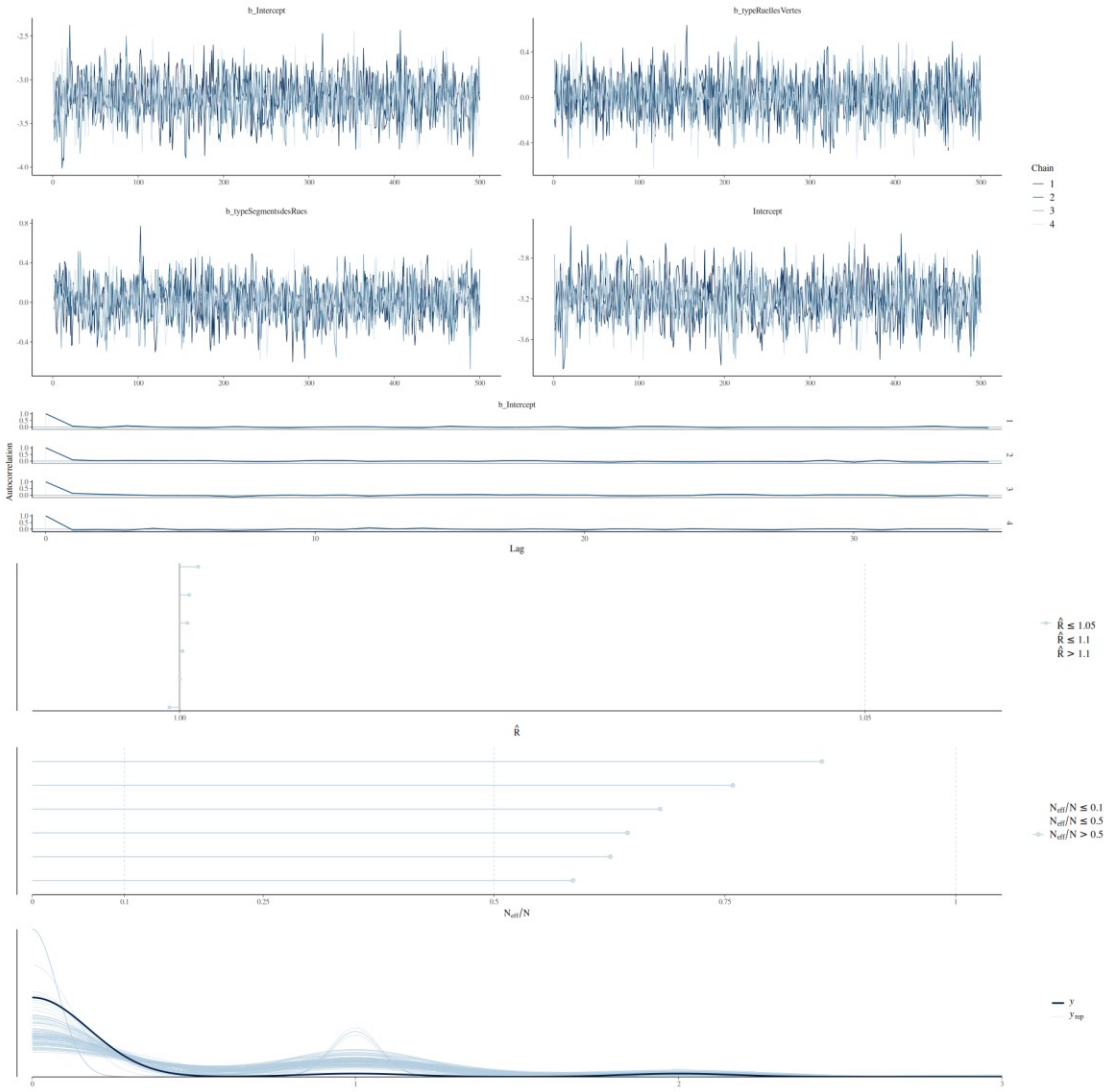
Trois-Rivieres



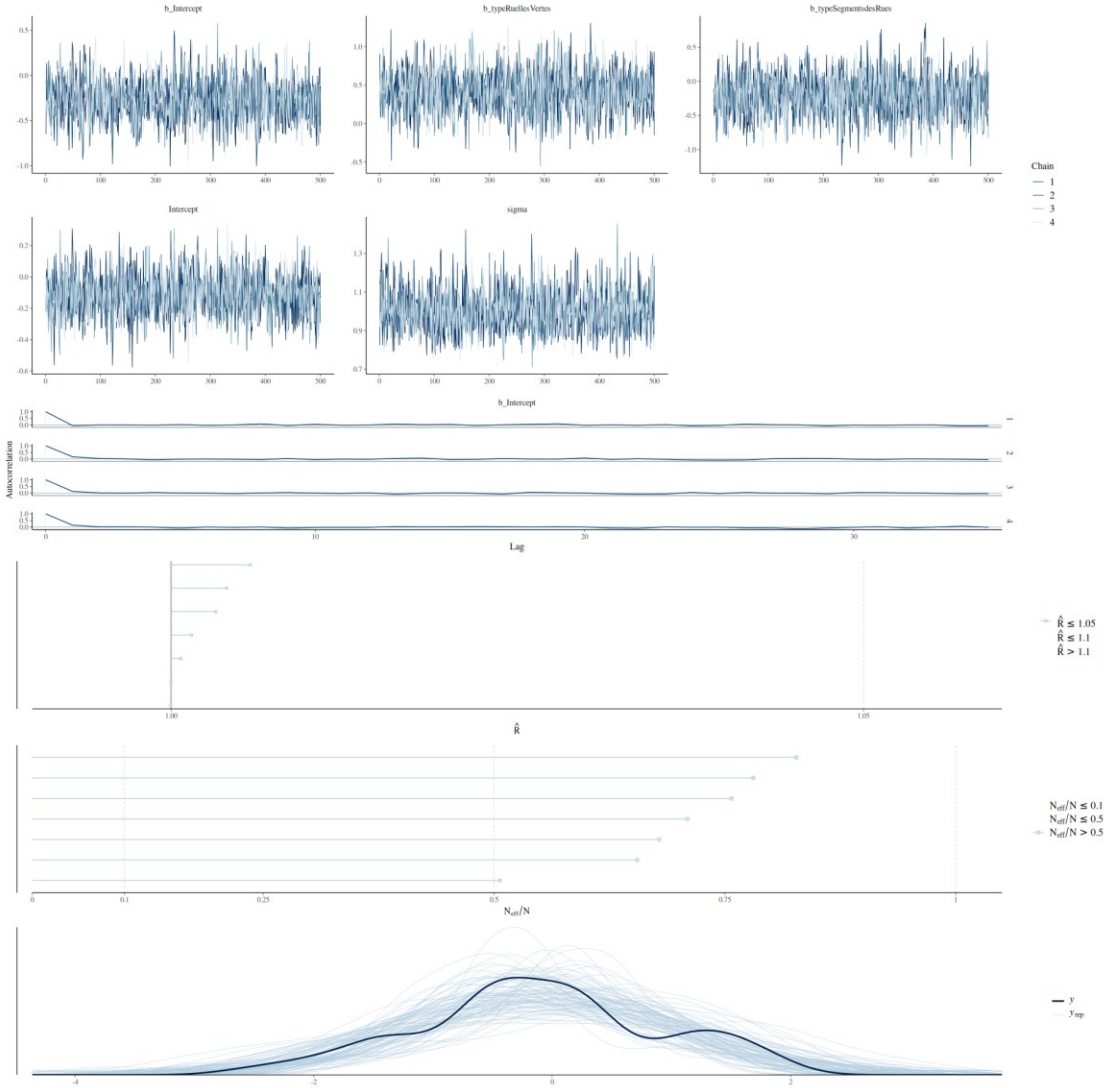
Species Richness



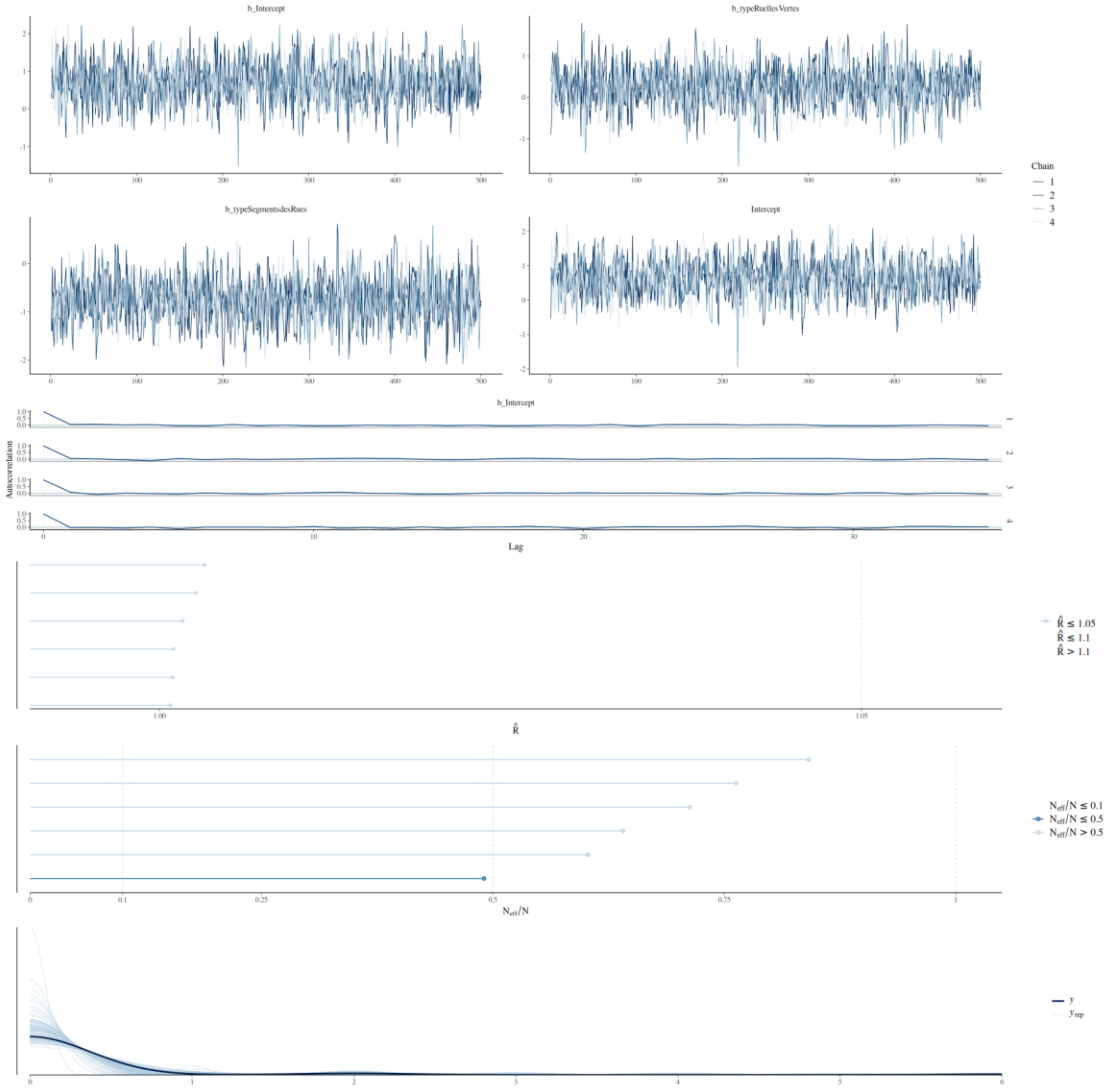
Functional Diversity

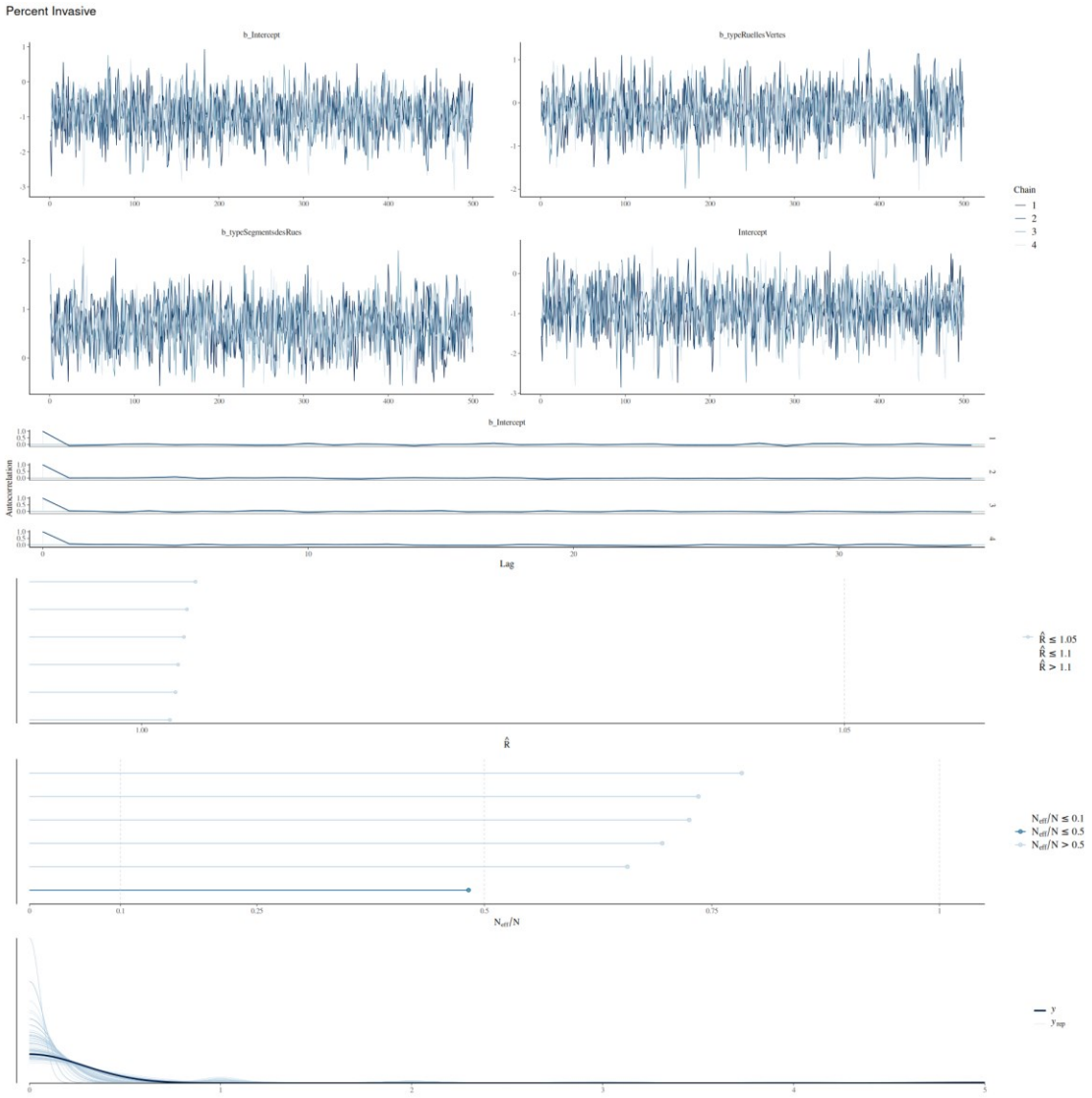


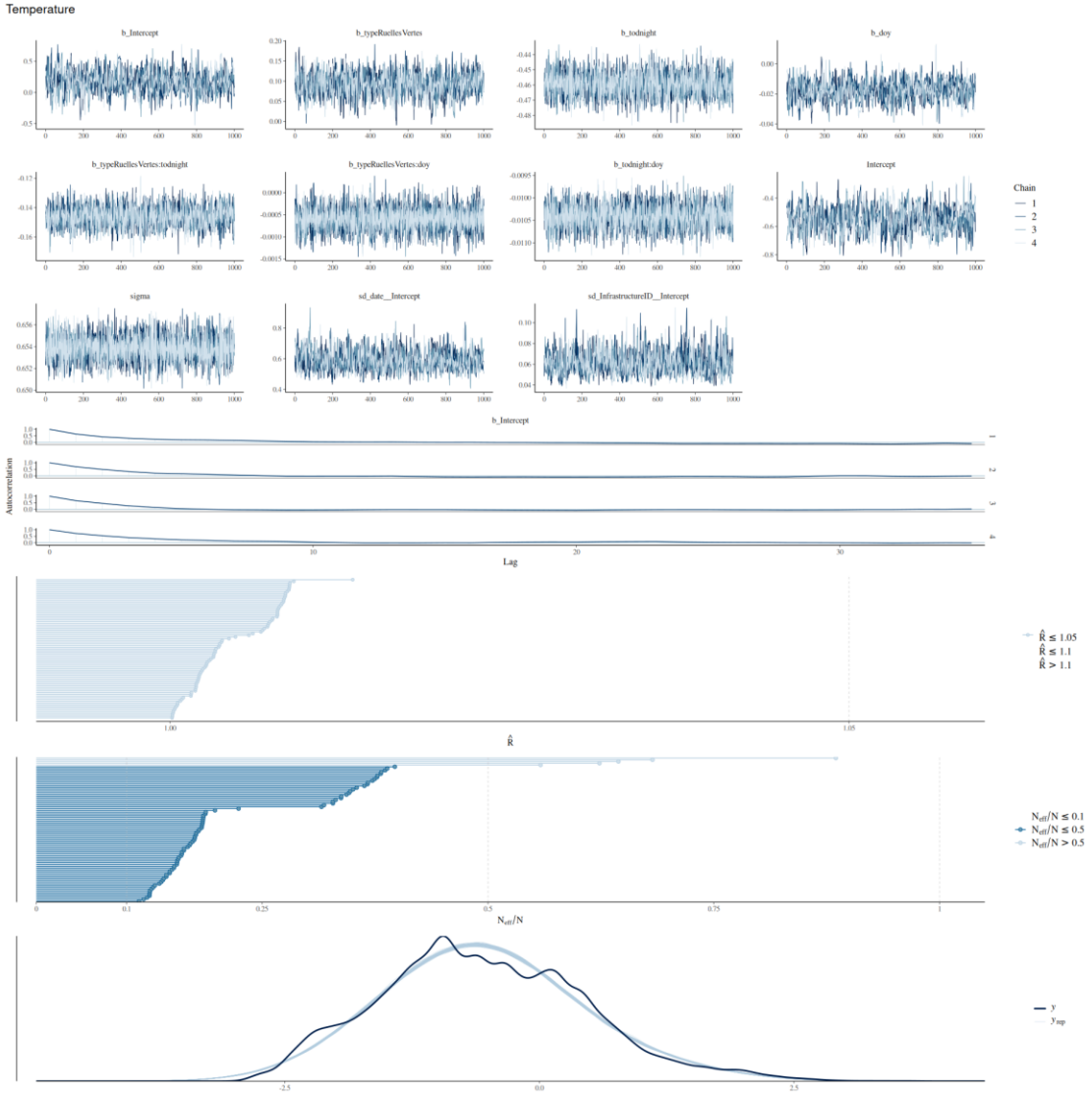
Vertical Complexity



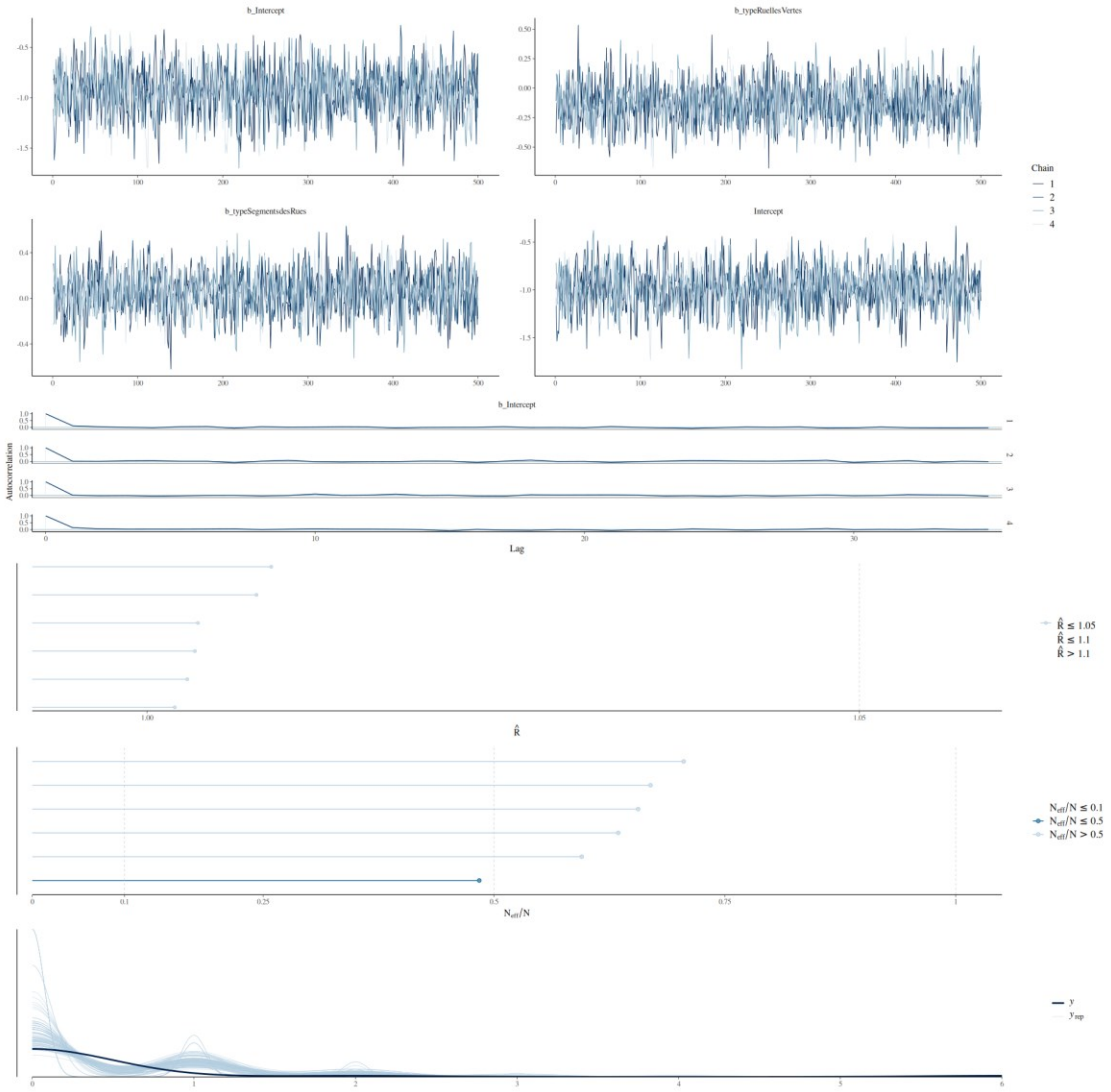
Percent Native



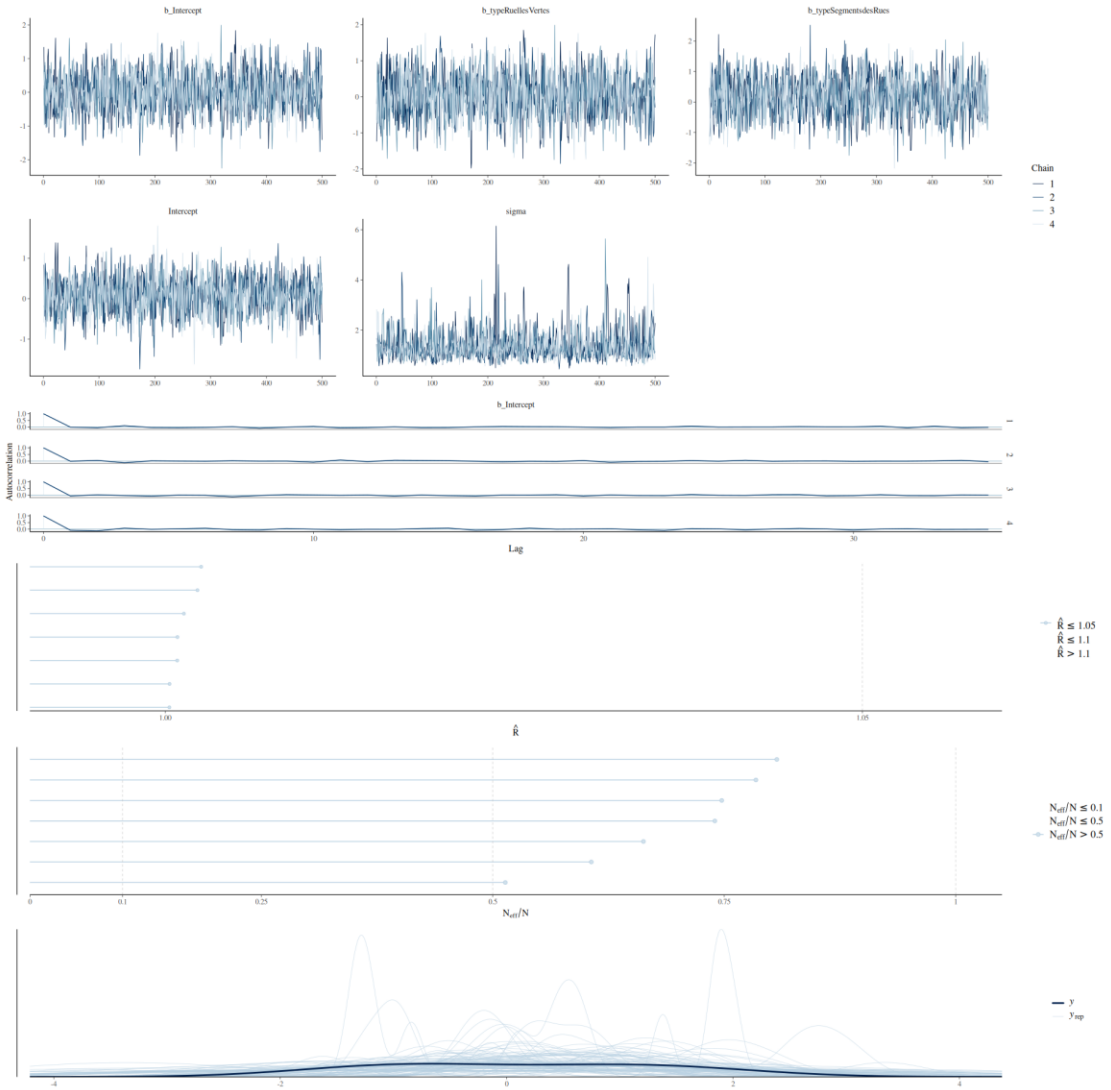

Percent Invasive
b_Intercept
b_typeRuellesVertes
b_typeSegmentsdesRues
Intercept
Chain
1
2
3
4
Autocorrelation
Lag
$\hat{R}$ ≤ 1.05
$\hat{R}$ ≤ 1.1
$\hat{R}$ > 1.1
N_{eff}/N ≤ 0.1
N_{eff}/N ≤ 0.5
N_{eff}/N > 0.5
N_{eff}/N
y
y_{rep}


Temperature
b_Intercept
b_typeRuellesVertes
b_todnight
b_doy
b_typeRuellesVertes:todnight
b_typeRuellesVertes:doy
b_todnight:doy
Intercept
sigma
sd_date__Intercept
sd_InfrastructureID__Intercept
Chain
1
2
3
4
b_Intercept
Autocorrelation
Lag
$\hat{R} \leq 1.05$
$\hat{R} \leq 1.1$
$\hat{R} > 1.1$
$\hat{R}$
$N_{eff}/N \leq 0.1$
$N_{eff}/N \leq 0.5$
$N_{eff}/N > 0.5$
N_{eff}/N
y
y_{rep}

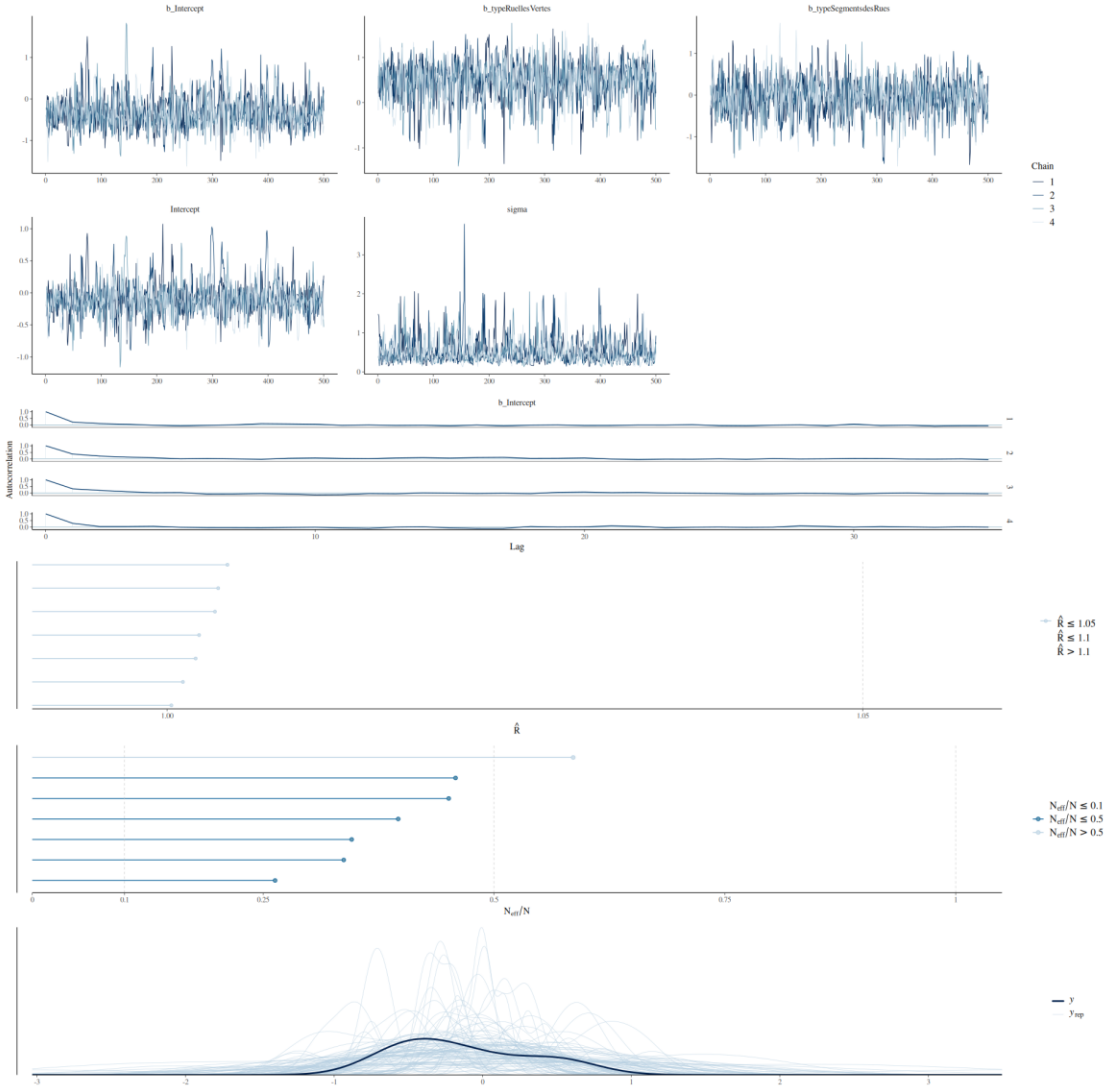
Tree Abundance

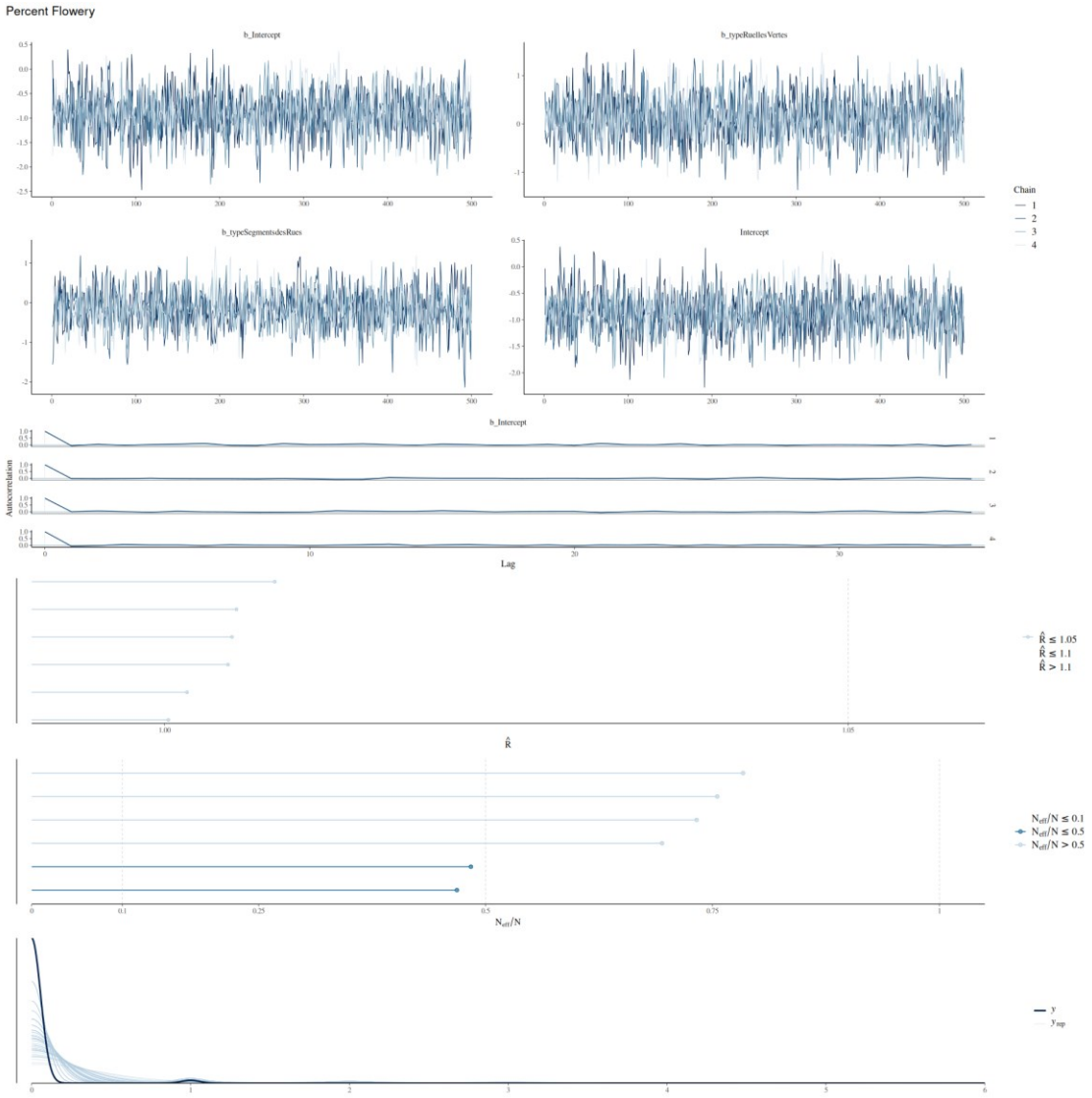


Tree Size (DBH)



Tree Height


b_Intercept
b_typeRuellesVertes
b_typeSegmentsdesRues
Intercept
sigma
Chain
1
2
3
4
Autocorrelation
Lag
$\hat{R} \leq 1.05$
$\hat{R} \leq 1.1$
$\hat{R} > 1.1$
$\hat{R}$
$N_{eff}/N \leq 0.1$
$N_{eff}/N \leq 0.5$
$N_{eff}/N > 0.5$
N_{eff}/N
y
y_{rep}


Percent Flowery
b_Intercept
b_typeRuellesVertes
b_typeSegmentsdesRues
Intercept
Chain
1
2
3
4
b_Intercept
Autocorrelation
Lag
$\hat{R} \leq 1.05$
$\hat{R} \leq 1.1$
$\hat{R} > 1.1$
$\hat{R}$
$N_{eff}/N \leq 0.1$
$N_{eff}/N \leq 0.5$
$N_{eff}/N > 0.5$
N_{eff}/N
y
y_{rep}

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Appendix 3: *Chapter 3 Supplementary Materials*

Table A3.1a: Mean and standard deviations of all response variables. Scale indicates the scale of the model/data. For the model data, pixel values from satellite images across a city, neighbourhood, or street area were averaged. For this table, the values for each neighbourhood or street in a city were then summarized at the city scale, taking the average and standard deviation. There are no air pollutant measurements at the street scale, as the data is too coarse. Temperature measurements are in degrees Celsius and air pollutant measurements are in mol/m^2.

City	Scale	Mean Temperature	Std Dev Temperature	Mean CO	Std Dev CO	Mean NO2	Std Dev NO2	Mean O3	Std Dev O3	Mean UV	Std Dev UV
Calgary	City	34	3.70	0.033	0.0100	2.9e-05	9.0e-06	0.15	NA	-0.24	0.69
Halifax	City	24	4.40	0.038	0.0070	1.7e-05	6.4e-06	0.15	NA	-0.69	0.51
Montreal	City	32	2.40	0.039	0.0082	4.1e-05	2.0e-05	0.15	NA	-0.39	0.65
Ottawa	City	28	0.79	0.039	0.0079	1.8e-05	8.5e-06	0.15	NA	-0.61	0.58
Toronto	City	35	2.40	0.038	0.0066	5.8e-05	2.7e-05	0.15	NA	-0.54	0.59
Vancouver	City	31	4.50	0.034	0.0076	5.5e-05	2.3e-05	0.15	NA	-0.38	0.73
Winnipeg	City	30	2.20	0.040	0.0120	1.8e-05	6.5e-06	0.15	NA	-0.31	0.75
Calgary	Neighbourhood	35	1.70	0.033	0.0098	3.1e-05	1.5e-05	0.15	0.0120	-0.19	0.74
Halifax	Neighbourhood	26	0.53	0.038	0.0075	1.9e-05	9.3e-06	0.15	0.0100	-0.65	0.62
Montreal	Neighbourhood	32	0.17	0.040	0.0084	3.9e-05	2.3e-05	0.15	0.0120	-0.38	0.67

City	Scale	Mean Temperature	Std Dev Temperature	Mean CO	Std Dev CO	Mean NO2	Std Dev NO2	Mean O3	Std Dev O3	Mean UV	Std Dev UV
Ottawa	Neighbourhood	30	2.00	0.039	0.0078	2.0e-05	1.1e-05	0.15	0.0091	-0.55	0.66
Toronto	Neighbourhood	34	0.78	0.039	0.0070	5.8e-05	3.2e-05	0.15	0.0095	-0.55	0.66
Vancouver	Neighbourhood	32	0.79	0.034	0.0078	5.5e-05	2.6e-05	0.15	0.0110	-0.37	0.76
Winnipeg	Neighbourhood	31	1.30	0.040	0.0130	2.0e-05	8.8e-06	0.15	0.0130	-0.24	0.78
Calgary	Street	34	3.80	NA	NA	NA	NA	NA	NA	NA	NA
Halifax	Street	32	1.30	NA	NA	NA	NA	NA	NA	NA	NA
Montreal	Street	32	1.90	NA	NA	NA	NA	NA	NA	NA	NA
Ottawa	Street	32	3.00	NA	NA	NA	NA	NA	NA	NA	NA
Toronto	Street	35	2.10	NA	NA	NA	NA	NA	NA	NA	NA
Vancouver	Street	32	3.50	NA	NA	NA	NA	NA	NA	NA	NA
Winnipeg	Street	31	3.10	NA	NA	NA	NA	NA	NA	NA	NA

Table A3.1b: Mean and standard deviations of all explanatory variables. Scale indicates the scale of the model/data. For the model data, values across the city, neighbourhood, or street area were averaged. For this table, the values for each neighbourhood or street in a city were then summarized at the city scale, taking the average and standard deviation.

City	Scale	Area (km2)	Basal Area (m2/m2)	Stem Density (ind/km2)	Species Richness	Shannon	Functional Group Richness	Functional Group Shannon	Mean DBH (cm)	Std Dev DBH (cm)	Population	Mean NDVI	Mean NDBI	Building Cover (buildings/km2)	Building Cover (km2/km2)	Proportion Highway	Road Density (km/km2)	Population Density (ind/km2)	Mean Building Height (m)	Std Dev Building Height (m)	Single Detached Homes (%)	Large Apt Building (%)	Semi-Detached Home (%)	Row House (%)	Duplex Apartment (%)	Small Apt Building (%)	Moving Dwelling (%)	Median Income ($)	Recent Immigrants (%)	Indigenous People (%)	Visible Minorities (%)	Highly Educated (%)	Low-Income (%)
Calgary	City	920.0	2.6e-05	500	170.0	3.1	5.0	1.30	19	17	1300000	0.27	-0.061	430	0.084	0.0710	8.0	4100	6.0	5.4	0.610	0.053	0.064	0.096	0.041	0.130	2.8e-03	42000	0.120	0.0300	0.41	0.43	0.090
Halifax	City	1100.0	6.4e-06	62	210.0	3.8	6.0	1.20	24	27	390000	0.48	-0.240	79	0.016	0.0670	2.0	3400	6.1	5.1	0.470	0.140	0.078	0.043	0.036	0.210	1.9e-02	38000	0.061	0.0360	0.18	0.42	0.130
Montreal	City	270.0	7.4e-05	770	260.0	3.4	6.0	1.20	26	23	1600000	0.26	-0.080	400	0.170	0.0430	13.0	12000	7.6	7.5	0.096	0.150	0.037	0.038	0.120	0.560	3.6e-04	35000	0.110	0.0061	0.36	0.46	0.170
Ottawa	City	3000.0	5.4e-06	79	140.0	3.5	5.0	1.30	22	20	1000000	0.48	-0.190	71	0.018	0.0370	2.4	4400	5.3	5.0	0.460	0.140	0.055	0.230	0.018	0.094	2.3e-03	46000	0.076	0.0260	0.32	0.48	0.091
Toronto	City	670.0	7.8e-05	890	180.0	3.7	6.0	1.20	25	22	2900000	0.30	-0.090	490	0.150	0.0570	9.7	14000	7.3	9.3	0.280	0.400	0.070	0.063	0.049	0.130	3.2e-05	38000	0.120	0.0058	0.56	0.48	0.130
Vancouver	City	120.0	1.5e-04	1200	370.0	4.2	6.0	1.10	30	24	690000	0.30	-0.100	840	0.160	0.0180	13.0	12000	7.6	9.0	0.180	0.260	0.016	0.039	0.220	0.280	5.0e-05	39000	0.110	0.0210	0.55	0.52	0.130
Winnipeg	City	570.0	3.4e-05	350	100.0	2.5	6.0	1.10	29	20	760000	0.32	-0.120	450	0.091	0.0490	6.8	4100	4.3	4.3	0.630	0.100	0.043	0.039	0.017	0.170	2.1e-03	36000	0.120	0.1200	0.34	0.36	0.130
Calgary	Neighbourhood	1.8	8.2e-05	1100	47.0	2.6	4.6	1.20	22	17	4100	0.23	-0.042	750	0.140	0.0730	12.0	3900	6.9	4.6	0.510	0.098	0.062	0.100	0.060	0.170	1.2e-06	43000	0.110	0.0300	0.36	0.49	0.110
Halifax	Neighbourhood	27.0	7.7e-06	120	83.0	3.2	4.9	1.10	16	16	20000	0.39	-0.180	140	0.025	0.0490	3.2	1300	4.9	3.3	0.620	0.050	0.120	0.020	0.022	0.100	5.9e-02	39000	0.031	0.0480	0.13	0.31	0.092
Montreal	Neighbourhood	22.0	7.4e-05	860	130.0	3.2	5.7	1.10	25	21	110000	0.22	-0.068	330	0.180	0.0500	13.0	12000	8.1	6.7	0.099	0.140	0.020	0.036	0.110	0.580	3.5e-04	35000	0.100	0.0080	0.35	0.47	0.180
Ottawa	Neighbourhood	27.0	4.3e-05	510	63.0	3.1	4.9	1.20	23	18	8800	0.37	-0.140	440	0.110	0.0350	9.2	4100	5.1	4.1	0.470	0.160	0.053	0.220	0.016	0.086	2.4e-03	45000	0.073	0.0270	0.30	0.48	0.095
Toronto	Neighbourhood	4.1	1.0e-04	1100	93.0	3.4	5.9	1.10	25	22	17000	0.28	-0.085	560	0.180	0.0460	11.0	14000	8.7	8.4	0.290	0.370	0.082	0.059	0.049	0.150	1.8e-05	40000	0.110	0.0067	0.51	0.51	0.130
Vancouver	Neighbourhood	5.6	1.4e-04	1200	180.0	4.0	5.6	1.10	31	23	29000	0.23	-0.056	890	0.160	0.0032	13.0	8100	6.6	3.8	0.210	0.100	0.023	0.059	0.250	0.340	0.0e+00	37000	0.095	0.0290	0.51	0.51	0.150
Win	Neigh	1.7	7.5	700	29.	2.0	4.6	1.00	27	1	320	0.	-	780	0.14	0.06	11.0	340	5.4	3.9	0.6	0.1	0.0	0.	0.01	0.1	2.1e	37	0.11	0.13	0.31	0.3	0.1

City	Scale	Area (km2)	Basal Area (m2/m2)	Stem Density (ind/km2)	Species Richness	Shannon	Functional Group Richness	Functional Group Shannon	Mean DBH (cm)	Std Dev DBH (cm)	Population	Mean NDVI	Mean NDBI	Building Cover (buildings/km2)	Building Cover (km2/km2)	Proportion Highway	Road Density (km/km2)	Population Density (ind/km2)	Mean Building Height (m)	Std Dev Building Height (m)	Single Detached Homes (%)	Large Apt Building (%)	Semi-Detached Home (%)	Row House (%)	Duplex Apartment (%)	Small Apt Building (%)	Moving Dwelling (%)	Median Income ($)	Recent Immigrants (%)	Indigenous People (%)	Visible Minorities (%)	Highly Educated (%)	Low-Income (%)
nipeg	bourhood		e-05		0					6	0	25	0.067		0	00		0			00	30	45	046	7	60	-03	0000	0	00		6	40
Calgary	Street	NA	1.7e-04	2700	6.6	1.4	3.1	0.87	22	14	30	0.20	-0.034	1100	0.150	NA	NA	3600	5.3	2.5	0.640	0.032	0.070	0.075	0.059	0.120	3.3e-05	44000	0.095	0.0290	0.32	0.45	0.085
Halifax	Street	NA	2.2e-04	1700	6.5	1.5	2.7	0.76	26	18	24	0.31	-0.110	850	0.110	NA	NA	3200	5.5	3.0	0.510	0.088	0.093	0.045	0.057	0.200	5.7e-03	39000	0.047	0.0340	0.16	0.46	0.110
Montreal	Street	NA	1.9e-04	2100	7.6	1.6	2.9	0.80	26	17	77	0.22	-0.061	650	0.190	NA	NA	10000	6.9	3.1	0.140	0.094	0.051	0.038	0.120	0.560	2.3e-04	35000	0.098	0.0058	0.35	0.46	0.160
Ottawa	Street	NA	1.5e-04	1900	7.3	1.6	3.0	0.88	24	15	30	0.30	-0.099	840	0.160	NA	NA	3900	4.8	2.5	0.550	0.069	0.070	0.190	0.021	0.093	1.1e-03	47000	0.058	0.0220	0.28	0.52	0.075
Toronto	Street	NA	2.3e-04	2200	9.8	1.8	3.2	0.84	28	20	50	0.25	-0.073	810	0.150	NA	NA	7400	6.3	3.4	0.450	0.140	0.110	0.057	0.074	0.170	0.0e+00	41000	0.082	0.0063	0.46	0.51	0.100
Vancouver	Street	NA	3.1e-04	2800	7.7	1.6	2.8	0.69	30	19	55	0.26	-0.073	810	0.110	NA	NA	7300	6.4	3.1	0.290	0.088	0.022	0.036	0.300	0.270	8.9e-05	38000	0.093	0.0180	0.56	0.51	0.120
Winnipeg	Street	NA	1.9e-04	2000	4.9	1.0	2.6	0.60	29	13	28	0.25	-0.063	910	0.130	NA	NA	3200	4.2	2.4	0.740	0.052	0.043	0.037	0.013	0.120	2.5e-03	39000	0.091	0.1100	0.28	0.38	0.100

Table A3.2: Data sources used in the study.

Dataset	Area/Link	Data Type
Neighbourhood	Halifax	Shapefile/CSV
	Montreal	
	Ottawa	
	Toronto	
	Winnipeg	
	Calgary	
	Vancouver	
Parks	Halifax	Shapefile/CSV
	Montreal	
	Ottawa	
	Toronto	
	Winnipeg	
	Calgary	
	Vancouver	
Street Trees	Halifax	
	Montreal	
	Ottawa	
	Toronto	
	Winnipeg	
	Calgary	
	Vancouver	
Census Metropolitan Areas	National	Shapefile
Roads	National	Shapefile
Dissemination Areas	National	Shapefile
2021 Census	National	CSV
Buildings	National	Shapefile

Dataset	Area/Link	Data Type
NDVI/NDBI	International - Sentinel 2 (5 day revisit frequency)	TIFF
Land Surface Temperature	International - Landsat 8 (2 week revisit frequency)	TIFF
Air Pollutants	International - Sentinel 5p TROPOMI (2 day revisit frequency)	TIFF

Table A3.3: Model Performance Metrics. For each model, the root mean squared error (rmse), R^2 (rsq), and mean absolute error (mae) were calculated for the testing and training datasets. A well fitted model should not have large differences in error metric values between the training and testing dataset.

Model	Scale	Dataset	Metric	Value
CO	City	test	rmse	6.4e-03
CO	City	train	rmse	5.4e-03
CO	City	test	rsq	5.2e-01
CO	City	train	rsq	6.7e-01
CO	City	test	mae	4.3e-03
CO	City	train	mae	3.7e-03
NO2	City	test	rmse	1.7e-05
NO2	City	train	rmse	1.4e-05
NO2	City	test	rsq	5.3e-01
NO2	City	train	rsq	5.5e-01
NO2	City	test	mae	1.1e-05
NO2	City	train	mae	1.0e-05
O3	City	test	rmse	9.5e-03
O3	City	train	rmse	8.0e-03
O3	City	test	rsq	4.2e-01
O3	City	train	rsq	5.5e-01
O3	City	test	mae	7.2e-03
O3	City	train	mae	6.1e-03
SO2	City	test	rmse	3.1e-04
SO2	City	train	rmse	3.5e-04
SO2	City	test	rsq	2.8e-02
SO2	City	train	rsq	6.6e-02
SO2	City	test	mae	2.3e-04
SO2	City	train	mae	2.2e-04
Temperature	City	test	rmse	2.3e+00
Temperature	City	train	rmse	3.1e+00
Temperature	City	test	rsq	4.0e-01
Temperature	City	train	rsq	5.3e-01

Model	Scale	Dataset	Metric	Value
Temperature	City	test	mae	1.8e+00
Temperature	City	train	mae	2.6e+00
UV	City	test	rmse	6.8e-01
UV	City	train	rmse	6.0e-01
UV	City	test	rsq	8.2e-02
UV	City	train	rsq	1.6e-01
UV	City	test	mae	5.3e-01
UV	City	train	mae	4.8e-01
CO	Neighbourhood	test	rmse	6.8e-03
CO	Neighbourhood	train	rmse	6.6e-03
CO	Neighbourhood	test	rsq	6.1e-01
CO	Neighbourhood	train	rsq	6.4e-01
CO	Neighbourhood	test	mae	4.7e-03
CO	Neighbourhood	train	mae	4.6e-03
NO2	Neighbourhood	test	rmse	1.6e-05
NO2	Neighbourhood	train	rmse	1.6e-05
NO2	Neighbourhood	test	rsq	4.2e-01
NO2	Neighbourhood	train	rsq	4.4e-01
NO2	Neighbourhood	test	mae	1.1e-05
NO2	Neighbourhood	train	mae	1.1e-05
O3	Neighbourhood	test	rmse	9.2e-03
O3	Neighbourhood	train	rmse	8.9e-03
O3	Neighbourhood	test	rsq	4.3e-01
O3	Neighbourhood	train	rsq	4.7e-01
O3	Neighbourhood	test	mae	7.3e-03
O3	Neighbourhood	train	mae	7.1e-03
SO2	Neighbourhood	test	rmse	5.4e-04
SO2	Neighbourhood	train	rmse	5.1e-04
SO2	Neighbourhood	test	rsq	6.3e-02
SO2	Neighbourhood	train	rsq	1.8e-01
SO2	Neighbourhood	test	mae	3.9e-04
SO2	Neighbourhood	train	mae	3.7e-04
Temperature	Neighbourhood	test	rmse	3.5e+00

Model	Scale	Dataset	Metric	Value
Temperature	Neighbourhood	train	rmse	3.4e+00
Temperature	Neighbourhood	test	rsq	4.6e-01
Temperature	Neighbourhood	train	rsq	5.1e-01
Temperature	Neighbourhood	test	mae	2.6e+00
Temperature	Neighbourhood	train	mae	2.5e+00
UV	Neighbourhood	test	rmse	6.1e-01
UV	Neighbourhood	train	rmse	6.0e-01
UV	Neighbourhood	test	rsq	3.3e-01
UV	Neighbourhood	train	rsq	3.8e-01
UV	Neighbourhood	test	mae	4.9e-01
UV	Neighbourhood	train	mae	4.8e-01
Temperature	Street	test	rmse	4.0e+00
Temperature	Street	train	rmse	3.4e+00
Temperature	Street	test	rsq	3.7e-01
Temperature	Street	train	rsq	6.3e-01
Temperature	Street	test	mae	2.8e+00
Temperature	Street	train	mae	2.4e+00

Figure A3.1: Values for independent variables across cities and scales.

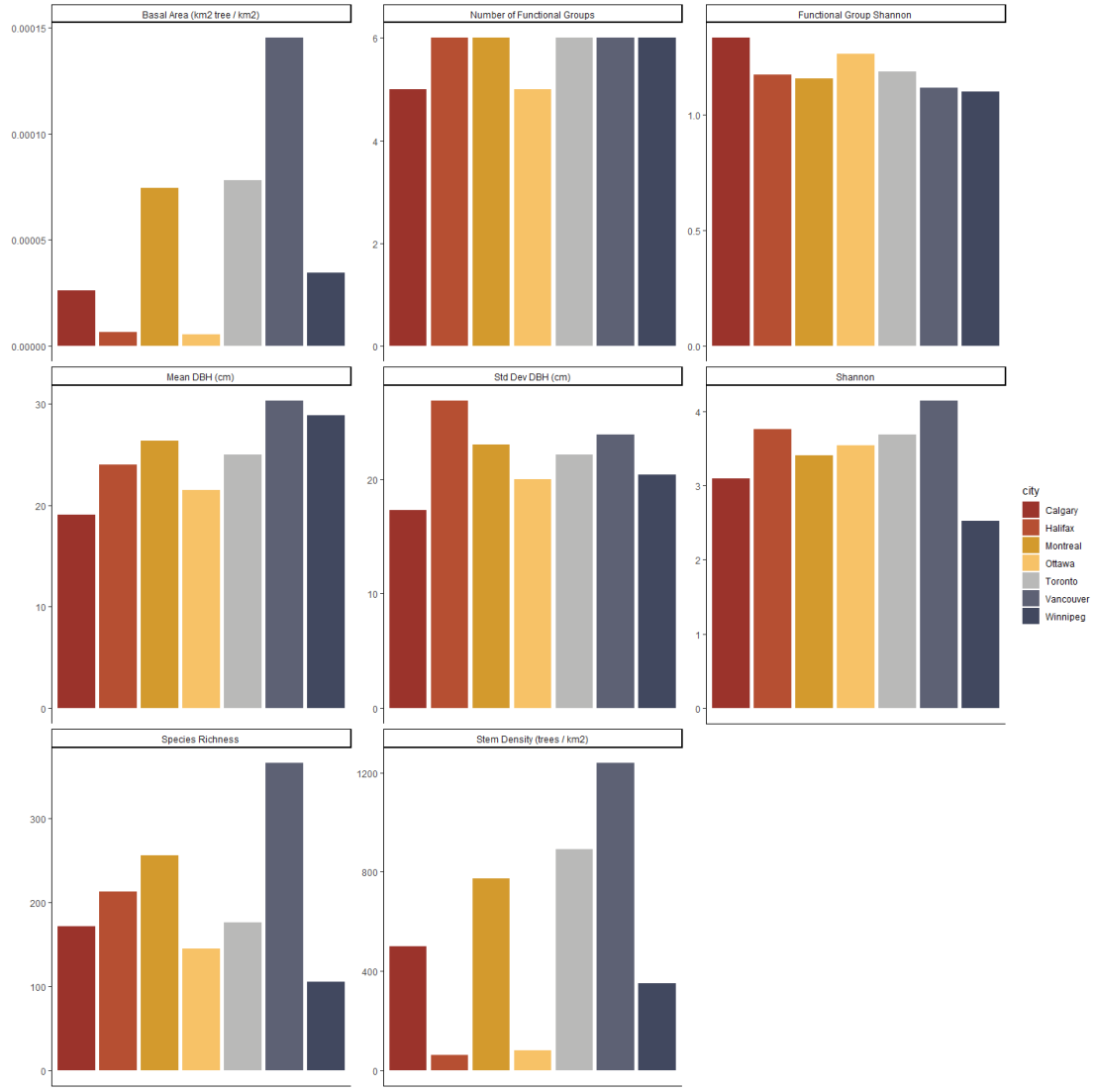


Figure A3.1a: Plot depicting the values for ecological form variables for each city at the city scale.

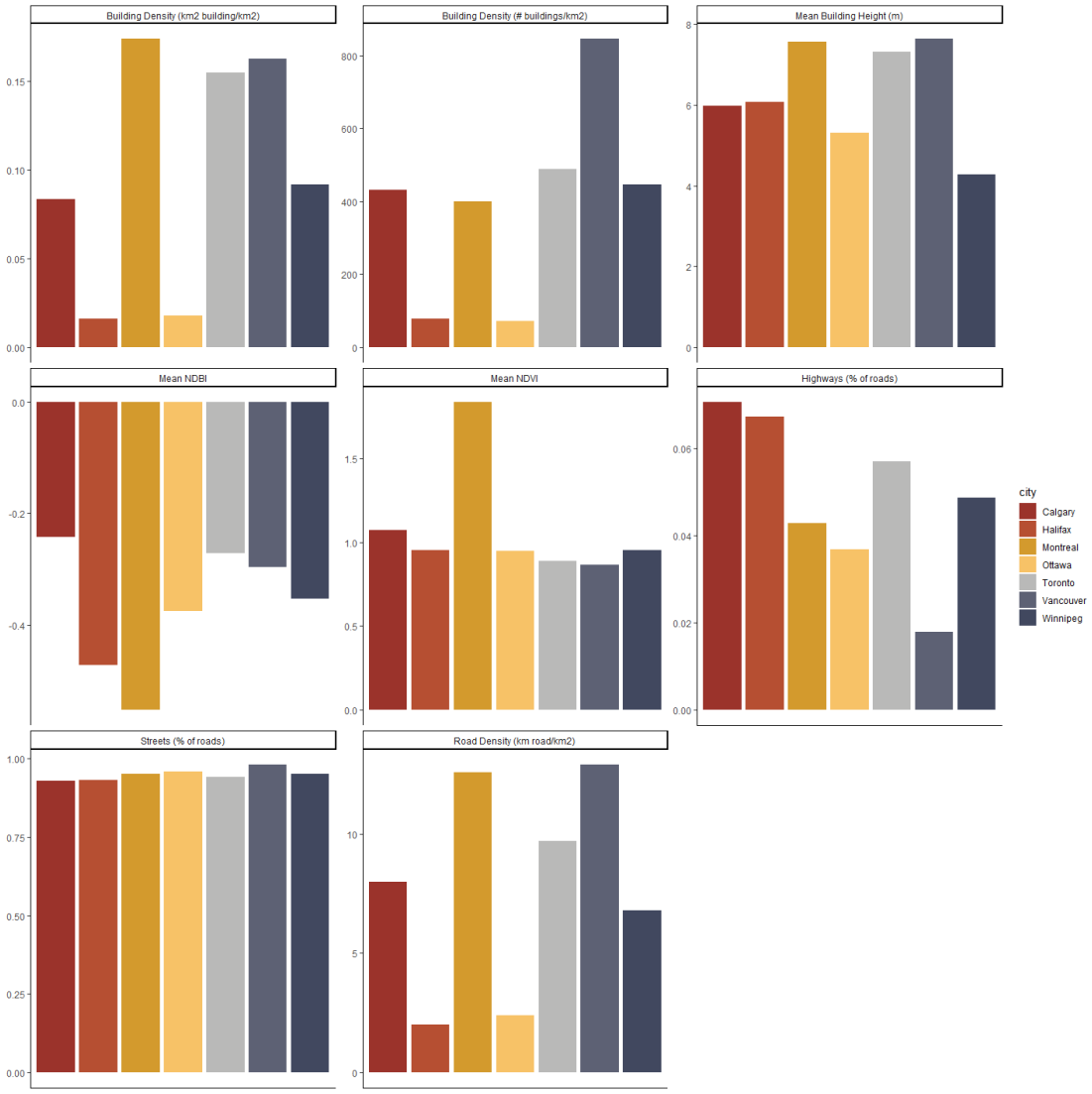


Figure A3.1b: Plot depicting the values for urban form variables for each city at the city scale.

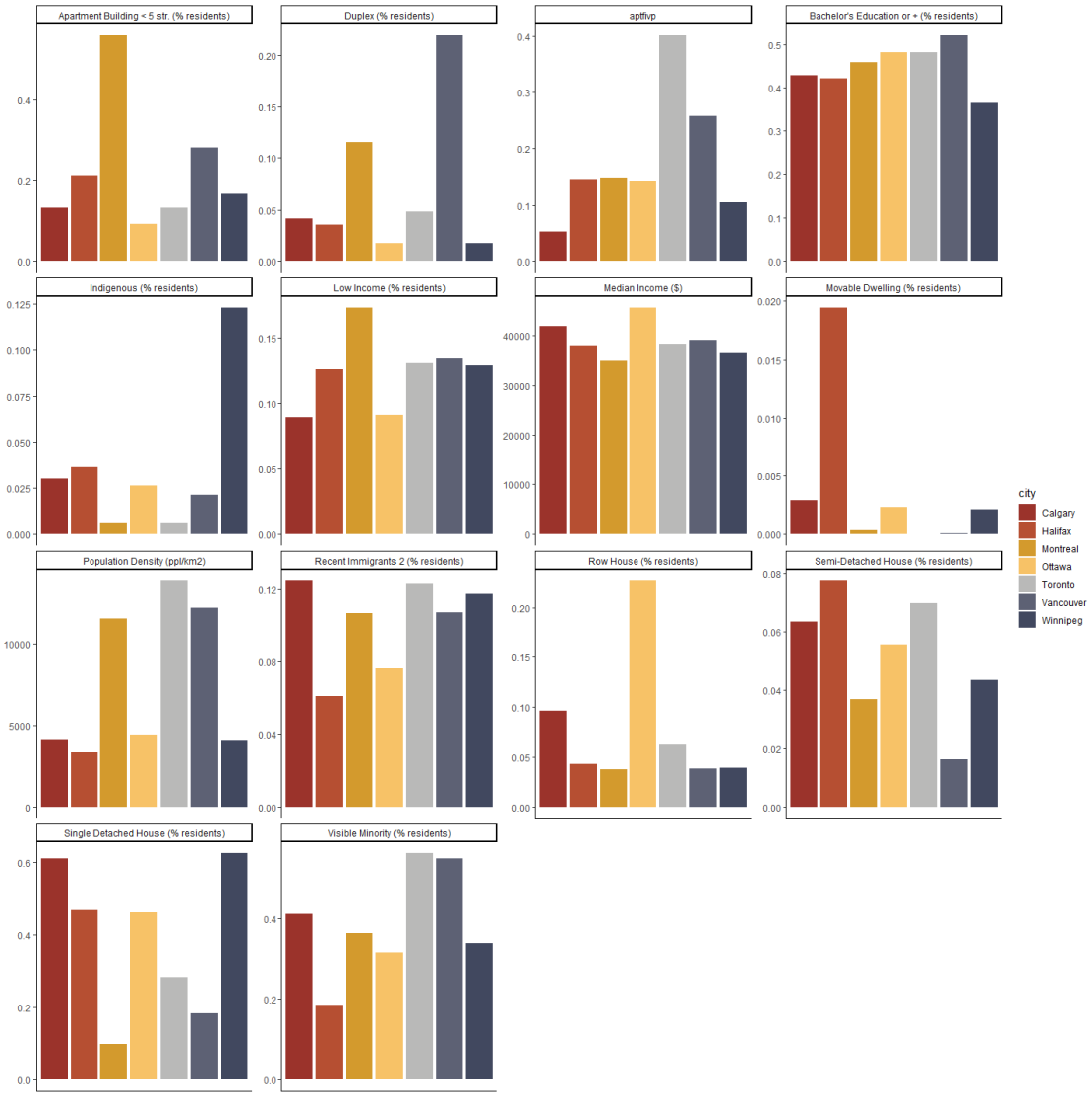


Figure A3.1c: Plot depicting the values for sociodemographic variables for each city at the city scale.

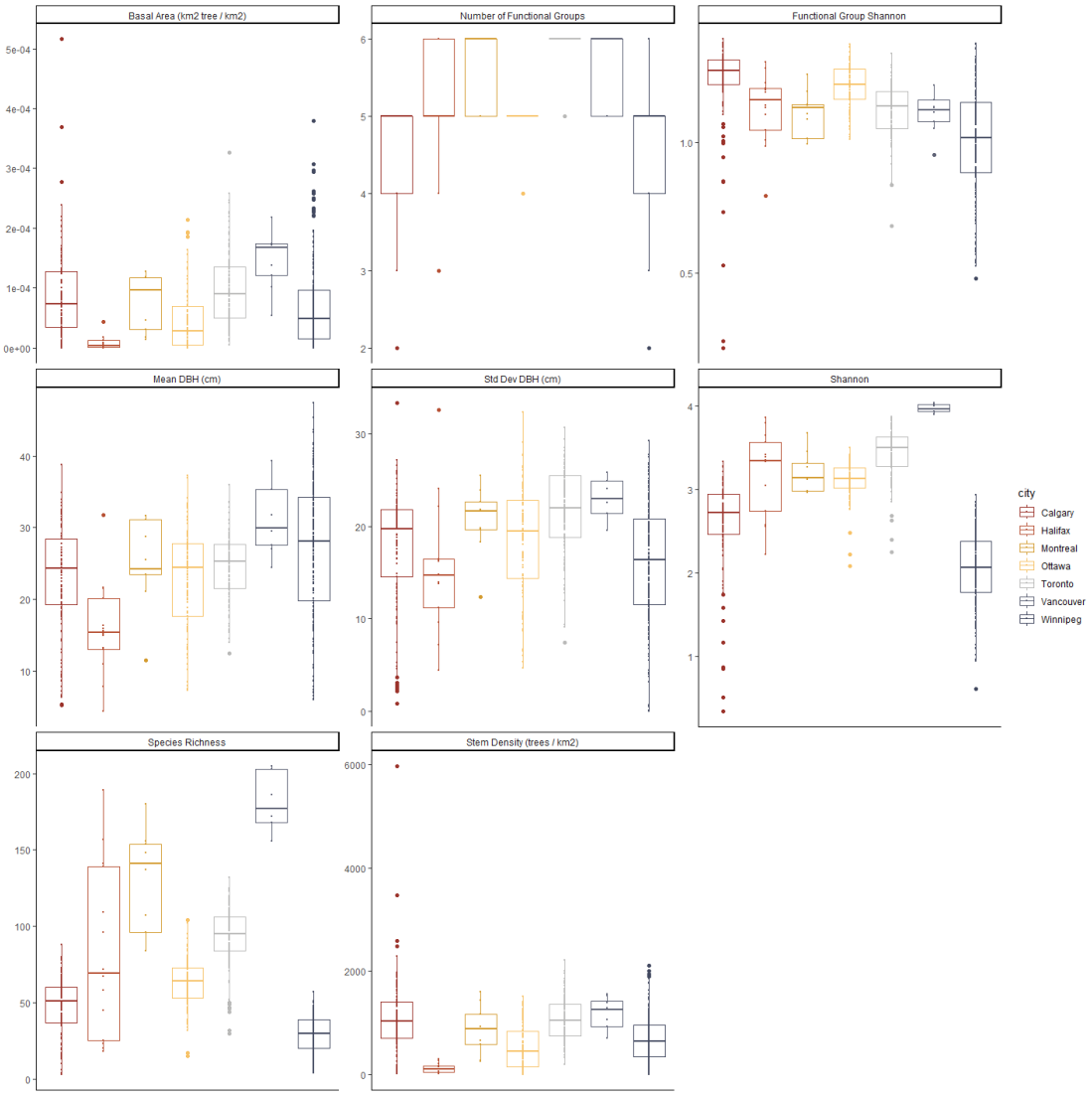


Figure A3.1d: Plot depicting the values for ecological form variables for each city at the neighbourhood scale.

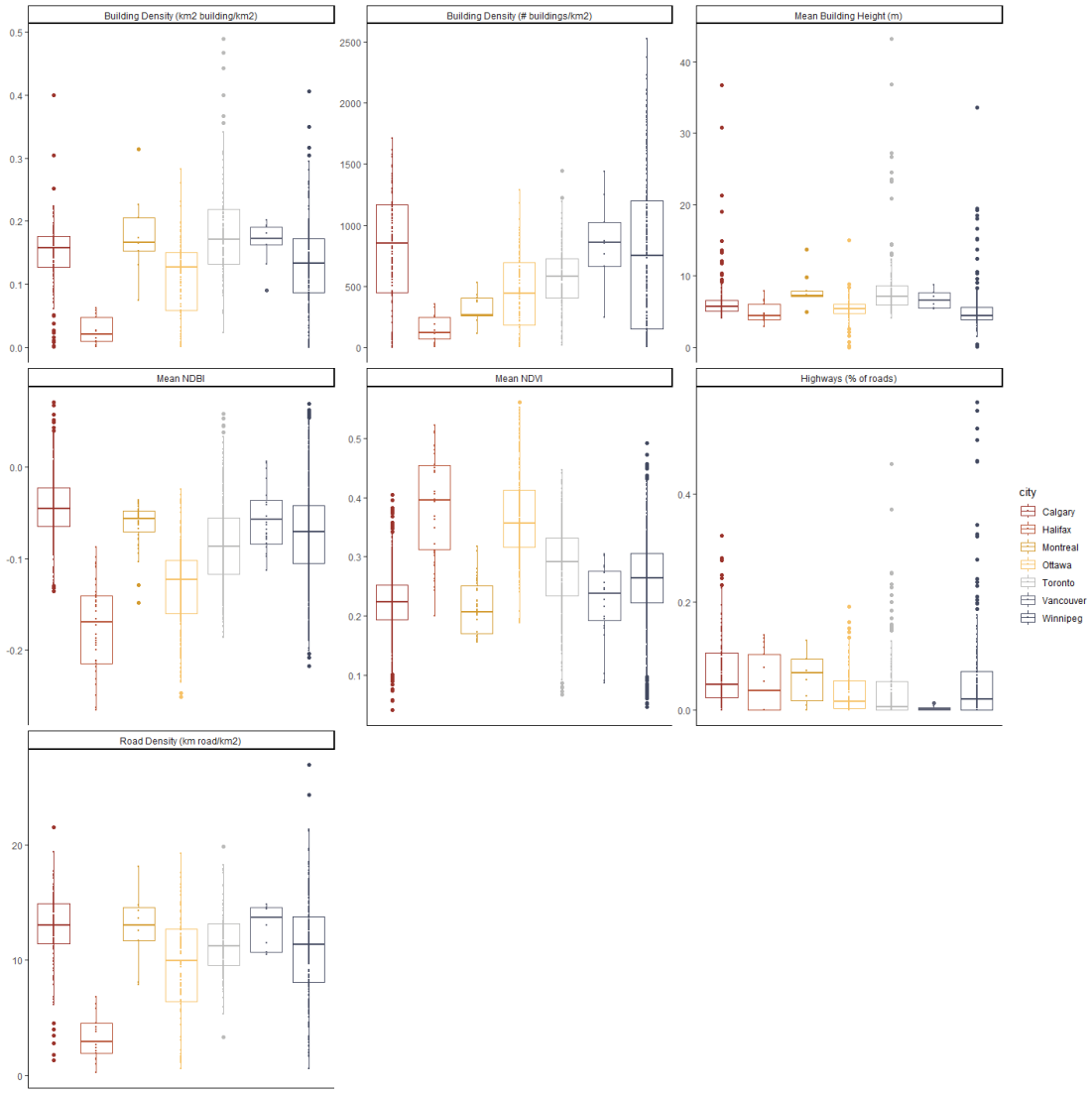


Figure A3.1e: Plot depicting the values for urban form variables for each city at the neighbourhood scale.

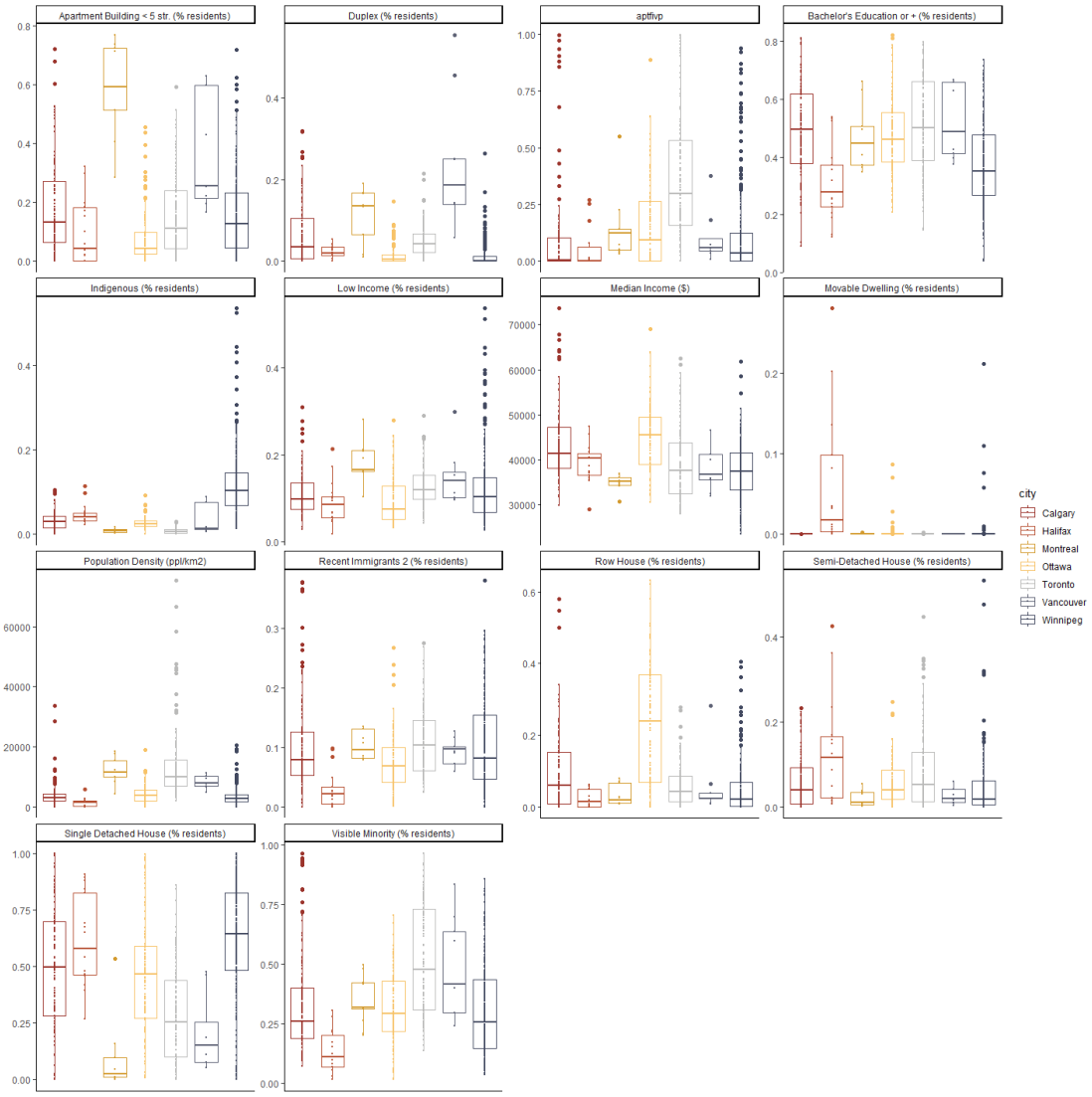


Figure A3.1f: Plot depicting the values for sociodemographic variables for each city at the neighbourhood scale.

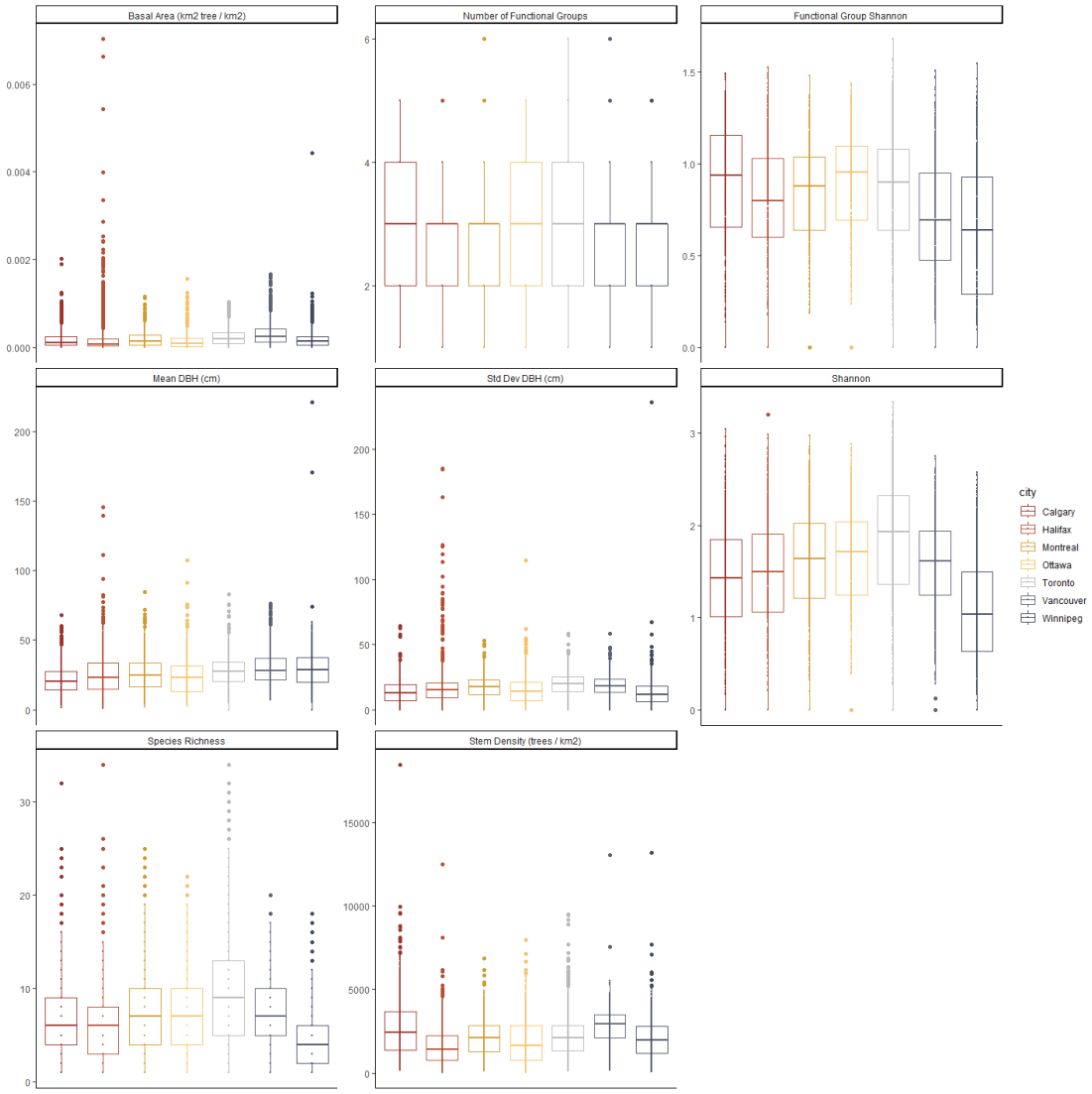


Figure A3.1g: Plot depicting the values for ecological form variables for each city at the street scale.

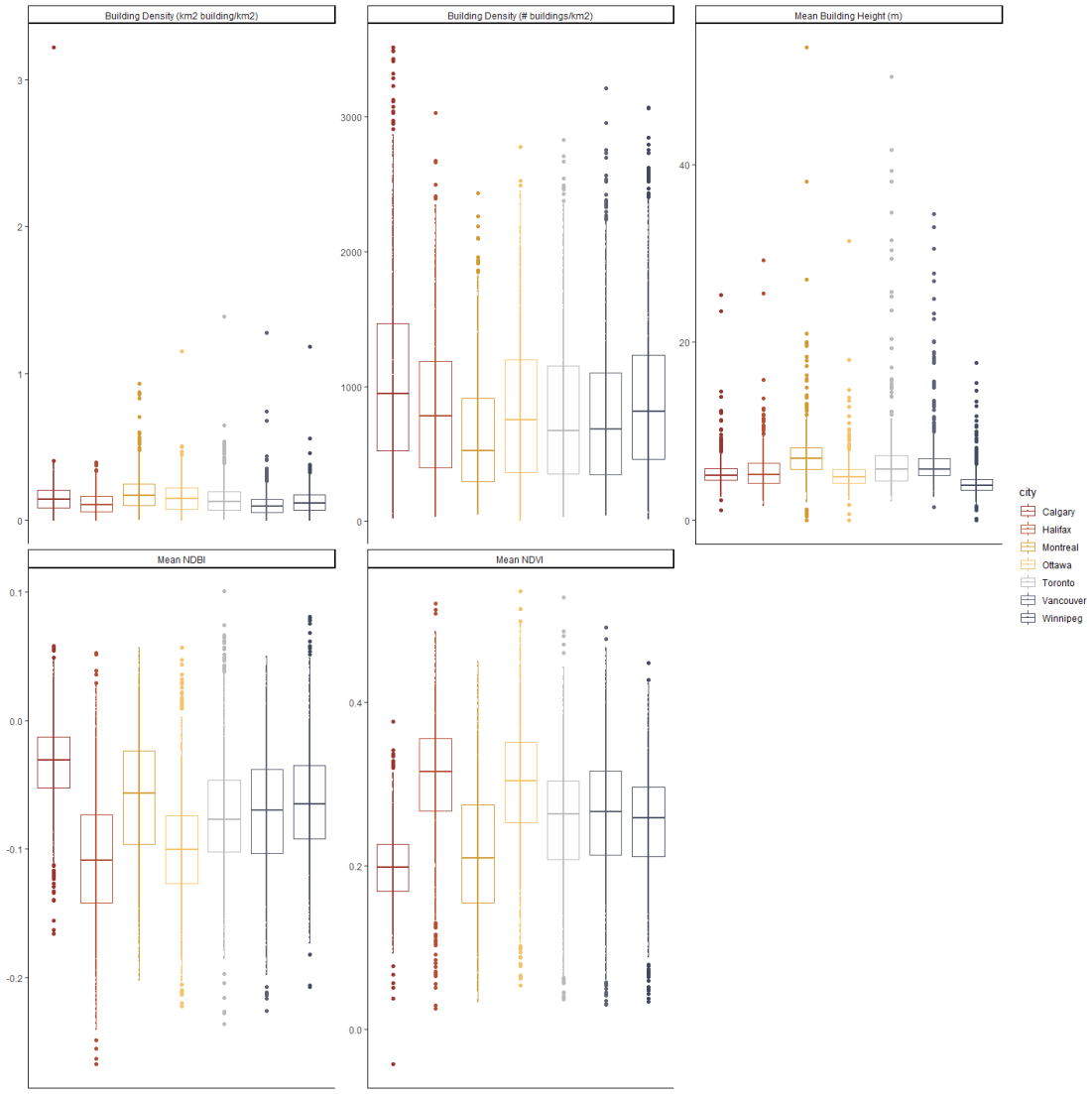


Figure A3.1h: Plot depicting the values for urban form variables for each city at the street scale.

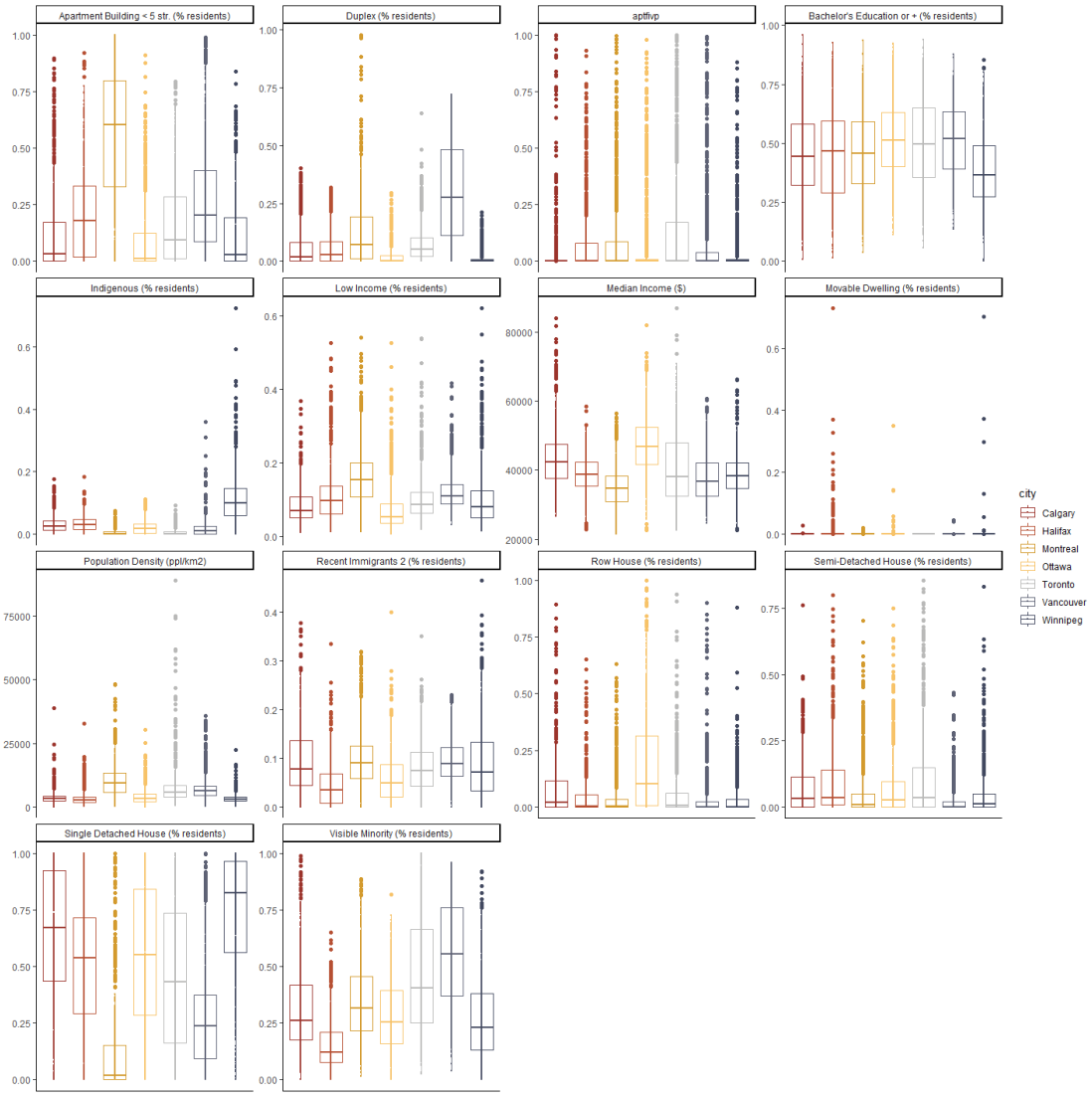


Figure A3.1i: Plot depicting the values for sociodemographic variables for each city at the street scale.

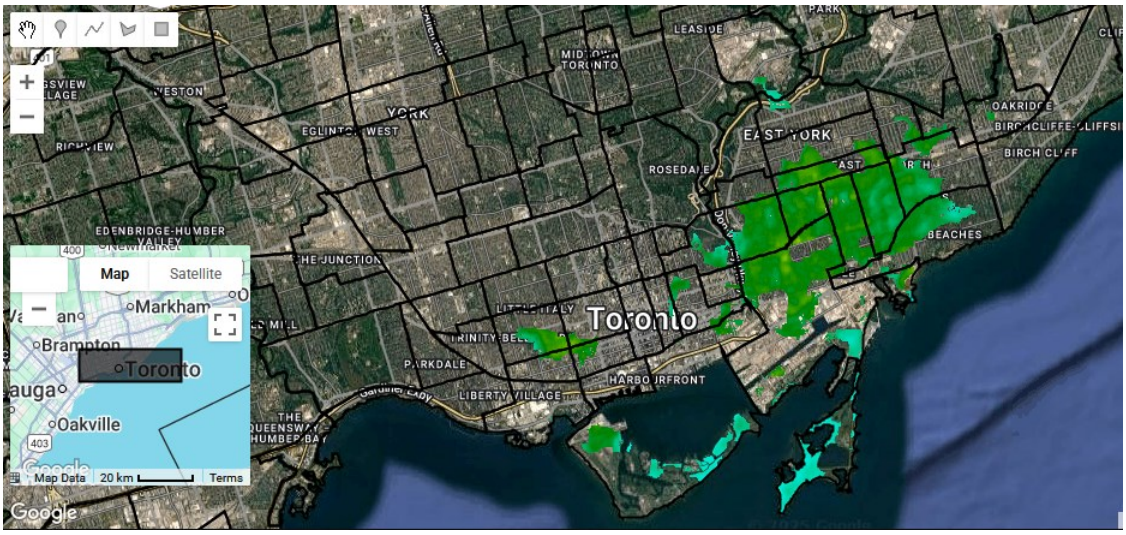


Figure A3.2: Example of satellite image coverage of Toronto neighbourhoods. Depicted is a single satellite image, with cloudy pixels removed. To be included in our analysis, satellite images had to cover an estimated 50% or more of the area of a city or neighbourhood, or 100% of a street area.

Figure A3.3: Variable importance plots.

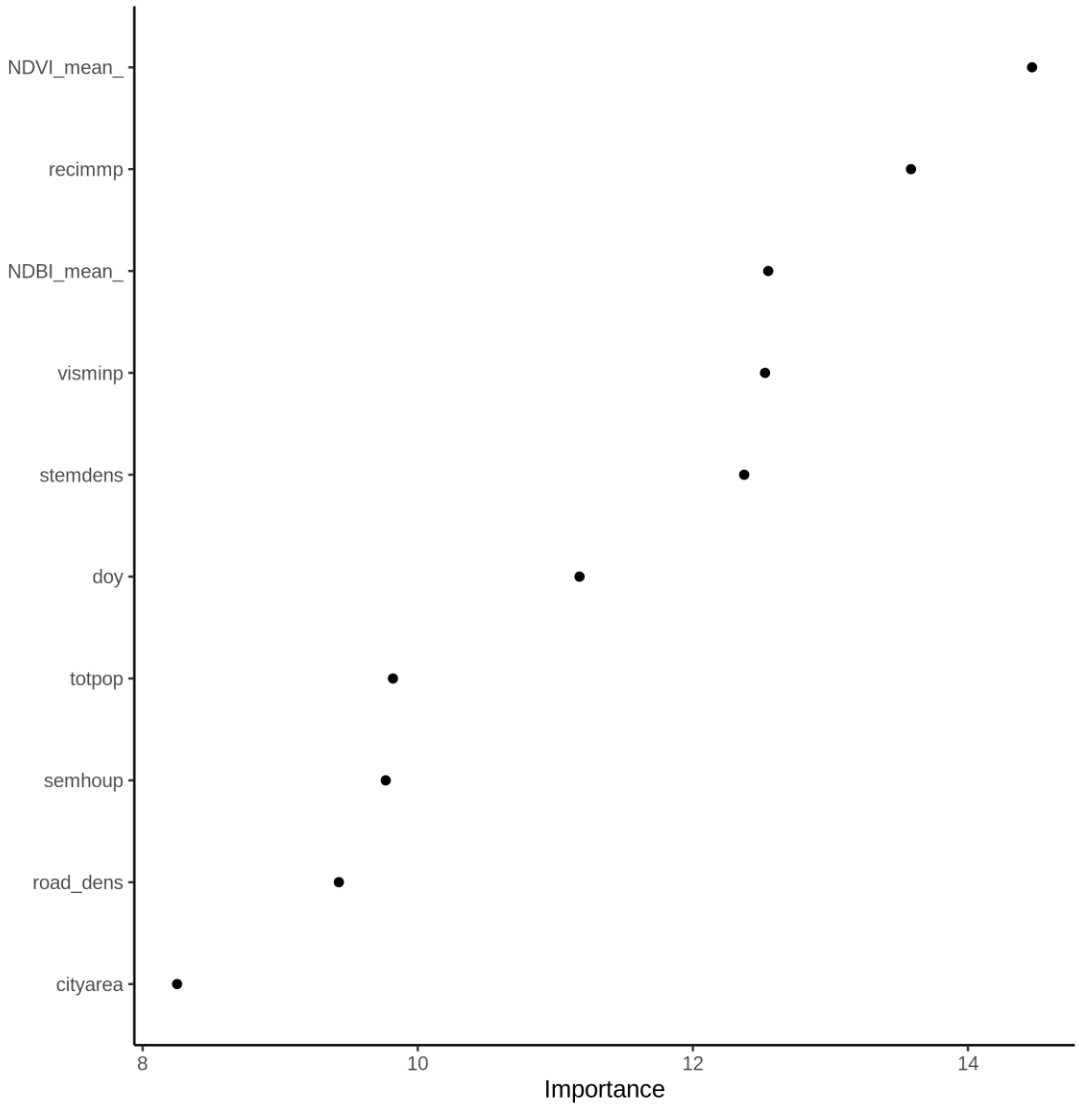


Figure A3.3a: Variable importance plot for temperature model at the city scale.

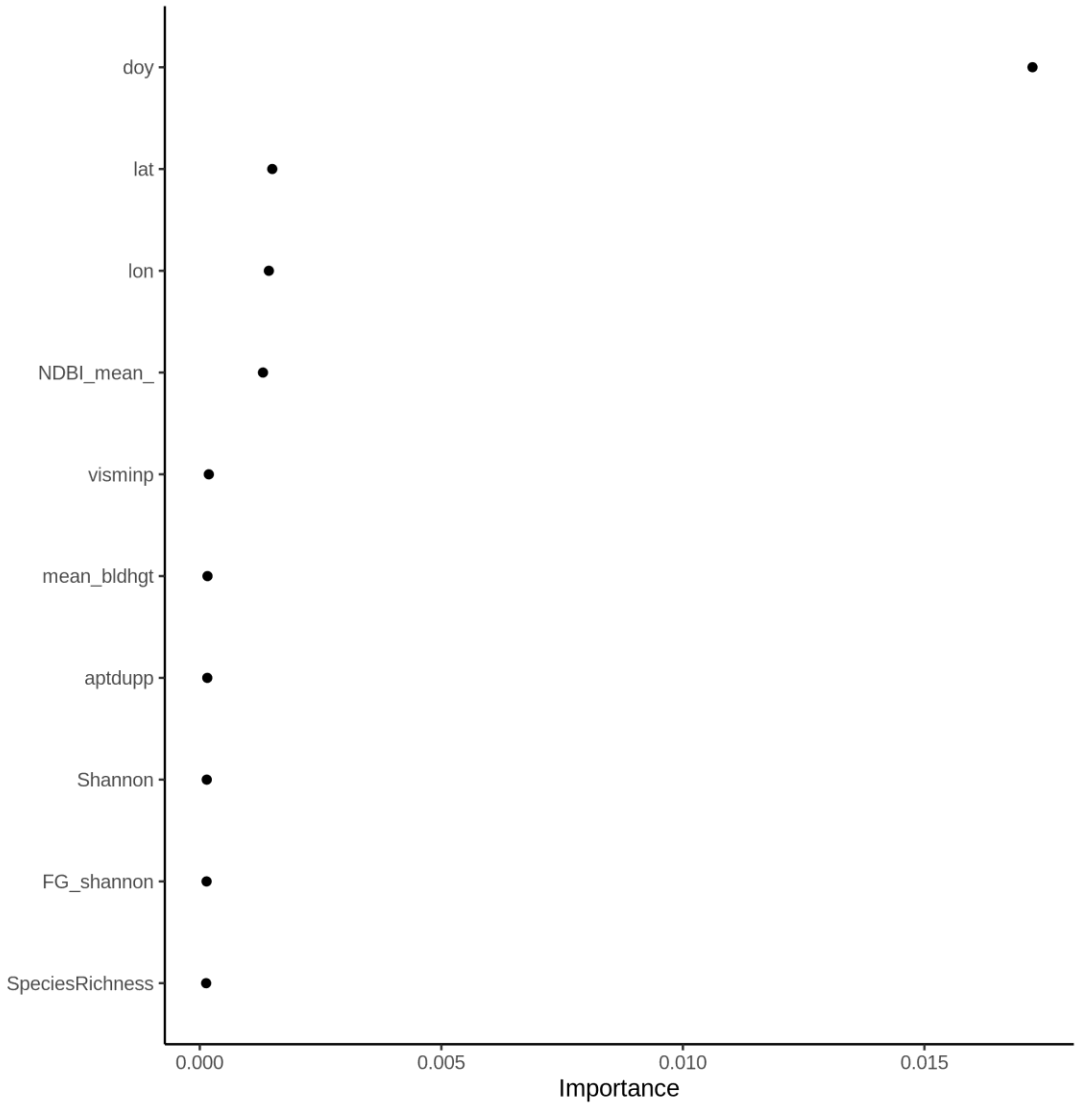


Figure A3.3b: Variable importance plot for carbon monoxide model at the city scale.

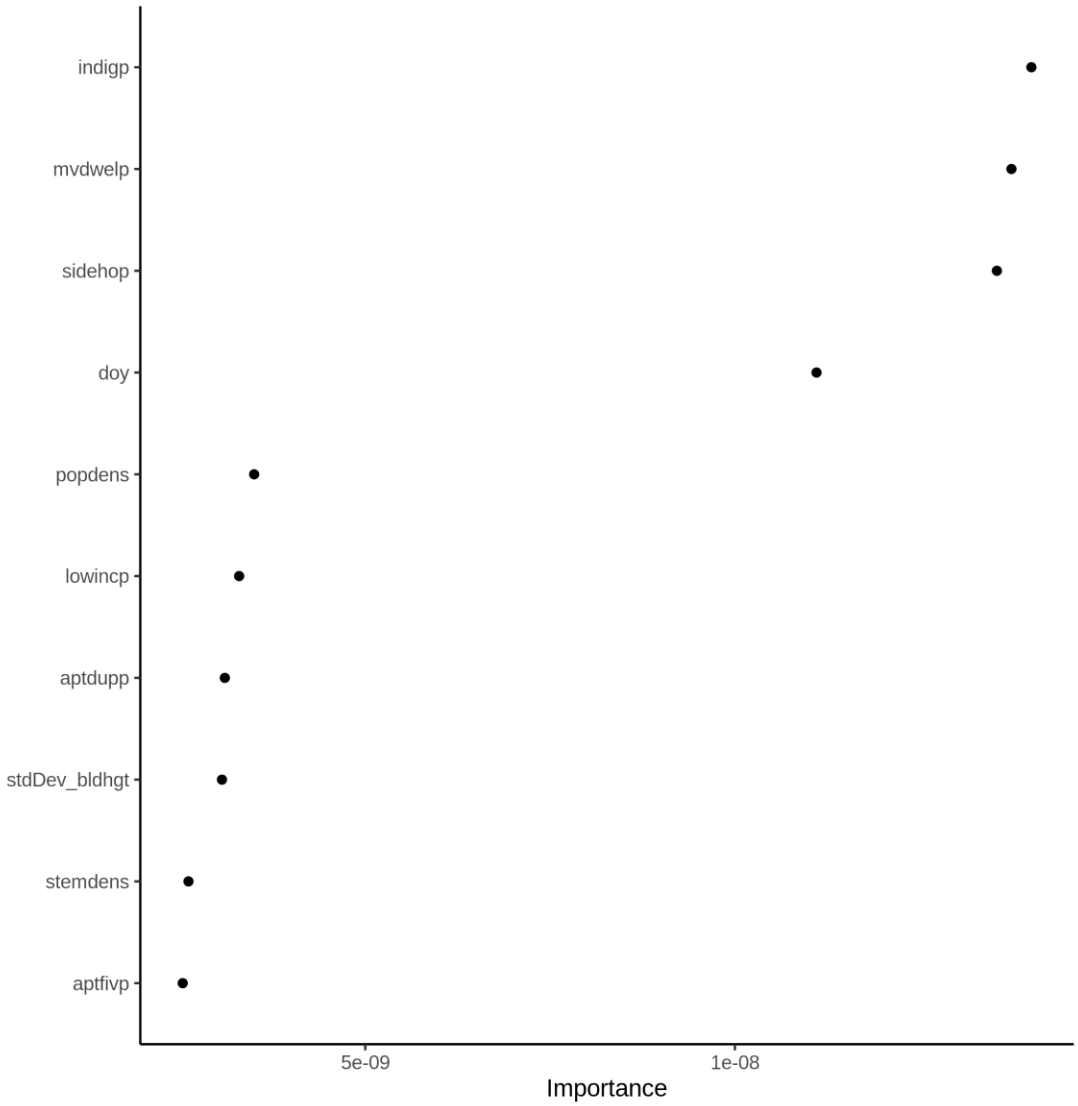


Figure A3.3c: Variable importance plot for nitrogen dioxide model at the city scale.

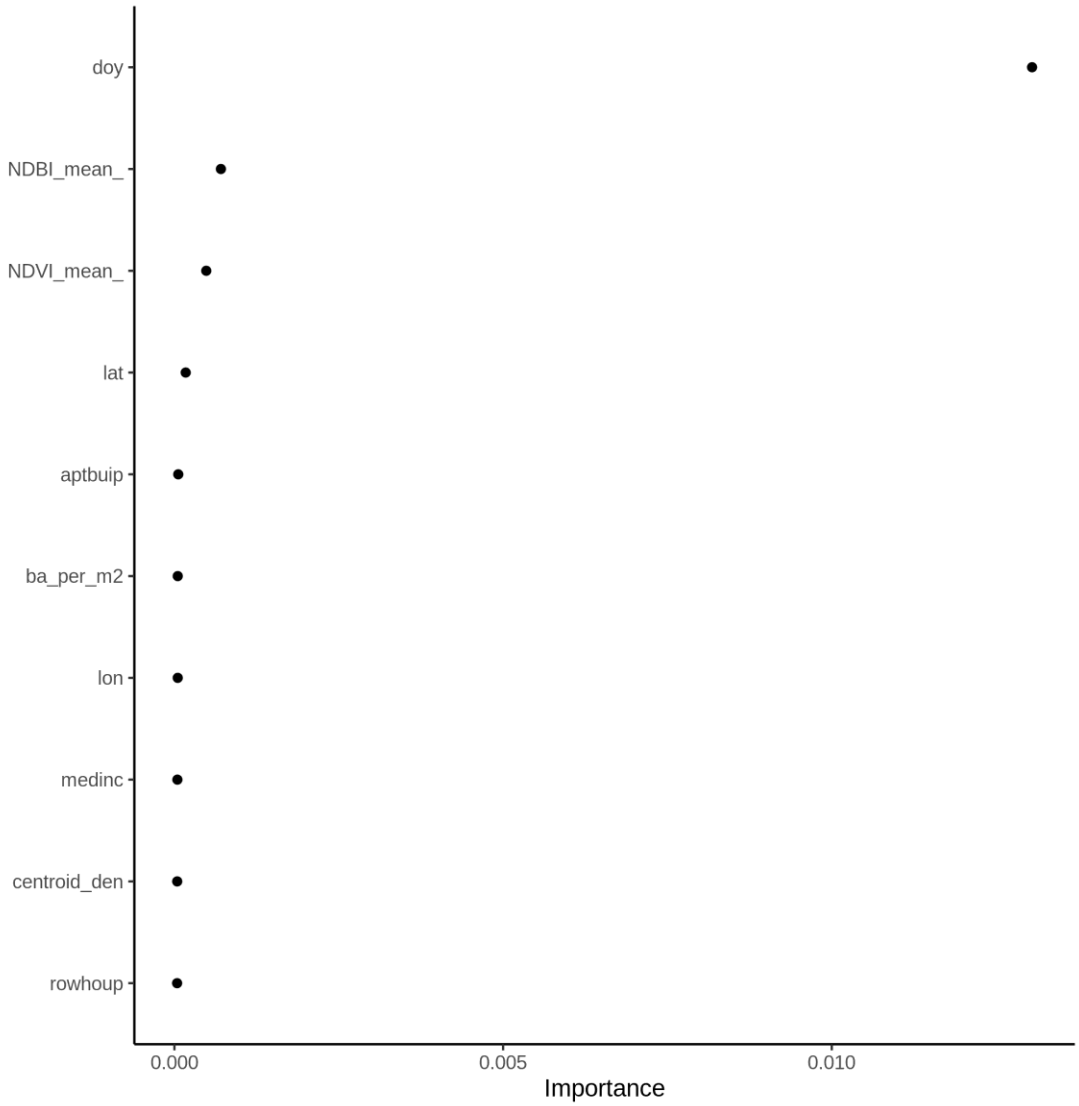


Figure A3.3d: Variable importance plot for ozone model at the city scale.

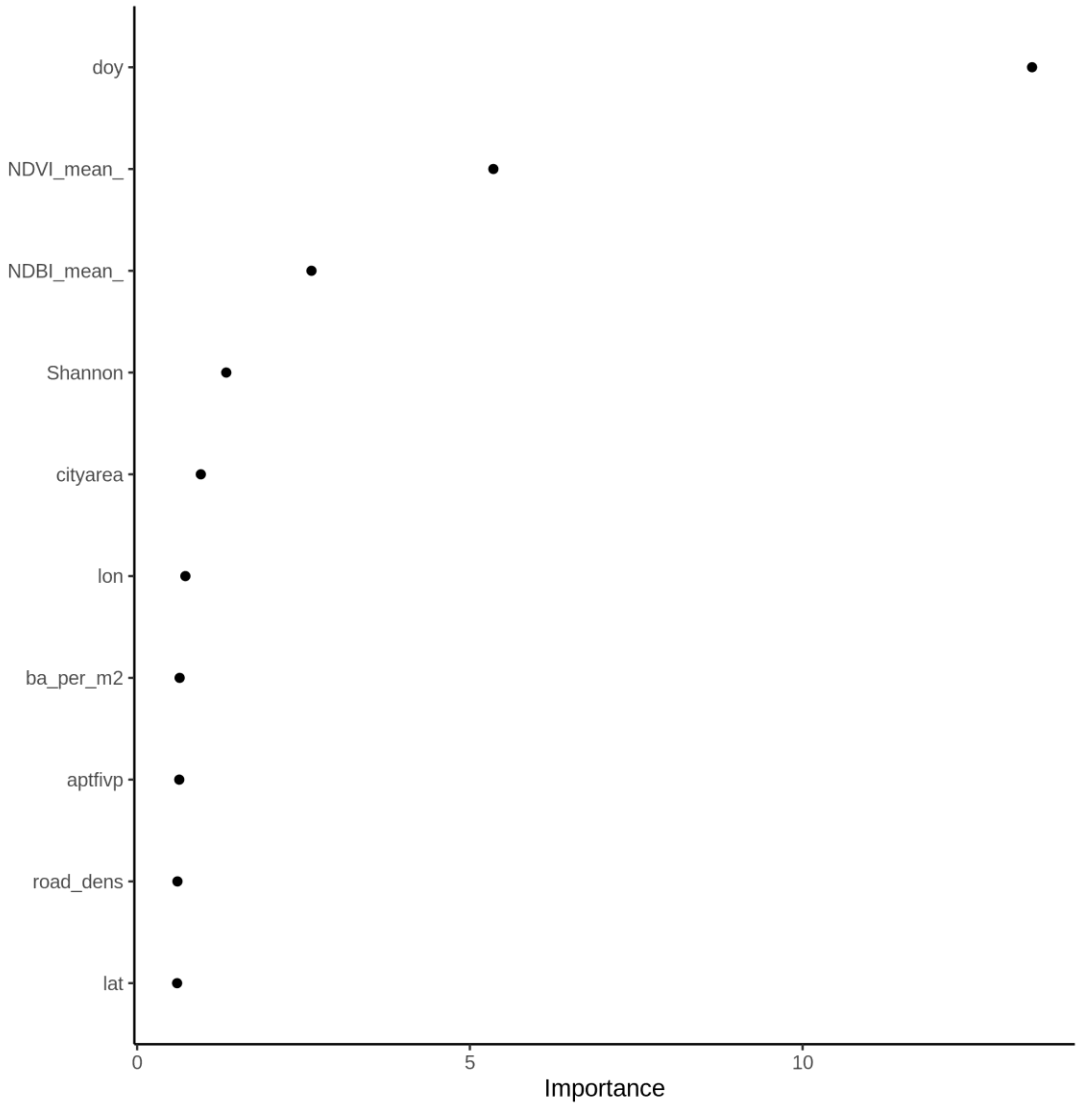


Figure A3.3: Variable importance plot for UV aerosols model at the city scale.

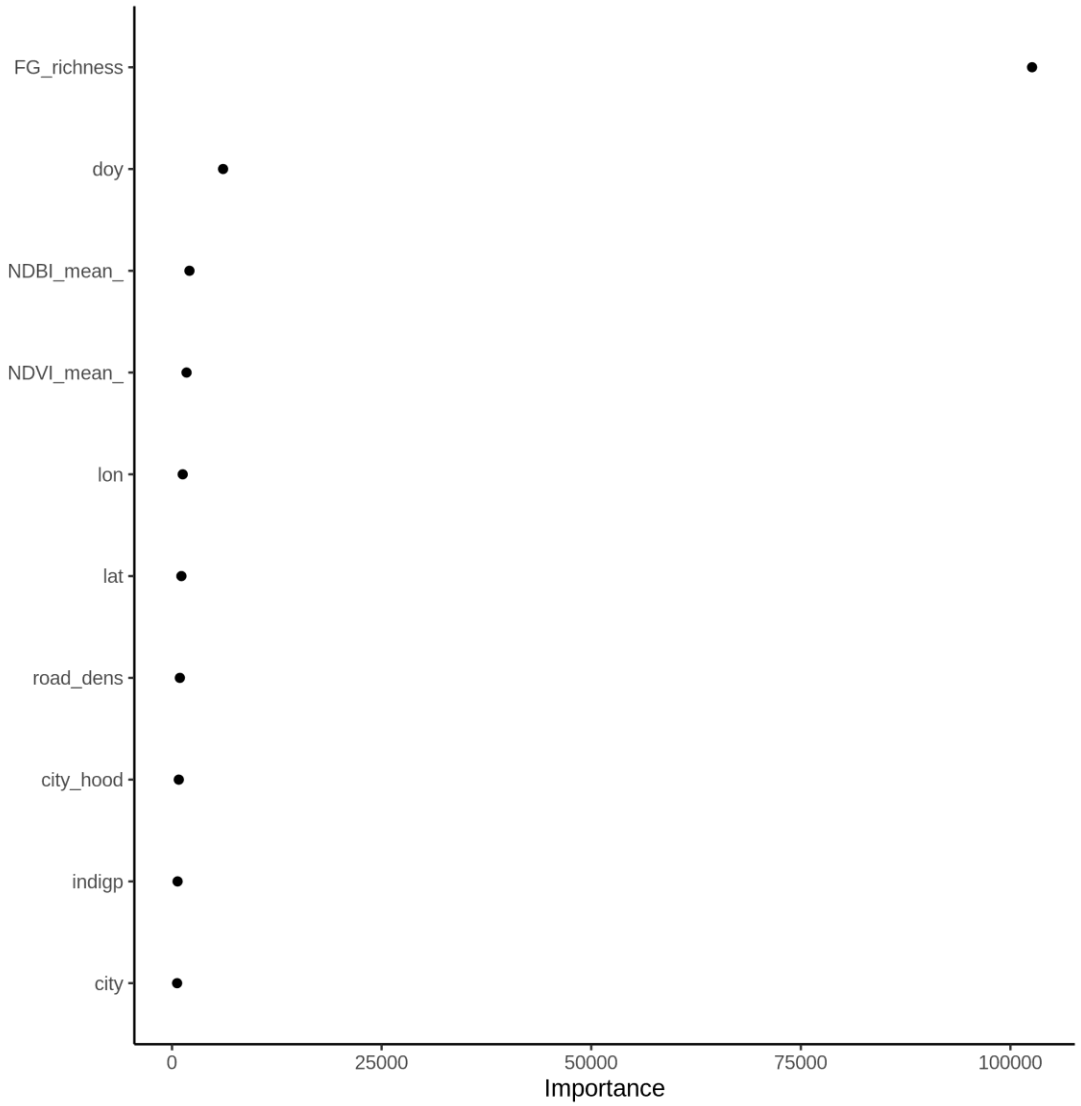


Figure A3.3f: Variable importance plot for temperature model at the neighbourhood scale.

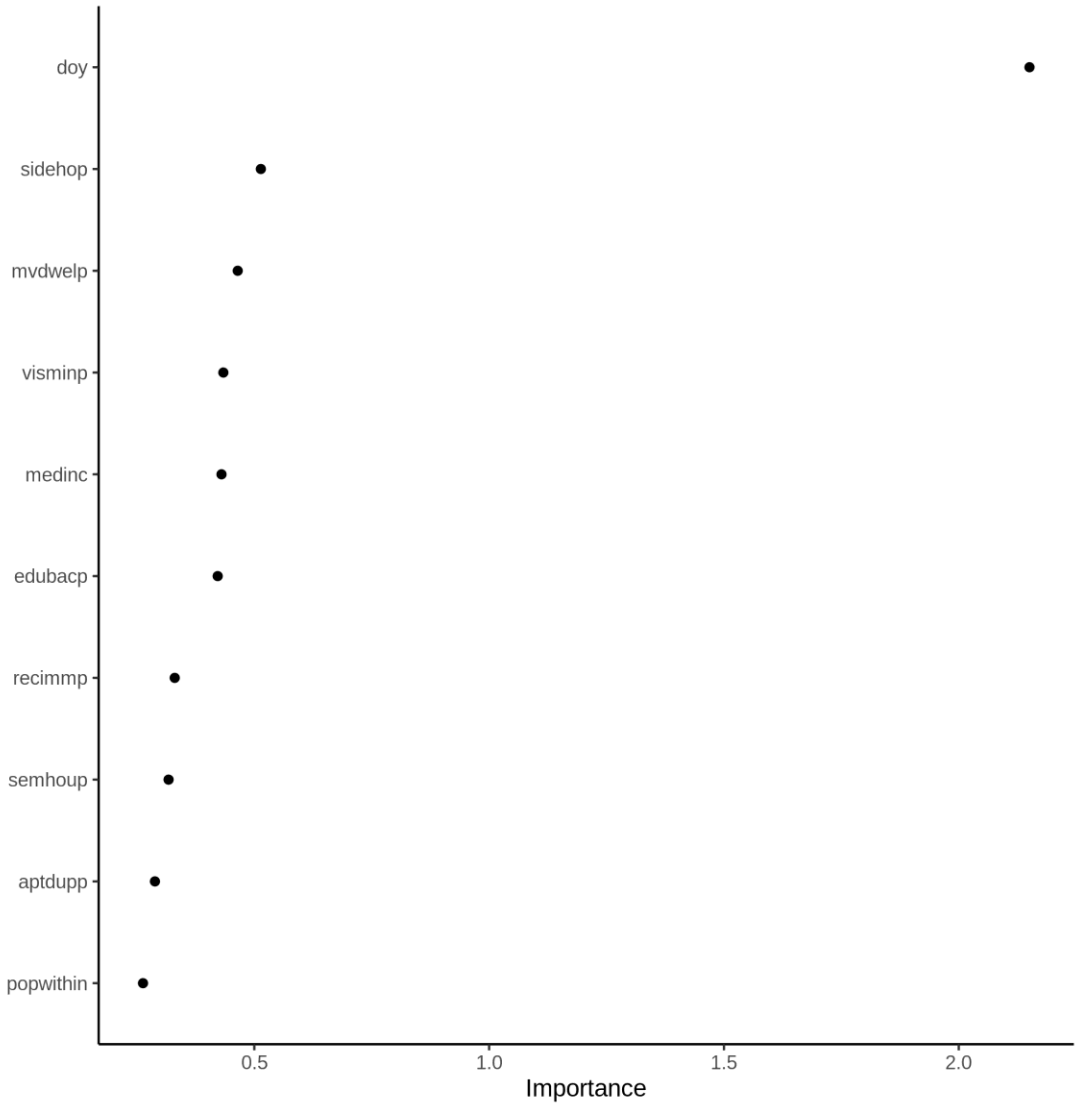


Figure A3.3g: Variable importance plot for carbon monoxide model at the neighbourhood scale.

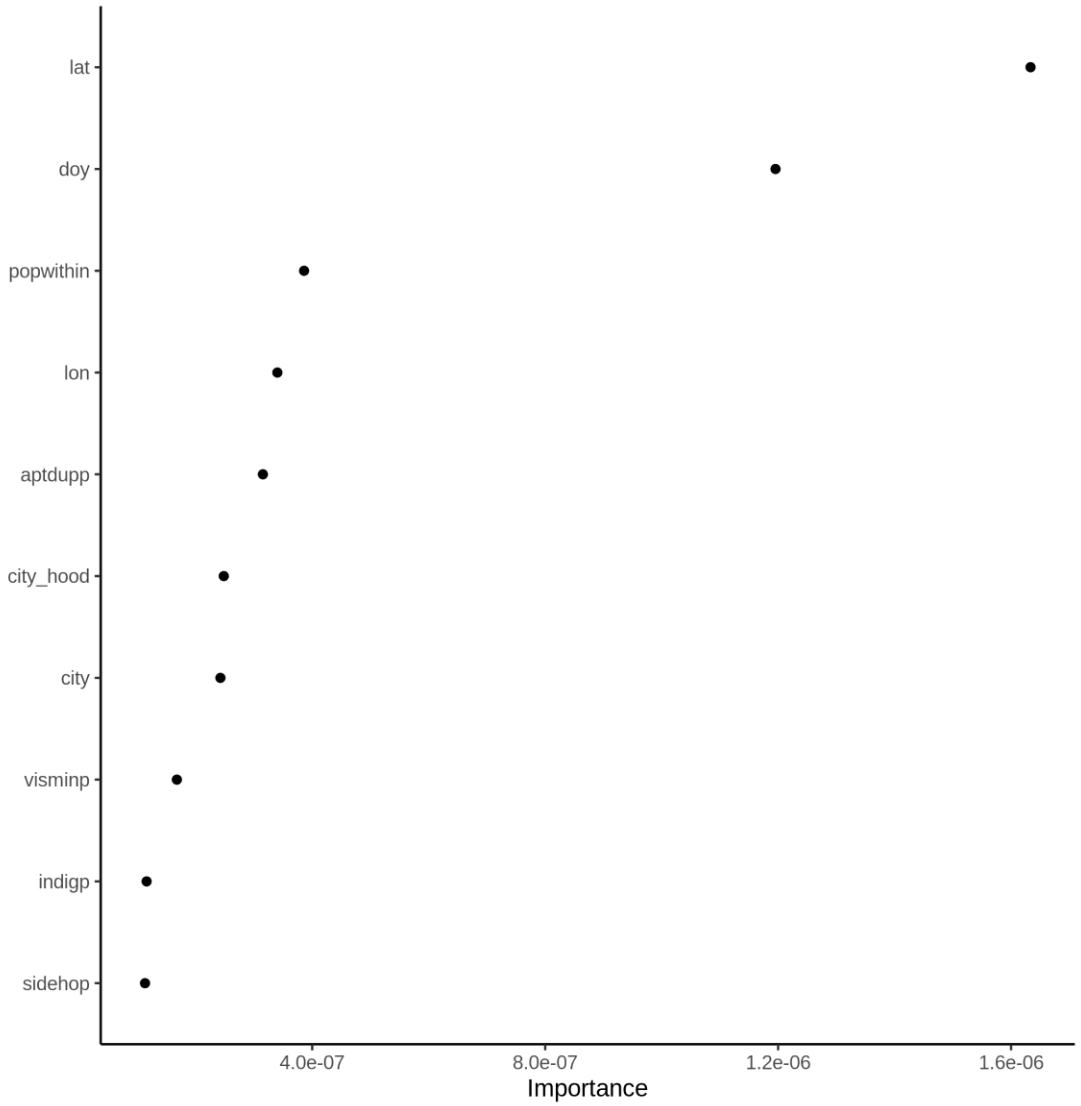


Figure A3.3h: Variable importance plot for nitrogen dioxide model at the neighbourhood scale.

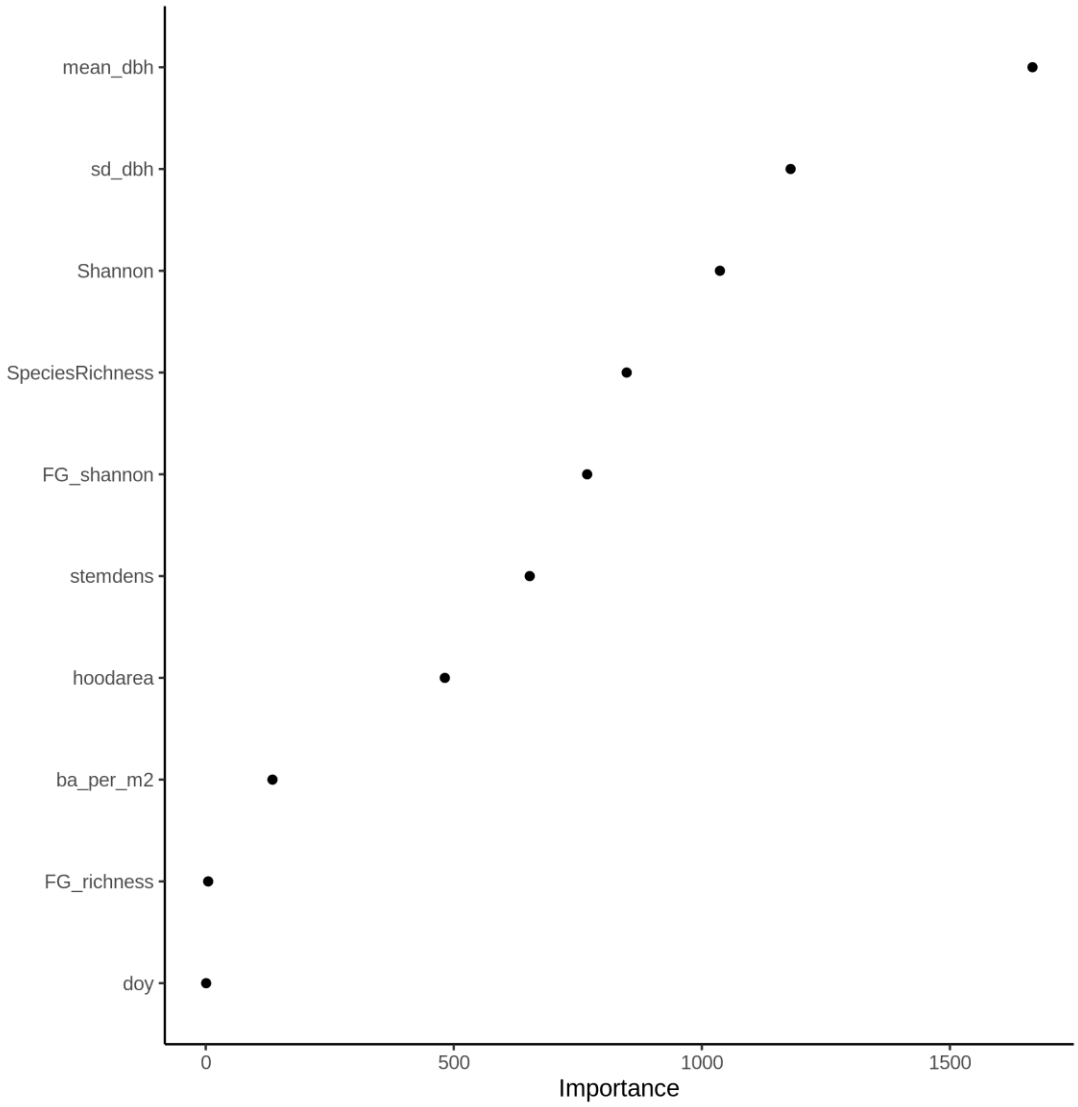


Figure A3.3i: Variable importance plot for ozone model at the neighbourhood scale.

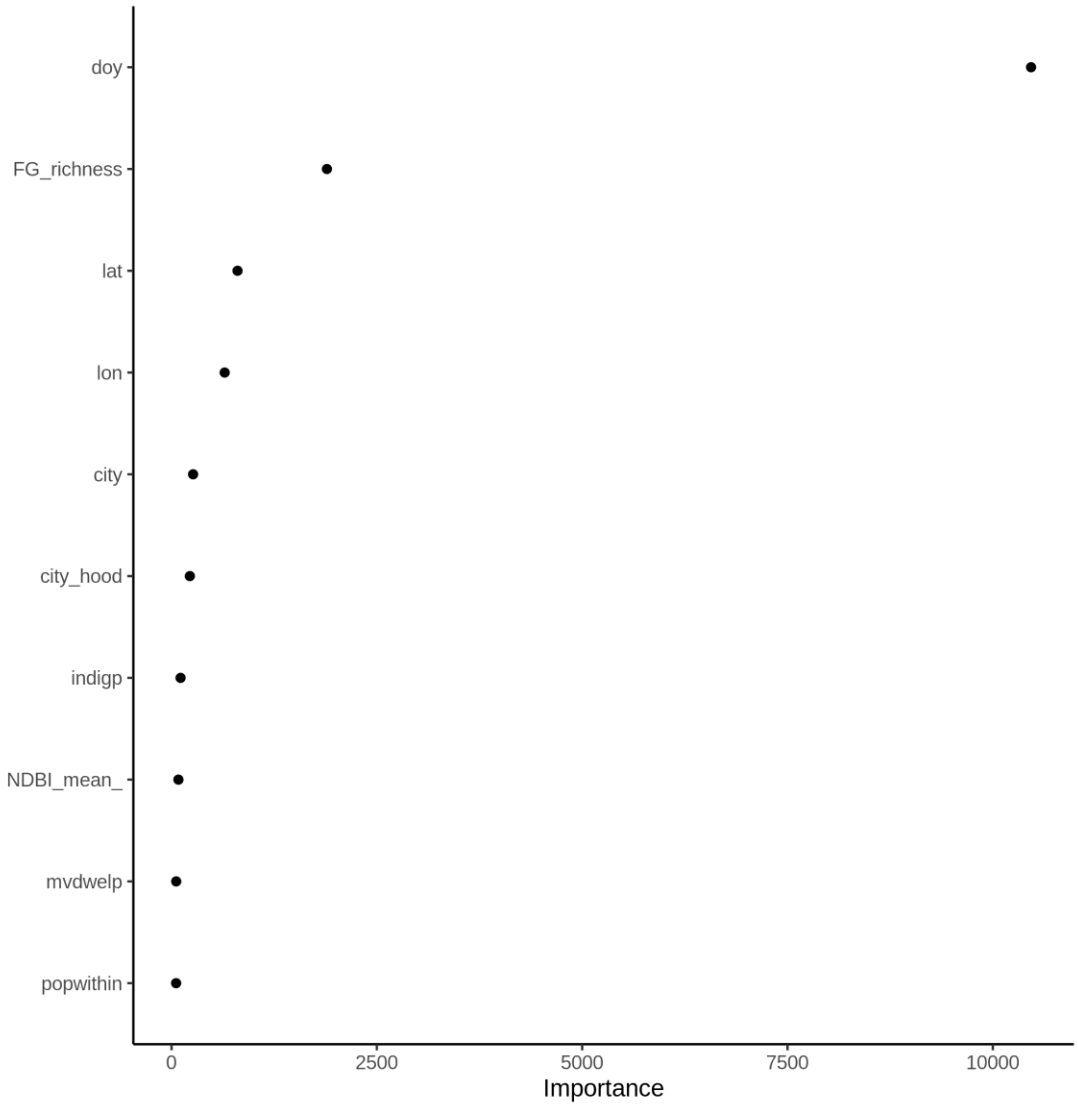


Figure A3.3j: Variable importance plot for UV aerosols model at the neighbourhood scale.

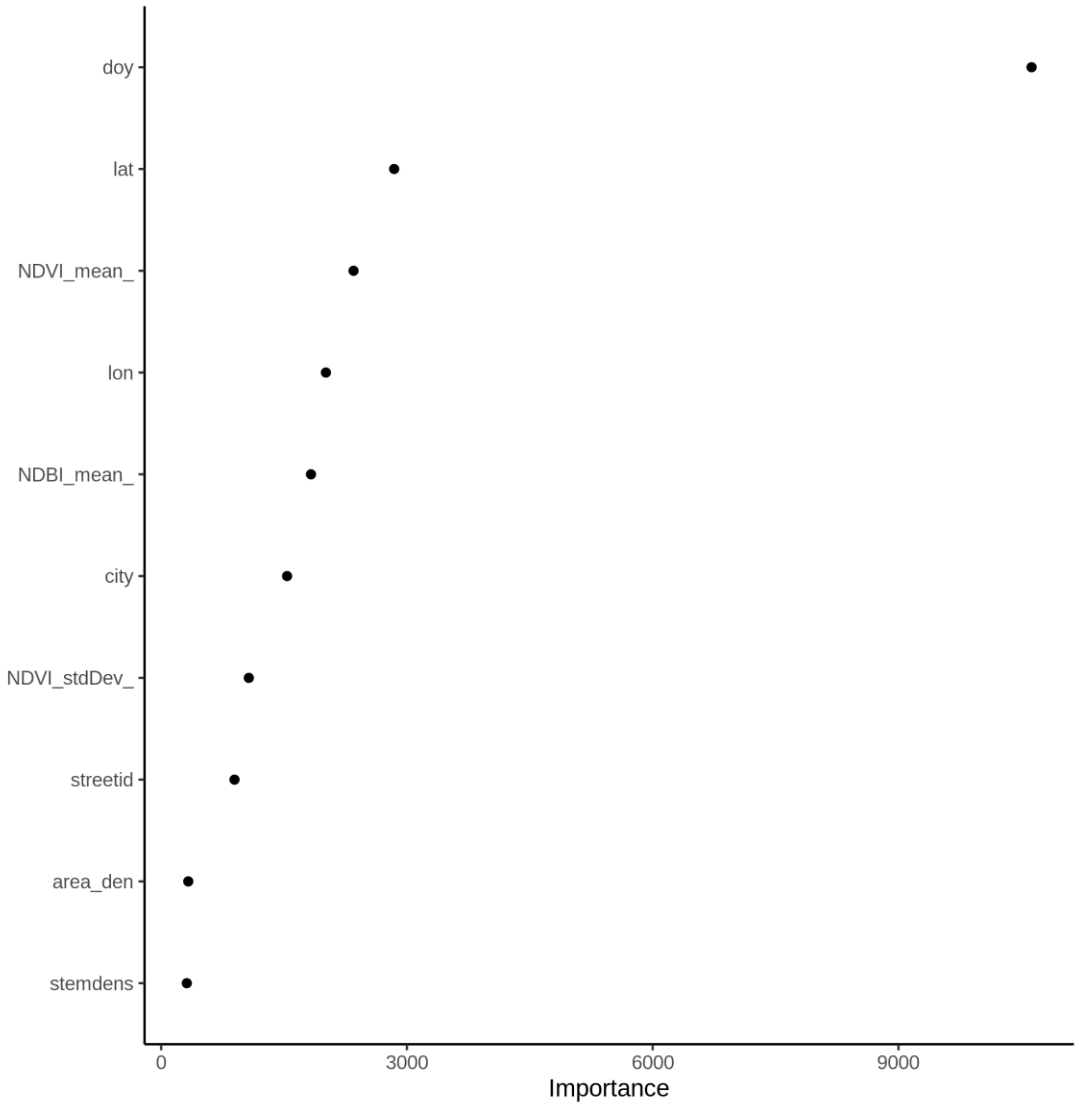


Figure A3.3k: Variable importance plot for temperature model at the street scale.

Figure A3.4: Model performance plots.

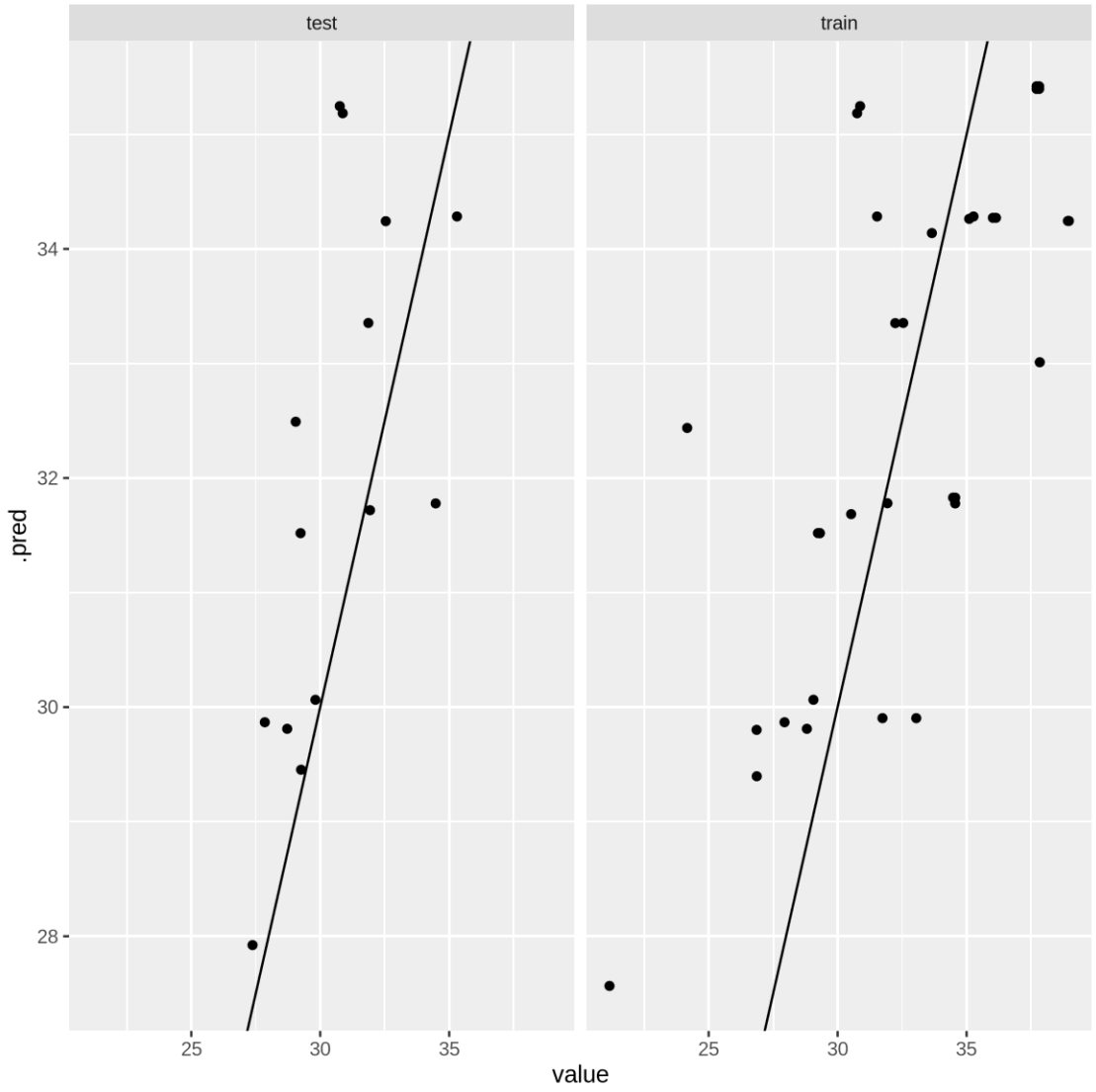


Figure A3.4a: Model performance plot for temperature model at the city scale.

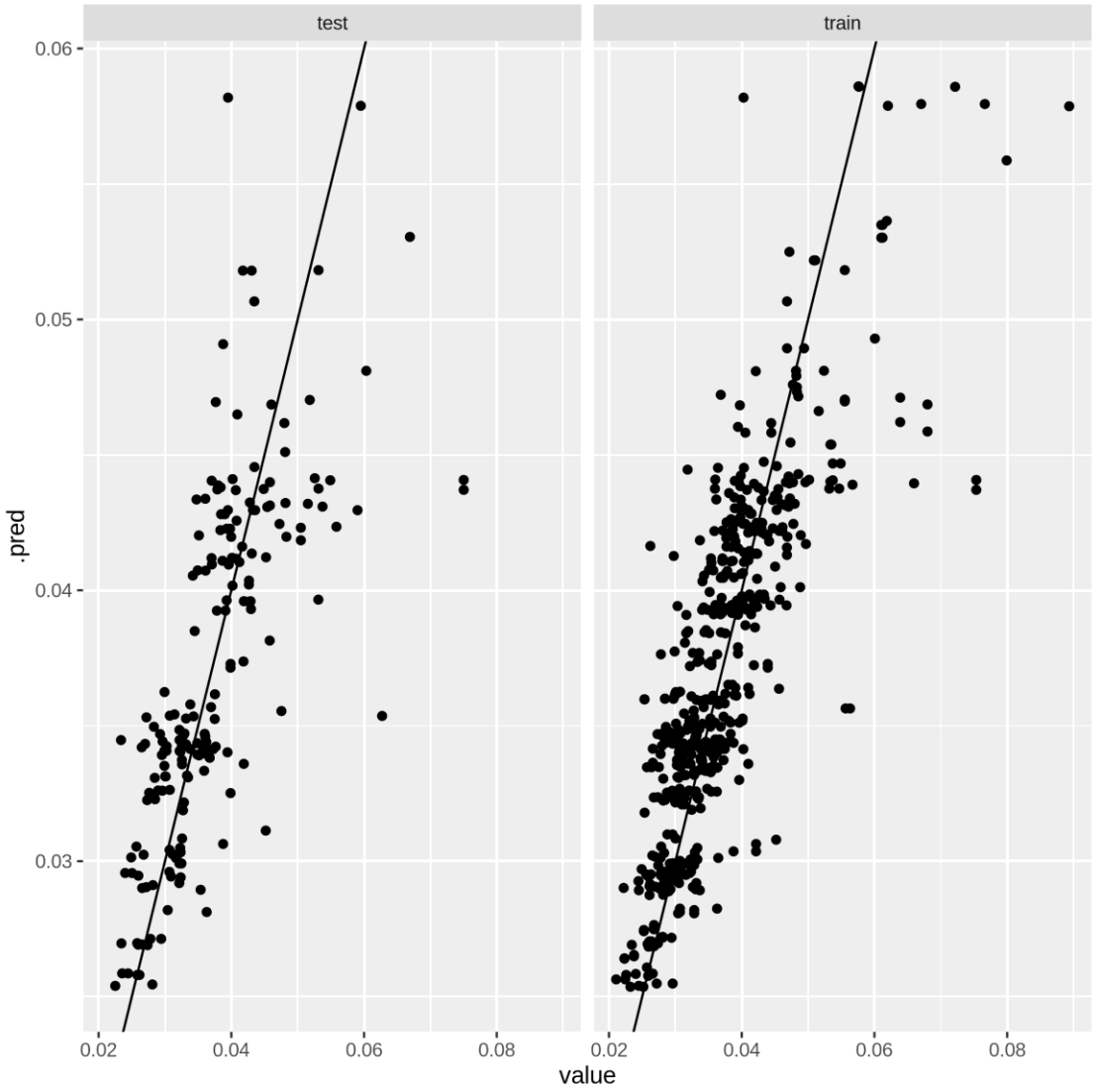


Figure A3.4b: Model performance plot for carbon monoxide model at the city scale.

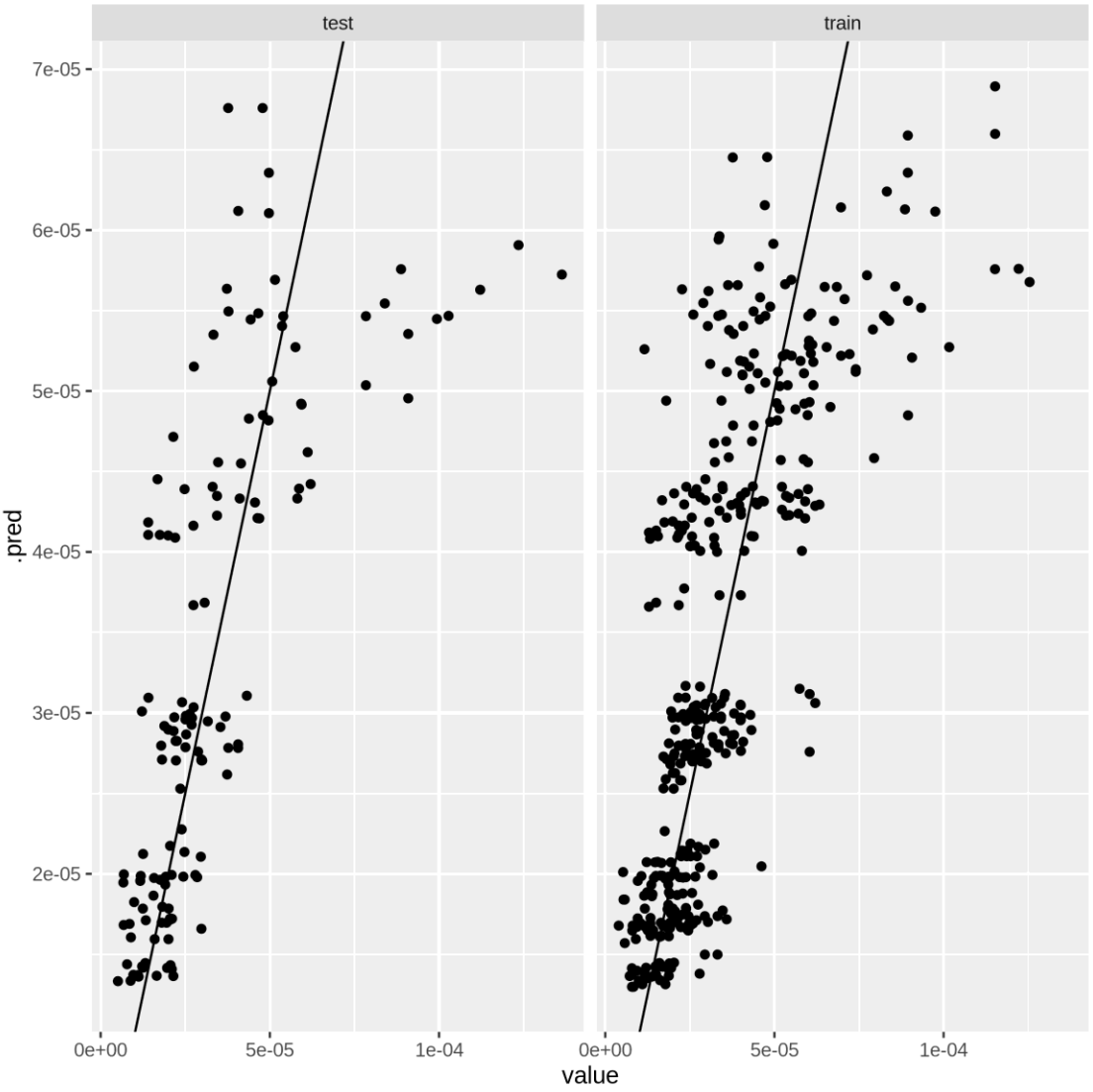


Figure A3.4c: Model performance plot for nitrogen dioxide model at the city scale.

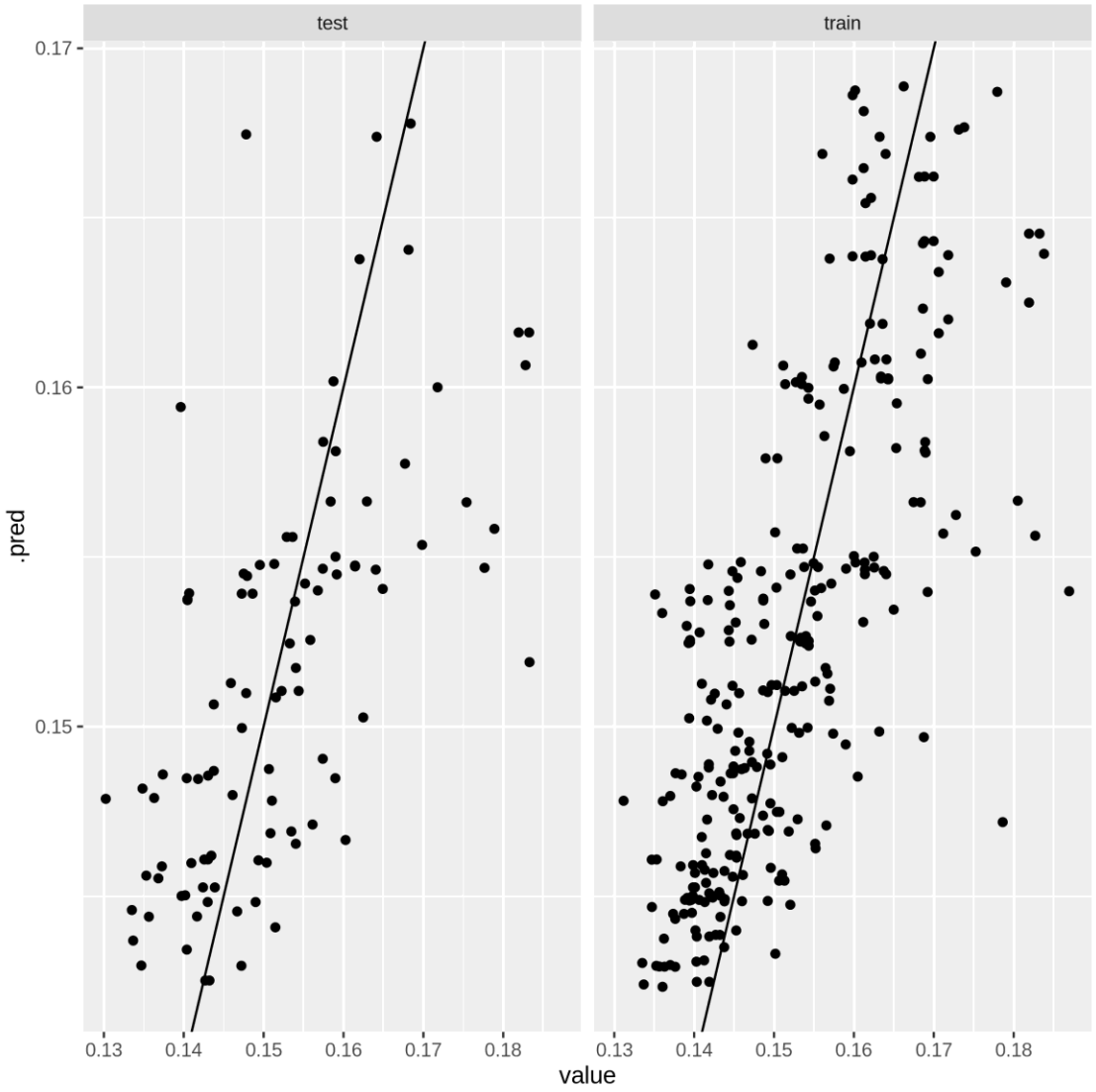


Figure A3.4d: Model performance plot for ozone model at the city scale.

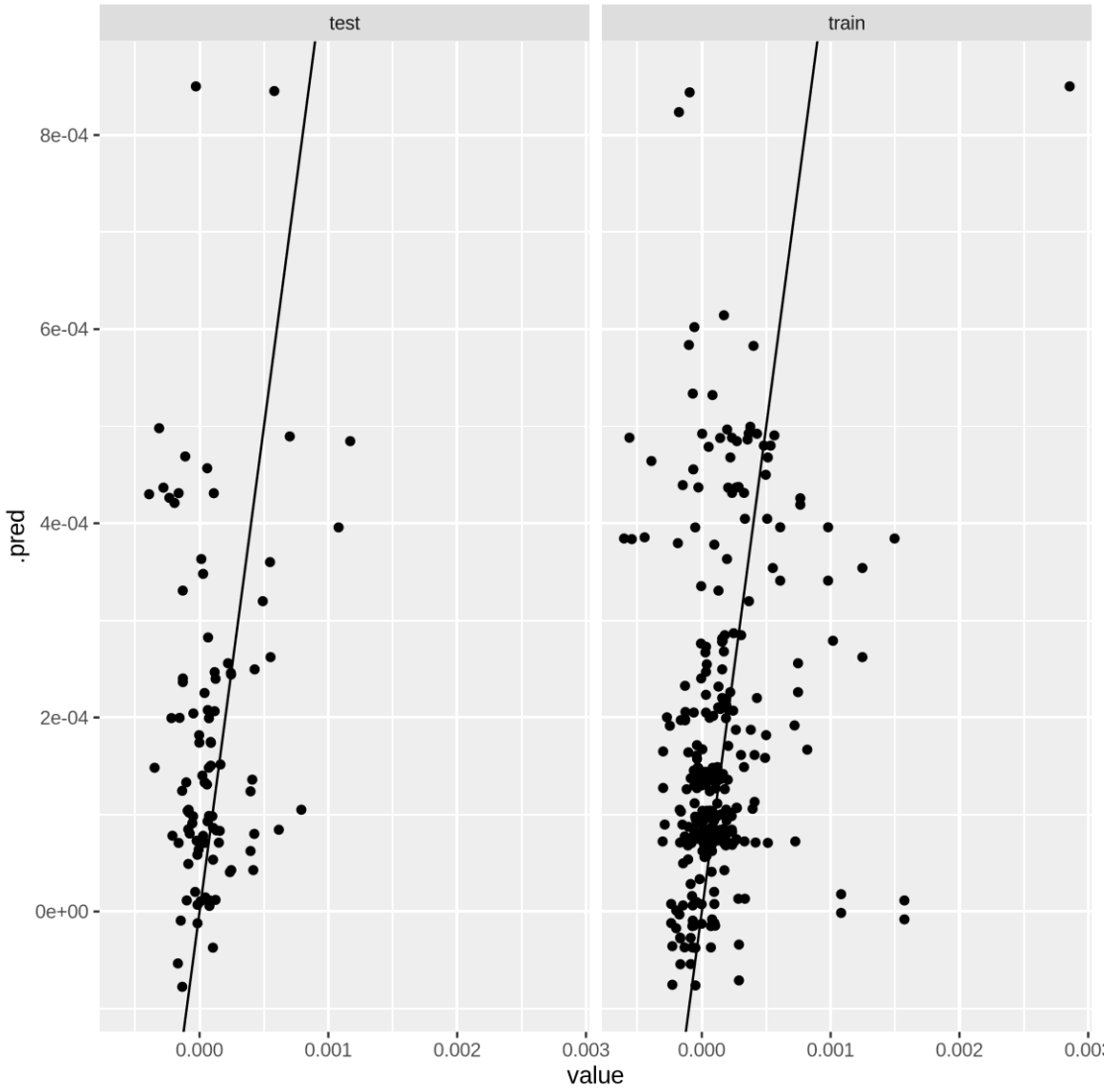


Figure A3.4e: Model performance plot for sulfur dioxide model at the city scale.

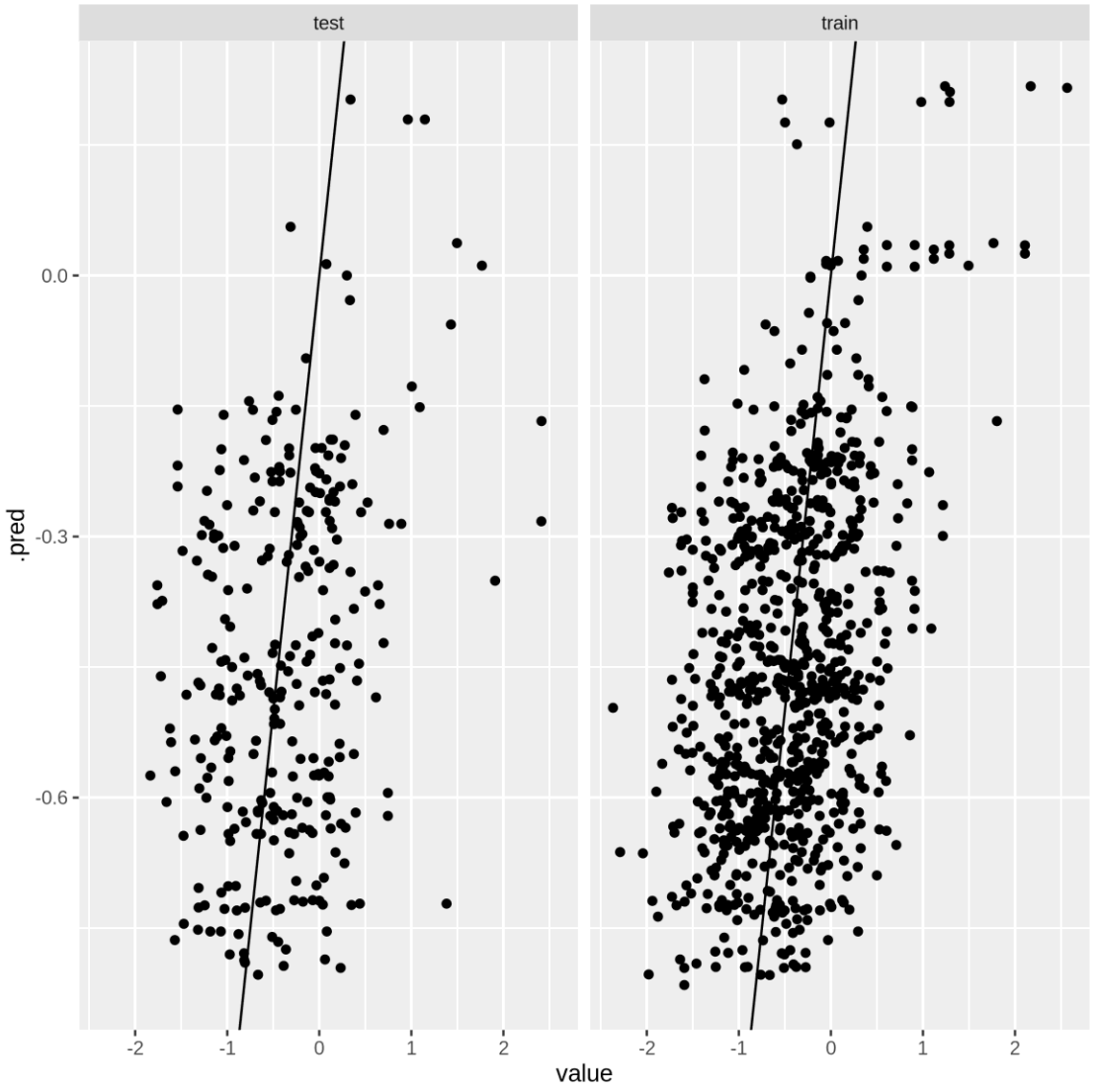


Figure A3.4f: Model performance plot for UV aerosols model at the city scale.

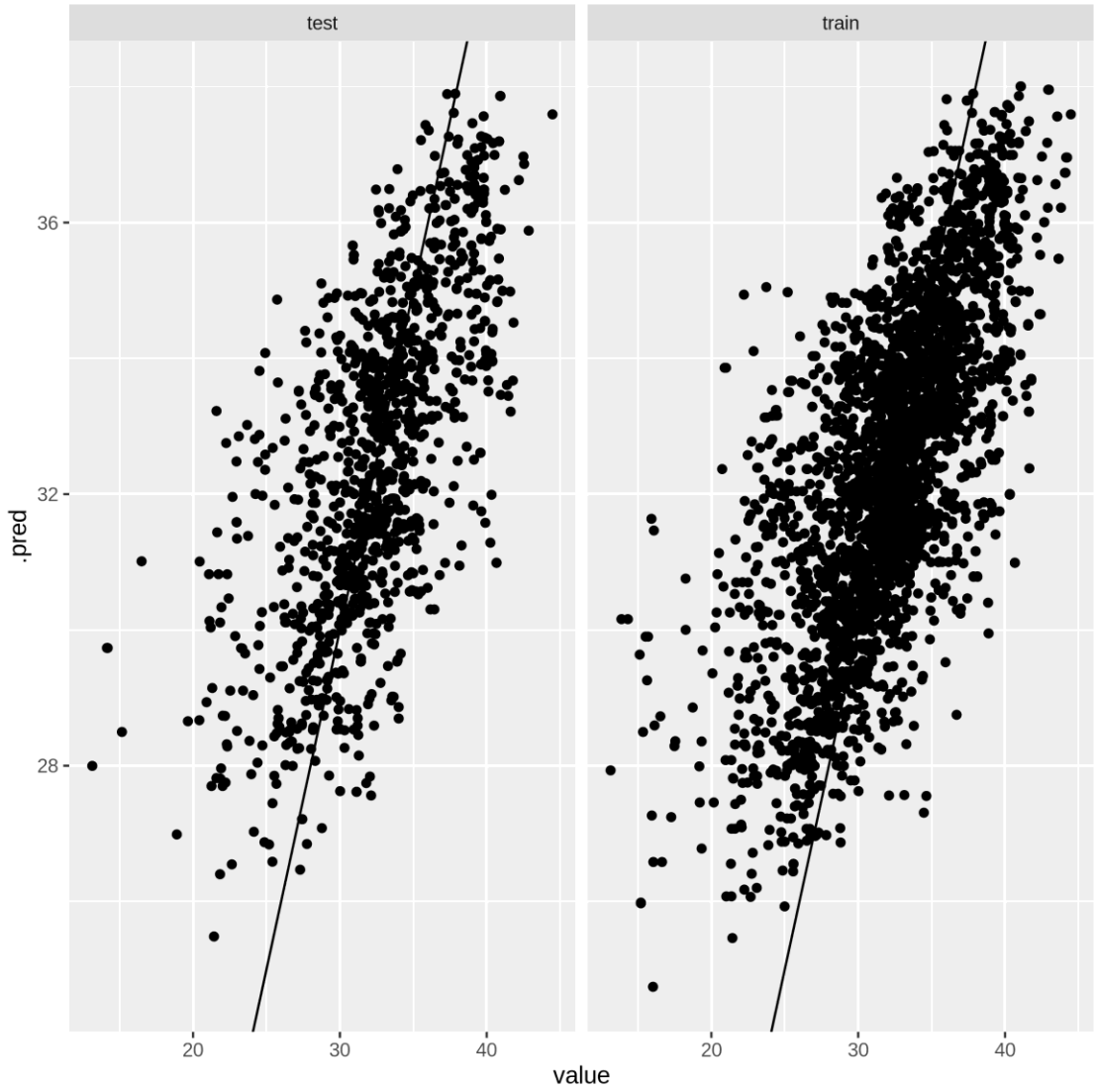


Figure A3.4g: Model performance plot for temperature model at the neighbourhood scale.

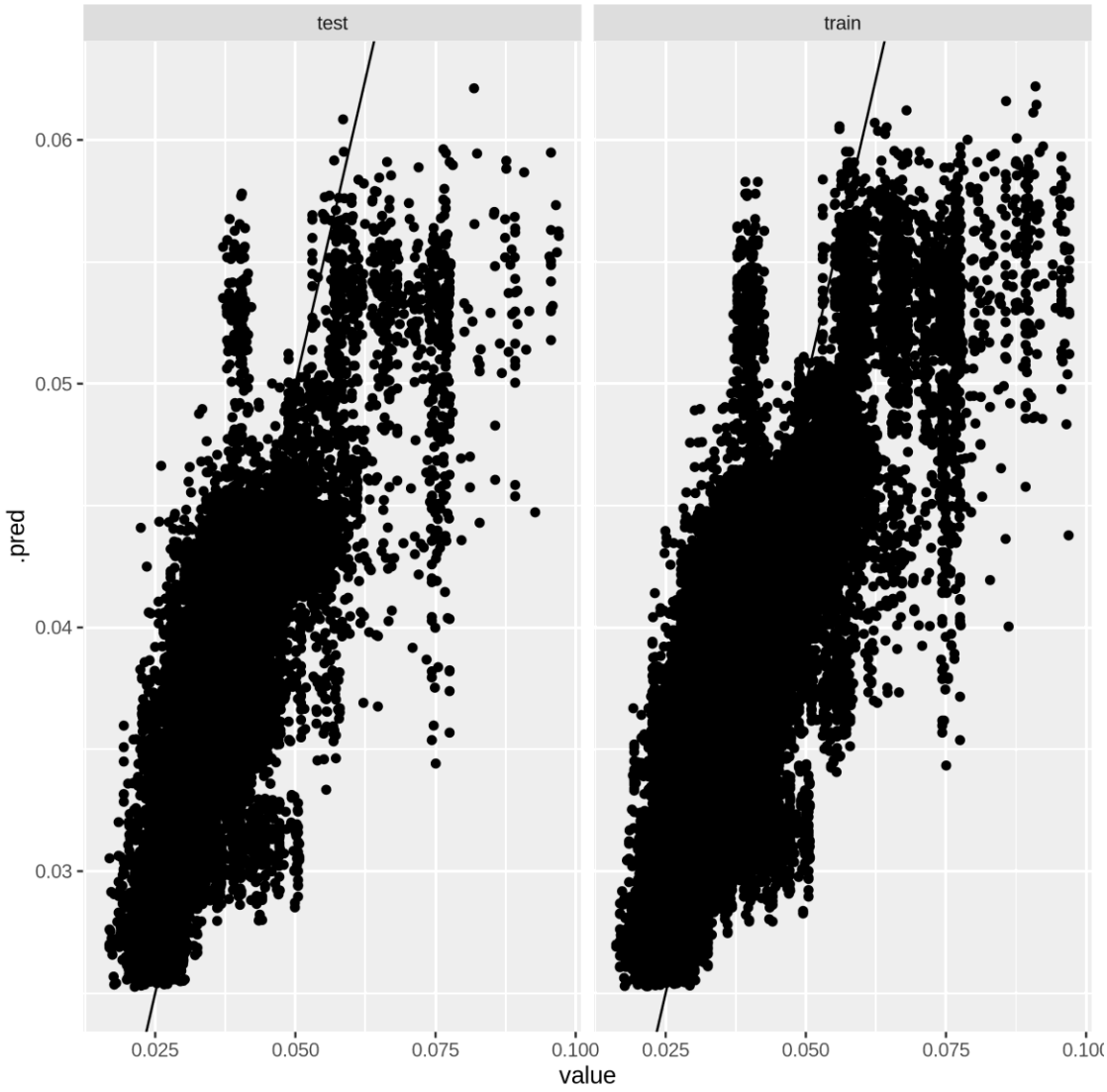


Figure A3.4h: Model performance plot for carbon monoxide model at the neighbourhood scale.

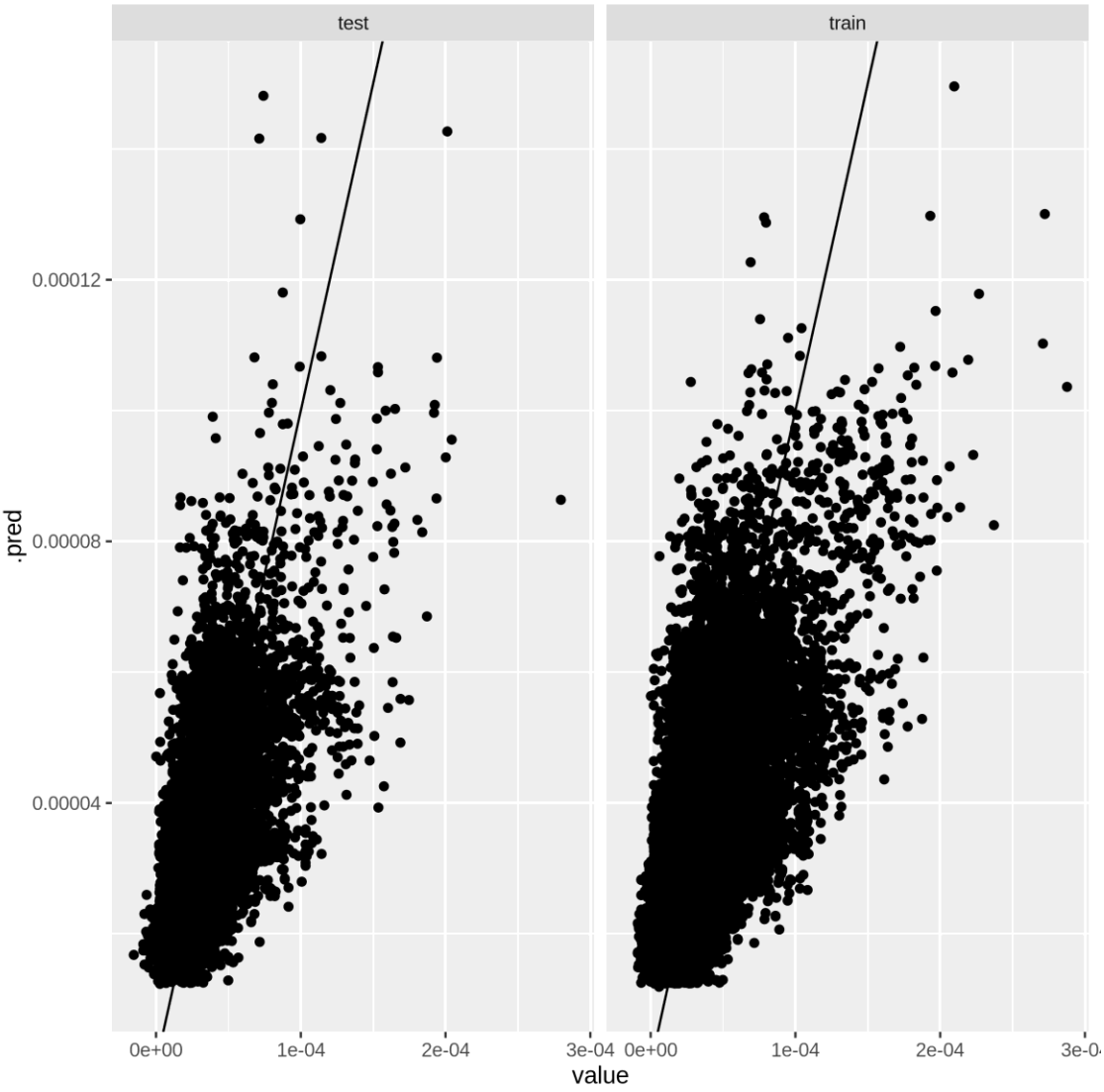


Figure A3.4i: Model performance plot for nitrogen dioxide model at the neighbourhood scale.

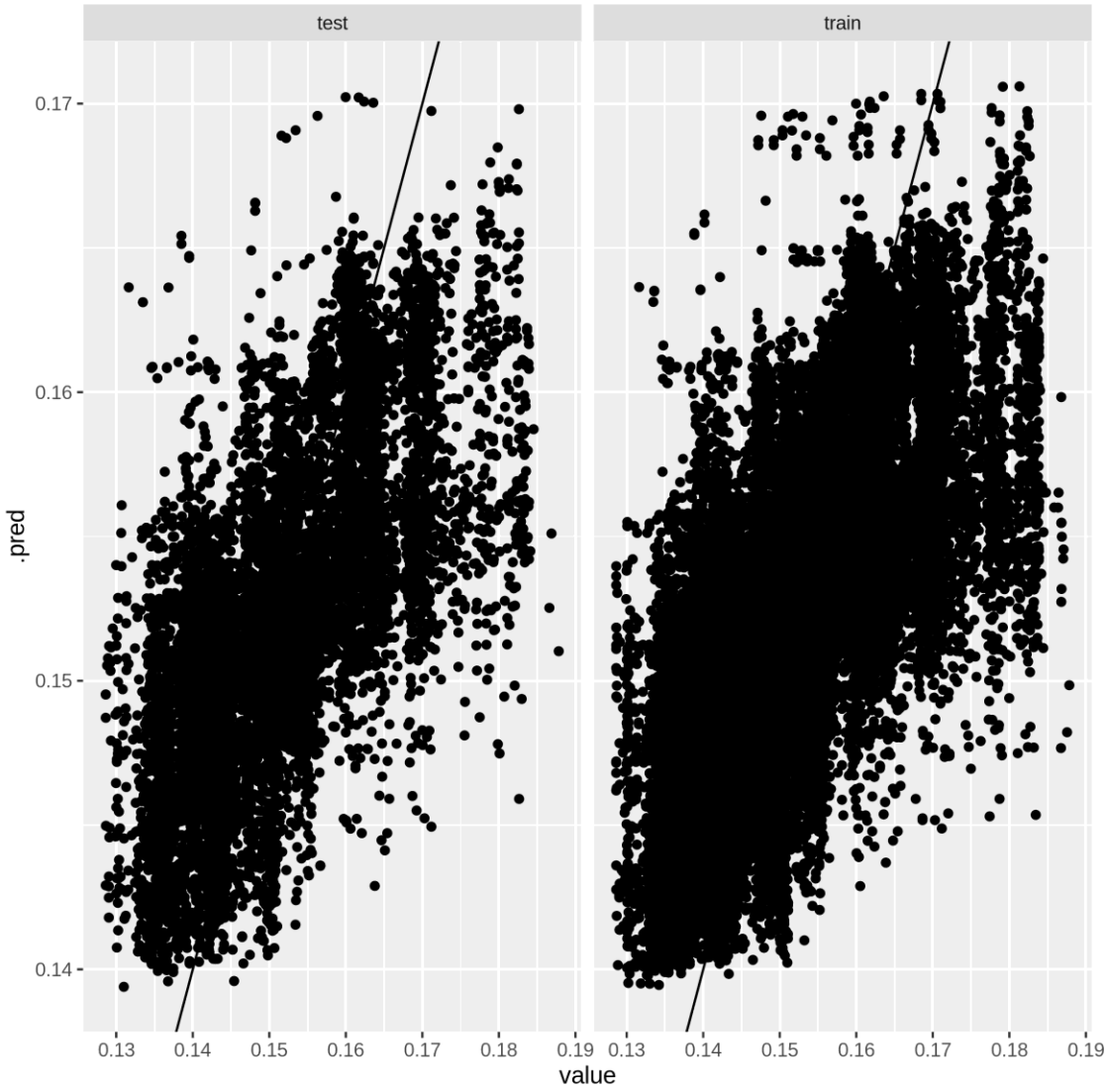


Figure A3.4j: Model performance plot for ozone model at the neighbourhood scale.

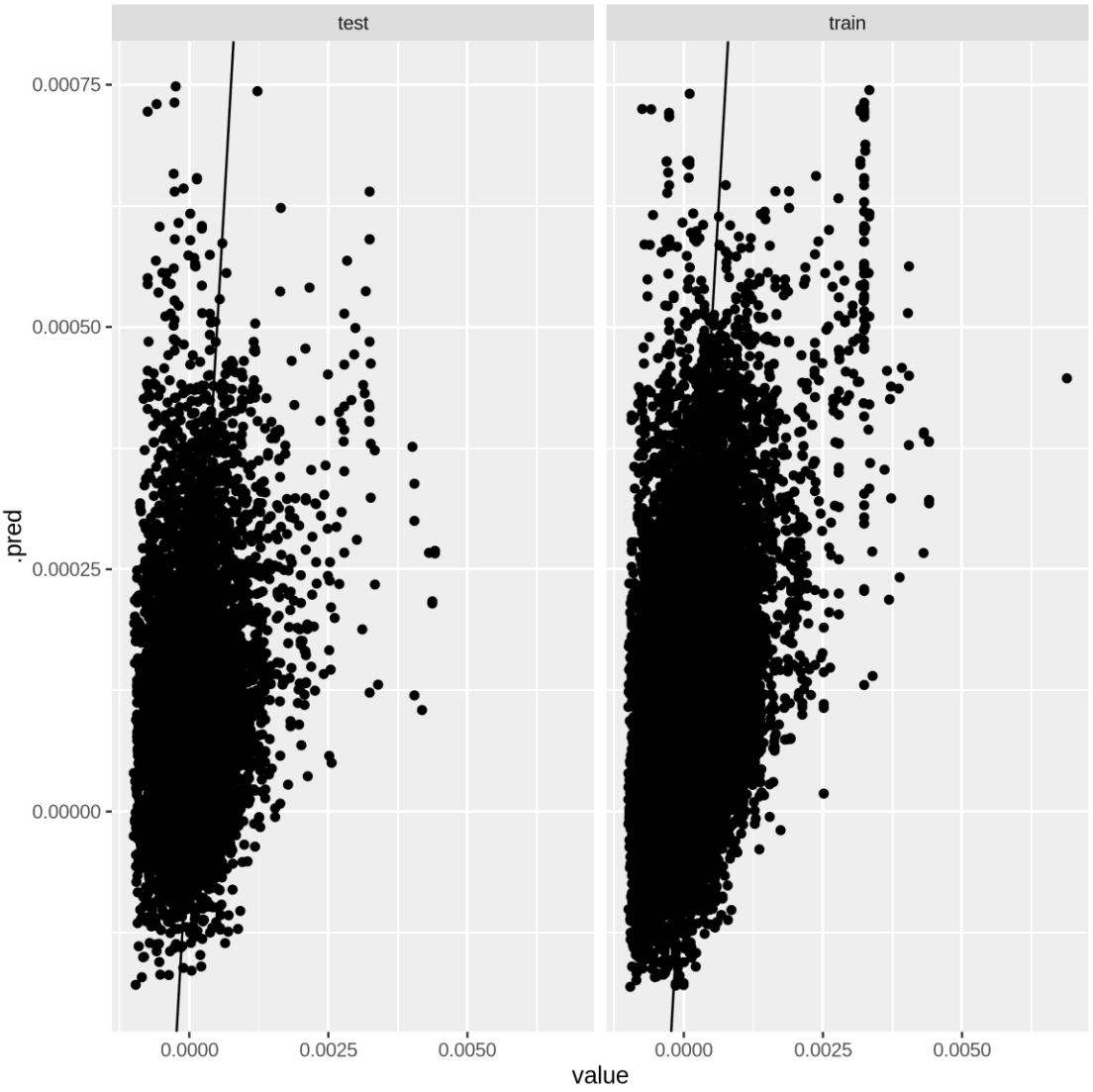


Figure A3.4k: Model performance plot for sulfur dioxide model at the neighbourhood scale.

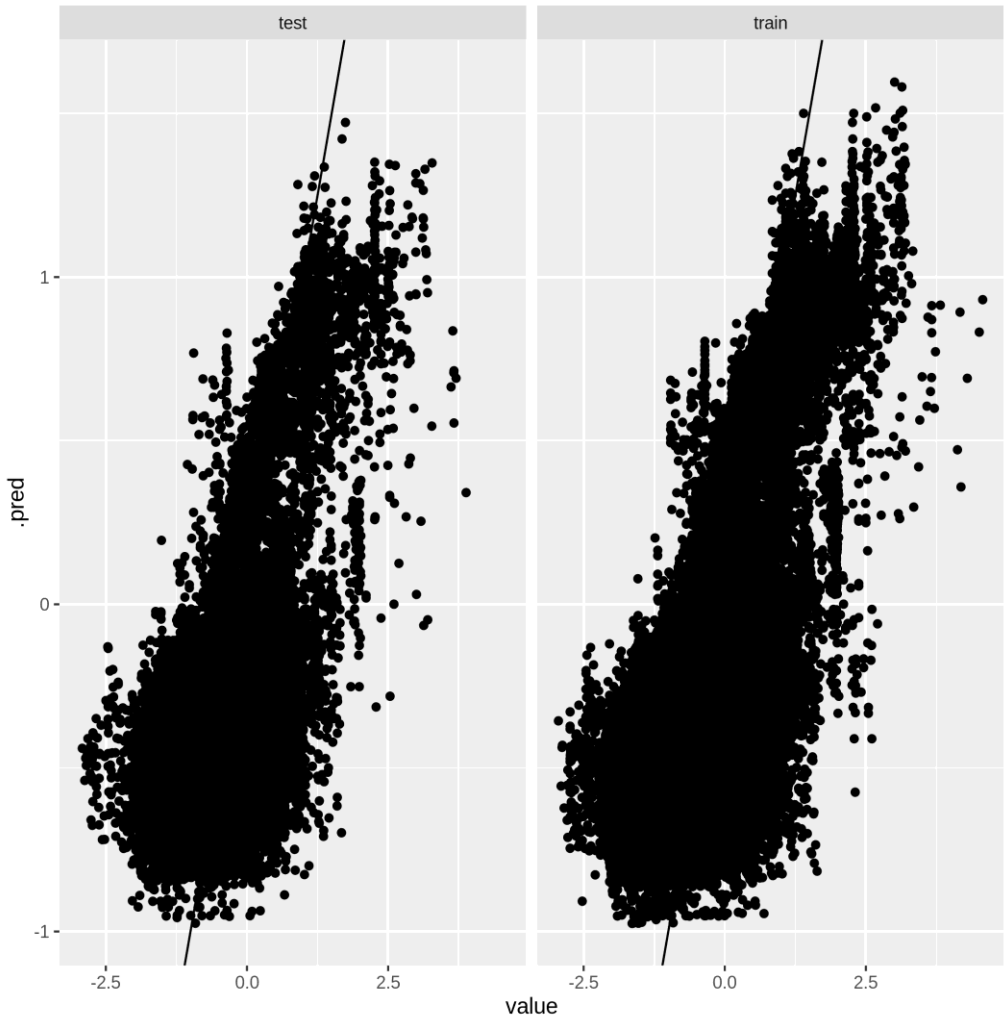


Figure A3.4l: Model performance plot for UV aerosols model at the neighbourhood scale.

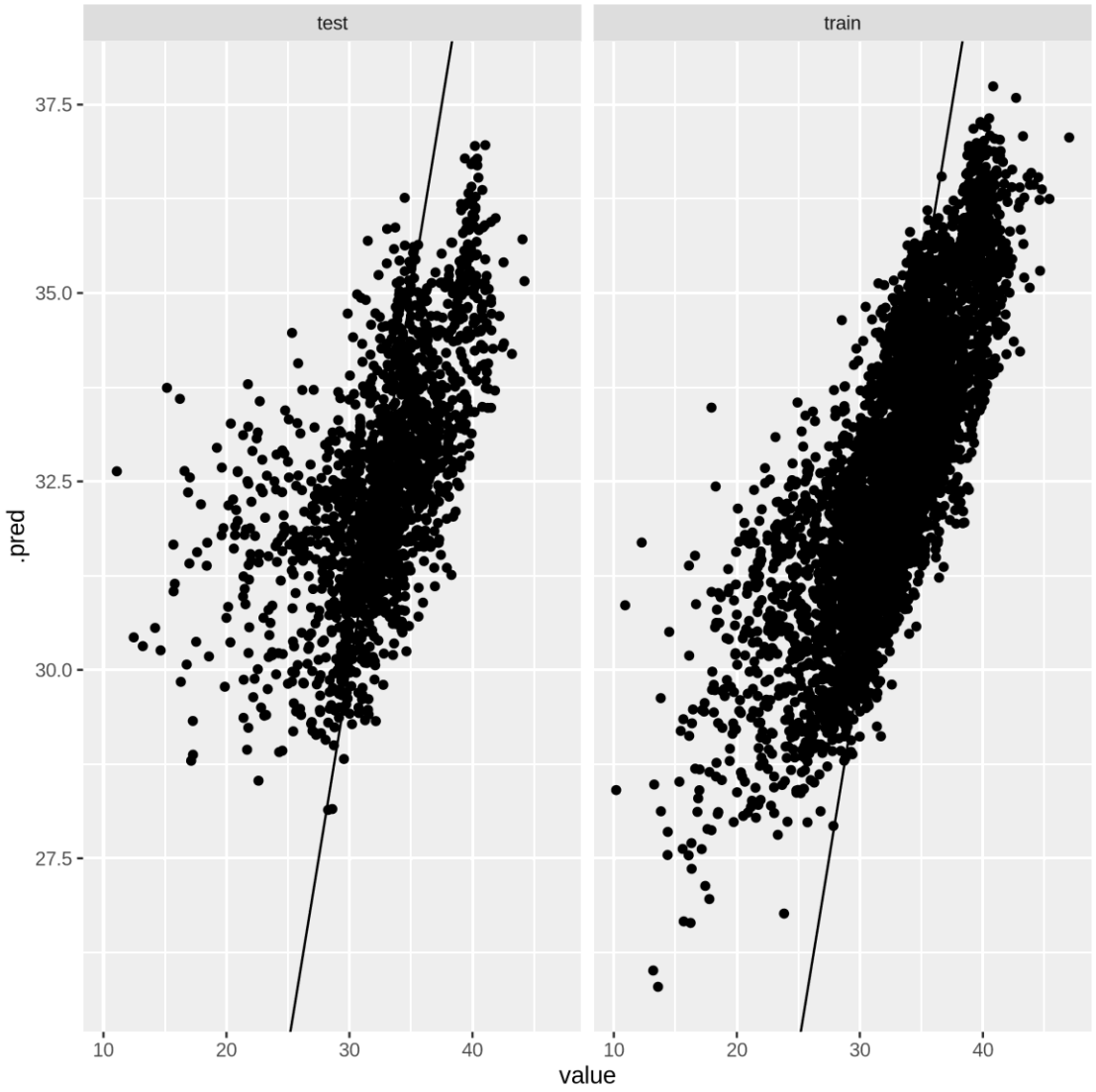


Figure A3.4m: Model performance plot for temperature model at the street scale.

Figure A3.5: Accumulated local effects (ALE) plots.

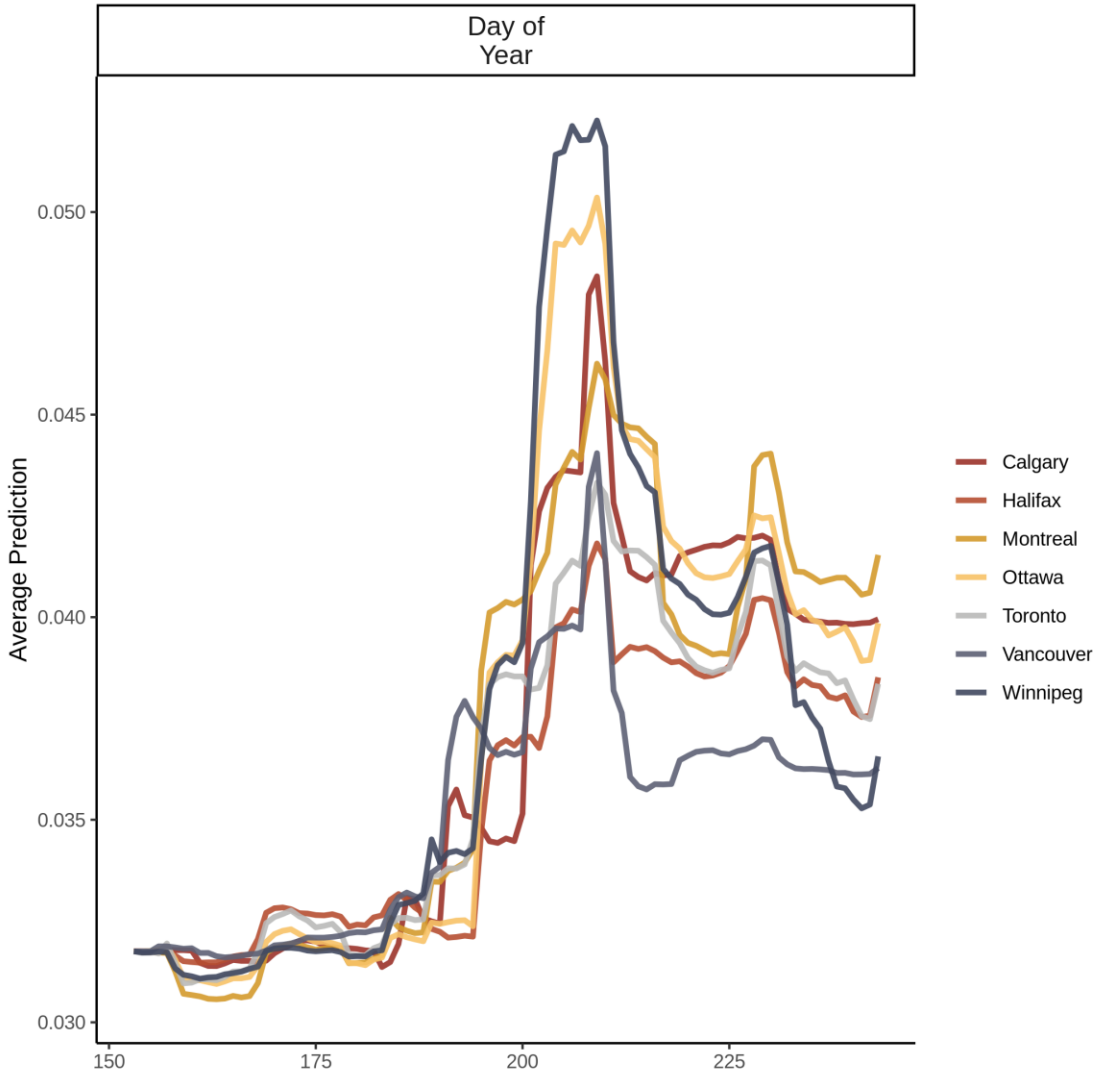


Figure A3.5a: Accumulated local effects (ALE) plot for carbon monoxide model at the city scale.

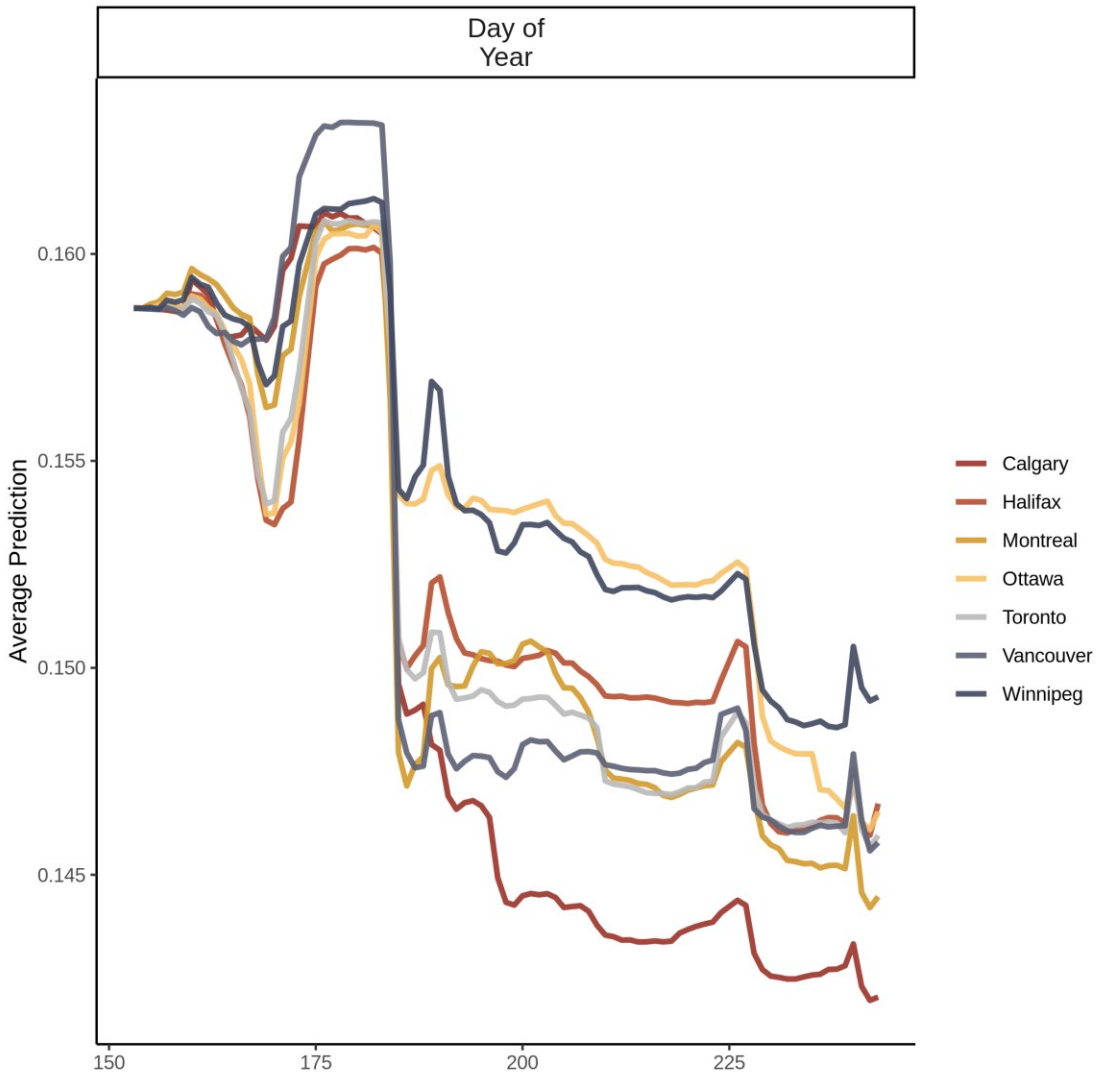


Figure A3.5b: Accumulated local effects (ALE) plot for ozone model at the city scale.

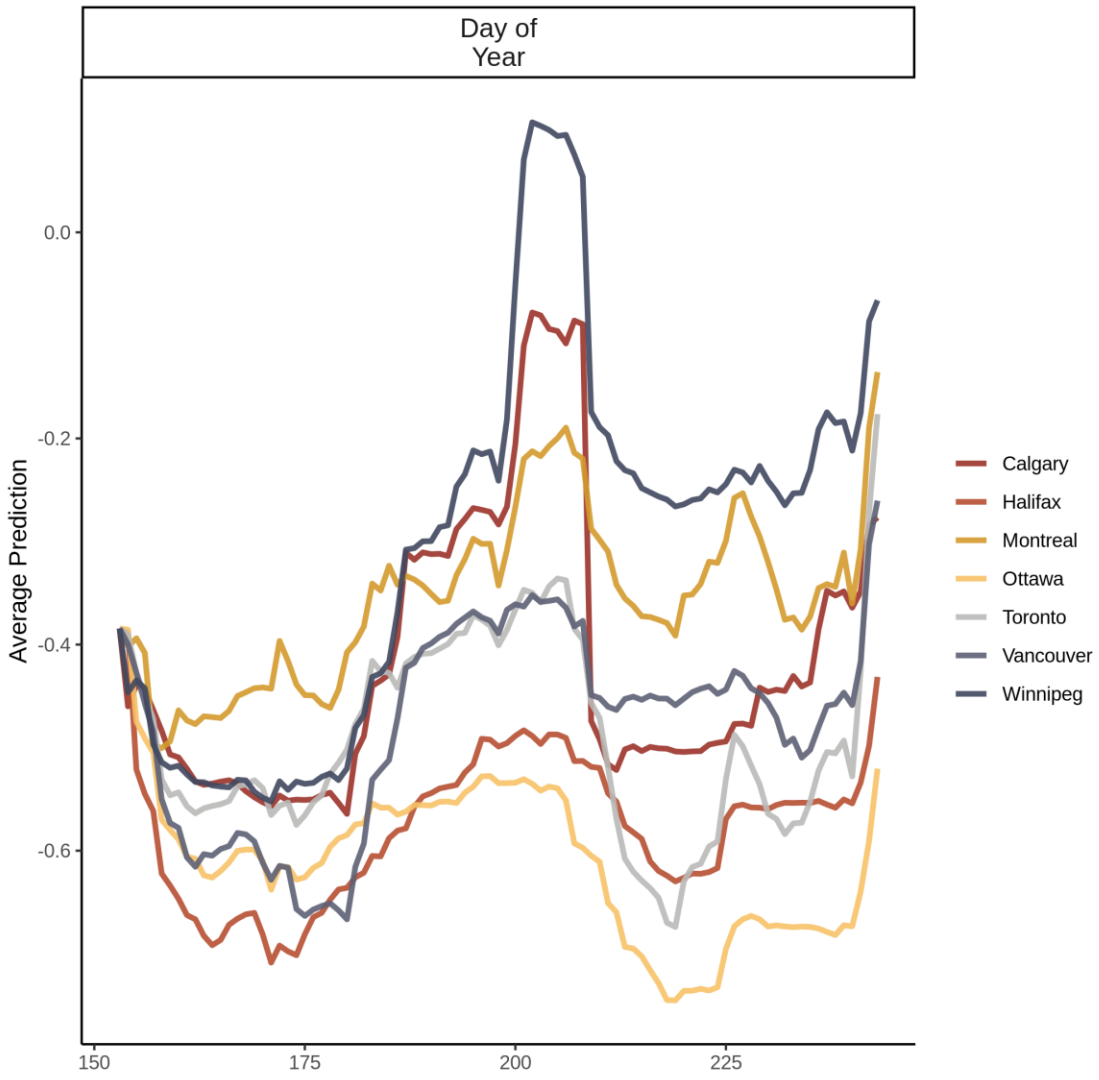


Figure A3.5c: Accumulated local effects (ALE) plot for UV aerosols model at the city scale.

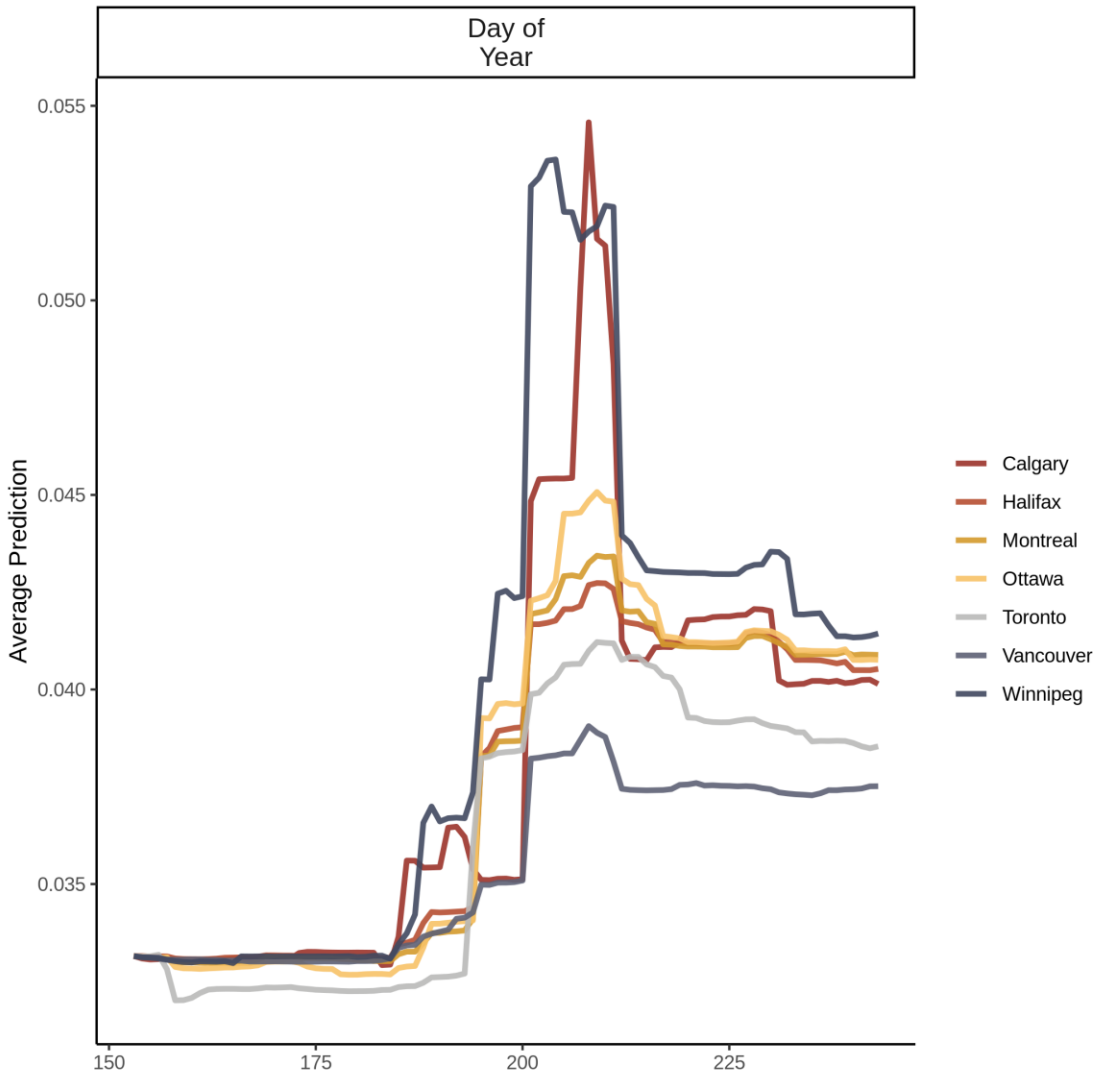


Figure A3.5d: Accumulated local effects (ALE) plot for carbon monoxide model at the neighbourhood scale.

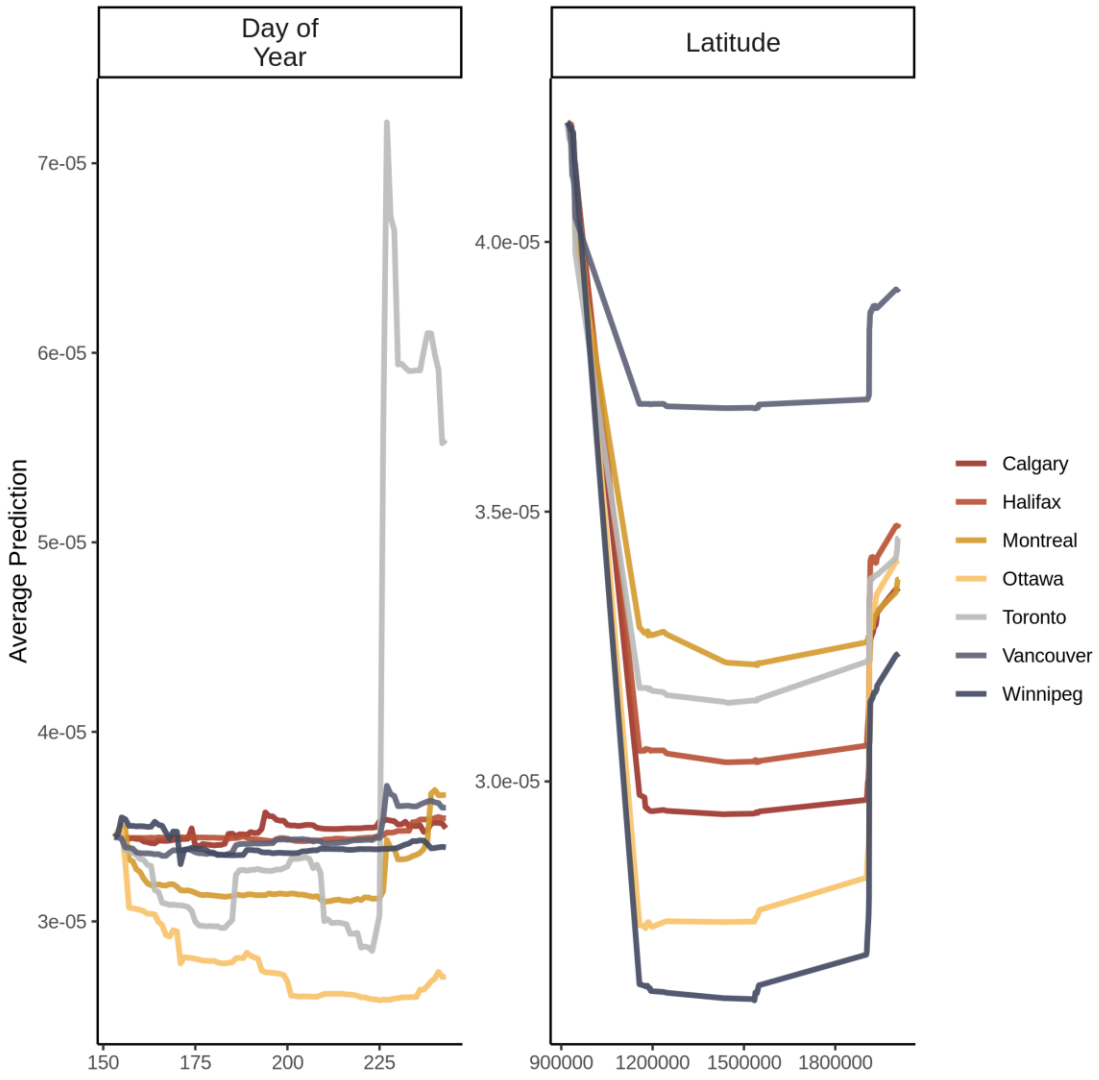


Figure A3.5e: Accumulated local effects (ALE) plot for nitrogen dioxide model at the neighbourhood scale.

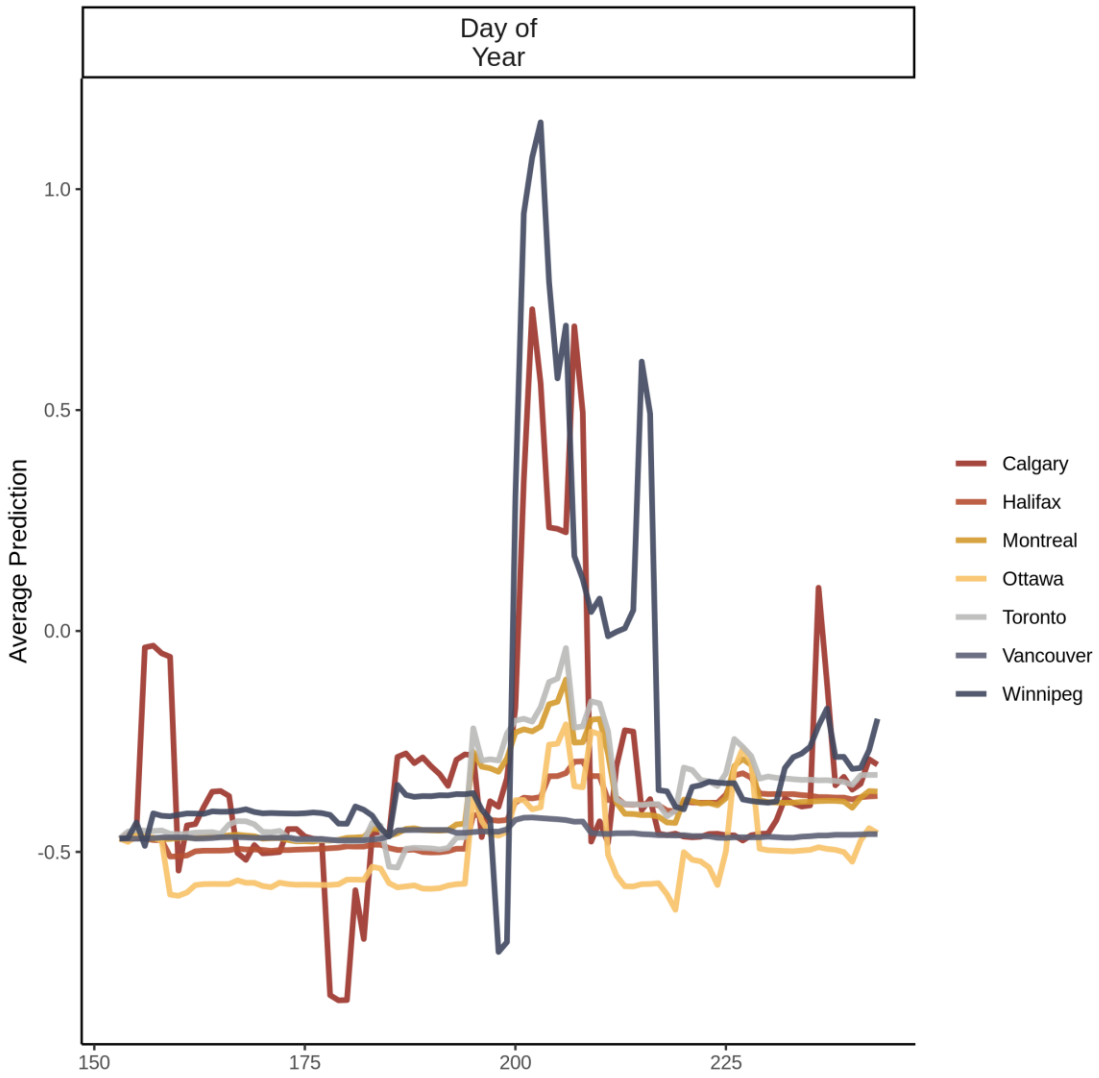


Figure A3.5f: Accumulated local effects (ALE) for UV aerosols model at the neighbourhood scale.

Figure A3.6: Partial dependency plots.

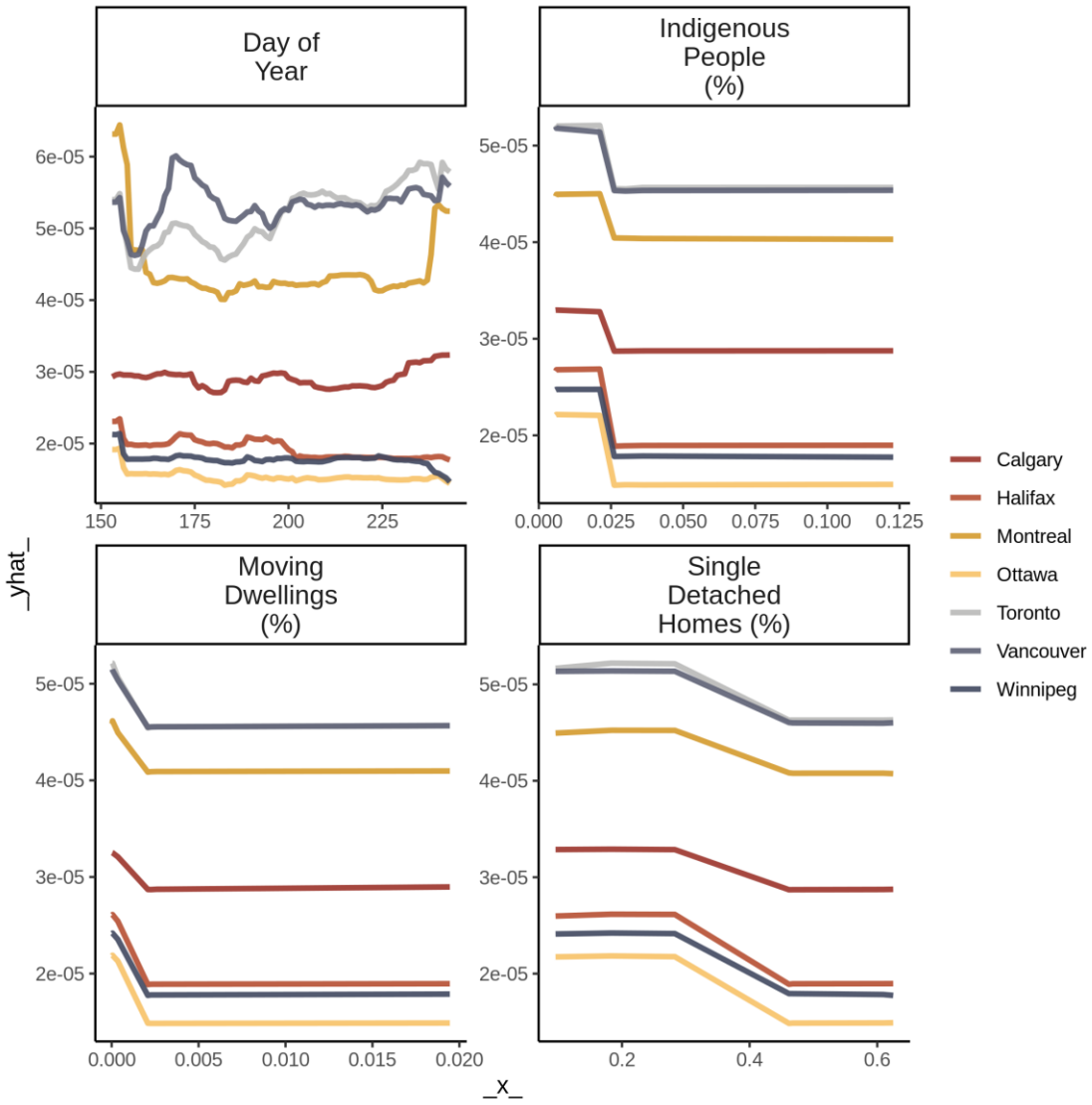


Figure A3.6a: Partial dependency plot for nitrogen dioxide model at the city scale.

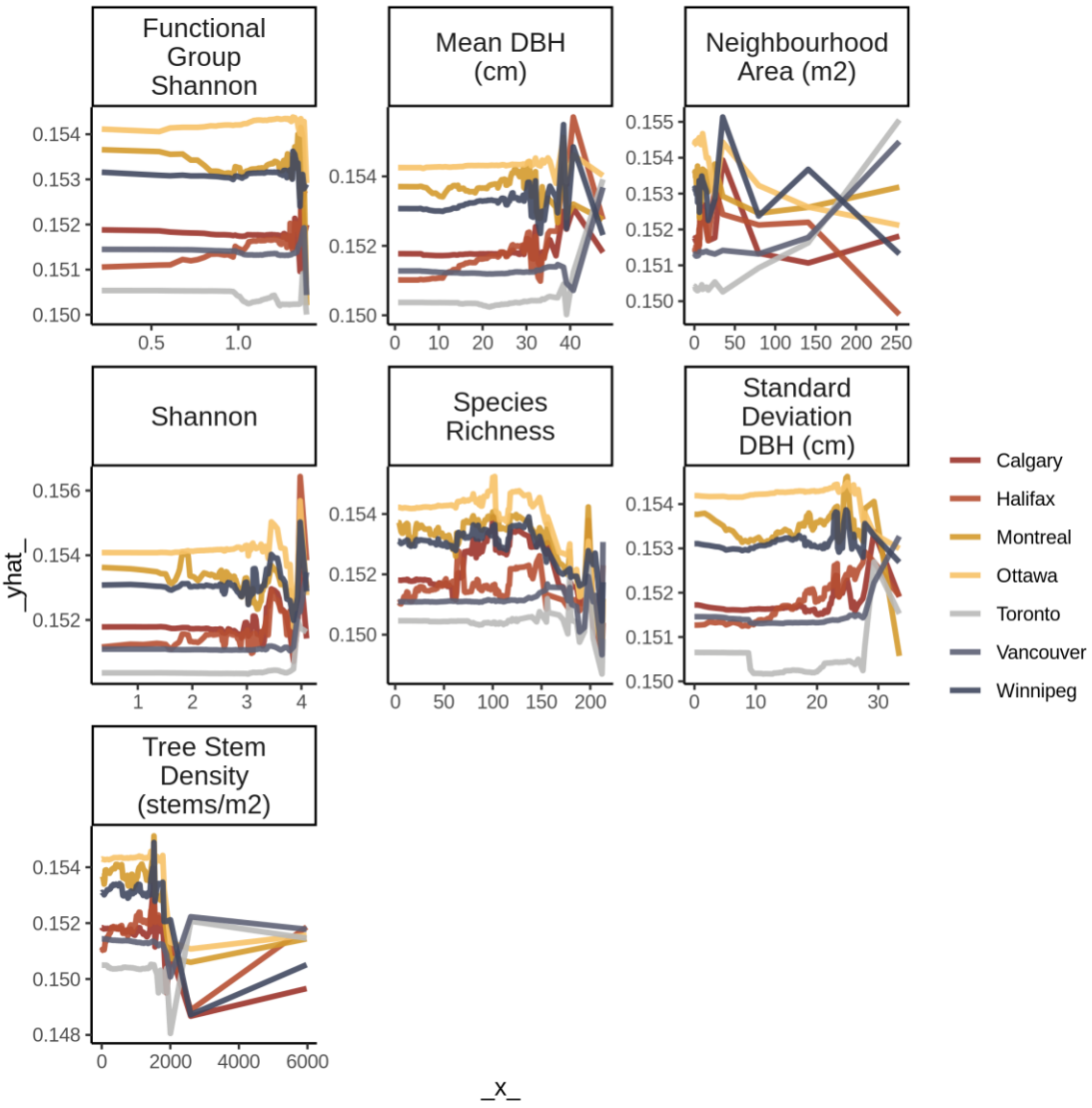


Figure A3.6b: Partial dependency plot for ozone model at the neighbourhood scale.