ROOM FOR CANOPY

Integrating Green Rainwater Infrastructure Boosts Urban Trees in Vancouver, Canada

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Disclaimer:

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Project Committee:
Alex Scott, Green Infrastructure Implementation Branch, Engineering Services
Reg Eddy, Urban Forestry Department, Vancouver Board of Parks and Recreation

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Project Interviewee
- Green Infrastructure Implementation Branch
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  - Jacob Kolic
  - Nick Mead-Fox
  - Robb Lukes
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- Vancouver Board of Parks and Recreation
  - Reg Eddy

Ming Cao
Vancouver, 2024

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EXECUTIVE SUMMARY

Trees accompany the city longer than humans. Street trees are not only the memory of the city but also the cultural heritage. Functionally, trees enhance urban aesthetics, intercept rainwater, improve air quality, and reduce urban heat island effects. The City of Vancouver is sticking with the vision to promote the expansion of its urban forests and has set the tree canopy target to achieve 30% by the 2050s.

Green rainwater infrastructure, or GRI, is a nature-based solution and an integrative, cost-effective design for stormwater management that reduces runoff, improves water quality, and enhances urban green spaces. The rationale of transitioning from grey to green infrastructure addresses many challenges Vancouver currently faces, such as increased urbanization and climate change, and affordability.

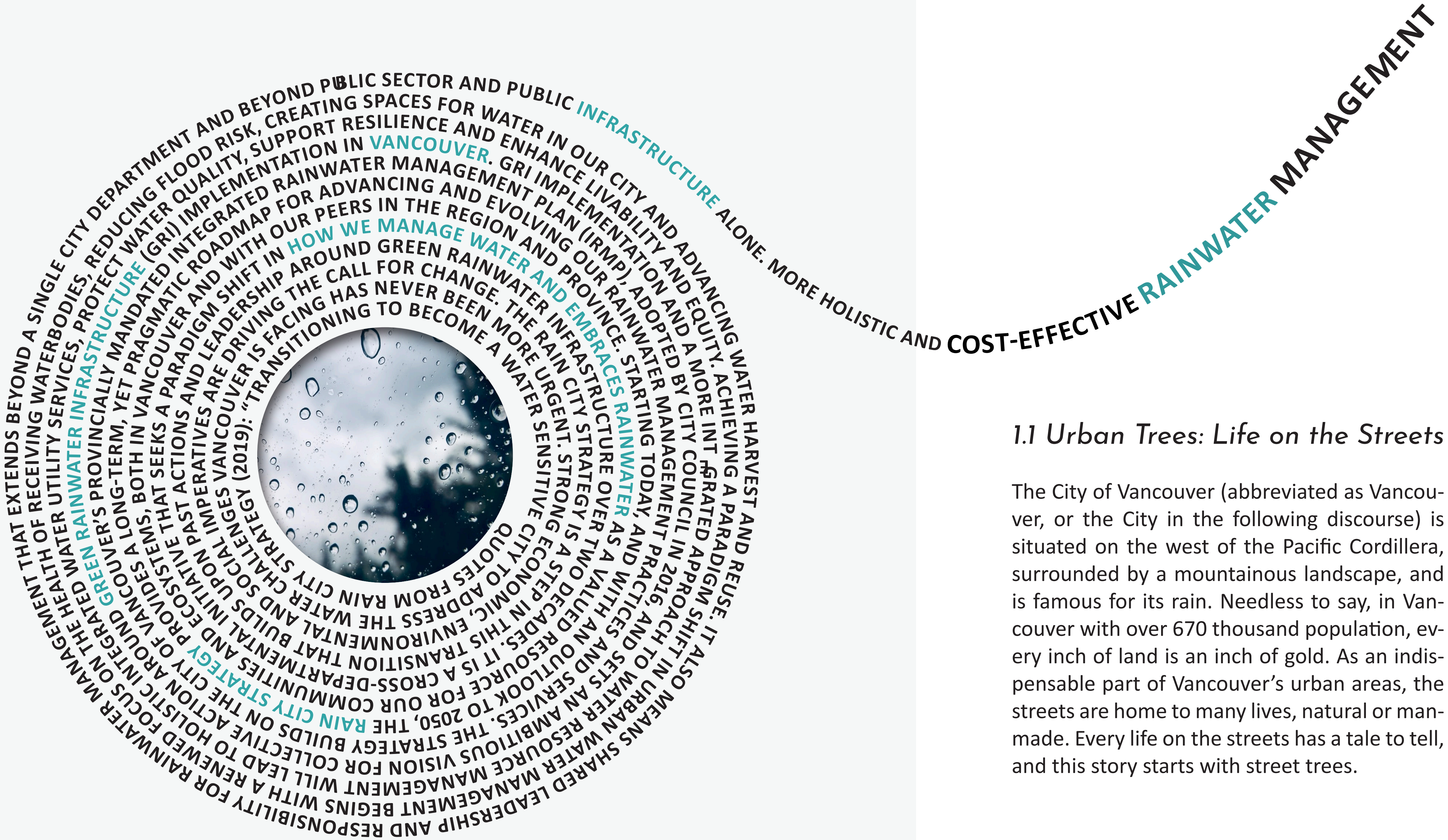
This study was motivated to test the hypothesis that GRI soils, such as structural soil and soil cells, could better enhance tree canopy growth compared to traditional planting areas in concrete pavement with limited soil space.

This project started with an overview of the current design considerations and mitigation strategies for projects involving trees and GRI through expert interviews with the City of Vancouver staff. Then, North American jurisdiction scans regarding BMPs for installing GRI to support new trees and case studies for installing GRI near existing urban trees were delved into.

Following this, street tree canopy analysis using the city-wide tree canopy cover (from 2018 and 2022) and GRI datasets was done to understand whether tree canopy grows faster when planted in GRI than in standard tree pits (concrete/cutout or grass boulevard), and how street tree canopy growth rates vary with distance from GRI assets. The take-home messages of the analysis are:

1. City-wide, street trees grown in GRI footprints have a statistically significantly higher canopy growth rate than street trees outside GRI footprints.
2. Average street tree canopy growth rates in structural soil and soil cells are higher than those in concrete/cutout or grass boulevard tree pits. however, this study didn't find significant canopy growth differences between trees in GRI tree pits (soil cell, structural soil) and standard tree pits (trees grown in open grass boulevards, back boulevards, concrete pavements or cutouts).
3. When assessing street tree canopy growth rates for both new and existing trees in proximity of GRI assets, the influence of distance to GRI types varies, with each type influencing tree growth differently. The observed variability in growth rates suggests that a variety of factors, including data discrepancy, water availability, soil conditions, and competition from other vegetation, may be influencing these outcomes.

Relevant legislation and guidelines for Vancouver's GRI and street trees.



"Architecture is the will of an epoch translated into space."

- Ludwig Mies van der Rohe

1. INTRODUCTION

1.1 Urban Trees: Life on the Streets

The City of Vancouver (abbreviated as Vancouver, or the City in the following discourse) is situated on the west of the Pacific Cordillera, surrounded by a mountainous landscape, and is famous for its rain. Needless to say, in Vancouver with over 670 thousand population, every inch of land is an inch of gold. As an indispensable part of Vancouver's urban areas, the streets are home to many lives, natural or manmade. Every life on the streets has a tale to tell, and this story starts with street trees.

Street trees provide a wide range of benefits for the urban landscape, including energy conservation, carbon dioxide sequestration, air pollution reduction, and stormwater management; they also contribute to economic growth by enhancing business income and property values and improving community aesthetics and recreational spaces (Bartens et al., 2009; Wang et al., 2018).

In Vancouver, street trees are placed in tree pits in many planting areas such as grass boulevards, back boulevards, sidewalks, and the medians. The street trees offer a glimpse into Vancouver's urban forest (Figure 1.1). In the municipal vision for urban forest development, Vancouver aims to increase the urban forest canopy to 30% by 2050. As part of planting on public lands, 2500 street trees are planted annually. However, increased impermeability due to urbanization has posed three main challenges for promoting street trees, according to the Urban Forest Strategy (2018): "

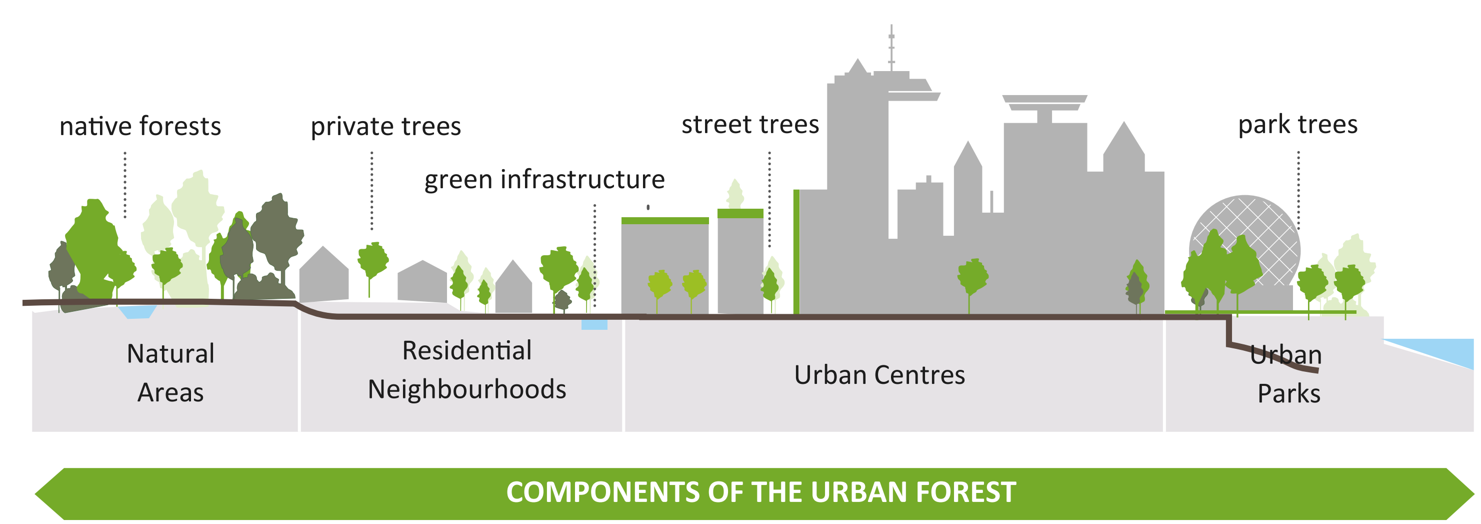


Figure 1.1: Vancouver urban forest elements. Source : from Urban Forest Strategy (City of Vancouver and Vancouver Park Board, 2018).

- Space to plant new or replacement trees.
- Soil volume for existing and new trees.
- Rainwater soil infiltration and storage."

Green rainwater infrastructure is one solution adopted by the City to address these key challenges.

1.2 Green Rainwater Infrastructure

Green rainwater infrastructure (GRI) refers to "both a set of engineered systems and an approach to rainwater management, which uses both engineered and ecosystem-based practices to protect, restore, and mimic the natural water cycle" (City of Vancouver, 2024b). This study uses Green Rainwater Infrastructure for consistency among wordings. Other terms referring to the same meaning may include Green Stormwater Infrastructure, Green Infrastructure, and Low Impact Development.

According to the GRI typologies in Vancouver's Rain City Strategy (2019c), the types of GRI include: Bioretention, Rainwater tree trench, Resilient roofs, Permeable pavements, Subsurface infiltration, Engineered wetlands, Non-potable systems, Absorbent landscapes, and Downspout disconnection.

The GRI type specific to supporting trees is the Rainwater Tree Trench, specifically engineered to sustain trees in urban settings. It achieves this by employing structural soil or soil cells, which construct supportive rooting areas capable of withstanding the weight load typical of urban environments.

Structural soil, or engineered soil, is a soil medium designed to provide pavement support while enabling root expansion. The structural soil is composed of 80% crushed stones and 20% soil that are compacted to 95% proctor density, allowing for some root growth in the small void spaces. This composition provides structural integrity while accommodating tree roots. Soil cells are hollow, modular systems, often cubic, filled with uncompacted soil volumes. They are enclosed at the top and bottom and typically have a top or deck that acts as a roof for the soil and a base for hard surface materials. Unlike structural soils, soil cells require a higher upfront cost but have a lower maintenance cost over time.

1.3 Equity Issues

The City of Vancouver is committed to addressing historical and current systemic inequities for healthier people, healthier places, and a healthier planet while working toward a more equitable, safe, and inclusive city (City of Vancouver, 2021). Despite this long-term vision, some equity challenges remain in the planning for GRI and urban trees.

Figure 1.2 summarizes the number of installed GRI assets by land use types in Vancouver between 2001 and 2023. So far, the total number of GRI assets in the right-of-ways has exceeded 360. Most of the assets have been developed on multiple dwelling districts, one/two dwelling residential, or mixed use/commercial land uses. The least used land use type is historical areas. This is because the implementation of GRI could be opportunistic, depending on whether the site conditions are suitable for GRI installation, and if there are projects that can integrate GRI design. With that said, the majority of GRI in Vancouver is in the right-of-ways, which signifies a legal authority for the City to use a designated strip of land for public access such as transportation. The right-of-way components include public infrastructure like streets, sidewalks, bike lanes, utilities, or parks. Properties and buildings adjacent to right-of-

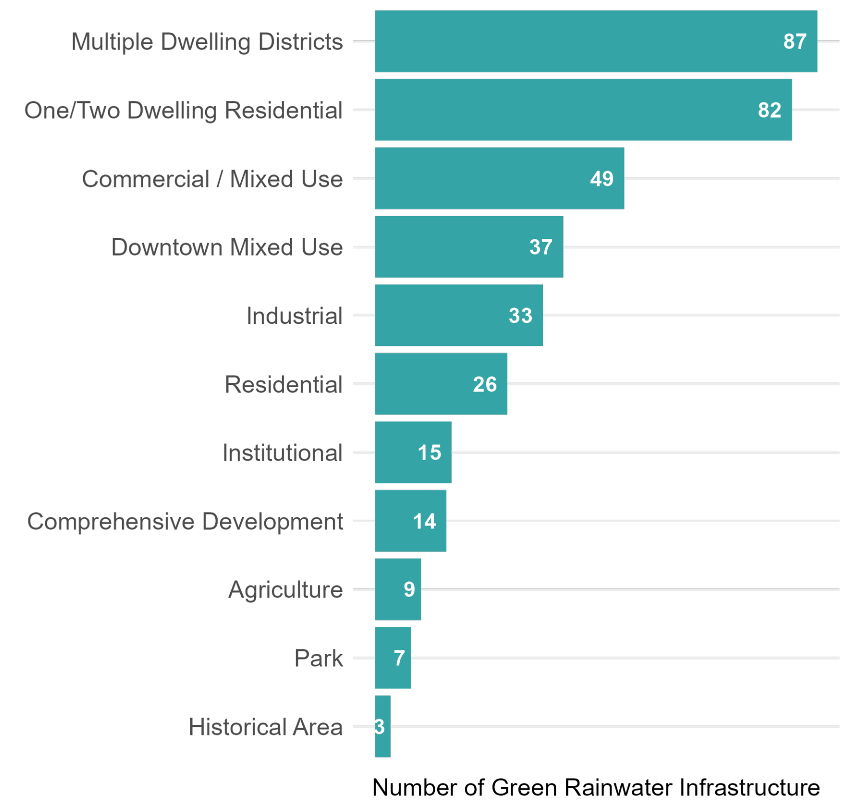


Figure 1.2: Number of GRI assets installed up to 2023, grouped by land use types.

ways are required to maintain a setback distance, which is the mandated space between a building and the property lines, as determined by local zoning regulations. Setbacks are crucial for maintaining safety, access, and aesthetics within the community. These setback requirements, influenced by the rights-of-way, ensure that buildings are not constructed too close to public right-of-ways like streets or sidewalks.

Speaking of unequal urban forest access, out of the 22 local neighborhoods, the City's urban forest canopy cover is less than 11% in Strathcona, Downtown, Sunset, Renfrew Collingwood, and Victoria Fraserview (City of Vancouver and Vancouver Park Board, 2018). In the previous scholar's work on improving the health of Vancouver's street trees in urban hardscapes done by Elliot Bellis (2023), the author furthered the urban forest equity analysis by overlaying the 2021 canopy cover with the Disproportionately Impacted Populations index and suggested tree-planting locations to prioritize in neighborhoods primarily in east and south Vancouver and retrofitting areas in Downtown and east Vancouver.

1.4 Objectives

This project was built upon the previous work in Bellis (2023) and the main objective of this study was to analyze Vancouver's urban tree canopy and GRI to inform design and construction practices. The specific research questions for this project were listed as below:

1. For Vancouver, what are the current design considerations and mitigation strategies for projects involving trees and GRI?
2. What can Vancouver learn from other North American jurisdictions regarding best management practices (BMPs) for installing GRI to support new trees, as well as installing GRI near existing urban trees?
3. Does the tree canopy in Vancouver grow faster when trees are planted in structural soils or soil cells (i.e., GRI) than when trees are planted in standard tree pits?
4. How do street tree canopy growth rates vary with distance from GRI assets for both new and existing trees?
5. Which tree species are best suited for planting in structural soils or soil cells in Vancouver?

To answer these questions, the approach was three-fold: Chapter 2 documented interviews with the City of Vancouver's staff involved in urban tree health and GRI implementation; Chapter 3 provided a scan of selected North American municipalities and summarized their GRI initiatives; lastly, Chapter 4 contained a geospatial and statistical analysis by cross-referencing Vancouver's urban tree canopy and GRI.

2. INTERVIEW SUMMARY

Here, a summary is put together to highlight the best practices, challenges, and innovative solutions in the City of Vancouver's GRI design and street tree regulations to improve tree health. This section coalesces responses from expert interviews and the City's documents or by-laws concerning GRI designs and street tree protection. Potential interview candidates were reached out from the City's Green Infrastructure Implementation Branch and the Urban Forestry Department in May 2024, and all interviews took place between 9 am to 5 pm on weekdays between May 2024 to July 2024. Each interview was a thirty-minute to one-hour in-person meeting or virtual via Microsoft Teams. The outcome was summarized by the themes shown below. Each theme is structured with individual questions followed by responses.

Roles and Responsibilities:

Which City departments are involved in the life cycle of GRI assets and urban street trees?

- GRI assets: To start with, the City's top-down organizational hierarchy is council>>department>>division>>branch. The **Green Infrastructure Implementation Branch**, under the Streets Division of the City's Engineering Services Department, is involved in the whole life cycle of GRI assets in the City's public space, which includes planning, tendering, designing, implementing, monitoring, maintaining, and rehabilitating. As many GRI assets dwell in streets and roadways, there is a lot of collaboration and coordination with other branches. For instance, specific to the GRI planning phase, the Integrated Sewer & Drainage Planning Branch is often involved in identifying where to build GRI assets. Within the City, from a broad project construction level, the Green Infrastructure Implementation Branch coordinates with the Project Division and Transportation Division to ensure GRI assets are designed to co-exist with ongoing street infrastructures or utilities (such as sewers, electrical conduits, water mains, traffic lights, light poles, etc.) and are delivered according to the City standards. Outside the City, the Green Infrastructure Implementation Branch collaborates with external contractors, such as soil suppliers, or landscape consultants.
- Street trees: **Urban Forestry Department** governed by the Vancouver Board of Parks and Recreation, is responsible for the whole life cycle of street trees encompassing sourcing, planting, monitoring, protecting, and removing (if necessary) street trees in the City. As illustrated in Figure 2.1, trees that live in streets share the space with various aboveground and underground utilities (e.g., gas mains, buildings, water mains, fire hydrants, electrical conduits, etc.). Likewise, the Urban Forestry Department works with other departments, divisions, or branches when the City's projects involve street trees. Outside the City, the Urban Forestry Department may collaborate with nurseries for sourcing nursery stocks or hire external Landscape contractors for tree planting.
- Street trees in GRI assets: During GRI construction, new street trees planted within GRI are temporarily managed by the Green Infrastructure Implementation Branch; this responsibility is transferred to the Urban Forestry Department after a GRI project is complete and the warranty of the new trees has expired. If new GRI assets are built near existing street trees, these existing trees are taken care of by the Urban Forestry Department.

Figure 2.1: Street utilities and infrastructure. Source: from Global Designing Cities Initiative (2024).

Design Considerations:

What requirements does GRI in the City need to meet?

- According to the Green Infrastructure Design Manual (2024b), the design prioritizes vegetation to favor urban biodiversity and ecology while aiming to:
  1. retain 48 mm of rainfall during a 24-hour storm,
  2. ensure GRI can drain aboveground volume within 24 hours and soil within 72 hours post-storm,
  3. remove 80% of total suspended solids during the initial 48 mm rainfall.
- Along with existing utilities, the evaluation of existing trees is included in the initial site assessment to determine the feasibility of installing GRI in the available space and understand system constraints for maximizing the GRI contributing drainage area. An earlier published toolkit, Integrated Rainwater Management Plan Volume II, Best Management Practices Toolkit (2016), provides the GRI selection criteria for different site conditions (e.g., one/two housing areas, industrial sites, streets, parks, or lanes), with the overall selection goal of minimizing maintenance cost and maximizing the proposed GRI longevity. For example, infiltration swales are a good candidate to build into local streets or street medians at the time of existing street tree replacement.

How does the design emphasis vary between GRI assets with new trees versus GRI assets with existing trees?

- When designing GRI, geotechnical survey and hydrological modeling will be used to understand specific site constraints, infiltration rates, grading, how much drainage area can be captured, and how best to fit the GRI inlet or outlet. Based on this information, certain areas will be sized for capturing the rainwater.
- Both scenarios emphasize the importance of integrating trees into urban infrastructure in a way that supports their health and longevity while also providing urban environmental benefits such as stormwater management, air quality improvement, and urban heat island effects mitigation. The key difference lies in the initial preparation for new trees versus the protective measures needed for existing ones.
- When incorporating new trees into GRI assets, the design considerations often focus on allocating the growing medium, growing space, and design for new planting. This includes ensuring that the soil conditions are suitable for tree growth, providing adequate space for root development, and selecting tree species that are appropriate for the local climate and soil conditions.
- On the other hand, existing trees with GRI assets are treated as existing infrastructure, which involves assessing the impact of GRI construction activities on existing trees and establishing a tree protection plan. This could include creating protective barriers, using soft surfaces around trees to minimize damage, and planning construction activities to avoid direct harm to the trees. Experts express that the City's tree bylaw has been fundamental in lessening the impacts of private trees during development projects.

How much soil volume is allocated to trees in GRI?

- In Vancouver, GRI is under the umbrella of engineering services; details about GRI soil specifications and tree planting are currently documented in the City of Vancouver Engineering Design Manual (2019b) and Construction Specifications (2019a). Depending on the size of the tree, soil volume ranges from $5m^3$ to $30\ m^3$ (Table 2.1).When native soil isn't available due to existing site conditions or construction practices, engineered soils can be used as a substitute but is calculated at 50% of the volume of native soil.

How are trees determined when designing GRI assets?

- Keeping in mind that the long-term vision for trees within GRI is to maximize the benefits of both trees and GRI. It is crucial

Table 2.1: Tree spacing and soil volumes. Source: from Engineering Design Manual (City of Vancouver, 2019b).

Tree Size Category	Average Spacing	Soil Volume Per Solitary Tree	Soil Volume (Shared /Row of Trees)
Large	9m - 11m	$30m^3$	$20m^3$
Medium	8m - 10m	$20m^3$	$15m^3$
Small	7m - 10m	$10m^3$	$5m^3$
Columnar	7m - 10m	$20m^3$	$15m^3$

VANCOUVER BOARD OF PARKS AND RECREATION

Park Board Tree Planting Guidelines

Tree selection and planting must be to BCLNA and ANSI A-300 standards and maintained in good health and vigor for two years following planting. Watering during May 1st – September 30th is crucial for maintaining tree health during this period.

The following items are to be completed for trees planted in the City boulevard.

- Correct Species
  City Tree species selection has been provided by the Parks Board (if unsure contact the Parks Board at pbdevelopment.trees@vancouver.ca)
- Caliper Size
  Minimum 6 cm caliper for deciduous trees and minimum 2.5 m height for coniferous trees
- Quality Stock
  Free of pests, disease, girdling roots, invasive weeds, or other defects
- Good Structure
  Single leader with the lowest branch at least 2 meters high on the stem. Exceptions to the 2 meter lowest branch height can be made – must obtain park board consent. Tree is symmetric with regular spaced branching.
- Planting Alignment
  Tree trunk is straight and vertical (for trees in hardscape they are to be centered in planting pit opening)
- Condition
  Good health, high vigor, and free of damage. Twig dieback, discolouration, and dead branches composes < 10% of the crown.
- Root Ball
  Top 1/3 of the root ball is free of twine, binding, or burlap. No part of the wire basket is exposed that presents a tripping hazard. Top of the root ball is level with the surrounding grades
- Root Barriers
  Must be installed in accordance with Engineering Specifications
- Watering
  Ensure that a plan is in place to water the trees from March 15th – September 30th for two years
- Appropriate Soil
  Structural soil installed with sufficient volume where needed. Refer to Engineering Specifications.
- Trunk Guard
  A plastic trunk guard is installed to protect the tree from line trimmers
- Mulch
  Wood chip mulch ring to be applied around the tree. Mulch must not be in contact with the tree stem
- Staking
  Tree stakes are to be removed after one year
- Planting Hole
  A wide hole is to be dug (2-3 times the width of the root ball whenever possible) with sides gradually sloping down to the bottom. The sides and bottom of the planting hole are to be scarified. Native soil for backfill is preferred otherwise use good quality soil

The Park Board must be notified at pbdevelopment.trees@vancouver.ca when trees have been planted for an inspection

Figure 2.2: Vancouver Park Board tree planting guideline. Source: from personal communication with Reg Eddy.

to select the right tree for the right place. When designing GRI, the primary criteria for determining what trees to plant are based on the City's tree inventory history, internal knowledge of their performance, anecdotes, information provided by tree experts, and morphological suitability for the site. Moreover, preference is given to tree species that have non-aggressive roots, to cope with underground utilities. A clear message is to avoid invasive species, but both native and non-native trees are given consideration. Proposed tree selection always needs approval from the Urban Forestry Department before planting.

How do Vancouver's unique climate and soil conditions influence the tree selection?

- Under climate change, Vancouver's climate is becoming drier in the summer, so drought tolerance has become a crucial tree species characteristic to prioritize. Though Vancouver's native soil falls into the Podzolic category, urban soil is highly heterogeneous, and soil conditions are heavily altered due to increasing urban development. Experts report that sites with compacted soil, dry soil, soil with high pH or poor drainage tend to lead to high street tree mortality.

What're the considerations for tree planting and post-planting?

- Referring to the detailed tree planting guideline in Figure 2.2, a minimum of 6-inch ball and burlap caliper has proven to be the optimal size for establishment success. Trees should have a single leader, with the lowest branch positioned at least 2 meters high on the stem. There are no trees intentionally planted in situ (via seed) in any tree planting pit. For post-planting, watering must occur from May 1st to September 30th during the first 2-year establishment for any new trees.

Design Challenges:

What are the primary risks associated with using engineered specialized soils in GRI projects, particularly near mature trees?

- The primary risks are damage to the existing roots and alteration of drainage patterns for existing trees. Not all mature trees are suitable for installing in GRI, as some tree species do not prefer excess water directed by GRI. Typically, the value of an existing tree will be determined first. Considerations include the age, size of the tree, how big the canopy is, whether it's in a heritage boulevard, etc. Mature, established trees in an old neighborhood are hard to work with, as their roots often heave up the sidewalks and they blend into existing nearby infrastructure. Making sure the roots are well preserved whether for retrofitting or rehabilitating are crucial for the success of both existing trees and GRI.

What are some of the common issues faced during GRI implementation and tree maintenance?

- Obtaining healthy soil volume under paved concrete has been a main issue concerning GRI implementation with trees.
- Access to water is another issue. Upon establishment, trees will be watered for the first two years to prevent trees from desiccation, after which period is mostly letting nature take its course. There is no is no way to prevent surface heating or or improve evaporative cooling for existing street trees planted in concrete conditions.
- The little wires from line trimmers that help cut grasses can hit the bottom of the tree and knock off the bark, which is a main cause of newly planted tree death. Trunk guards are placed to prevent tree mortality from line trimmers.

How does re-zoning affect the City's ability to preserve street trees?

- "Tremendously. The re-zoning of an area may completely change the building parcel of private property adjacent to public property. This could impact the street trees if a building is built at, or close to the property line."

How does the City reduce conflicts between street trees and sidewalks?

- Root barriers: typically made of plastic materials, the City installs root barriers to deflect tree roots downward and away from sidewalks, preventing them from causing damage.
- Tree grates: In places like downtown with high pedestrian traffic, metal grates are placed around the base of trees on sidewalks to reduce soil compaction.
- Root pruning: tree roots might be selectively pruned during excavation for project development to minimize harm to the tree and reduce future conflicts to sidewalks.
- Routine field maintenance: inspections and maintenance of both trees and sidewalks are regularly conducted to help identify and address potential issues early.

Looking Forward:

Are there any technologies or materials that have been particularly beneficial in enhancing tree health?

- Experts report that "GRI built with large soil volumes has proven to be effective for tree growth."
- Selecting drought tolerant species to better suit the Vancouver's changing climate.
- Mulching. Mulching around trees regulates soil temperature, helps retain soil moisture during hot days, and provides additional buffer for new trees to establish.
- Air spading. It is a tool that uses compressed air to blow soil away from tree roots. Experts reported to have used this method to avoid root damage when rehabilitating existing trees in GRI.
- To minimize damage to existing trees, ground-penetrating radar can be employed to map underground tree roots and dig potholes around mature trees to understand the extent of the root systems.

In limited urban space, buildings or gray infrastructure seem to be more prioritized than GRI, what emerging trends in urban design and green infrastructure do you believe will shape the future of GRI?

- One trend the City trying to push forward is blue green roof, which is a green roof with water storage underneath it. Unlike cities in east Canada, Vancouver does not get as much rainfall in summer as it is in winter. The thrive of green roof requires watering in the summer, which is a huge ask as Vancouver is encountering water scarcity. The water storage acts like groundwater banks for vegetations to extract during dry periods.

What GRI design changes is the City considering proposing?

- Due to the logistical infeasibility of the

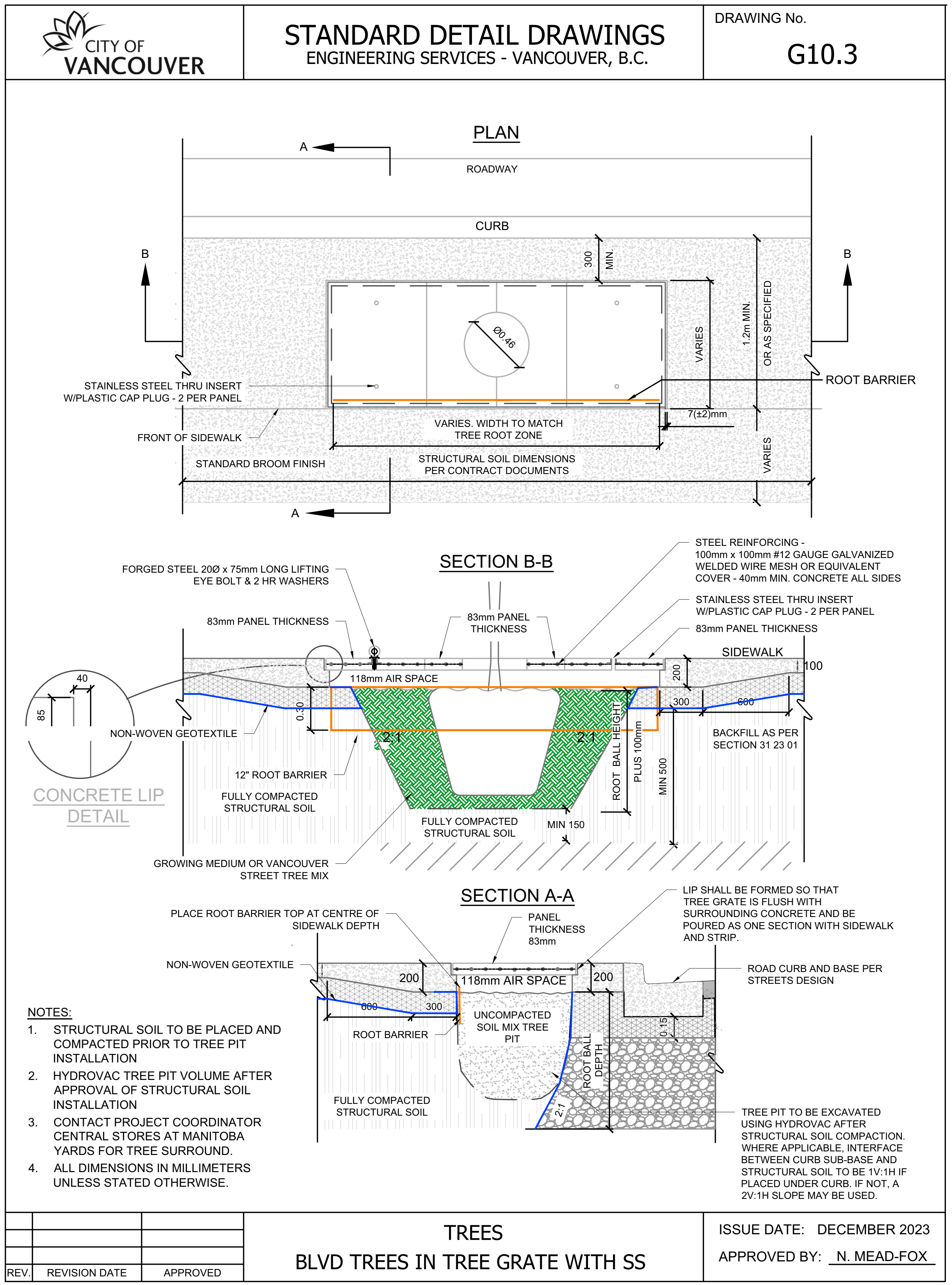


Figure 2.3: Proposed drawing standards for street tree pit design. Source: from personal communication with Nick Mead-Fox.

urban areas, the space assigned to street trees are at the mercy of other street infrastructures. Aware of these constraints, experts are proposing to increase the tree pit space safely.

- According to experts, projects have recently been launched to test the impervious/permeable ratio in pavement conditions, with the aim of creating more space for GRI construction and consequently for tree root expansion.
- The City is running a Street Tree Standards Working Group to improve the street tree space. Figure 2.3 shows the proposed street tree pit design standard the Street Tree Standards Working Group is working towards. Some highlights of the moves are listed in the following:
    - lower the current depth of root barriers from 18 inches to 12 inches;
    - decrease the 300 mm setback to curbs for residential roads with less traffic;
    - excavate tree pit after structural soil compaction. Maintain a 1V:1H slope between curb sub-base and structural soil if placed under the curb. Otherwise, use a 2V:1H slope;
    - design the trunk hole to be adjustable to accommodate the growth of tree roots, with the design suspending the grate a minimum of 1 cm above grade;
    - use a tree grate that is easier to remove without heavy equipment, which accommodates tree trunk growth as well;
    - when possible, backfill the tree pit with structural soil. Additionally, provide clear guidelines on acceptable dimensions of uncompacted fill behind the curb.

Key Takeways:

- Gathering from various perspectives by the interviewed staff, the City of Vancouver recognizes the value of street trees and emphasizes the importance of GRI design and tree protection.
- Compared to traditional concrete growth spaces, GRI with increased soil volumes is perceived to support tree growth better. However, not all tree species are suitable for planting in GRI. The increased directed rainwater may negatively impact some species. Therefore, carefully selecting tree species is essential to ensure compatibility with GRI conditions.
- Securing soil medium for tree growth is a key challenge, and proposed considerations are focused on expanding the tree pit space for trees. Proper watering regimes need to be established to support tree health, and tree root protection after tree establishment is also critical.
- While all interviewees recognize the importance of protecting root systems, the practical implementation often involves compromises. During construction projects, theoretical best practices for root protection may be challenging to uphold due to constraints such as space, budget, and conflicting project priorities.
- Currently, there are no one-size-fits-all design standards for incorporating existing trees into GRI, and often design practices are discretionary. The City's projects involving GRI and trees often span a range of departments/branches. Negotiation and resolution of conflicts between design, construction, and tree protection are crucial, and the Street Tree Working Group is working to address these issues.

3. BMPS FOR NEW AND EXISTING TREES

This section sought to provide municipal scans as well as specific cases of current best management practices (BMPs) in regard to GRI with both new and existing trees. The scope of the municipal scan targeted at jurisdictions in Canada and the United States, as findings from these municipalities would be more transferable to the Vancouver context due to similarities in governance structures, policy frameworks, and socio-economic factors. The selection of other jurisdictions looked at the greening program and plan with GRI initiatives and strived for a matching climate like Vancouver. According to the Köppen classification (Kottek et al., 2006), the climate for Vancouver is classified as temperate oceanic climate (code = Cfb). Table 3.1 lists the BMPs of Vancouver and selected jurisdictions. Table A.1 provides an overview of selected jurisdictions along with their GRI guidelines reviewed.

After the municipal scan, specific cases were expanded to include BMPs documented around the world. The cases focused particularly on the preservation of existing trees and strategies to avoid conflicts with sidewalks, as these areas were encouraged to pivot from expert interviews.

3.1 Lessons Learned

3.1 1 How is Vancouver doing?

Vancouver's commitment to GRI exemplifies a forward-thinking mindset to urban sustainability, integrating environmental conservation, community resilience, and innovation. Similar to other jurisdictions, in Vancouver, GRI goes through phases that encompass budget planning, designing, design revisioning, approval for construction, operation, and maintenance in order to successfully land as an environmentally friendly infrastructure asset that will last for many years.

In general, the GRI design guidelines and the tree planting guidelines serve as a starting

Table 3.1: BMP checklist for selected jurisdictions. Cells are shown as x if information is not found in the scanned documents.

Category	BMPs checklist	City/Jurisdiction					
		Victoria	Vancouver	Toronto	San Francisco	Portland	Philadelphia
Regulations for trees and GRI management	Tree protection bylaw	☑	☑	☑	☑	☑	☑
	City-wide environmental policies or strategies	☑	☑	☑	☑	☑	☑
	Departmental specialization	☒	☑	☑	☑	☑	☑
	Funding from government or private organizations	☑	☑	☑	☑	☑	☑
Planning and designing for trees in GRI	Site feasibility assessment	☑	☑	☑	☑	☑	☑
	Design details for new trees	☑	☑	☑	☑	☑	☑
	Design details for existing trees	☒	☒	☑	☒	☑	☑
	Setback distance from various utilities	☑	☑	☑	☑	☑	☑
	Soil specifications	☑	☑	☑	☑	☑	☑
	Tree selection	☑	☑	☑	☑	☑	☑
	General plant list	☑	☑	☑	☑	☑	☑
	Specific tree list for GRI	☑	☒	☒	☑	☒	☑
Operation and maintenance for trees in GRI	Tree protection in construction	☒	☑	☑	☑	☑	☑
	Tree planting guideline	☑	☑	☑	☑	☑	☑
	Tree and/or GRI warranty	☒	☑	☑	☒	☑	☑
	Regular site inspection	☑	☑	☑	☑	☑	☑
Public participation	Rainwater or tree credit	☑	☒	☒	☑	☑	☑
	Community education	☑	☑	☑	☑	☑	☑

point, and accommodations could occur to suit specific site constraints or project-specific barriers. According to the Green Infrastructure Standard Drawings (2023), Vancouver is equipped with detailed design guidelines to support new trees primarily in rainwater tree trench GRI type. The tree trench drawing details differentiate between structural soil and soil cell, and considerations for proposed tree pits in bioswale boulevards or streets are included. On a different note, the standard drawings treat existing trees as existing utilities, which are incorporated into designing for new GRI. A maximum 2:1 slope is recommended for vegetated slopes within GRI systems, with a preference for a 3:1 slope under all conditions (City of Vancouver, 2024b). For species selection, currently, no specific GRI tree list is found, but a recommended plant list for GRI and a street tree list is documented by Vancouver (City of Vancouver, 2019b, 2024a). Planting guidelines for trees in GRI are absent, but the general street tree plant requires: The curbside edge of a tree surround must be at least 0.3 m from the back of the curb; at least 3 m away from existing spreading trees, at least 2 m away from existing columnar trees; space trees appropriately away from the existing street and private trees.

The City's Construction Specifications (2019a) recognizes the importance of minimizing disturbance to tree roots and providing adequate protection during construction activities to maintain tree health. For instance, a tree protection zone during construction, stay clear of trees by at least 1.5 m measured at 1.4 m high from the trunk, or six times the trunk diameter at the same height; limit root removal to 33% of the total mass and 25% from one side; use fencing for tree protection that allows pedestrian passage, maintains visibility of essential features, and is placed a minimum distance from curbs and sidewalks.

3.1.2 Opportunities to Improve

As a high-level summary for Section 3.2, Victoria pays detailed attention to its GRI species plantings and planting zones. Both Toronto and Portland have relatively complete guidelines for GRI and street tree protection plans, with Toronto focusing on promoting continuous tree trench systems accompanied with a suite of drawing plans, and Portland on being more systematic and strategic in providing alternatives to different GRI site constraints. One uniqueness for San Francisco lies in its conditional setback requirements for GRI construction. Lastly, Philadelphia is highlighted for its extensive GRI landscape plans and reinforced regulations for existing tree protection zones.

Drawing insights from Section 3.2 and Section 3.3, for improving tree health in GRI projects in the Vancouver context, main opportunities are:

- Provide a detailed landscape plan that includes a planting plan with information on existing vegetation preservation, the location of landscape elements, and the specifics of proposed plantings which ideally include size, species, and planting zones.
- Amend the current GRI design drawings involving trees to incorporate alternatives that reflect different substrate materials (e.g., porous asphalt, soil with planter curbs, soil with tree fences), and append standard drawing scenarios for sidewalk retrofit/repair around existing trees with root pruning.
- In addition to a minimum soil volume requirement, set a minimum soil depth for supporting tree root penetration and nutrient storage.
- Standardize the GRI construction guidelines, and field assessment inspection for evaluating tree health before and after the GRI implementation, including performance criteria for soil quality, existing vegetation, and site microclimate.
- Consider planting tree species that are smaller at maturity or slower-growing to reduce sidewalk conflicts.
- When tendering for contractors for constructing GRI involving soil cells or structural soil, consider adding qualification requirements to hunt for trustworthy partners.
- Promote and implement non-invasive techniques for GRI excavations.
- Continue GRI data management, and public engagement to amplify the impact of the City's GRI projects. Consider:
    - Collaborate with schools: Partner with schools to incorporate GRI topics into the curriculum or offer special educational programs and field trips related to urban sustainability.
    - Citizen-science monitoring: Engage with volunteers in tracking tree health, soil moisture, or water quality to provide valuable data and insights.

3.2 *Jurisdiction Scan*

3.2.1 Victoria, BC, Canada

Victoria recognizes that the use of structural soils and soil cells are a desired method to support tree planting. A minimum of 30 m^3 soil per tree is required when designing structural soil cells for healthy root development and long-term tree growth. Key setbacks for these cells include 3 m from property lines and 1.5 m from foundations, ensuring sufficient space for root expansion and preventing structural damage. The use of permeable pavers above tree trenches is also recommended to enhance water infiltration and reduce surface runoff.

For installing GRI around existing trees, setbacks are not provided with a fixed distance, but are universally worded as "outside root protection zone". If trees need to be removed, Victoria recognizes the replacement tree to meet the tree canopy lost from the trees removed and is required to meet a minimum tree number according to the lost area.

To work in riparian areas and protected habitats unique to the Victoria's landscape, only non-invasive techniques are allowed to test infiltration rates or conduct GRI excavation. In light of species selection, Victoria provides detailed planting templates and species lists to ensure that the selected trees and other plants are well-suited to the local environment. These templates consider factors such as soil type, hydrological zones, flooding frequency, microclimate conditions, and plant hardiness. Victoria expresses a clear preference for columnar tree variety, which requires less maintenance cost and had less interaction with the overhead transmission lines.

3.2.2 Toronto, ON, Canada

Toronto's GRI legislation covers all aspects comprehensively, yet a highlight lies in its detailed documentations of the continuous tree trench system, which aims to provide ample space, proper soil volume, and supportive infrastructure for tree growth, allowing the trees to establish to maturity in the urban environment.

For placing trees in various growing conditions in proposed tree trenches, Toronto has a series of tree opening typical drawings including with planter curbs, with tree fences, and tree grates. Using the typical drawing of a tree opening involved in a soil cell system with tree grates as an illustration (Figure 3.2), the tree openings in the continuous tree trench design have a minimum dimension of 1.5 m x 1.5 m. Toronto specifies that the soil volume for each tree should be a minimum of 30 m³. The depth of the growing medium should be between 800 mm and 1600 mm, measured from the sidewalk surface. In areas with high groundwater, a shallow trench with a minimum depth of 600 mm can be used. However, shallow trenches need larger horizontal dimensions to meet the minimum soil volume requirements. The sides of continuous soil trenches must be engineered to maintain a stable angle of repose while providing the necessary soil volume. The use of geofabric or other solid materials around the trench perimeter should be avoided, as they can hinder lateral root growth.

To qualify for GRI installers or field supervisors for soil tree trench projects in Toronto, potential contractors need to meet the City's background check. This includes having successful soil trench installation experience and demonstrating the ability to handle project complexity, as evidenced by the companies

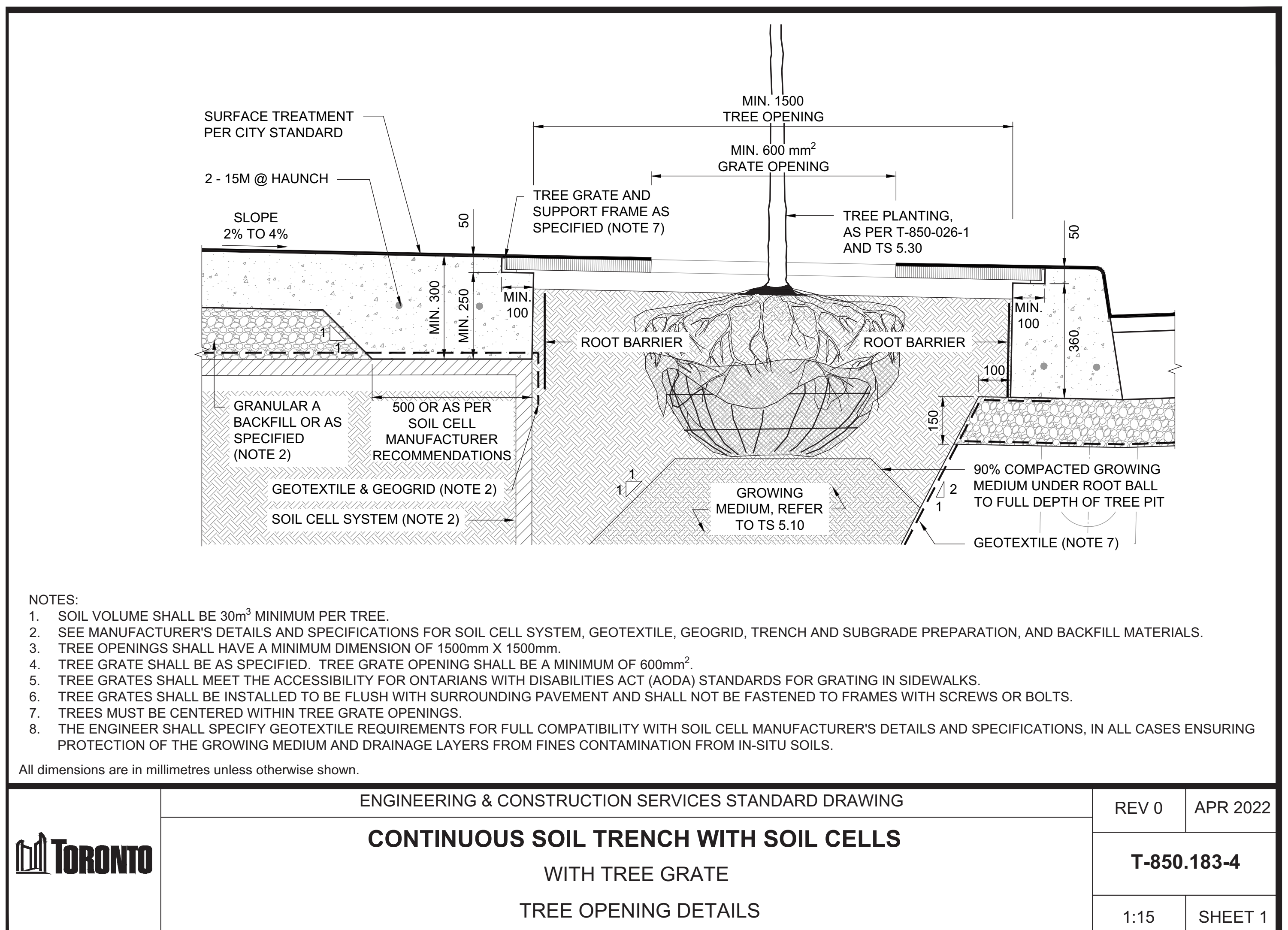


Figure 3.2: Continuous soil trench with soil cells – with tree grate – tree opening details. Source: from Construction Specifications and Drawings for Green Infrastructure (City of Toronto, n.d.).

Table 3.2: Setback requirements for San Francisco. Source: from San Francisco Stormwater Management Requirements and Design Guidelines Appendix C (City of San Francisco, 2016).

Standard Setbacks for Infiltration BMPs in San Francisco		
Distance (ft)	*Setback from*	*Conditions*
5	Property line	Standard for all infiltration facilities
10	Downgradient from adjacent foundations	Standard for all infiltration facilities
100	Upgradient from adjacent foundations	Standard for all infiltration facilities
100	Upgradient from ground slopes 15% or greater	Standard for all infiltration facilities
150	Drinking water well	Standard for all infiltration facilities
Conditional Setbacks for Infiltration BMPs in San Francisco		
Distance (ft)	*Setback from*	*Conditions*
0	Foundations	The BMP is a waterproof, lined, flow-through facility with no infiltration.
0	Foundations	There is no run-on to the BMP facility and a waterproof separation barrier is provided between the BMP drain rock and adjacent foundations.
0	Downgradient from newly proposed foundations	If the drainage area < 1000 ft²; OR if drainage area < 5000 ft² and adjacent buildings do not have basements or are designed with wall drains AND A signed letter from both a professional geotechnical engineer and a professional structural engineer is submitted with the SCP stating that the reduced setback will not result in negative structural impacts on newly proposed adjacent foundations.
50	Upgradient from newly proposed foundations	If the drainage area < 1000 ft²; OR if drainage area < 5000 ft² and adjacent buildings do not have basements AND A signed letter from both a professional geotechnical engineer and a professional structural engineer is submitted with the SCP stating that the reduced setback will not result in negative structural impacts on newly proposed adjacent foundations.
50	Upgradient from existing foundations	If a signed letter from a professional geotechnical engineer is submitted with the SCP stating that the system was designed to protect existing adjacent foundations.

they have worked for in the past five years.

3.2.3 San Francisco, CA, United States

Apart from meeting targets shared across jurisdictions such as stormwater infiltration and water quality, the GRI design concept in San Francisco is specified to minimize chances of land slippage and seismic risk.

San Francisco documents a BMP fact sheet for its GRI design considerations, which deserves recognition. It is speculated that San Francisco's commitment to GRI and street trees is siloed, as no information regarding the rainwater tree trench GRI type or engineered soil products exists in its design guidelines or the standard drawings. The integration of trees is vaguely mentioned in other GRI types including vegetated roofs (like green roofs), permeable pavement, and bioretention. A decent amount of space in San Francisco's GRI design guidelines is dedicated to bioretention systems. Table 3.2 outlines the setback requirements of GRI in San Francisco. A flexible characteristic is that San Franciso allows conditional setbacks to be applied to approved circumstances. The absence of setback requirements applies to waterproof, lined, flow-through systems and planted areas with no incoming water, as long as a waterproof separation barrier is installed between the bioretention aggregate and nearby building foundations.

Like Vancouver, all street trees in San Francisco are protected under its municipal tree protection by-laws. These measures include tree fence zone establishment, root protection, soil management, and construction debris management. Within the city's street trees, San Francisco further identifies individuals as significant trees and landmark trees, whose coordinates are digitally mapped for public access and require additional protection space in terms of construction protection plans.

3.2.4 Portland, OR, United States

Out of the chosen municipalities, the City of Portland has the most detailed GRI management guidelines and offers a systematic walk-through. Portland's guidelines mandate regular maintenance practices for GRI systems, including the removal of dead or stressed vegetation and replanting per the original planting plan or with approved substitutes. This ensures the long-term health and functionality of GRI installations. Moreover, Portland is strategic in going around site constraints and best fits GRI in any existing context. For example, the guideline mentions that incorporating planting strips into curb extensions is encouraged to accommodate larger trees, thus enhancing canopy cover and stormwater management.

Surprisingly, there is no mention of soil cells or structural soils in the City of Portland's GRI guideline. Instead, Portland uses a blended soil for vegetated stormwater facilities. The blended soil is a mixture of loamy soil, sand, and compost. It must contain 30 to 40 percent compost by volume and meet other criteria specified in its guidelines.

Portland's guidelines provide detailed specifications for soil depth depending on the type of GRI facility. For facilities with no subsurface storage, the blended soil depth typically ranges from 1 to 12 inches. Facilities with partial or full subsurface storage have more complex requirements, often ranging from 12 to 36 inches or more, to ensure effective stormwater management and plant growth.

3.2.5 Philadelphia, PA, United States

The GRI design guidelines written by the Phila-

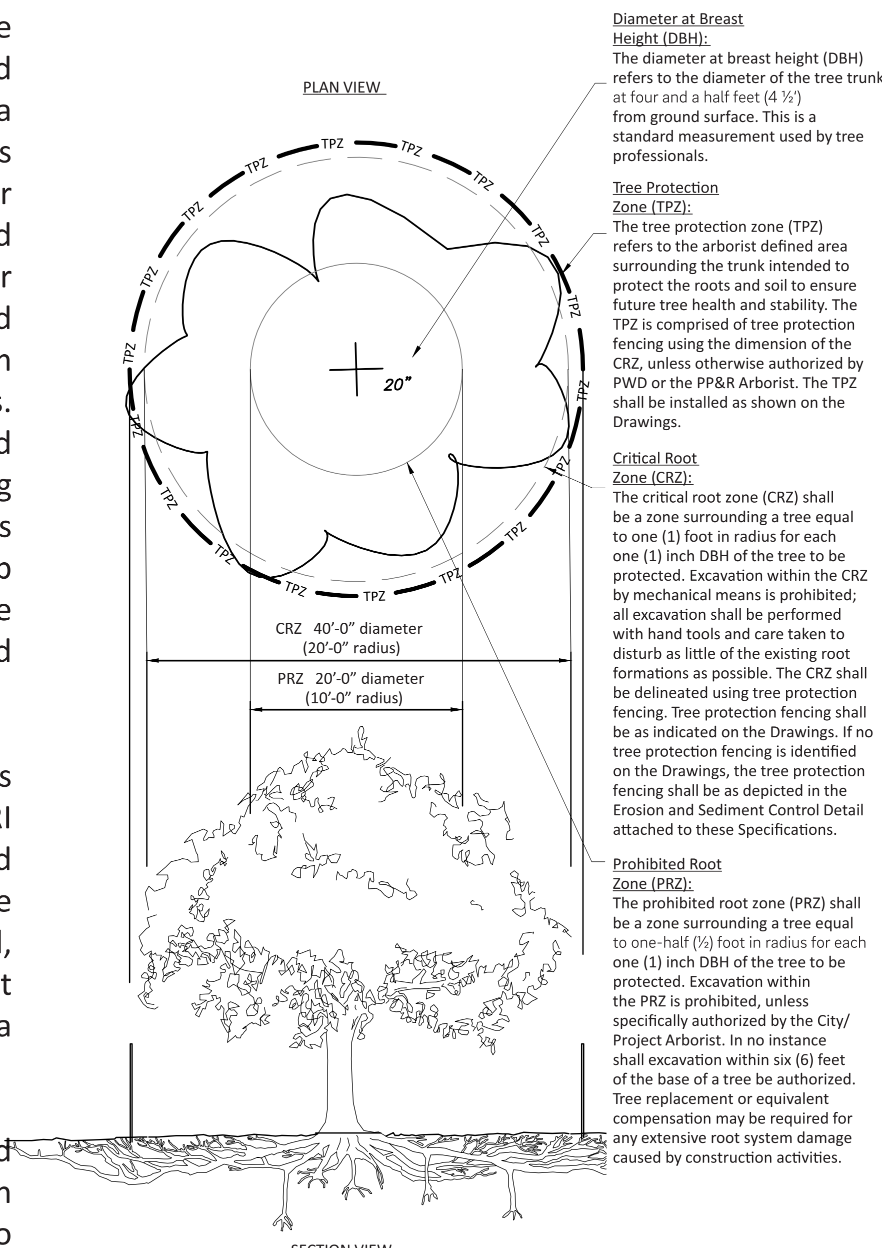


Figure 3.3: Typical Construction Tree Protection. Source: from Green Stormwater Infrastructure Landscape Design Guidebook (Philadelphia Water Department, 2020).

delphia Water Department emphasize the importance of soil depth, appropriate tree species selection, and detailed construction protection strategies.

In Philadelphia, a minimum soil depth of 36 inches is specified for tree pits in GRI systems. In cases where the subgrade is conducive to plant growth and there is no stone beneath the tree pit, a reduced soil depth of 24 inches may be acceptable, subject to the Philadelphia Water Department approval. Distinctions are made between "stormwater soil," used where runoff passes through the soil profile, and "planting soil," used in areas not subjected to runoff. Both types should be topped with 3 inches of compost and mulch before planting. GRI Designers are required to choose species from the approved list in Chapter 3 of the manual, ensuring compatibility with local hydrologic conditions and tolerance to environmental stressors like salt.

Existing trees must be accurately documented starting from the GRI design survey, including canopy dripline and trunk diameter at breast height (DBH). The Philadelphia Water Department mandates the establishment of Critical Root Zones (CRZ) and Prohibited Root Zones (PRZ) to protect tree roots during construction (shown in Figure 3.3):

- The CRZ is determined by a radius of one foot per inch of tree DBH, and no mechanical excavation is allowed within this zone. The Tree Protection Zone (TPZ) surrounds the CRZ and must be delineated with fencing to prevent any construction activity within this area. The TPZ radius equals one foot per inch of tree DBH.
- For trees within the Limit of Disturbance (LOD), additional protective measures such as mulch layers and planking may be required if access within the CRZ is necessary. This is to prevent soil compaction and root damage.
- Trees smaller than 12 inches DBH are not considered to have a CRZ but still possess a PRZ that requires protection.
- The guidelines provide detailed instructions for the installation of tree protection fencing and temporary root buffer protections. For example, when access roads must traverse the CRZ, a protective buffer consisting of shredded wood chips over geotextile fabric, covered by plywood, is required to prevent root damage.
- The root buffer must be at least 6 inches deep and kept clear of the tree trunk. This buffer must be detailed in the project drawings.

3.3 Existing Tree Preservation

3.3.1 What to consider for retrofitting existing tree pits?

Retrofitting established urban trees is becoming more popular as walkable neighborhoods have gained increasing interest over recent years. Below summarizes the key points discussed in a DeepRoot blog discussed best practices in retrofitting tree pits (Staehli, 2018), with a focus on working around GRI.

Field assessment: Field assessment of individual and contextual tree needs, considering factors like trunk flare, surficial roots, pedestrian area width, grade, pavement conditions, curb lane use, utilities, and structures in proximity. This ensures that the GRI design accommodates the specific requirements of each tree, promoting optimal growth and health.

Expanding tree pit space: Increase the surface area of tree pits to enhance soil volume and improve root health. Use excavation methods to avoid root damage, ensuring sufficient space for water infiltration and air circulation.

Grade adjustment: To provide better soil cover over exposed roots, adjust surrounding grades. Employ techniques like air spading to loosen soil and encourage root resettlement, maintaining proper tree-scape integration. This enhances the tree's ability to absorb rainwater, reducing runoff and improving soil moisture levels.
Accommodating adjacent uses: GRI should be designed to work around nearby structures, providing additional water resources to the tree while maintaining urban functionality. Consider nearby parking, curb ramps, and utility structures when expanding tree pits. Ensure compliance with accessibility guidelines and accommodate utilities without compromising tree health.

Surface treatment: Select appropriate surface materials (e.g., wood chips, gravel) based on location and maintenance responsibilities. Coordinating with local authorities or property managers ensures that the chosen materials support both tree health and effective rainwater management, reducing soil compaction and enhancing water infiltration.

3.3.2 Case Study: Successful implementation of the skeleton soils to retrofit existing trees

Context: The Stockholm system, also known as stone skeleton substrates, is a tree-rooting environment built with large stones. It facilitates stormwater infiltration and ensures gas exchange. Below documents key lessons of a project reported by Trees and Design Action Group (2014). The project took place in Kornhamnstorg, Sweden, a public square in Stockholm's old town. the Stockholm system was implemented to improve lime trees which exhibited early signs of poor health (Figure 3.4).

Figure 3.4: Great lime tree growth after project completion. Source: from Trees and Design Action Group (2014).

Tips for Success:

1. **Technical Supervision**: Rigorous implementation and good technical site supervision are crucial. Train the construction manager thoroughly.
2. **Water Needs Estimation**: Estimate tree water needs during the growing season and ensure sufficient surface water runoff. Consider drainage rates and possibly install an overflow drain to the sewer system.
3. **Stone Grading**: Ensure consistent stone fractions to maintain voids for root growth. Verify specifications upon delivery.
4. **Soil Composition**: Avoid high clay or organic matter content to facilitate soil watering. Keep fines under 8% and organic matter between 2-4%.
5. **Layered Construction**: Compact stones first, then water in soil layer by layer without pre-mixing.
6. **Geotextile Membrane**: Place a membrane between the aeration layer and the surface subgrade, but not between the aeration layer and the skeleton soil mix to ensure proper system function.
7. **Root Ball Protection**: Cover and irrigate root balls using green watering bags around each tree.
8. **Careful Root Pruning and Clearing**: Use non-inva-

Figure 3.5: High-quality soil application around pruned and cleared root balls. Source: from Trees and Design Action Group (2014).

Some non-invasive tools are:
- Hydro-vacuum: which uses high-pressure water to loosen soil around roots, allowing for careful excavation without damaging the roots.
- Air spading: which employs compressed air to break up soil, exposing roots gently and minimizing harm to root systems.

To avoid damage to root balls:
- In the report by Costello and Jones (2003), documented root loss guidelines vary among cities; the authors suggest that roots smaller than 2.5 cm in diameter can generally be cut without restriction, but roots larger than 5 cm typically require approval.
- It is generally suggested that pruning be done as little as possible, and there is no universal specification on how much root pruning can be done to not endanger tree's survival (Randrup et al., 2001).
- For the timing of root pruning, it is recommended to conduct in the fall, followed by transplanting in the spring, which lets plants develop new feeder roots in the pruned area during winter (PennState Extension, 2023).

3.3.3 Case Study: Practices to avoid for enhancing tree protection

Context: Arthur Lierman Landscape Architecture was tasked with preserving a mature Black Walnut tree for a construction project in the 366 Hill Street Townhomes in London, Ontario, Canada. The construction was to build a three-storey stacked townhome complex on a vacant asphalt parking lot. Key takeaways were distilled from Tree Preservation Report Hill Street Development (Arthur Lierman Landscape Architecture, 2021).

DO NOT:

- Create Physical Damage to the Tree:
  - Do not allow equipment, materials, or construction activities to come into contact with tree branches, trunks, or roots.
  - Do not wrap rigging cables around trees or install them in trees.
  - Do not let construction equipment abrade or damage tree limbs.
- Introduce Soil Compaction:
  - Do not permit heavy equipment or stockpiling of materials within the Tree Protection Zone.
  - Install a 100 mm layer of **wood chips** covered by 19 mm thick plywood over the root zone to prevent soil compaction.
  - Alternatives to plywood, such as **interlocking steel plates** or **plastic ground protection mats**, may be used over the wood chips.
- Disturb Roots:
  - Avoid open trenching within tree root zones; use trenchless techniques or careful hand excavation instead.
  - Use non-invasive digging methods like **hydro-vacuums with controlled pressure**: “maximum operating pressure 900psi until roots show, then 300-400psi to remove soil around and under roots.”
- Dry Out Roots:
  - Keep roots constantly damp and protected from sun and wind during excavation.
  - Avoid discharging rainwater leaders adjacent to trees to prevent overly moist conditions that can cause root rot.
  - Use techniques like a **plywood box retainer** and backfill to maintain root moisture.
- Downgrade Protection During Excavation:
  - Do not remove tree protection fencing during construction without proper authorization and immediate replacement.
  - Avoid exposing roots for extended periods; backfill excavation holes immediately to maintain moisture.
- Create Grade Changes:
  - **Avoid making significant grade changes** within the Tree Protection Zone without proper consultation and approval from a certified arborist.
  - Do not make significant grade changes without using protective measures like **retaining walls or tree wells** to protect roots.

3.3.4 Case Study: Silva Cells provide additional soil volume for the mature street tree

Context: In 2021, Gallant Avenue in North Vancouver’s Deep Cove neighborhood underwent streetscape improvements (Deeproot, n.d.). A preexisting Bowhall maple tree with originally 1-2 m^3 of healthy soil medium was successfully preserved by using hydro-vacuum excavation under a certified arborist’s supervision to expose its roots. Silva Cells were then installed around the roots, significantly increasing the available soil volume and promoting healthy root growth without causing root damage.

With the support of the City of Vancouver’s Urban Forestry Department and in consultation with Michael James, Deeproot’s general manager and project lead for the Gallant Avenue initiative, the following are highlights of this case study:

- Non-Invasive Root Exposure:
  - Technique: Hydro-vacuum was used for exploratory excavation, a non-invasive method that safely exposed the tree’s roots. A certified arborist oversaw the process to ensure the roots were handled with care.
- Flexible Silva Cell Installation:
  - Depth Flexibility: Silva Cells closest to the critical root zones were stacked in two layers, providing ample soil depth for roots to access healthy soil and penetrate deeper.
  - Modular System: Shallower Silva Cells were used further from the root zones to accommodate varying root depths and spacing needs.
  - Root Accommodation: The design allowed roots to be gently folded into the stacked Silva Cells, preventing damage and promoting healthy growth.
- Case-Specific Approach:
  - Adaptability: Each project involving existing trees is unique. As emphasized by Michael James, the specifics of working around a mature tree can only be determined after excavation and exposure of the root system.
  - Arborist’s Role: The acceptable level of root pruning and other critical decisions were made by the arborist on-site, ensuring the tree’s health and stability.

Figure 3.6: Installing Silva Cells and carefully folding the roots of the preserved Bowhall maple tree into the cells to provide access to increased soil volume. Source: from Deeproot (n.d.).

4. CANOPY ANALYSIS

4.1 Study Area

In implementing GRI, trees have often been treated as an excellent aesthetic and functional feature for reducing the urban heat island effects and improving stormwater management in limited urban space. Currently, most discourse involving GRI has been centered on reporting the establishment of GRI, ensuring the success of stormwater infiltration, and rainwater capture, and the benefits GRI brings to the local communities. Yet, the health of trees within GRI is seldom monitored or quantified. The GRI assets have been designed with a vision of becoming long-lasting ecological legacies in the urban areas, and a better understanding of their efficacy for tree growth would shed light on the city's future planning and design considerations. Taking advantage of Vancouver's status as an early adopter of GRI and the availability of urban forest datasets, this section focused on examining GRI effects on urban tree canopy growth rates on public lands in the City of Vancouver, Canada. To the author's knowledge, this analysis was the first of its kind to examine the effects of GRI (specifically, structural soils and soil cells) on urban tree growth performance to a city-wide extent.

To specify, the term, standard tree pit, encompassed: 1) trees grown in open grass boulevards, or back boulevards ("Grass"); and 2) trees grown in concrete pavements or cutouts ("Concrete/cutouts"). Trees in GRI were classified as any trees which grow in any type of GRI found in Vancouver. Trees in structural soils and soil cells were narrowed down to those that grow within the Rainwater Tree Trench GRI. This section did not consider trees grown in other conditions, such as in laneways or in streets without sidewalks.

Table 4.1: information about data sources and data accuracy.

Data	Year	Description	Accuracy
Vancouver GRI assets	2024	Showing the location and extent of all GRI assets in Vancouver, this database has been monitored by the Green Infrastructure Implementation branch.	The GRI assets aretraced from georeferenced Auto-CAD drawings and the accuracy is ~ 1 meter.
Vancouver tree canopy	2018, 2022	The Urban Forestry department combined 4-band leaf-on orthoimagery and LiDAR remote sensing to generate the city-wide canopy map using machine learning.	Manual editing was done to remove artifacts, and tree height and crown area metrics were calculated based on a 3m height cut-off. As deciduous trees tend to be overestimated by the algorithm, the canopy precision is higher for coniferous trees.
Vancouver street trees	2024	As part of the ongoing efforts to monitor and manage Vancouver's urban trees, the Urban Forest Strategy has identified and maintained the street trees with various tree characteristics (i.e., diameter, height, species name, etc.) in Vancouver.	Tree coordinates and attributes are frequently updated to ensure relevance, yet some tree attributes are updated less frequently, potentially spanning multiple years.
Vancouver local area boundary	2023	This dataset depicts the 22 neighbourhood boundaries in Vancouver and do not change over time.	The boundaries are delineated to algin with the median lines of streets.

4.2 Methods

4.2.1 Data Source

Tree canopy growth rate was used as a proxy for urban tree health. Tree canopy expansion is one of the key indicators for assessing forest vigor, and recent measurement advances envision a transition from repeated, in-situ forest surveys to LiDAR remote sensing (Song et al., 2016). Moser et al. (2020) pointed out that canopy growth indicates how well a tree adapts to its environment. Additionally, in urban settings, tree canopy cover is extensively used as a management target by urban forest planners, underscoring its practical applicability (Chen et al., 2020). While other years' data were also available, the tree canopy performance was based on city-wide tree canopy in 2018 and 2022 because of data consistency. The main data sources were provided by the City's Green Infrastructure Implementation Branch and the Urban Forestry Department, and the rest were acquired via the City of Vancouver's Open Data Portal. Table 4.1 displays the dataset information.

4.2.2 Data Processing

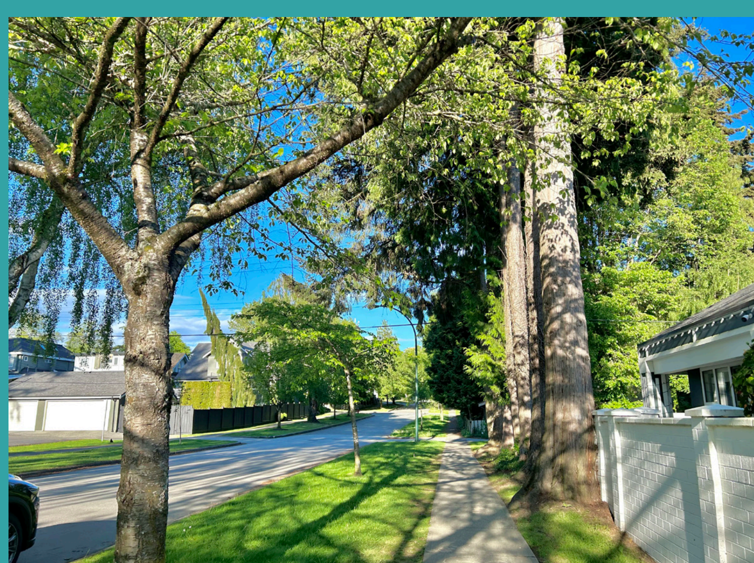
The geospatial data was processed in ArcGIS Pro 3.3.0 (ESRI Inc., 2024). All data was projected to the NAD 1983 UTM Zone 10N coordinate system. Firstly, a one-to-one spatial join was performed on the street tree point layer with the tree canopy layers from 2018 and 2022. The tree canopy was spatially joined to the street tree point if the tree canopy was within a 1-meter search radius of the street tree point. The 1-meter search zone tolerance was based on the assumption that street tree coordinates were recorded closer to the tree trunk and considering that the canopy might grow towards the sun or due to slope/building barriers, sometimes the canopy might not be directly on top of the tree trunk. Next, using the Select Attribute by Location tool, the street tree is categorized as within or not within the footprints of GRI assets. Street trees outside GRI assets were further classified as grass boulevards or concrete/cutouts based on planting locations.

Since each GRI is designed to capture water and direct the flow through its system to alleviate rainwater runoff and reduce the pressure on the City's sewers, it is important to assess whether trees located at different distances from the GRI exhibit varying canopy growth rates. This assessment is crucial because GRI may alter the hydrological content of the surrounding soils, affecting tree health. Multiple ring buffers were conducted to assign street trees as 0 m-1 m, 1 m-2 m, 2 m-3 m, and 3 m-5 m in proximity of GRI footprints. Additionally, only street trees that grow along the same side of the GRI were carried out with multiple-ring buffers. This is because technically speaking, the rainwater overflow created by GRI will be directed to trees planted on the same street side of that specific GRI, due to impervious pavement and blockage of various utilities (i.e. GRI on the odd side of a street can hardly direct rainwater to a tree which grows on the even side of the same street).

4.2.3 Data Analysis

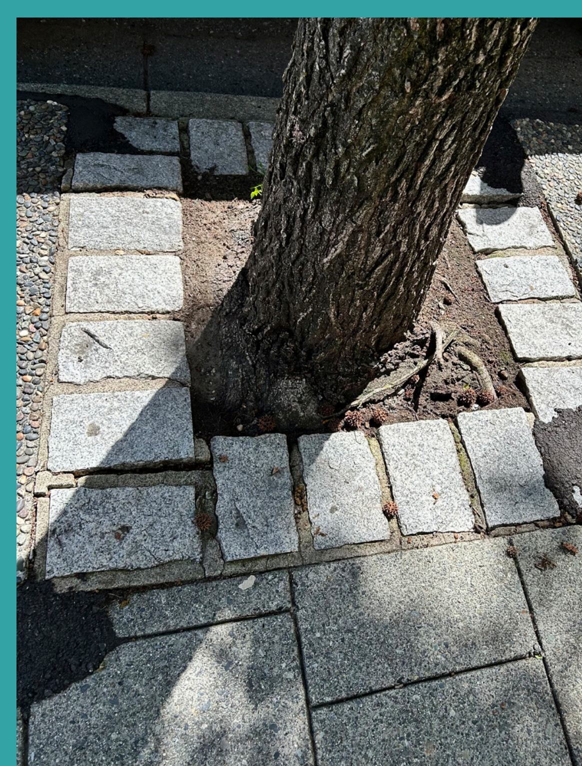
The geospatial data was then exported to R 4.3.2 (R Core Team, 2024). At the initial ex-

A tree in open grass boulevards. Photo taken in Sunset Park.



Trees in grass boulevards. Photo taken in Kerrisdale neighbor-hood, Vancouver. Trees closer to the street are in a 12-feet open grass boulevard, and trees closer to the white property fence are in back boulevard.

A tree in an upheaved tree grate. Photo taken in Granville Street, downtown.



A tree in concrete pavement. Photo taken in Carrall Street, downtown.

A tree in a bioretention system. Photo taken in Carrall Street, downtown.

A tree in a rainwater tree trench system with strucural soil underneath the pavement. Photo taken in Richards Street, downtown.

ploratory analysis, the data was found to be skewed upon histogram visualization and the QQ plot normality check. Data points that distributed outside 1.5 times of the interquartile range were considered as outliers and were removed before proceeding to data analysis.

Trees typically exhibit exponential growth patterns, especially in their early years; also, tree canopy size differs across species. Rather than comparing the mere difference in crown canopy between 2018 and 2022, these factors prompted the normalization of canopy growth according to the baseline canopy size, which allows for comparison across different tree species and age groups. Canopy growth rates were calculated using the equation: Normalized Canopy Growth Rate (%) =

(Canopy 2022- Canopy 2018)
*Canopy 2018 * 100%*

where Canopy 2018 and Canopy 2022 are in m^2.

T-test was used to confirm whether the canopy growth rates are significantly higher for trees grown in GRI soils than in standard tree pits:

t.test(Trees Outside GRI, Trees Within GRI, alternative = “less”)

ANOVA was used to 1) compare the 2018-2022 canopy growth rates across tree pit locations; and 2) compare the 2018-2022 canopy growth rates across distance to GRI, tree status (new vs existing), and their interaction effects:

(Growth Rate ~ Tree Pit Location)
*(Growth Rate ~ Tree Status * Distance)*

For each ANOVA analysis, the Tukey test was used for post-hoc pairwise comparisons in order to understand which pair(s) of factors significantly differed from each other. For all statistical analyses, p-value = 0.05 was chosen in interpreting the significance of analysis results (for instance, if p > 0.05, there is no sufficient evidence to conclude that the effect is statistically significant).

4.3 Results

4.3.1 What Trees Are Found in GRI?

As an overview, to date, the City has had nearly seven hundred unique tree species. Out of all species records, fifty-seven tree species have been found within GRI footprints. Figure 4.1 displays the dominant tree genus within GRI. The four most common tree genus types are maple (21.8%), followed by hornbeam (18.6%), oak (15.2%), and birch (8.6%).

Of the canopy growth data available, 47 within-GRI tree species’ canopy growth rates were assessed. As shown in Figure 4.2, species are arranged based on the ascending order of their normalized canopy growth rates from 2018 to 2022. In reference to the city-wide (regardless of trees located in GRI or not) median canopy growth rates, 21.6%, depicted in the dashed

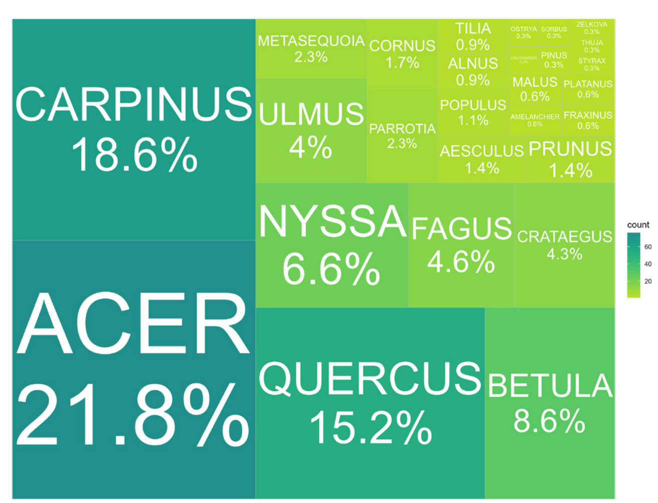


Figure 4.1: The percent of genus occurrence for trees within GRI footprints.

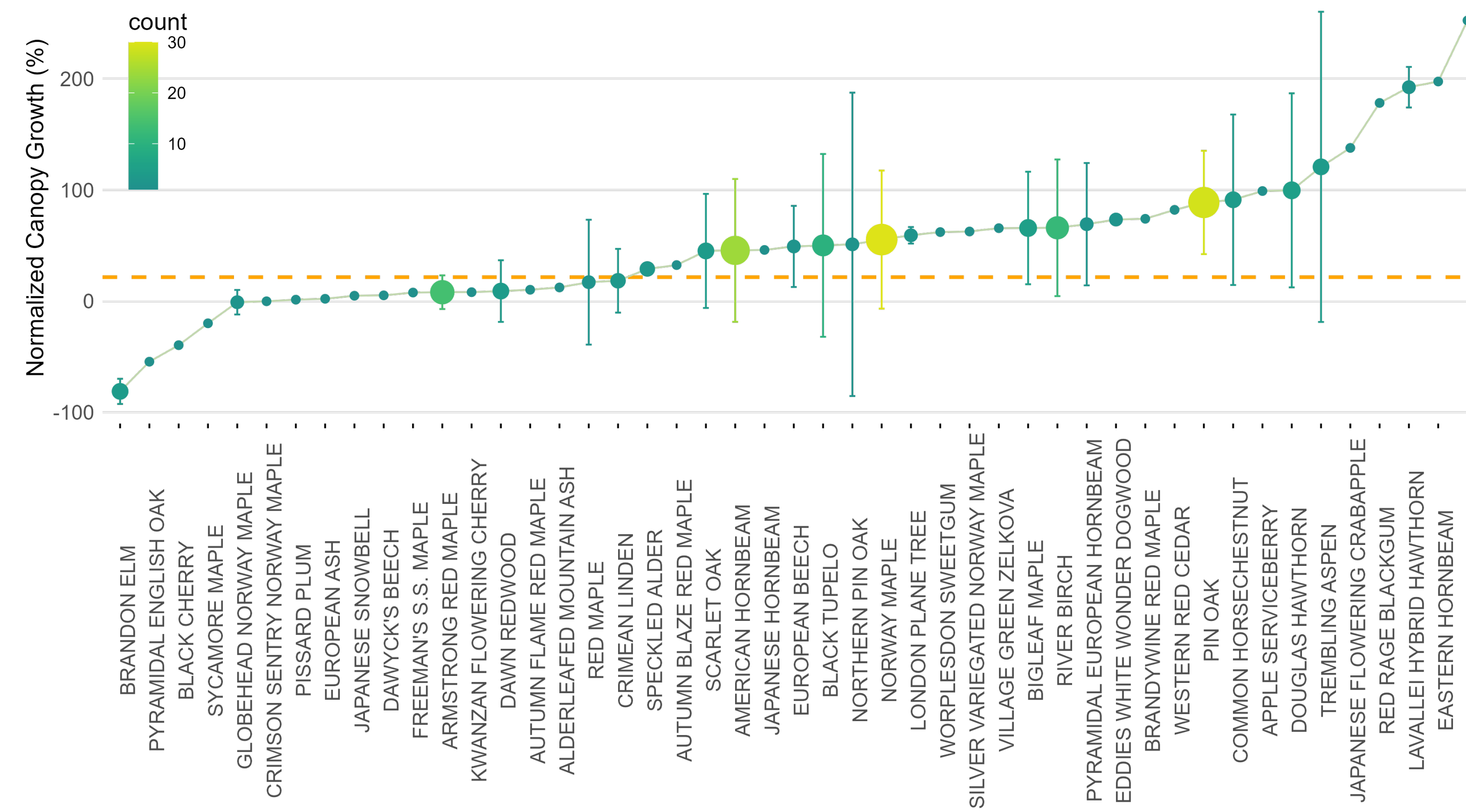


Figure 4.2: Mean 2018-2022 normalized canopy growth (%) by tree species within GRI footprints. The Orange dashed line indicates the median canopy growth city-wide. Error bars represent mean ±1 standard deviation. The absence of error bars indicates insufficient data for assessing species-specific canopy growth.

orange line, 29 species outperformed this baseline. Looking at the extreme growth values, Trembling aspen has the maximum canopy growth rate, 241.5%, and Brandon elm has the minimum canopy growth rate, -69.2%.

When analyzing species-specific canopy growth, not all trees were guaranteed with more than two samples having both available canopy data detected from 2018 and 2022. This might partially explain the large spread of standard deviations observed in species depicted in Figure 4.2. It is worthwhile to note that Lavallei hybrid hawthorn, Pine oak, Pyramidal European hornbeam, Bigleaf maple, and European birch display rather stable canopy growth performance.

4.3.2 Canopy Growth Rates of Trees in GRI vs. Trees in Standard Tree Pits

Figure 4.3 shows the mean canopy growth rates with standard errors from 2018 to 2022 of trees grown within or outside GRI footprints. To test the hypothesis of whether the average canopy growth rate from 2018 to 2022 of trees outside GRI footprints is statistically less than that of trees within GRI footprints, a one-sided t-test was conducted. The results showed a t-statistic of -3.4961 and a p-value of 0.0002924 which is smaller than the alpha level of 0.05, providing strong evidence to reject the null hypothesis. The 95% confidence interval for the difference in means is (-Inf, -8.992418). In other words, trees grown within GRI footprints show statistically significantly higher average canopy growth rates compared to those grown outside GRI footprints.

Figure 4.4 shows the average canopy growth rates with standard errors from 2018 to 2022 by four tree pit locations: cutouts/concrete, grass, structural soil, and soil cells. ANOVA was used to compare the mean canopy growth rates from 2018 to 2022 across the four selected tree pit locations. The results indicated a significant effect of tree pit location on canopy growth rates ($F = 6.47$, $p = 0.000225$).

Tukey's test was conducted for post-hoc pairwise comparisons. It was found that trees in cutouts/concrete locations had statistically significantly lower mean canopy growth rates in contrast to those in grass locations (mean difference = 3.52, $p = 0.0001836$). No significant differences were found between any other pairs of tree pit locations, as shown by the letters above the ANOVA bar plots in Figure 4.4.

4.3.3 Canopy Growth Rates of New Trees vs. Existing Trees

Figure 4.5 shows the canopy growth rates for both new and existing trees by distance to the major types of GRI footprints (encompassing bioretention, rainwater tree trench, subsurface infiltration, and permeable pavement). The statistics displayed in Figure 4.5 can be found in detail in Table A.2.

The following discusses findings about how street tree canopy growth rates vary with distance from GRI assets for both new and existing trees. In short, the mean canopy growth rate tends to vary with distance from GRI footprints. New trees generally show higher growth rates across all distances and typologies compared to existing trees, possibly due to better adaptation, water availability, and intrinsic exponential growth patterns. Some categories have extremely high variability, such as new trees 1-2 m near rainwater tree trench (standard error = 76.7%). This could be due to small sample sizes

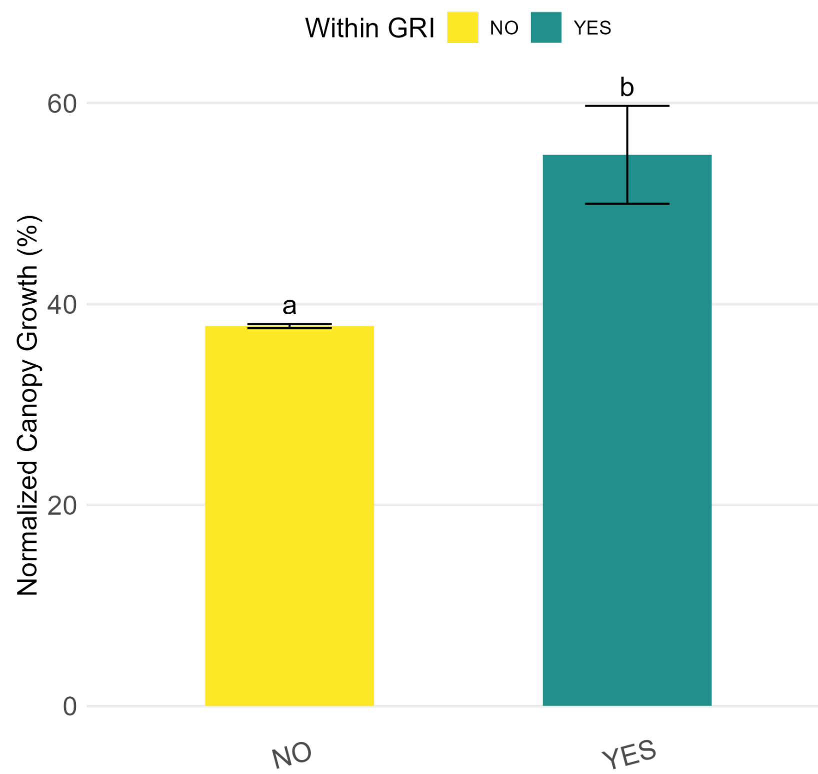


Figure 4.3: Mean 2018-2022 normalized canopy growth (%) by GRI influence. Error bars represent mean ±1 standard error.

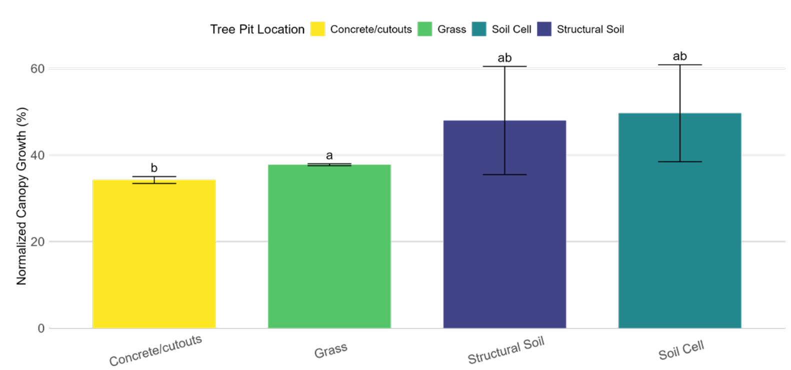


Figure 4.4: Mean 2018-2022 normalized canopy growth (%) by selected tree pit locations. Error bars represent mean ±1 standard error.

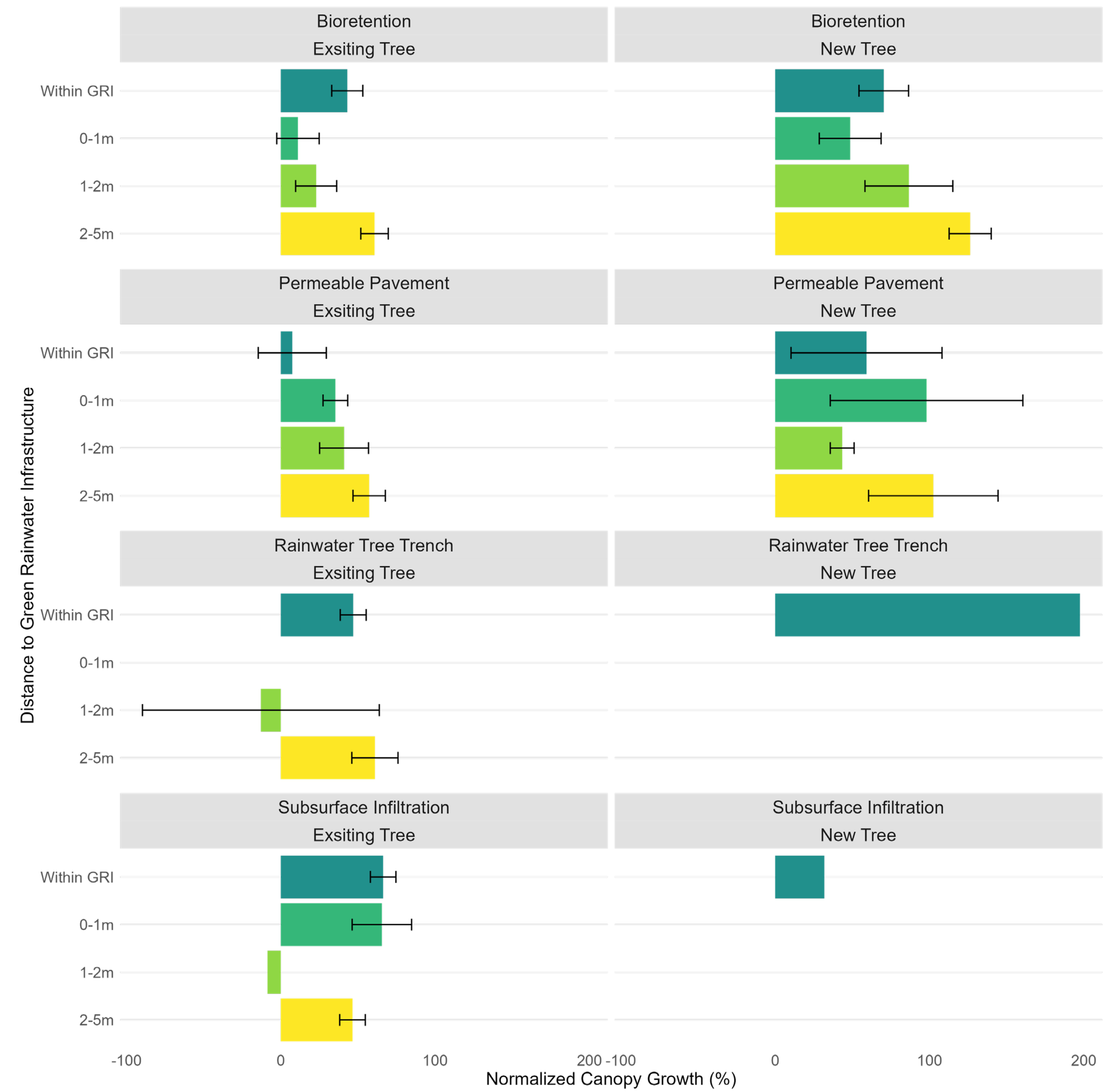


Figure 4.5: Mean 2018-2022 normalized canopy growth (%) by distance (m) to GRI footprints: in GRI footprints (Within GRI), 0-1m from GRI footprints, 1-2m from GRI footprints, and 2-5m from GRI footprints. Error bars represent mean ±1 standard error. The absence of error bars indicates insufficient data for assessing species-specific canopy growth.

(e.g., entries having only 1 or 2 trees), leading to less reliable estimates of mean growth and higher standard errors.

For existing trees that are 0-1 m from bioretention GRI, the mean canopy growth rate (11.13%) is relatively low compared to other distances. The relatively high standard error (13.75%) also suggests less consistent growth. This implies that bioretention may not be as effective at enhancing tree growth for existing trees at such proximity, potentially due to insufficient soil aeration and drainage. Permeable pavement could be a more suitable GRI type for areas where trees are located within 0-1 m, which is approximately 3.2 times higher than that for bioretention (35.38% vs. 11.13%). With that said, subsurface Infiltration is the most effective to install 0-1 m around existing trees, showing approximately 5.9 times better growth than bioretention and 1.9 times better than permeable pavement. It is speculated that bioretention systems could lead to periodic soil saturation after high-intensity rainfall. Subsurface infiltration systems might be able to maintain a more consistent water supply, acting as a sponge to get trees through drought periods, while not suffocating the root systems when soil moisture is overloaded.

For new trees, while data is limited, both within GRI and 2-5 m distances show promising growth, though variability is higher within GRI. Keeping in mind that new trees in the City have been planted in recent years and their canopy growth might not yet be detected by the LiDAR technique. Given the limited sample sizes and the high variability in growth rates, it is important to interpret the data for new trees with caution.

To back up the findings from Figure 4.5 with statistical evidence, ANOVA and post-hoc Tukey tests were performed to compare the effects of tree status (new tree or existing tree), the distance to GRI footprints, as well as their interaction effect. None of the pairwise comparisons for the interaction effect were significant. The post-hoc pairwise comparison showed a statistically significant difference between new and existing trees, with new trees having a higher growth rate (p adjusted = 0.0086503). Speaking of the distance effects, even though the comparison between 2-3 m and 0-1 m approached significance (p adjusted = 0.0552689), pairwise comparisons of canopy growth rates across different distances to GRI showed that most differences were not statistically significant after adjusting for multiple testing. This suggests that while proximity to GRI influences growth, new trees generally exhibit better growth irrespective of their distance from the GRI.

4.4 Limitations

To enhance the accuracy of GIS data, suspicious projections of GRI and street trees were checked using Google Map Street views, past GRI project drawings and selected site visits were conducted to confirm whether trees are within or outside GRI. Despite this, the project was completed in a limited time frame, and the author acknowledges that the data quality could be further refined.

It is worthwhile noting that while LiDAR point cloud data enabled precise mapping of tree canopy, trees with a height of less than 3 meters were not captured, such as young or shorter trees. This resulted in some canopies being unrepresented during the spatial join, despite their presence in reality. For the buffer analysis, the data analysis did differentiate the street sides of the trees, yet the spread of the tree root zones was not incorporated as root growth patterns vary substantially in heterogeneous urban areas.

5. RECOMMENDATIONS

Gone are the days of ample space and a tranquil pacing. Nowadays, the City of Vancouver has become a rapidly modified and developed urban area with multiple priorities to address simultaneously in the face of climate change and the rising housing crisis. Amid all these backdrops, in order to favor street tree growth and urban forest management, it is encouraged:

5.1 For Regulations

That the City ensure continued discourse of street tree integration with GRI implementation

- It is concluded from the above statistical analysis that the canopy growth rates of trees in GRI significantly outperform that of trees in non-GRI areas. This could contribute to numerous City of Vancouver Climate Change Adaptation Strategy's equity outcomes such as A1.4, H3.1, H3.2, R2.3, that are related to addressing urban tree canopy cover in Vancouver (2024c).

That the City promote inter-departmental coordination involving street tree health and GRI implementation

- The GRI design process is iterative, and so does tree planting. Vancouver has been standardizing regulations for GRI and tree protection. Yet, different regulations exist in different departments which sometimes trigger grey areas in terms of governing street assets. If inter-departmental coordination is improved, this would facilitate and accelerate tree-related project launching.

That the City increase public participation regarding street trees and GRI

- Interviewed experts reveal that obtaining a consistent water supply has been a threat to the survival of urban trees in dry periods. Engaging the public through citizen science programs, such as "tree health monitoring" or "watering volunteers", or by launching incentive programs, like "tree credit" and "rainwater credit" other North American jurisdictions are adopting, could facilitate the issue effectively.

5.2 For New Trees

That the City adjust nursery schedules and practices to adapt to the ongoing changing climate conditions

- The Metro Vancouver region is projected to see a reduction in frost days from 79 to 33 by the 2050s (Metro Vancouver, 2016). Tree dormancy and chilling requirements are critical for successful transplantation. Nursery stocks that have not experienced sufficient chilling may struggle to adapt to their new environment. Future frost day length will be essential for determining transplantation timing. Trees that are not adequately chilled may not exit dormancy properly, and frost exposure after chilling requirements are met can be lethal, causing significant damage or death to young trees.
- Additionally, some native species may need to be phased out in the future, and non-native species may outperform native species under these new conditions, requiring a re-assessment of species selection to ensure resilience and sustainability.

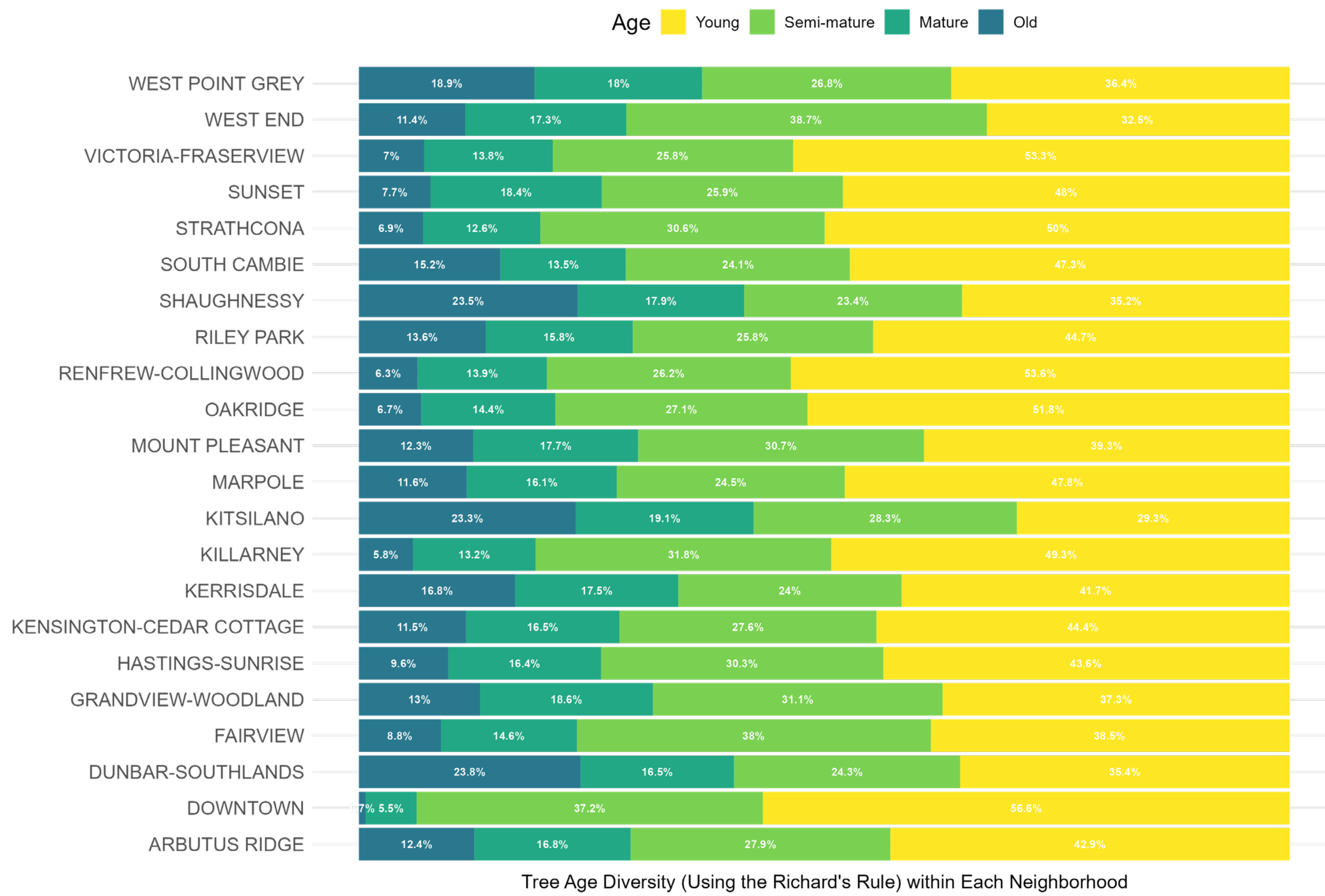


Figure 5.1: Tree Age distribution based on the Richard's Rule, grouped by local neighborhoods in Vancouver.

That the City increase city-wide tree pit space

- Rather than simply basking under the shade, we should not forget the roots that sustain our urban canopy. This suggestion speaks to the success of achieving equity outcomes H3.1, H3.2 in the Climate Change Adaptation Strategy (City of Vancouver, 2024c). Inspired by Toronto's focus on continuous tree trench systems and Portland's strategic guidelines for various GRI site constraints, Vancouver could enhance the GRI drawings by incorporating alternative substrate materials like porous asphalt, soil with planter curbs, and tree fences. These updates would support tree health more effectively and reducing long-term damage to both trees and infrastructure.

That the City provide a comprehensive landscape plan for GRI installation

- As a learning opportunity from the jurisdiction scan, Vancouver could enhance its GRI practices by adopting a detailed landscape plan similar to Philadelphia's approach. This plan can include a planting strategy that preserves existing vegetation, outlines the locations of landscape elements, and provides specifics on proposed plantings, including size, species, and planting zones.

That the City consider conditional setback distances for new GRI

- Based on the jurisdiction scan, San Francisco implements flexible setback requirements when GRI designs meet specific criteria (refer to Table 3.2 for details). As highlighted in the expert interview, one of the proposed changes by the City's Street Tree Standards Working Group is to reduce the 300 mm clearance from curbs for standard tree pits. To balance the need for sidewalk stability with the goal of maximizing GRI space, this could be achieved through further examination, such as conducting risk analyses.

5.3 For Exisitng Trees

That the City intentionally consider implementing GRI in more needed neighborhoods

- To address the City's equity issues on extreme heat and poor air quality (City of Vancouver, 2024c), it is crucial to prioritize the implementation of GRI in neighborhoods that need it the most. While the installation of GRI has often been opportunistic, a more strategic approach is ideal to ensure all communities benefit from its advantages. As shown in Figure 5.1, the tree age distribution varies across local neighborhoods. For example, neighborhoods like Downtown and Renfrew-Collingwood, which have a higher proportion of young trees (56.6% and 53.6%, respectively), present future opportunities to integrate GRI with existing urban forestry efforts to support the growth and health of these young trees.

That the City evaluate potential GRI implementation sites with the following distance considerations

- First, retention of existing trees in GRI implementation must ensure species compatibility with improved stormwater runoff.
- Existing trees can be manipulated and designed to fit within 2-5 m of future GRI (types include stormwater tree swale, bioretention, permeable pavement, and subsurface infiltration), as based on available data, the optimal planting location for existing trees is approximately 2-5 m from GRI footprints.
- Subsurface infiltration and permeable pavement GRI type could be prioritized if trees are located within 0-1 m, as it appears to support better growth and consistency for existing trees based on the results of the statistical analysis above.
- It may be beneficial to avoid existing trees within 0-2 m of the bioretention areas. Alternatively, it may be useful to improve soil conditions and ensure proper drainage and aeration in the immediate vicinity to improve growth rates, but perhaps at the cost of more labor.

That the City include tree mortality to facilitate future growth performance evaluation

- This study did not account for tree mortality rate at the species level. Implementing long-term monitoring programs can track tree health and mortality rates over time. This will provide insights into the lifespan of different tree species and the effectiveness of current planting and maintenance practices, which helps to optimize resource inputs.

That the City use non-invasive techniques to minimize disturbance of critical root zones of existing trees during excavation

- Leverage practices from case studies explored in Section 3.3 that focus on existing tree preservation. While these case studies did not specifically address stormwater management for existing trees, the principles and techniques used can be adapted and applied to GRI installations.

That the City consult with certified arborists for ongoing maintenance and care of trees influenced by GRI installation

- Arborists bring specialized knowledge that is crucial for the effective care of trees impacted by GRI projects. It is important to understand that standardizing methods for preserving existing trees is challenging due to the unique characteristics of each site. Engineers should acknowledge the variability and case-specific nature of tree preservation and collaborate closely with arborists who have the expertise to tailor solutions to individual situations.
- Encourage a collaborative approach where arborists have a significant voice in the planning and implementation of GRI projects. This ensures that the expertise of arborists is integrated into the design and execution phases, leading to better outcomes for both tree health and stormwater management.

5.4 Recommended Tree List

Here, the recommended tree lists for GRI is displayed. The first part is based on preliminary data analysis from the city-wide extent and it includes species with canopy growth rates exceeding the city-wide median value, as shown in Figure 4.2. The second part is drawn and cross-referenced from various sources: available species used by scanned municipalities (see Appendix), Metro Vancouver's climate-adapted urban tree list, and USDA's i-Tree Species simulator using the San Diego climate.

Common Name	Scientific Name	Part one or two
Bigleaf Maple	*Acer Macrophyllum*	Part one
Norway Maple	*Acer Platanoides*	Part one
Red Maple	*Acer Rubrum*	Part one
Common Horsechestnut	*Aesculus Hippocastanum*	Part one
Speckled Alder	*Alnus Rugosa*	Part one
River Birch	*Betula Nigra*	Part one
Pyramidal European Hornbeam	*Carpinus Betulus*	Part one
American Hornbeam	*Carpinus Caroliniana*	Part one
Eddies White Wonder Dogwood	*Cornus Xx*	Part one
Douglas Hawthorn	*Crataegus Douglasii*	Part one
Lavallei Hybrid Hawthorn	*Crataegus Lavallei X*	Part one
European Beech	*Fagus Sylvatica*	Part one
Black Tupelo	*Nyssa Sylvatica*	Part one
London Plane Tree	*Platanus Acerifolia X*	Part one
Trembling Aspen	*Populus Tremuloides*	Part one
Scarlet Oak	*Quercus Coccinea*	Part one
Northern Pin Oak	*Quercus Ellipsoidalis*	Part one
Pin Oak	*Quercus Palustris*	Part one
Crimean Linden	*Tilia Euchlora X*	Part one
Strawberry tree	*Arbutus unedo*	Part two
Incense cedar	*Calocedrus decurrens*	Part two
Sugar berry	*Celtis laevigata*	Part two
Hinoki false cypress	*Chamaecyparis obtusa*	Part two
Ginkgo	*Ginkgo biloba*	Part two
Honey locust	*Gleditsia triacanthos*	Part two
Sweetgum	*Liquidambar styraciflua*	Part two
Tulip tree	*Liriodendron tulipifera*	Part two
Swiss mountain pine	*Pinus mugo*	Part two
Longleaf pine	*Pinus Palustris*	Part two
Loblolly pine	*Pinus Taeda*	Part two
Douglas-fir	*Pseudotsuga menziesii*	Part two
Callery pear	*Pyrus calleryana*	Part two
Garry oak (Oregon white oak)	*Quercus garryana*	Part two
Bur oak	*Quercus macrocarpa*	Part two
Pacific willow	*Salix lucida*	Part two
Sitka willow	*Salix sitchensis*	Part two
Japanese tree lilac	*Syringa reticulata*	Part two
Zelkova	*Zelkova serrata 'Green Vase'*	Part two
Zelkova	*Zelkova serrata 'Village Green'*	Part two

6. CONCLUSION

The City of Vancouver is doing a good job in comparison to other municipalities in North America in integrating GRI with street trees. Vancouver effectively identifies opportunities for GRI installation and adapts its approach to various urban environments. The City has policy regulations for tree protection and departmental specialization for building GRI projects. Additionally, Vancouver showcases the value of GRI to the local communities.

Street trees are manipulated and designed to fit into the urban landscape, reflecting a cultural significance that transcends mere engineering and urban construction. It is crucial that the design stage prioritizes tree growth, acknowledging the historical and societal value of urban trees. However, recognizing this need does not necessarily translate to effective solutions. The gap between theory and practice highlights the necessity for flexible, context-specific approaches and effective communication among stakeholders to balance tree health with urban development goals.

In reality, street trees are frequently compromised to accommodate other infrastructure priorities. Given that it takes decades for trees to mature, it is crucial not to remove existing trees during development projects as much as possible. Integrating new trees into GRI has been shown to positively impact tree growth, offering benefits such as improved soil conditions and water management.

As an outlook, public perception of green space importance may steer the conversation towards favoring tree planting and protection. By fostering a societal appreciation for urban green space, Vancouver might be able to better advocate for and implement practices that support tree health and sustainability.

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APPENDIX

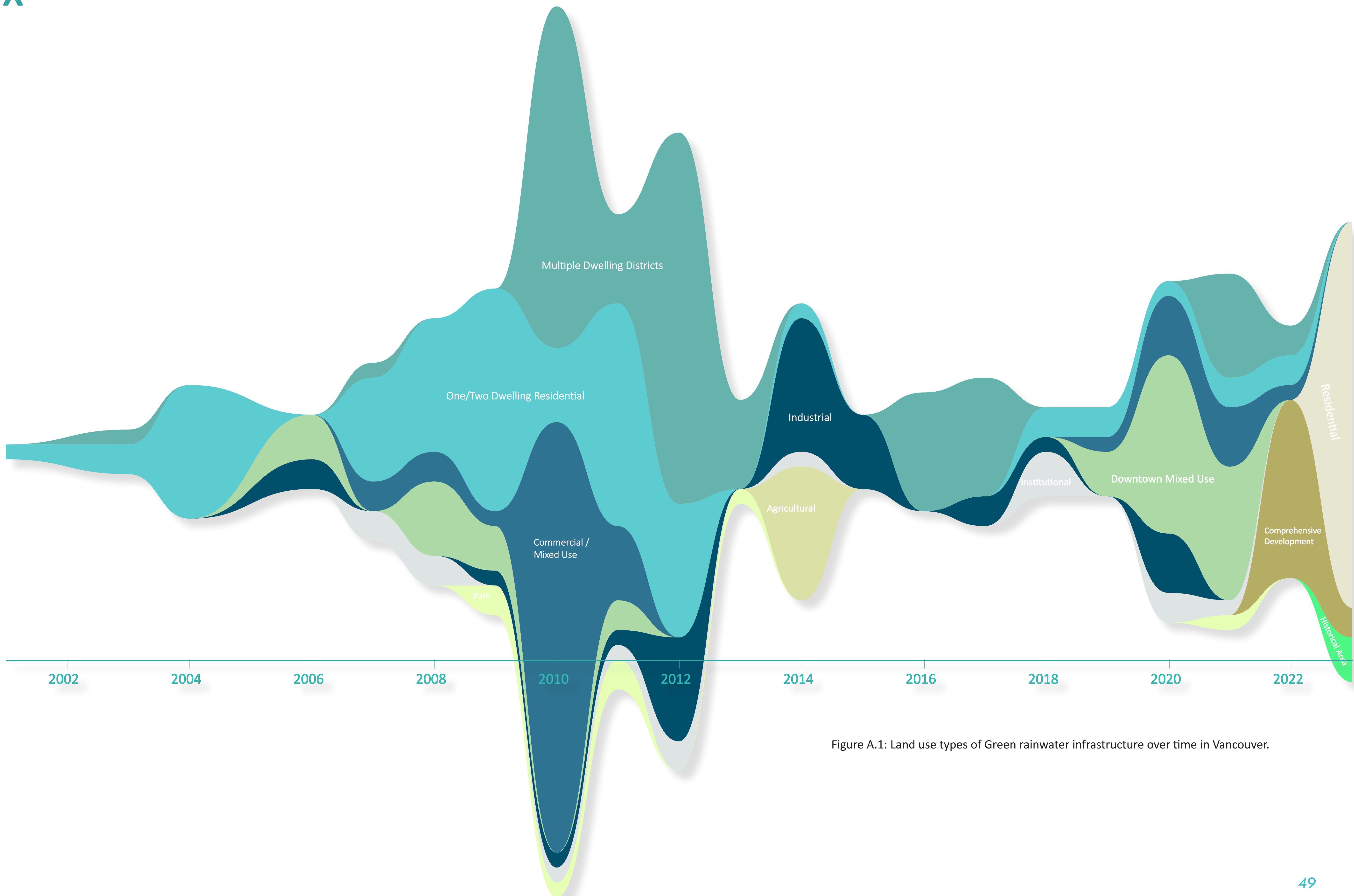

Figure A.1: Land use types of Green rainwater infrastructure over time in Vancouver.

Table A.1: Information of selected jurisdictions.

City	Population	Köppen climate scheme	Sewage system	Regional GRI Plans/Guidelines
Vancouver	662,248	Temperate (Cfb)	Combined sewer out-flows	Engineering Design Manual (2019), Green Infrastructure Design Manual (2024) , Construction specifications (2019), Integrated Rainwater Management Plan Volume II Best Management Practices Toolkit (2016), Green Infrastructure Standard Drawings (2023).
Victoria	95,717	Temperate (Csb)	Combined sewer out-flows	Green Stormwater Infrastructure Common Design Guidelines (2019).
Toronto	2,794,356	Continental (Dfa)	Combined sewer out-flows	Design Criteria for Green Infrastructure in the Right-of-way (2021), Tree Protection Policy and Specifications for Construction Near Trees (2016), Construction Specification for Continuous Soil Trench with Trees for New Construction (2023), Standard Drawings - Tree Planting Details (2021), Standard Drawings - Continuous Soil Trench with Soil Cells (2022).
San Francisco	746,481	Temperate (Csb)	Combined sewer out-flows	Tree Protection by San Francisco Public works (n.d.), San Francisco Stormwater Management Requirements and Design Guidelines (2016)
Portland	616,840	Temperate (Csb)	Combined sewer out-flows	2020 City of Portland Standard Construction Specifications (2020), Standard Soil Specification for Vegetated Stormwater Systems (2023), 2020 Stormwater Management Manual (2020).
Philadelphia	1,533,916	Temperate (Cfa)	Combined sewer out-flows	Green Stormwater Infrastructure Planning and Design Manual (2021), Green Stormwater Infrastructure Landscape Design Guidebook (2020), Green Stormwater Infrastructure Maintenance Manual (2016), Complete Streets Design Handbook (2017).

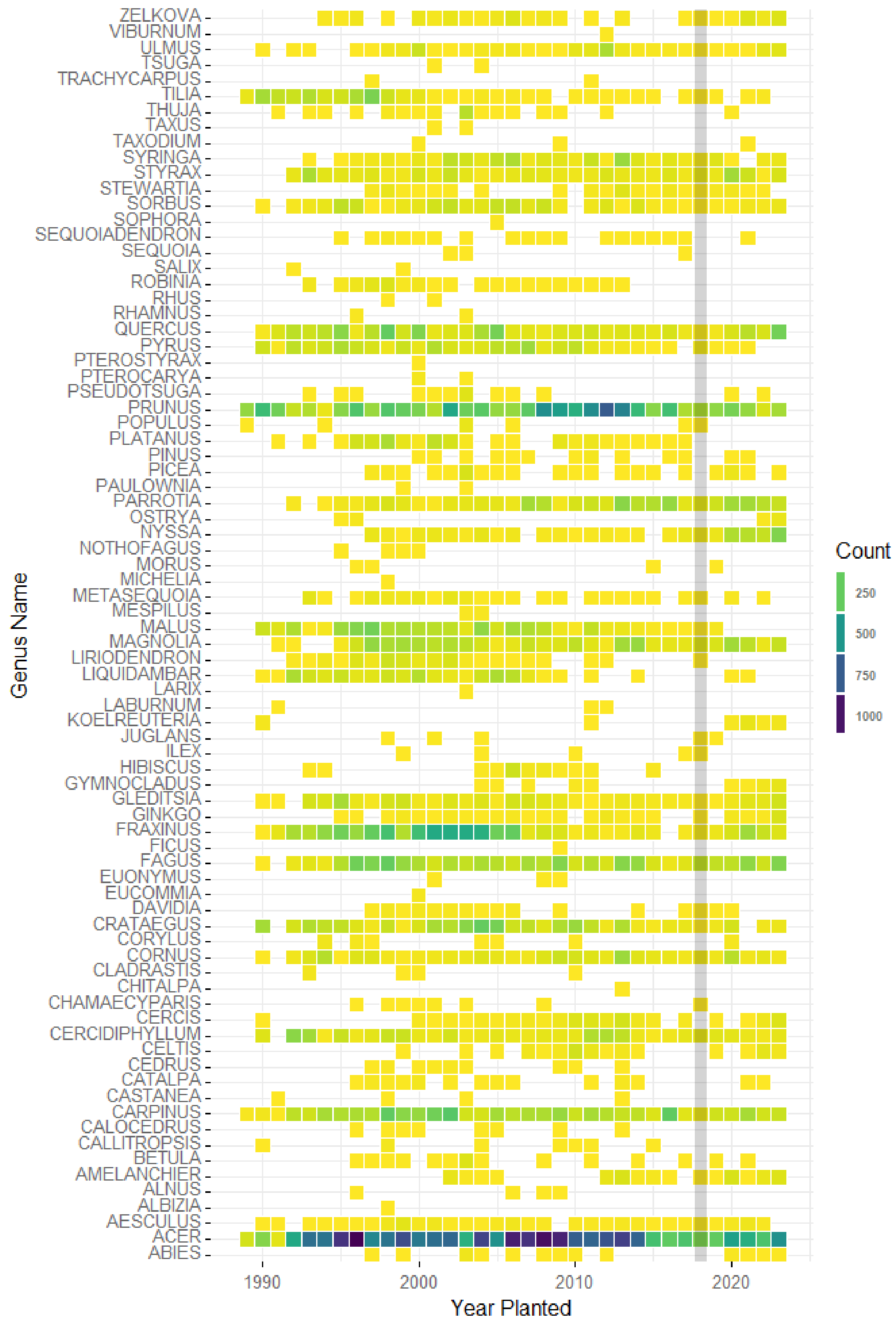

Figure A.2: Genus occurrence of street trees planted by planting year. Street tree data as of June 1, 2024.

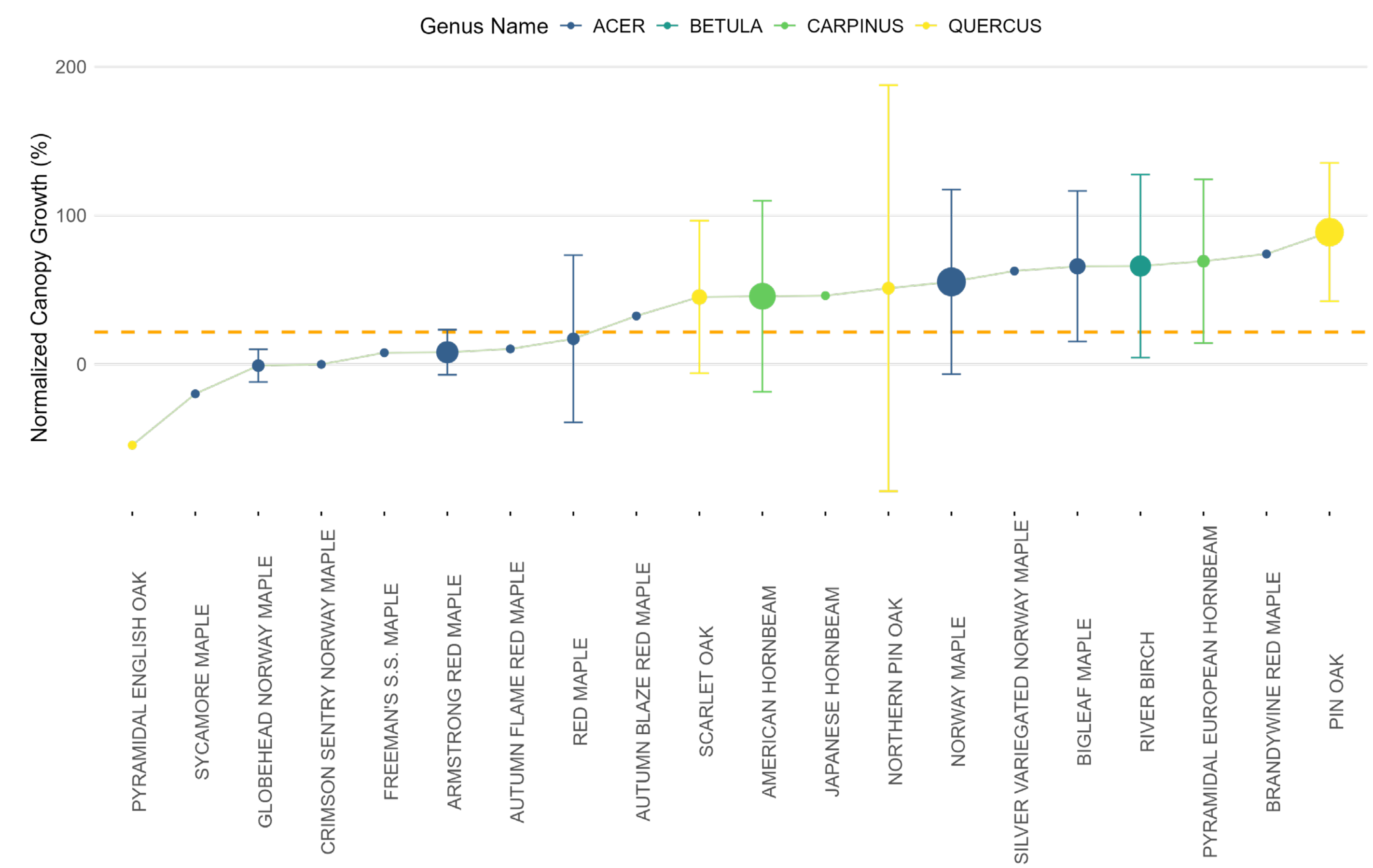

Figure A.3: Mean 2018-2022 normalized canopy growth (%) by tree species of the four most common genus types (Acer, Caprinus, Quercus, and Betula) within GRI footprints. The Orange dashed line indicates the median canopy growth city-wide. Error bars represent mean ±1 standard deviation. The absence of error bars indicates insufficient data for assessing species-specific canopy growth.

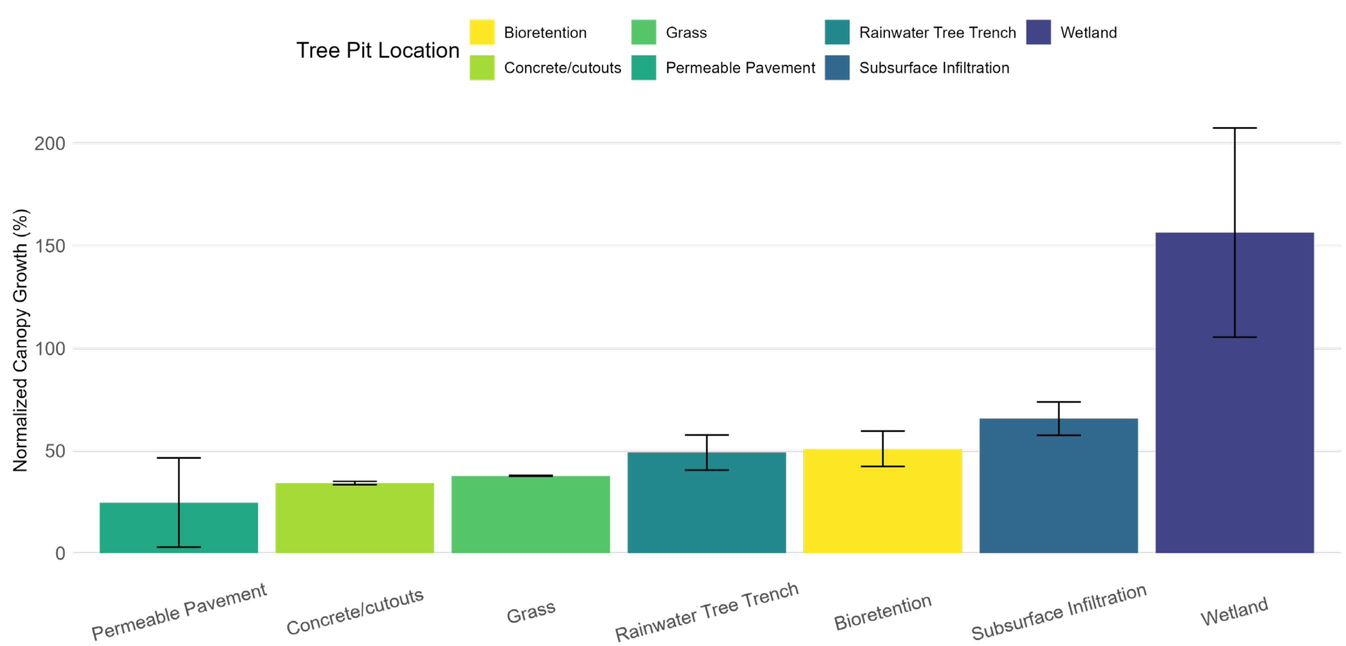

Figure A.4: Mean 2018-2022 normalized canopy growth (%) by tree pit locations. Error bars represent mean ±1 standard error.

Table A.2: Detailed information for Figure 4.5.

Distance to GRI	Tree Status	Typology	Count	Mean	Standard Error
0-1m	Exsiting Tree	Bioretention	23	11.1	13.7
0-1m	Exsiting Tree	Permeable Pavement	37	35.4	8.0
0-1m	Exsiting Tree	Subsurface Infiltration	13	65.5	19.3
0-1m	New Tree	Bioretention	13	48.6	20.0
0-1m	New Tree	Permeable Pavement	2	98.1	62.4
1-2m	Exsiting Tree	Bioretention	17	22.9	13.3
1-2m	Exsiting Tree	Permeable Pavement	18	41.0	15.8
1-2m	Exsiting Tree	Rainwater Tree Trench	2	-12.9	76.7
1-2m	Exsiting Tree	Subsurface Infiltration	1	-8.6	NA
1-2m	New Tree	Bioretention	3	86.7	28.5
1-2m	New Tree	Permeable Pavement	2	43.4	7.7
2-5m	Exsiting Tree	Bioretention	36	60.7	8.9
2-5m	Exsiting Tree	Permeable Pavement	40	57.3	10.5
2-5m	Exsiting Tree	Rainwater Tree Trench	10	61.0	15.0
2-5m	Exsiting Tree	Subsurface Infiltration	45	46.5	8.3
2-5m	New Tree	Bioretention	2	126.4	13.6
2-5m	New Tree	Permeable Pavement	4	102.5	41.9
Within GRI	Exsiting Tree	Bioretention	47	43.1	10.1
Within GRI	Exsiting Tree	Permeable Pavement	4	7.5	22.1
Within GRI	Exsiting Tree	Rainwater Tree Trench	68	46.9	8.4
Within GRI	Exsiting Tree	Subsurface Infiltration	49	66.3	8.3
Within GRI	New Tree	Bioretention	19	70.4	16.1
Within GRI	New Tree	Permeable Pavement	2	59.2	48.9
Within GRI	New Tree	Rainwater Tree Trench	1	197.5	NA
Within GRI	New Tree	Subsurface Infiltration	1	31.9	NA

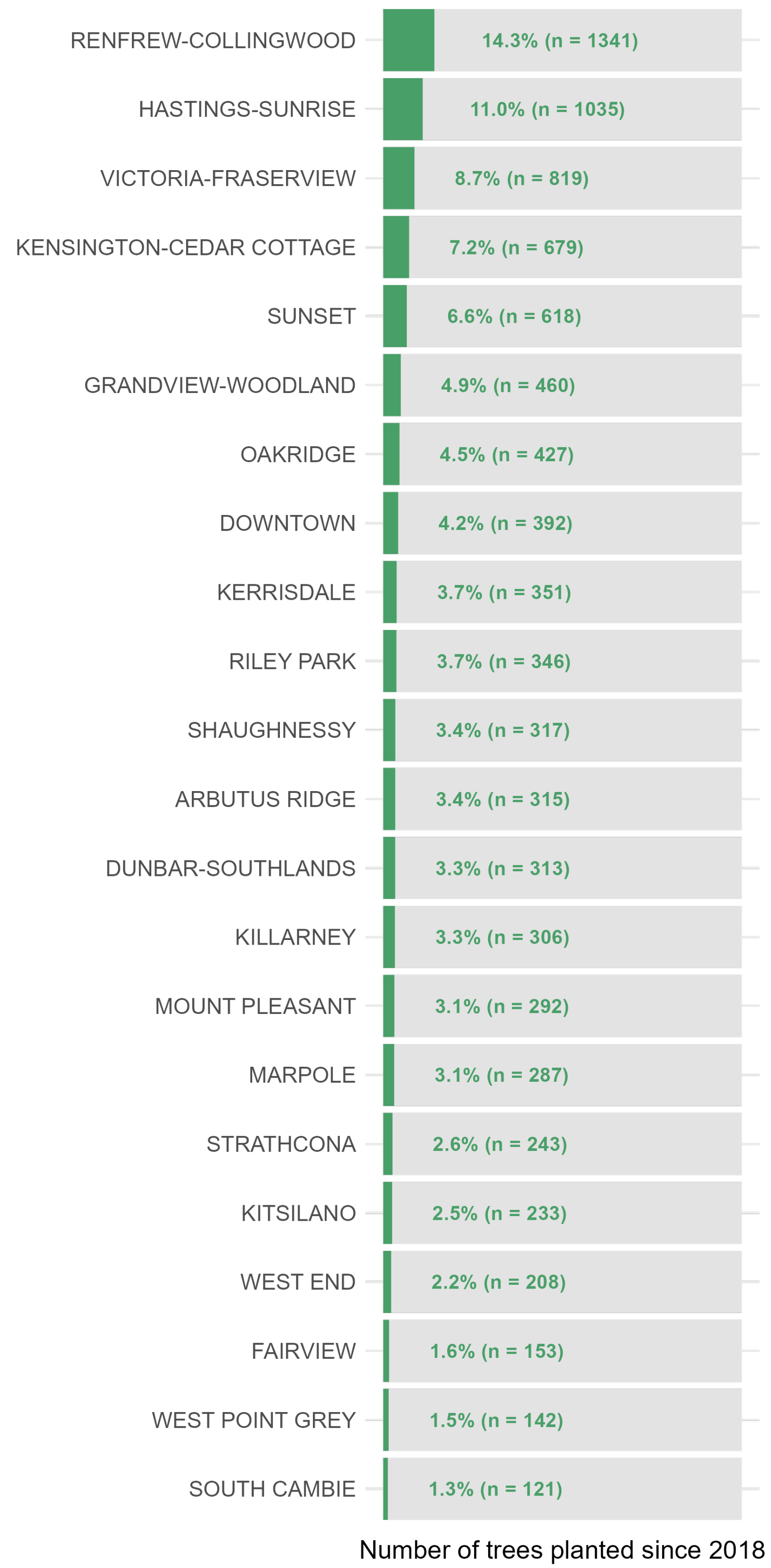

Figure A.5: Number of new street trees planted from 2018 to 2024 by local neighborhoods. Street tree data as of June 1, 2024.

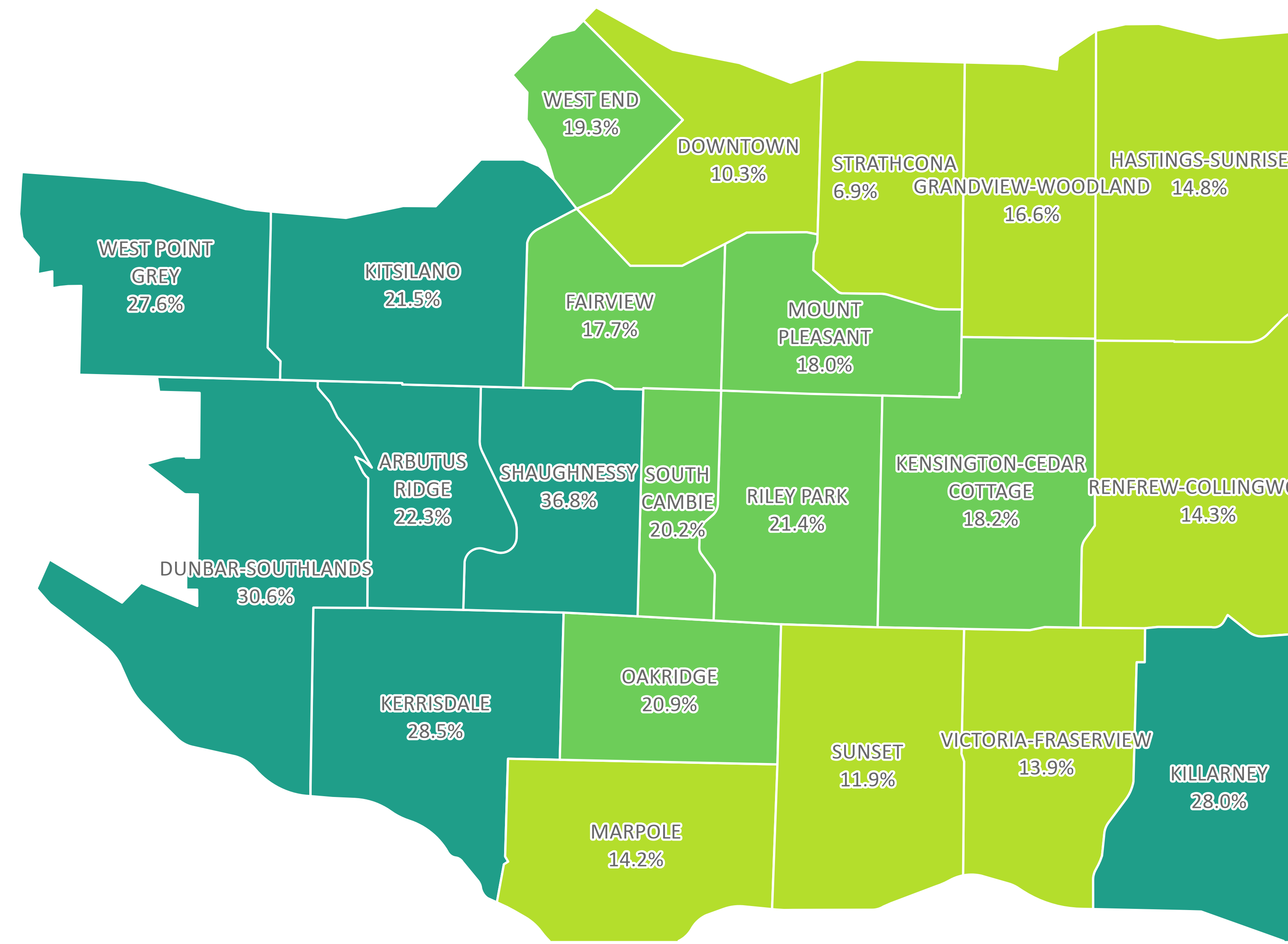

Figure A.6: 2022 tree canopy proportion (in relation to each neighborhood's total area) by local neighborhoods in Vancouver.

Table A.3: Victoria's tree list for GRI. Source: from Green Stormwater Infrastructure Common Design Guidelines' Supplemental 1-Planting Templates & Plant Lists (Capital Regional District, 2019).

Common name	Scientific name
Red alder	*Alnus rubra*
Pacific willow	*Salix lucida*
Oregon ash	*Fraxinus latifolia*
Pacific crab apple	*Malnus fusca*
Pacific sunset maple	*Acer truncatum*
Western serviceberry	*Amelanchier alnifolia*
Beaked hazelnut	*Corylus cornuta*
Black hawthorn	*Crataegus douglasii*
Raywood ash	*Fraxinus oxycarpa*
Cascara sagrada	*Rhamnus purshiana*
Sitka willow	*Salix sitchensis*
Dogwood	*Cornus spp.*
Bitter cherry	*Prunus emarginata*
Douglas-fir	*Pseudotsuga menziesii*
Garry oak (Oregon white oak)	*Quercus garryana*
Strawberry tree	*Arbutus unedo*
Incense cedar	*Calocedrus decurrens*
Hinoki false cypress	*Chamaecyparis obtusa*
Swiss mountain pine	*Pinus mugo*
Japanese black pine	*Pinus thunbergiana*

Table A.4: San Francisco's tree list for GRI. Source: from San Francisco Stormwater Management Requirements and Design Guidelines Appendix D: Vegetation Palette for Bioretention BMPs.

Common name	Scientific name
vine maple	*Acer circinatum*
big leaf maple	*Acer macrophyllum*
red maple	*Acer rubrum*
California buckeye	*Aesculus californica*
white alder	*Alnus rhombifolia*
water birch	*Betula occidentalis*
birch	*Betula species*
pecan	*Carya illinoinensis*
river she-oak	*Casuarina cunninghamiana*
common hackberry	*Celtis laevigata*
western redbud	*Cercis occidentalis*
Chinese fringe tree	*Chionanthus retusus*
lemon-scented gum	*Corymbia citriodora*
persimmon	*Diospyros virginiana*
red-cap gum	*Eucalyptus erythrocorys*
Oregon ash	*Fraxinus latifolia*
Australian willow	*Geijera parvifolia*
maidenhair tree	*Gingko biloba*
honey locust	*Gleditsia triacanthos 'Shademaster'*
silk oak	*Grevillea robusta*
California black walnut	*Juglans hindsii*
Norfolk Island hibiscus tree	*Lagunaria pattersonii*
American sweet gum	*Liquidambar styraciflua*
Catalina ironwood	*Lyonothamnus floribundus asplenifolius*
southern magnolia	*Magnolia grandiflora cultivars*
sweet bay	*Magnolia virginia*
black tea tree	*Melaleuca stypheloides*
weeping bottle brush	*Melaleuca viminalis*
cajeput tree	*Melaleuca viridiflora rubriflora*
Pacific wax myrtle	*Morella californica*
white mulberry	*Morus alba*
tupelo, black gum	*Nyssa sylvatica*
American sycamore	*Platanus occidentalis*
California sycamore	*Platanus racemosa*
Fremont's Cottonwood	*Populus fremontii*
flowering plum & cherry	*Prunus spp.*
coast live oak	*Quercus agrifolia*
canyon live oak	*Quercus chrysolepis*
valley oak	*Quercus lobate*
bur oak	*Quercus macrocarpa*

red willow	*Salix laevigata*
arroyo willow	*Salix lasiolepis*
shining willow	*Salix lucida ssp. Lasiandra*
American arborvitae	*Thuja occidentalis*
water gum	*Tristaniopsis laurina*
California bay laurel	*Umbellularia californica*
bur oak	*Quercus macrocarpa*

Table A.5: Portland's tree list for GRI. Source: from 2020 City of Portland Stormwater Management Manual's Table 4-5 Tree List for Stormwater Facilities (Green Streets) (City of Portland, 2020).

Common name	Scientific name
Common Hackberry	*Celtis occidentalis*
Skyline Thornless Honeylocust	*Gleditsia triacanthos var. inermis 'Skycole'*
Black Tupelo	*Nyssa sylvatica*
Black Tupelo	*Nyssa sylvatica 'Gum Drop'*
White Oak	*Quercus bicolor Swamp*
Shumard Oak	*Quercus shumardii*
Cascara Buckthorn	*Rhamnus (Frangula) purshiana*
Green Vase Japanese Zelkova	*Zelkova serrata 'City Sprite'*
Green Vase Japanese Zelkova	*Zelkova serrata 'Green Vase'*
Village Green Japanese Zelkova	*Zelkova serrata 'Village Green'*

For Philadelphia's tree list for GRI, see pages 46 through 53 of the Green Stormwater Infrastructure Landscape Design Guidebook at https://water.phila.gov/pool/files/gsi-landscape-design-guidebook.pdf (Philadelphia Water Department 2020).