QUANTIFYING CARBON CAPTURE FROM STREET INFRASTRUCTURE ASSETS

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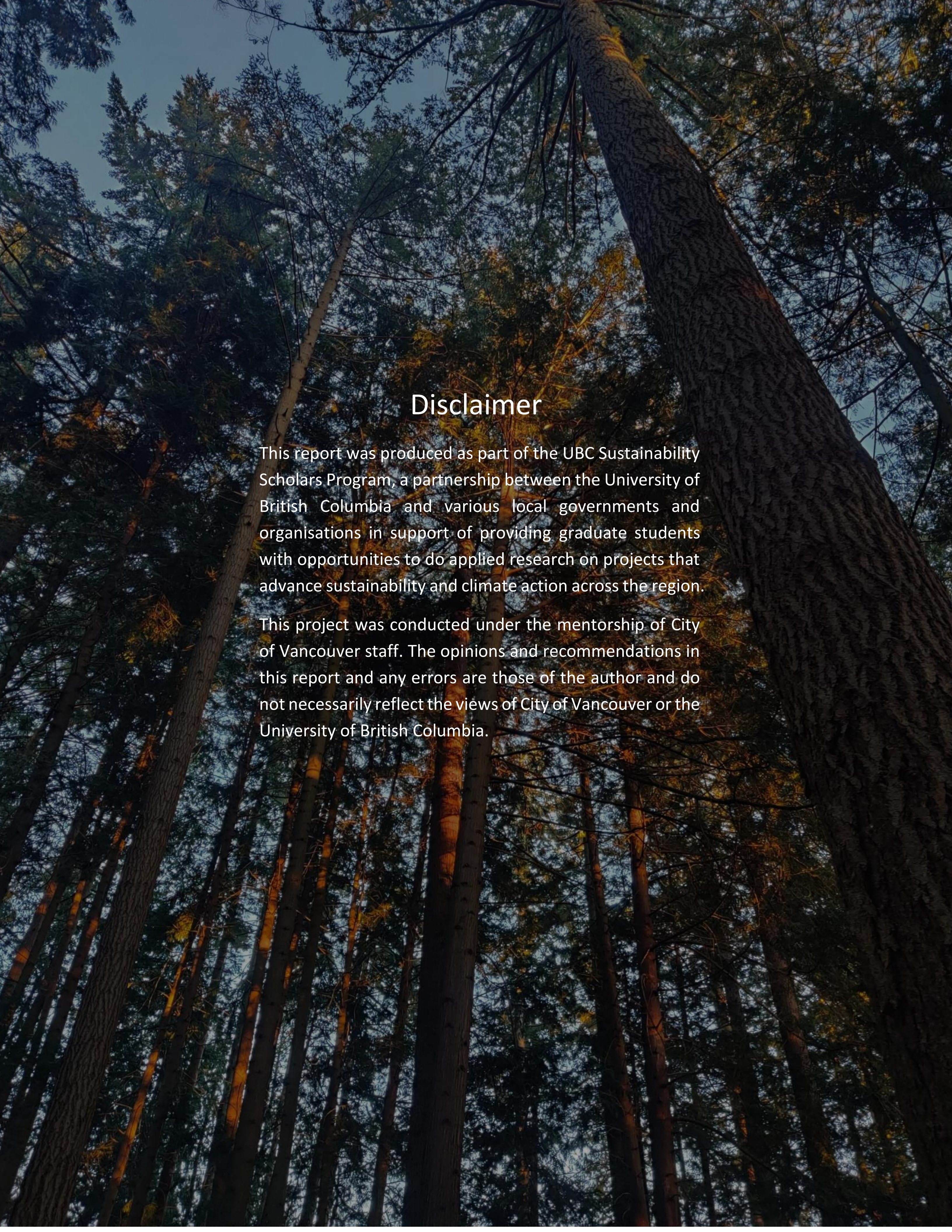

Disclaimer

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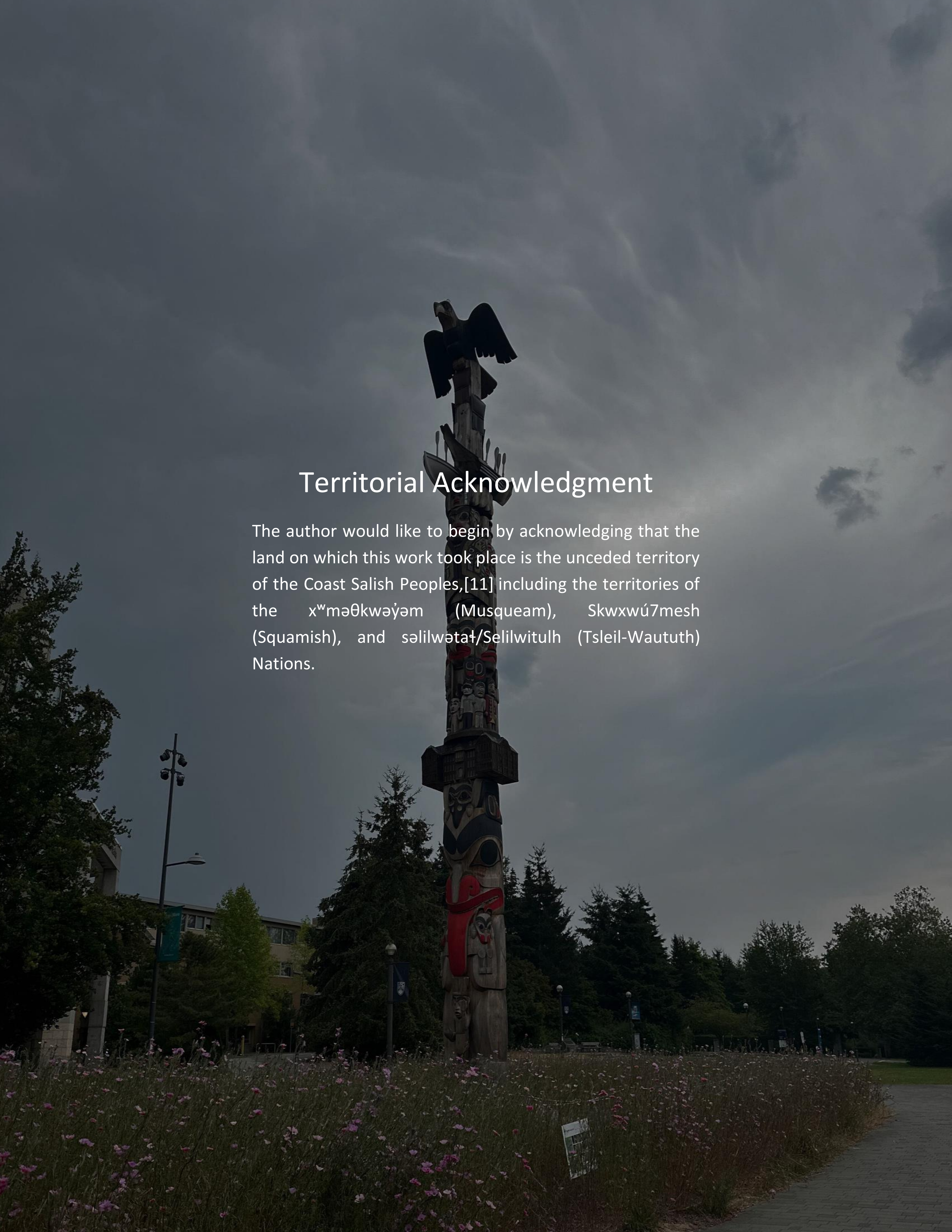
This project was conducted under the mentorship of City of Vancouver staff. The opinions and recommendations in this report and any errors are those of the author and do not necessarily reflect the views of City of Vancouver or the University of British Columbia.



Territorial Acknowledgment

The author would like to begin by acknowledging that the land on which this work took place is the unceded territory of the Coast Salish Peoples,[11] including the territories of the xʷməθkwəy̓əm (Musqueam), Skwxwú7mesh (Squamish), and səlilwətaɬ/Selilwitulh (Tsleil-Waututh) Nations.

Executive Summary

With global warming fueling climate change, organizations are looking at ways to do their part in mitigating its effects. Road transportation is one of the leading emitters of green house gases (GHG), forming 40% of emissions in the Vancouver region. Other sectors in construction such as building construction benefit from a lower carbon footprint by use of materials such as engineered wood; and/or high efficiency systems such as heat pumps. But very few advancements beyond recycled asphalt pavement (RAP) have been made in the asphalt industry. Hence, these emissions can be captured/offset by the use of sustainable infrastructure such as street trees, green rainwater infrastructure (GRI); and transit and bike lanes. In order to quantify emissions, one needs to look at all 5 phases – material production, construction, use, maintenance and rehabilitation. **This study proposes a way to quantify offsets within the use and maintenance phases**; allowing the City officials to measure the impacts of the in-use sustainability measures and drive future policy and planning decisions.

A detailed analysis for carbon offset from street trees, bike lanes and GRI [permeable pavement (PP) and rainwater tree trench (RTT)] has been conducted in this study. For street trees, it is found that the net effects are a result of carbon sequestration, energy savings from decreased cooling needs for buildings due to reduced heat island effect, and emissions due to maintenance. Energy savings from decreased cooling needs a detailed breakdown of energy use of structures over two to three years, which could not be accommodated within the timeframe available. Hence, it is left out of this study. Bike lanes help with emission reduction by driving mode shift from automobiles to bikes. The degree of mode shift highly depends on the demographics, making it difficult to quantify. A less complex approach is suggested by using changes in mode split over the past years indicated in the annual transportation survey. For GRI, emission savings come from reduced energy use for pumping and/or treatment in the sewer system/treatment plant, and for cooling buildings due to reduced heat island effect. The former can be found by quantifying the amount of water retained by the GRI system to determine energy savings and using energy emission factors to quantify emission savings from reduced energy needs. As stated for street trees, the latter is difficult to analyze and is left out of scope for this study.

This study is to be looked at in conjunction with the city's work to quantify emissions from the other phases – material production, construction and rehabilitation; in order to get the complete picture of the lifecycle analysis. Significant partnerships will be needed with other departments to develop a picture of complete emissions.

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Chapter 1.
Introduction

Carbon is the backbone of life on earth. Our bodies and everything around us, is made out of carbon. Carbon flows in nature from one reservoir to the other in a constant cycle called as the carbon cycle. Carbon is fundamental for life, but is also the reason for one of the biggest problems being faced by civilization –global climate change (Riebeek H.,2011) The Carbon cycle has been self-regulating from time immemorial. But in the past 200 years, with the discovery of fossil fuels, humans have released significant amounts of carbon stored in fossil fuels back in our environment, creating an imbalance. Around the same time, with the Industrial Revolution catching pace, a large number of forested areas were cleared to make way for developments or farmlands to accommodate the needs of a growing population. Forests and other lands around the world help absorb one third of this carbon emitted by human activities (Government of Canada, 2024). With increased emissions and reduced uptake capacity, the imbalance in the cycle intensified. Climate change brings with it a change in weather patterns and increased number of extreme events, which have a host of effects on direct and indirect effects on our lives.

With the projected 3-4 °C rise in temperature (City of Vancouver, 2020), we are looking at resulting effects such as sea level rise and frequent extreme weather events such as flooding, storms, etc., which will have a direct effect on our infrastructure systems. In an effort to combat climate change the City of Vancouver has set goals to reduce carbon emissions by 50% in 2030 and be carbon neutral by 2050 (City of Vancouver, 2020). The City owns and maintains over 4000 km of walking, cycling and vehicle networks along with other assets in the right of way (ROW) such as street lights, street furniture. Street infrastructure is very carbon intensive to build and maintain. The main sources of GHG emissions are use of materials like bitumen, lime and concrete which have high embodied carbon; and use phase from street assets which represents emissions from vehicles running on them. This is the biggest contributor of emissions from street assets. Increased frequency of maintenance and rehab increases fuel consumption due to increased idling times, thus increasing emissions (Bhardwaj et.al., X Chen et.al.) Also, a rougher pavement surface needs a vehicle to use more energy, increasing emissions.

As per Transport Canada, road transportation emitted 156 Megatons equaling 84 % of Canada's transportation related emissions and 21% of all Canadian GHG emissions (Transport Canada, 2022). Attributed to the sparsely populated and wide spread landscape of Canada, making it uneconomical to run public transit services, most people end up relying on automobiles as their main mode of transportation. Nearly 40% of carbon emissions in Vancouver come from burning fossil fuels for transportation (City of Vancouver, 2020).

For other sectors such as building construction, use of materials such as engineered wood has allowed us to develop carbon negative/neutral structures. With road construction, only partial substitution has been possible up until now by the use of recycled asphalt pavement (RAP). RAP can reduce emissions in the construction stage by up to 20%. The use of RAP is attributed to reduced service life thus increasing maintenance needs and related emissions (Chen et.al.). Based on input from City officials, the mix utilized by the City has similar performance to that of conventional asphalt. According to Chen et.al., this can help reduce emissions by up to 5% depending on mix proportion, blending efficiency and moisture content of the mix.

Since transportation is vital to the society and road transportation provides last mile connectivity, we cannot avoid constructing pavements. With the necessary construction of street assets, research and development has progressed to reduce these emissions to some extent with current asphalt technology. In order to reach set targets, we need to find more ways to reduce, capture/offset our emissions and to map it to monitor progress.

The City has developed strategies such as Rain City Strategy, Complete Street Policy and Climate Emergency Action Plan in an attempt to make street assets greener and allow for people to move in a more efficient way by promoting active transportation use. These strategies also informed the development of Vancouver Plan 2050. The Vancouver Plan 2050 helps establish the vision of a greener city. “A city where nature has made its way back into the urban fabric.” This vision is mainly driven by the goal of establishing a climate resilient city. One of the foundational ideas revolves around “protecting and making space for nature” (Vancouver Plan 2050). This idea works because the best weapon in fighting nature is nature itself. Creating people first streets and densifying neighborhoods by allowing the missing middle housing helps in creating walkable neighborhoods, that reduce dependance on cars, in turn decreasing the carbon footprint of transportation. Most of these measures defined are long term.

The City has started to move in this direction by using GRI to manage stormwater, street trees to combat heat island effect; and bike and transit lanes to promote cleaner transportation; but lacks a way to quantify the effects these assets have on the carbon footprint of streets. This project aims at filling this knowledge gap by developing a framework to quantify carbon capture/reduction from the following assets:

1. Street trees
2. Bike lanes
3. GRI – Permeable Pavement (PP) and Rainwater Tree Trench (RTT)

Figure 1-1 Street trees

Figure 1-2 Bike Lanes

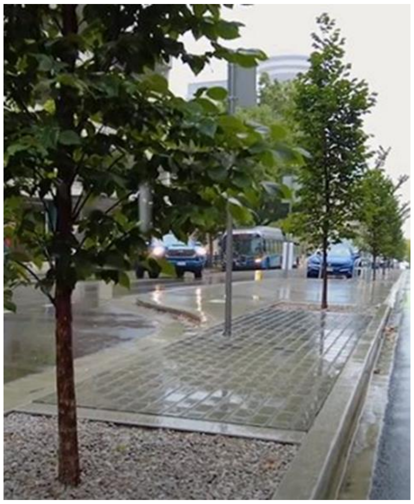


Figure 1-3 Green Rainwater Infrastructure - Permeable Pavement

Source – Daily hive, Viewpoint Vancouver

Chapter 2.
Literature Review

This chapter provides a review of the documents studied pertaining to the methodologies and concepts for calculating the carbon footprint of street infrastructure assets. This review covers carbon sequestration through trees in an urban setting, the use phase of life cycle analysis for carbon accounting of bike lanes and GRI development to understand the effects of urban greenery.

2.1. Street trees

Carbon is a major component of all cellular life forms. Carbon flows from one life form to another in the fast carbon cycle (Riebeek H.,2011). Trees play a significant role in the carbon cycle as they remove carbon from the atmosphere through photosynthesis, extracting carbon dioxide from the air and separating the carbon atom from the oxygen atom and returning oxygen to the atmosphere. This carbon is used as a building material to form trunks, roots, stem, branches and leaves; which supports the growth of trees. In doing so, trees store a tremendous amount of carbon in their structures and annual growth increases the amount of carbon stored (Kiran et.al.).

Trees store carbon at differing rates based on factors such as size, maturity, life span and growth rate. Urban trees can require significant amount of maintenance such as pruning and disaster mitigation. These activities can release carbon back to the atmosphere due to the use of fossil-fuel based maintenance equipment. Thus, some of the carbon gains are offset by these activities. After a tree is removed at the end of its life, it is decomposed in some form, leading to the carbon being released back to the atmosphere. (Nowak et.al.)

Apart from playing an active role in balancing carbon in the atmosphere, trees provide other benefits as follows:

1. Energy conservation – Trees, if planted in the right location can decrease energy requirements of a building. In a study done by Nowak et.al., The shade effects of a 7.6 m red maple was modelled for a one story, 139 m^2 residence. The net carbon emission from increased heating and decreased cooling needs was 27.7 kg of carbon per year. A tree between 4.6 m and 7.6 m had an energy effect proportional to its height, with trees less than 4.6 m giving no energy effects and trees 7.6 m or taller equaling 27.7 kg C/year.
2. Counter heat island effect – Urban landscapes are notorious for getting hotter than the rural environment due to the use of materials such as asphalt and concrete that retain heat, increasing the ambient temperature. Street trees affect urban environment by transpiration, shading from solar radiation and blocking wind. A study done in Montreal

to monitor the effects of street trees in mitigating urban heat island effect found that street trees that have a height of 20 m were able to reduce air temperatures by 4°C at the tree height and by 2°C at 60m height (Wang et.al.).

3. Safe streets - The presence of trees around roads can cause drivers to perceive the width of road lesser than usual, leading them to drive slower, making roads safer and reducing fuel consumption, which consequently lowers carbon emissions. For instance, one study reported a speed reduction of 4.87 km/h, while another noted a decrease of 12.8 km/h, when street trees were planted on either side of the roads. A case study on Quadra Street in Victoria, BC, demonstrated that average speeds dropped from 30 mph to 25 mph, largely due to new landscaping, including street trees, and revitalized commercial development along the corridor (Parsons Transportation Group, 2003). Additionally, slower vehicular speeds encourage walking and cycling, improving comfort level for active transit users, helping fuel mode shift (Marritz et.al.) This will help further in reducing carbon emissions.

2.2. Bike lanes

Bike lanes play an important role in limiting the effects of global warming by reducing dependance on automobiles and increasing use of active transportation modes such as biking and walking, and also transit adoption, with protected bike lanes having the most effect. Studies in Melbourne and London have found that women and older people are more likely to ride on protected bike lanes than on typical roads, making way for more equitable development of cities. Also, users are less likely to wear helmets on protected bike lanes which speaks for the increase in perceived level of safety. Most of the cross-sectional studies noted a positive correlation between bike lanes and bike ridership. (Hwang et.al., Zahabi et.al.).

According to a study done by the European cycling federation, cycling releases 21 gm of CO_2 per passenger km. A bus releases 101 gm of CO2 per passenger km and driving a car is 271 gm of CO2 per passenger km. (European Cyclists' Federation, 2016). The primary reduction in carbon emissions will be achieved by mode shift from automobiles to active modes of transportation. As per a study done in Thailand in the municipality of Mahasarakham city, a reduction of 0.2 million tons of CO2e was achieved after introducing a bike lane to the streets, 100% of which was attributed to the use phase of the bike lane. The main reason highlighted was less burning of fossil fuels due to mode shift from cars and motorcycles to bikes. It was concluded that a substantial reduction in carbon emissions can be achieved with a mode shift rate of 26% . (Prasara et.al.) A study to identify the probability one chooses bike commuting over other modes done in five counties around New York found that a 1% increase in bike lanes increases the probability of bike commuting by 1.13% (Hwang U et.al.).

Even though an increase in bike lanes is attributed to more active transit users, emission savings brought about by them can be minimal as they might not have an effect on current modal split but lead to new trips generated, mainly for recreation. A study by Brand et.al. in three regions across the UK explored the relation between new walking and cycling routes on CO_2 emissions from transportation. Survey participants were asked to submit a questionnaire detailing their travelling behavior for seven days prior to the receival of the questionnaire. A very small amount of emission reduction (3%) was noted even though the new infrastructure was heavily used. This was attributed to an increased trip generation rate, mainly for recreation, along these routes and very less actual mode shift from automobiles to biking or walking.

From the literature studied, it can be concluded that quantifying mode shift is a complex phenomenon which is highly dependent on population characteristics and human behavior. For quantifying carbon reductions, from surveying people to constructing multinomial logit models, the available methods range in complexity and allow various predictions to be made by people with different levels of expertise and to comply with available resources.

2.3. GRI development

A significant amount of research shows that there is a direct correlation between increasing temperatures due to global warming and the frequency of high intensity and short duration rainfall events. (Min et.al., Wasko et.al.). Traditional drainage systems are limited to the design capacity value, hence making the system prone to overflowing or flooding due to extreme weather events. The use of sustainable urban drainage systems such as GRI allows designers and planners to introduce flexibility in the system while mimicking the natural hydrological cycle in urban areas and allowing an increase in evapotranspiration and infiltration capacity. (Antunes et.al.)

The City of Vancouver has defined the following GRI for use within its jurisdiction (City of Vancouver, 2019): -

1. Bioretention practices – These refer to landscapes designed to retain rainwater runoff and allow infiltration into subsoil, filtering out impurities in the process. They typically feature a shallow depression or basin built up by layers of layers of rock, engineered soils, and resilient vegetation that can tolerate extreme rain and drought events. The different kinds of practices in use are: -
    a. Rain Gardens
    b. Bioswales
    c. Bioretention cells
    d. Bioretention planters

    e. Bioretention corner bulges
2. Rainwater tree trench – These are underground arrangements that provide storage for rainwater and support for street trees. This involves using either soil cells or structural soils. Soil cells are plastic frames with soil filling the voids. The frame supports superimposed loads while the soil accommodates tree roots. Structural soil is a mix of large, crushed stones and soil where stones provide structural strength and soil accommodates tree root growth.
3. Permeable Pavements – Pavements with pervious surface absorb rainwater and allow it to infiltrate into the subsoil while providing a hard surface for vehicular or pedestrian traffic. It can be made up of permeable concrete pavers, porous concrete/asphalt.

This list is not exhaustive and only includes GRI relevant to this study. Readers are encouraged to refer the source material for detailed information about various GRI practices.

Since GRI are populated with trees, shrubs and grass, they also sequester carbon. For most GRI this can be overshadowed by the high embodied carbon of materials used for construction and maintenance related emissions during its lifespan, especially if done by fossil-fuel based equipment (Kavehei et.al., Moore et.al.), which the City currently uses. GRI's have also been found to reduce the urban heat island effect, as these surfaces do not absorb as much heat as compared to conventional materials, hence reducing energy consumption of buildings for cooling during the summer months. (Choi et.al., Antunes et.al.).

It can be concluded that GRI can prove to be useful assets in the cityscape with multiple attached benefits. They can make the traditional drainage systems resilient by adding flexibility to the capacity and reduce peak flows (Spraakman et.al.), reduce urban heat island effect and improve biodiversity in the area.

Chapter 3.
Materials and Methods

Based on the extensive literature review, a framework to analyze the carbon capture/reduction from street infrastructure assets will be defined in this chapter. The data needed is highlighted and the approach of our analysis is explained subsequently. It is understood that in order to capture the complete picture, we need to make a life cycle analysis looking at all stages – Material production, construction, use, maintenance and reconstruction. Due to time limitations, **this work will focus on the use and maintenance phase**. The other phases will be studied by the City staff internally.

3.1. Study area

The study is based in the jurisdiction of the City of Vancouver that has a temperate oceanic climate. Flanked by mountains towards the north that serve as a barrier for the cold northern climate and warmed by the Pacific Ocean currents, Vancouver experiences some of the mildest winters in Canada, mostly characterized by rain during the months of October to March. The current study focuses on selecting three street segments across Vancouver which represent different conditions based on their "greenness". In order to categorize greenness, we look at the availability of the following three categories of assets:

1. Comprehensive GRI solutions such as Rainwater Tree Trench, Bioswale and Grass swales. These help with stormwater runoff management; help support street tree growth and manage urban heat.
2. Street trees - Help sequester carbon and manage urban heat through shading.
3. Sustainable transportation facilities such as bike and transit lanes.

Based on availability of the above three assets, we classified the segments as:

1. *Green street* - Has all three kinds of assets, designed to work together as a single unit and all benefits associated with them are achieved. The assets are symbiotic and help complete the hydrological cycle, making the immediate environment self sufficient in terms of stormwater runoff management.
2. *Green-Grey street* - One or two types of these assets available. The systems are designed separately with no integration. Only partial benefits are achieved. For example, the use of street trees to mitigate urban heat and sequester carbon, with no GRI for maintaining soil moisture.
3. *Grey streets* - Lack all kinds of listed assets or their presence has minimal effect. such as one or two street trees or a single rain garden serving a small catchment around the segment.

Care was taken to select street segments that are on the same hierarchical level to draw an even comparison. The following arterial streets were selected to do a sample analysis for demonstrating the viability of the work:

1. *Green street* - Richards Street between Dunsmuir Street and W Georgia Street
   Richard Street is a street located in Downtown Vancouver that stretches between Cordova Street and Pacific Street. The street underwent a comprehensive overhaul in 2021 to install blue green infrastructure for improving rainwater management and urban forest cover. Rainwater tree trench was added between Dunsmuir Street and Pacific Street which supports tree growth along this segment. This helps in increasing the pervious area, mitigating urban heat island effect and enhancing biodiversity. A protected AAA bike lane was also installed on this street as part of this initiative to provide safe active transportation routes. All these measures help make the street self-sufficient and sustainable.

Figure 3-1 Green Street Segment - Richard Street b/w Dunsmuir and W Georgia Streets

2. *Green - Grey section* - W Georgia Street between Howe Street and Hornby Street
   This street represents a typical street in Vancouver where a unilateral effort has been made to include natural assets within the street ROW. The only green assets are street trees which help with urban heat island mitigation and improve the area's aesthetic appeal. The health of these trees are threatened by hotter, drier summers, and rely on human intervention through the drought season. They help improve the canopy coverage however we must consider the reliance on fossil fuel based equipment. Since it rains for a significant time throughout the year in Vancouver, some maintenance activities like manual watering requirements are minimal compared to other Canadian cities with different climates.

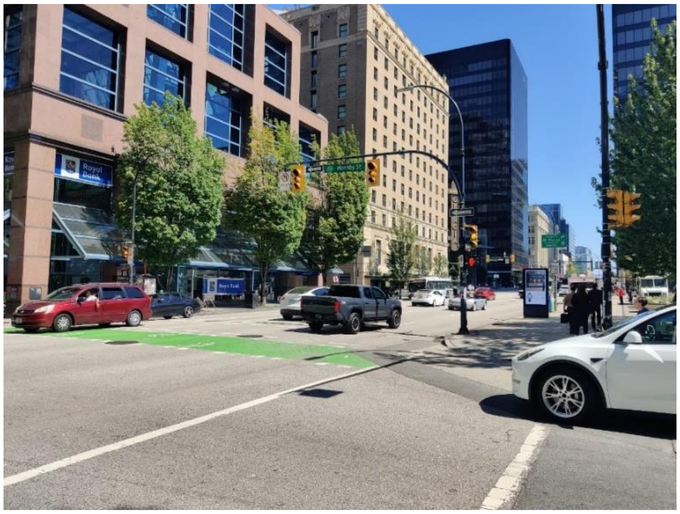


Figure 3-2 Green-Grey Street Segment - W Georgia Street between Howe Street and Hornby Street

3. *__Grey Section__* – Clark Drive between E Pender Street and Frances Street
   This street lacks green assets and relies on engineered grey assets to maintain functionality. Stormwater runoff is captured and disposed of using storm sewers. A few grass patches line the street. The absence of green assets such as street trees or GRI makes the area highly susceptible to urban heat island effect, which is reflected in the heat map with an average temperature rise of 2°C compared to adjacent areas. Plus, the use of grey assets makes the system very rigid in terms of runoff management capacity, making it susceptible to overflows and cause surface ponding during heavy rainfall events. It also makes the environment unwelcoming for biodiversity to flourish.

Figure 3-3 Grey Street Segment - Clark Drive between E Pender Street and Frances Street

Table 1 Summary of asset availability on selected street segments

Asset to be Studied	Asset availability		
	Green Richard Street b/w Dunsmuir and W Georgia Street	Green Grey W Georgia Street b/w Hornby and Howe Street	Grey Clark Drive b/w E Pender and Frances Street
Street Trees	✓	✓	×
Bike Lanes	✓	×	×
GRI	✓	×	×

3.2. Street trees

As stated earlier, street trees are very effective in sequestering carbon. The carbon sequestration rate changes from species to species and is directly proportional to growth rate. Based on literature, the following methodology has been used to derive the carbon stored by a tree over its lifetime:

1. Tree data is extracted from Vanmap for the area or street segments to be studied. The data obtained contains the following parameters – Tree identification parameters such as Object ID, Tree ID; Height Range ID, Diameter at Breast Height (DBH) in inches, Date Planted, Genus Name, Species Name, and location details including x and y coordinates. (Available dataset included in Appendix A
2. Convert DBH from inches to centimeters. To Interpret the Height Range ID, use the following scale:

Table 2 Height Range ID interpretation

Height Range ID	Height Range (ft)
1	1-10
2	11-20
3	21-30
4	31-40
5	41-50
And so on....	

Convert height from feet to meters.

<u>Assumption</u> – Height value from the range is considered on the maximum end; i.e., for a tree having height range ID as 3, its height is considered as 30 ft.

<u>Note</u> – Ideally, in order to predict the carbon sequestration over a period of time, one needs to look at the growth rate of trees and predict the DBH and height at the end of the analysis

period based on the age of the tree. In absence of any studies to establish growth rate of trees within the Vancouver region, we make use of available data to arrive at carbon sequestration value **till date**. Needless to say, the use of predicted values instead of the current values will give us the sequestration at the end of prediction period.

3. Biomass estimation – Tree biomass equations established by Lambert et.al. will be used to estimate the Above Ground Biomass (AGB). These equations are based on tree biomass data collected during the 1980's as part of the ENergy from the FORest research program (ENFOR). The equations are as follows:

$$y_{wood} = b_{wood1} D^{b_{wood2}} H^{b_{wood3}} + e_{wood}$$

$$y_{bark} = b_{bark1} D^{b_{bark2}} H^{b_{bark3}} + e_{bark}$$

$$y_{foliage} = b_{foliage1} D^{b_{foliage2}} H^{b_{foliage3}} + e_{foliage}$$

$$y_{branch} = b_{branch1} D^{b_{branch2}} H^{b_{branch3}} + e_{branch}$$

$$y_{total} = y_{wood} + y_{bark} + y_{foliage} + y_{branch} + e_{total}$$

Where y_i is the dry biomass of the component *i* of a living tree (kilograms), *i* stands for wood, bark, foliage, branch and total; b_{ij} are the coefficients estimated in the model where j equals 1, 2 or 3; D is the diameter at breast height in centimeters, H is height in meters and e_i is the error term. The values of coefficients and errors will be taken for "All" species to simplify the analysis. The coefficients are as follows:

Table 3 Coefficient values for tree biomass estimation

Variable	Wood	Bark	Branch	Foliage	Total
b_1	0.0348	0.0139	0.0346	0.1822	-
b_2	1.9235	1.5429	2.6706	2.2864	-
b_3	0.7829	0.8189	-0.6033	-1.1203	-
e	51.6	40	12.9	7.9	85.5

The value of above ground biomass of vegetation is multiplied by 1.256 to account for the below ground biomass (root system). (Pati et.al., Srour et.al.)
Therefore, Total Biomass (TB) = 1.256×AGB

4. Carbon stock is found by using the conversion factor of 0.5 Mg of C per Mg of oven dry biomass. (Pati et.al., Srour et.al.)
Carbon stock = 0.5 × TB
5. Carbon dioxide sequestered by each tree can be found by multiplying carbon stock by 3.67 (Molar ratio of carbon dioxide to carbon = 44/12). (Pati et.al.)

Completing the above analysis will give us the carbon sequestered by street trees. But as pointed out in the literature review, street trees are also responsible for carbon emissions due to the use of fossil-fuel based equipment for maintenance. Based on input from Vancouver Park board, the list of equipment commonly used for maintenance of street trees was obtained. Emission calculations for the equipment is based on the following formula:

$$C = N \times HRS \times HP \times LF \times E_i$$

where C = carbon emissions (g), N = number of units, HRS = hours used, HP = average rated horsepower, LF = typical load factor, and E_i = average emissions of i^{th} pollutant per unit of use (g/hp-hr) (U.S. EPA 1991). Average HP and Typical load factors, along with the list of equipment used is as follows:

Table 4 Tree maintenance equipment used along with average HP and load Factor

Equipment used	Average HP	Load Factor
Honda Generator	22	0.74
Wood Chipper	99	0.37
Chainsaw	2	0.5
Boom lift	35	0.505

Table 5 Different Carbon emissions from tree maintenance equipment

Equipment	Emissions (grams/hp-hr)					
	HC (Crank)	HC(Exhaust)	CO2	CO	NO_x	SO_x
Honda Generator	1.2	0.02	-	5	8	0.93
Wood Chipper	1.2	0.02	-	5	8	0.93
Chainsaw	625.8	NA	-	1328.1	0.96	0.54
Boom lift	1.57	0.03	-	6.06	14	0.93

Note -No source for CO2 emissions could be found for the above listed equipment. In order to get a complete analysis, the CO2 quantity needs to be included in the analysis for quantifying emissions from equipment.

These carbon emissions can be subtracted from the carbon stock of trees obtained during the sequestration analysis. Multiplying the net carbon with the molar ratio of carbon dioxide to carbon (44/12 = 3.67) will give the net CO_2 sequestered.

Due to lack of data regarding frequency of maintenance or a defined way of quantifying this, this work does not account for emissions due to maintenance operations. But with the availability of above data, if the frequency of use can be mapped, one can easily quantify emissions due to maintenance and find the net sequestration by trees. As pointed out in the literature review, one can also quantify the carbon savings from energy conserving trees. This is not conducted as part of this work as it demanded analyzing detailed energy use breakdown of a neighborhood to determine the heating and cooling needs. Cumulative net carbon for trees can be calculated by (Nowak et.al.):

$$N_c = S_c + A_c - E_m - E_d$$

Where, N_c – Net cumulative carbon sequestered, S_c is Carbon sequestered by trees, A_c is Avoided Carbon emission due to energy conservation, E_m is Carbon emitted due to maintenance operations and E_d is carbon emitted due to decomposition of removed trees.

3.3. Bike lanes

The emission savings after installing a bike lane are attributed mainly to mode shift that it supports by allowing more people to take active transportation modes such as walking, biking or other battery propelled vehicles. As concluded in the literature review, this can be quite a tricky question to tackle as the presence of a bike lane might not replace the existing automobile trips but might generate new trips. The degree of mode shift happening will depend on demographics of the population such as cars per household, annual income or age. In order to quantify this, we need to look at transportation demand modelling exercises which can be quite complicated due to the degree of data involved.

Looking at Richards Street in Downtown Vancouver as an example, when it went from two vehicle lanes with a painted bike lane in 2020 to one vehicle lane with a AAA grade protected bike lane in 2021, a decrease in vehicular traffic is imminent because of the reduced capacity of the road. People using Richards Street for their commute will not suddenly switch from automobiles to other modes of transportation but may change their route in a bid to avoid congestion. This will shift vehicular traffic on to adjacent streets like Granville Street and Homer Street increasing traffic congestion on these streets, thus increasing fuel consumption due to increased idling times and resulting in an increase in GHG emissions (Bhardwaj et.al., X Chen et.al.). On the other hand, People biking on adjacent streets will choose to be on Richards Street due to the availability of safer and more accessible facilities. This will result in a higher active transit user count on the newly installed bike lane, which is not driven by mode shift, but is merely a factor of route selection. Only after vehicular congestion on the adjacent streets gets bad enough, people will consider other modes such as walking, biking or transit over using an automobile to save time. Also, the mode they choose to shift to will depend on their trip distance, where shorter trips (usually under 3 km) are likely to be taken by walking or biking and longer trips will be taken by transit. In conclusion, quantifying mode shift will require extensive modelling efforts and one needs to look at it from a network perspective. Having a project-based perspective will lead to inflated values in our projections.

Talking to an expert in the field of transportation demand modelling, Mr. Clark Lim (Adjunct Professor, UBC, Vancouver and Principal, Acuere Consulting), to get the most accurate results, one can rely on the current regional transportation model VanSAM. The City of Vancouver currently uses a city-wide model VanSAM (Vancouver Sub Area Model), built upon TransLink's Regional Transportation Model (RTM), to predict traffic flows for Transit and vehicles in the region. This model currently is incapable of modelling bike or pedestrian traffic. In its current configuration, the model can be used to identify the difference in vehicle kilometers travelled that can help us quantify GHG emission savings and capture the degree of mode shift happening on a larger scale. One can generate the vehicle kms travelled when Richards Street had two vehicle lanes using the model. Then Richards Street can be updated to have only one vehicle lane and the model can be run again. Ideally, there should be a decrease in the vehicle kilometers traveled on Richards Street and in the area around it. This change in vehicle kilometers travelled can be used to determine the change in GHG emissions due to removal of one vehicle lane which in turn was removed to accommodate the bike lane. Hence, this change can be attributed to the addition of the bike lane. This method won’t give an accurate number for mode shift but is capable of giving reasonable and justifiable results. In order to get an accurate picture of the different modes being used, the addition of trip distance data will allow for predicting the allocation of each mode within the vehicle kilometers reduced. This analysis requires extensive modelling experience and access to resources, which the author lacked. Hence no such analysis is being conducted as part of this study.

For this study, based on the feedback received, the analysis is being simplified by only looking at the active transit traffic counts on the bike lane and assuming that by providing a bike lane, we prevented these people from driving, and that brings about the associated emission savings.

Emission savings from bike lane = (Automobile emission × bike traffic volume) - (Bike emissions × bike traffic volume)

3.4. Green Rainwater Infrastructure (GRI)

As pointed out in literature, GRI’s come with multiple attached benefits. These lead to emission savings in two major ways – By absorbing stormwater runoff, we save energy needed to pump stormwater to, and treat it at a wastewater treatment plant; and energy savings in cooling of buildings due to reduced urban heat island effect. We will calculate the former as part of this study but will forgo the latter to balance our scope to fit the time requirements of this project. In order to analyze the latter, one needs to find an energy breakdown of the buildings in an area before and after the installation of the green asset. The difference in energy use can be compared over a set period of time. Ideally there should be a decrease in energy use, mainly for cooling purposes. A study done in the city of Xiamen quoted a 30% reduction in the community's energy use by adopting green rainwater infrastructure. (Shao et.al.).

For analyzing the emission savings from the sewer system, we will follow the following outline:

1. Sewer system layout – we begin by looking at the type of sewer system and whether pumping is involved in disposing of the effluent. The GHG savings will be greater in areas of combined sewer system as emissions from both treatment plant and pump station energy use can be avoided. In areas of separate sewer system, the impact will depend on whether there is any pumping needed along the storm mains.
2. Rainfall data collection – The City of Vancouver has a tipping bucket rain gauge network set-up across the city. Raw rainfall data is available at 5-minute intervals from the nearest rain gauge to each site and is downloaded through FlowWorks. A rainfall event is defined as having a minimum cumulative rainfall of 2.0 mm and a minimum 6-hour antecedent dry period. Rainfall events are separated for analysis into three categories (Spraakman et.al.)
    - Normal Event: ≤24mm;
    - Large Event >24mm & ≤ 48mm; and
    - Extreme Event >48mm
3. Catchment area - This is the area from which runoff will drain into the GRI during a rainfall event. This can be found in design drawings. After obtaining this, we can find the amount of water entering the system.

    Volume of water entering the GRI (m^3) = Rainwater depth(m) × Catchment area(m^2)

4. Water absorption rate – Not all water entering GRI will be absorbed by the system. The volume of water being absorbed will depend on the intensity of rainfall and infiltration rate of the subsoil. As per a study done by the City on the rainwater tree trench along Richards Street, it was found that all water directed into the trench was filtered and 84% of the annual runoff volume was captured. This indicates 84% of the annual runoff was retained by the system hence reducing stormwater volume by 84% in the adjoining storm sewers.

    Volume of water diverted from the sewer system (m^3) = Efficiency × Volume of water entering the GRI (m3)

    Drawdown rates for permeable pavements – For permeable pavements, the drawdown rates will help identify the efficiency of absorption. In the study done by City officials (Spraakman et.al.), it can be noted that five of the seven sites studied have greater drawdown rates than the design rates. Most areas are designed with a drawdown rate of 10 mm per hour. In absence of the actual drawdown rates, it will be assumed that the actual drawdown rates are equal to the design drawdown rates, i.e., 10 mm per hour. To get the volume of water absorbed by permeable pavements, we can multiply the surface area by the depth of rainfall and check if the rainfall intensity ever goes over the actual drawdown rates. This will help us synthesize the efficiency of the pavement in absorbing rainwater. It is understood that the assumed drawdown rate might be a huge underestimation of the capacity in a lot of circumstances but helps us lean towards the side of caution.

Volume of water absorbed by Permeable Pavement(m^3) = Surface Area (m^2) × Rainfall depth(m)

5. The volume of water absorbed by GRI is the volume of water that would have ended up in the sewers and would have needed either treatment or pumping, based on the characteristics of the sewer system. According to one study, the average energy used for pumping of wastewater in Canada is between 0.02 to 0.1 KW h/m^3. (Plappally et.al.). In order to get an accurate estimate of the energy required for pumping, we can use the following equation(Shao et.al.):

$$E_s = \frac{\rho g h Q}{3.6 \times 10^6 \times \eta}$$

Where E_s is is the energy use of pumping station (KWh); ρ is the density of water (kg/m^3); g is the acceleration of gravity (m/s^2); h is the average head of pumping station (m); Q is the amount of stormwater discharge through pumping station; η is the engine efficiency, which is generally taken as 0.75.

Q can be calculated using the following equation (Shao et.al.):

$$Q = P_a F \phi - V$$

Where P_a is mean annual precipitation (in meters); F is the service area of the pumping station (in m^2); ϕ is the comprehensive runoff coefficient; V is the amount of annual stormwater re-utilization, which can be assumed 0 in absence of any available data.

6. When the pump station is running, the emissions will be mainly due to energy use. Hence carbon emissions of the pumping station can be found by (Shao et.al.):

Carbon emissions = E_s × Emission Factor

The Electricity Emission Factor for BC's grid, as published by BC Hydro is 11.3 tCO_2/GWh for the year 2023. (Ministry of Environment and Climate Change Strategy, 2024)

7. Like pump stations, part of emissions from treatment plant comes from energy use. Another part comes from the decomposition of organic matter. Carbon emissions saved at the treatment plant by using GRI can be found by:

Carbon emissions saved = Vol. Of water absorbed by GRI × Carbon emission per unit of water treated at the plant

In pursuit of this study, carbon emission data from Iona Wastewater Treatment Plant and pumping stations serving the Vancouver sub-area in the lower Mainland was obtained from Metro Vancouver. The said data is enclosed in Appendix B.

Chapter 4.
Calculations

In a bid to demonstrate the usability of the above-described framework, this chapter will exhibit carbon accounting of the street assets on the three street segments picked earlier in the project.

4.1. Richards Street

Carbon impact of trees – Initial data used for analysis will be obtained from ArcGIS by selecting the trees in the area that need to be studied. Then, we program the equations, described in Section 3.2, in an excel sheet. Care should be taken to convert the values into the appropriate units. The analysis is enclosed Appendix A. Based on our analysis, the carbon sequestered by trees along Richard Street is 14.66 Tons till date. It is important to note that these values are based on current DBH and height estimates as available in Vanmap. For obtaining estimates over a period of time, one needs to establish growth rate equations to predict the DBH and height at the end of the estimation period. This demands a separate study that contextualizes the growth rate of trees in the City based on available data. It should be noted that the sequestration rate will slow down as the tree reaches maturity and growth rate decreases.

Based on available data, It is difficult to establish maintenance needs of street tree assets. Due to high variability of maintenance needs for trees based upon weather conditions, the maintenance analysis with the limited dataset available will yield highly variable results. Hence doing an analysis for the maintenance activities will not bring enough value to this work. Additional data such as tree mortality rates and intensity of maintenance needs to be considered in the analysis. As per a study done by Nowak et.al., If tree maintenance directly affects life span, increased maintenance will increase the sequestration. Furthermore, in a study done by Strobach et.al., an emission reduction of 62% was noticed when the frequency of maintenance was reduced from 10 times annually to once per year of lawn mowing. This shows the highly sensitive nature of this variable hence justifying the need for establishing some guidelines for making assumptions in order to proceed with the study.

For the added bike lane, Quantifying mode shift is difficult owing to the complexity of data and limited availability of time and resources. Hence, as per feedback received, a simpler approach is used to calculate the GHG emission savings. Pedestrian and bike traffic counts were obtained from Vanmap and Transportation division. The ideal value to look at will be the annual average daily traffic for weekdays and weekends, and scale up these values to get annual values. The latest traffic count survey done at Richard and Dunsmuir was only for one day, 12th August 2023.

For demonstration purposes we will use the traffic count values available and scale it up to determine annual GHG emission savings.

Bike traffic volume at Richard and Dunsmuir = 97 + 168 + 152 = 417

In absence of any demographic data to accompany the said dataset, an arbitrary assumption is made based on the transportation survey report, 2022; that 5% of these people are capable of driving, own a car and would have made the same trip by automobile before the bike lane was installed.

Hence, total number of cars taken off the road = 0.05 × 417 = 21

Using the carbon footprint values for different modes of transportation published by the European Cycling Federation, we can find the carbon emission saved as follows:

Carbon emissions saved = Carbon emissions from no. of cars taken off the road – Carbon emissions from Biking

$$\text{Carbon emission saved} = (21 \times 271) - (21 \times 21) = 5{,}250 \text{ gms of } CO_2 \text{ / day}$$

The annual emission savings from the project will amount to 1.9 MT annually. This number is arbitrary, and the use of VanSAM will help the City get accurate results.

To measure GRI impact we can start by looking at rain gauge data. As per Creekside rain gauge, the average rainfall received over the last four years in the vicinity of Richards Street is 1555 mm. Based on drawings made available by the City, the catchment area served by the RTT along Richard Street is 1409 m^2. The volume of water entering the GRI will be:

$$\text{Volume of Water entering RTT} = \text{Catchment area}(m^2) \times \text{Rainfall depth (m)}$$

$$= 1409 \times 1.555 = 2191 \ m^3$$

According to the Green Infrastructure performance monitoring report, the efficiency of RTT along Richard Street in retaining and allowing water infiltration is 84%. Using this we can find the volume of water absorbed by the RTT as follows:

Volume of water absorbed by the RTT = Volume of Water entering RTT × efficiency

$$= 2191 \times 0.84 = 1840 \ m^3$$

Similarly, the PP along Richard Street will help absorb the amount of water that directly falls over it. To quantify it, we multiply the depth of rainfall by the area of the pavement. As per original stated assumption, we assume the design and actual infiltration rate are equal to 10mm/hr.

The volume of water that is retained and absorbed by the RTT is the amount of water that will not enter the sewer system. Hence this water won’t need any pumping or treatment.

Volume of Water Absorbed by PP = Area of PP × Rainfall depth (when intensity ≤ infiltration rate)

$$= 105.45 \times 1.555 = 164 \text{ m}^3$$

Hence, Total stormwater runoff diverted from sewer system = 1840 + 164 = 2004 m^3

Looking at Vanmap, the closest catch basins are located on either ends of street segment, i.e., at the intersections of Richard St. @ Dunsmuir St., Richard St. @ W Georgia St. The system in the area is completely separated. Tracing the flow of storm mains in this area, one can find the entire flow is under gravity and the storm main discharges the runoff into False Creek underneath Drake Street. In conclusion, there is no pumping, neither treatment involved. Hence there are no quantifiable carbon emission reductions happening from sewer system due to presence of RTT and PP along our street segment. With that, one cannot say that the RTT does not come with benefits. The RTT still helps provide flexibility to a rigid and engineered storm sewer, adding to the system’s resiliency. The RTT also supports tree growth along Richard Street, helping reduce urban heat island effect and support biodiversity within the city boundaries. I strongly believe adding up benefits of reduced cooling needs for buildings in the vicinity will lead to healthy amounts of energy savings, justifying decreased carbon emissions.

Figure 4-1 Catch Basin location along selected segment of Richard Street

Figure 4-2 Stormwater runoff disposal into False Creek using Gravity system from the Richard Street segment

Source: Vanmap

4.2. W Georgia Street

Since this street only had street trees within its ROW to advocate for its greenness, the sequestration analysis of trees was done as outlined in Section 3.2. It was concluded that the trees along W Georgia street sequestered 5.8 MT of CO2 till date. Calculations are shared in Appendix A

4.3. Clark Drive

This street has none of the selected assets available within its ROW that need to be analyzed. Hence the carbon reduction/sequestration will be nil.

Chapter 5.
Conclusion

The above study builds out a framework for analyzing carbon capture/reduction from street infrastructure assets. It can be seen that the assets bring savings of differing magnitudes but due to limited availability of time and resources, the analysis is unidimensional. A lot of influential characteristics have been left out due to limited time and resources and these will help in making the study more holistic. Saying that, this study will benefit by working with other branches to fill the following knowledge gaps to make the analysis more holistic:

1. Establish guidelines that allow estimating tree maintenance to help produce consistent net sequestration analysis for street trees.
2. Study to estimate tree growth rates to estimate sequestration capacity over a defined time period.
3. A concerted modelling effort using VanSAM to estimate the emission savings from bike lanes.
4. Quantify energy savings from buildings due to reduced heat island effect.

The above knowledge gaps can be individual study projects in itself. This study makes the best use of data available with the City to meet the current demands of analyzing the sustainability of street assets in terms of carbon capture/reduction.

This work serves as a good starting point in analyzing the effects of use phase of the assets studied. Combining this with the City's work regarding the other phases – Material production, construction and rehabilitation; one can get the full life cycle emission analysis, helping reach credible emission savings/reduction values that come by using said assets.

The next steps in this analysis will be to use the defined framework in this study to fulfill the bigger scope of calculating net CO_2 emissions and establishing green score for roads in the City network.

References

Antunes, Lucas Niehuns, et al. “Permeable Pavements Life Cycle Assessment: A Literature Review.” Water, vol. 10, no. 11, 3 Nov. 2018, p. 1575, https://doi.org/10.3390/w10111575.

“Appendix B - GRI Typologies.” City of Vancouver, 5 Nov. 2019. https://vancouver.ca/files/cov/one-water-gri-typologies.pdf

Bharadwaj, Shashank, et al. “Impact of congestion on greenhouse gas emissions for road transport in Mumbai metropolitan region.” *Transportation Research Procedia*, vol. 25, 2017, pp. 3538–3551, https://doi.org/10.1016/j.trpro.2017.05.282.

Brand, Christian, et al. “Evaluating the impacts of new walking and cycling infrastructure on carbon dioxide emissions from motorized travel: A Controlled Longitudinal Study.” *Applied Energy*, vol. 128, Sept. 2014, pp. 284–295, https://doi.org/10.1016/j.apenergy.2014.04.072.

Canada, Natural Resources. “Forest Carbon.” *Natural Resources Canada*, Government of Canada, 21 June 2024, natural-resources.canada.ca/climate-change/climate-change-impacts-forests/forest-carbon/13085.

Chen, Xiaodan, and Hao Wang. “Life cycle assessment of asphalt pavement recycling for greenhouse gas emission with temporal aspect.” *Journal of Cleaner Production*, vol. 187, June 2018, pp. 148–157, https://doi.org/10.1016/j.jclepro.2018.03.207.

Chen, Xue, et al. “Quantifying on-road vehicle emissions during traffic congestion using updated emission factors of light-duty gasoline vehicles and real-world traffic monitoring Big Data.” Science of The Total Environment, vol. 847, Nov. 2022, p. 157581, https://doi.org/10.1016/j.scitotenv.2022.157581.

Choi, Changsoon, et al. “The climate benefits, co-benefits, and trade-offs of Green Infrastructure: A Systematic Literature Review.” *Journal of Environmental Management*, vol. 291, Aug. 2021, p. 112583, https://doi.org/10.1016/j.jenvman.2021.112583.

“Climate Emergency Action Plan.” City of Vancouver, 2020. https://vancouver.ca/files/cov/climate-emergency-action-plan-summary.pdf

Garge, Sandhya Kiran, and Shah Kinnari. “Carbon Sequestration by Urban Trees on Roadsides of Vadodara City.” *Research Gate*, International Journal of Engineering Science and Technology, Apr. 2011, www.researchgate.net/publication/267771547_Carbon_sequestration_by_urban_trees_on_roadsides_of_Vadodara_city.

Hwang, Uijeong, and Subhrajit Guhathakurta. “Exploring the impact of Bike Lanes on Transportation Mode Choice: A Simulation-based, route-level impact analysis.” *Sustainable Cities and Society*, vol. 89, Feb. 2023, p. 104318, https://doi.org/10.1016/j.scs.2022.104318.

Kavehei, Emad, et al. “Carbon sequestration potential for mitigating the carbon footprint of Green Stormwater Infrastructure.” *Renewable and Sustainable Energy Reviews*, vol. 94, Oct. 2018, pp. 1179–1191, https://doi.org/10.1016/j.rser.2018.07.002.

Lambert, M-C, et al. “Canadian national tree aboveground biomass equations.” *Canadian Journal of Forest Research*, vol. 35, no. 8, 1 Aug. 2005, pp. 1996–2018, https://doi.org/10.1139/x05-112.

Leda Marritz, Kala Hunter. “Trees Are a Tool for Safer Streets: Deeproot Blog.” *Deeproot*, Deeproot, 31 Mar. 2021, www.deeproot.com/blog/blog-entries/trees-are-a-tool-for-safer-streets-2/.

Min, Seung-Ki, et al. “Human contribution to more-intense precipitation extremes.” *Nature*, vol. 470, no. 7334, 16 Feb. 2011, pp. 378–381, https://doi.org/10.1038/nature09763.

Ministry of Environment and Climate Change Strategy. “Electricity Emission Intensity Factors for Grid-Connected Entities.” *Province of British Columbia*, Province of British Columbia, 16 Feb. 2024, https://www2.gov.bc.ca/gov/content/environment/climate-change/industry/reporting/quantify/electricity

Moore, Trisha L.C., and William F. Hunt. “Predicting the carbon footprint of Urban Stormwater Infrastructure.” *Ecological Engineering*, vol. 58, Sept. 2013, pp. 44–51, https://doi.org/10.1016/j.ecoleng.2013.06.021.

Nowak, David, et al. “Effects of urban tree management and species selection on atmospheric carbon dioxide.” *Arboriculture & Urban Forestry*, vol. 28, no. 3, 1 May 2002, pp. 113–122, https://doi.org/10.48044/jauf.2002.017.

Parsons Transportation Group. “Relationship Between Lane Width and Speed - Review of Relevant Literature .” National Association of City Transportation Officials (NACTO), Sept. 2003. https://nacto.org/docs/usdg/review_lane_width_and_speed_parsons.pdf

Pati, Pranab Kumar, et al. “Evaluating the role of roadside vegetation in atmospheric carbon dioxide mitigation: A case study.” *Arboricultural Journal*, vol. 46, no. 2, 19 July 2023, pp. 97–119, https://doi.org/10.1080/03071375.2023.2233868.

Plappally, A.K., and J.H. Lienhard V. “Energy requirements for water production, treatment, end use, reclamation, and disposal.” *Renewable and Sustainable Energy Reviews*, vol. 16, no. 7, Sept. 2012, pp. 4818–4848, https://doi.org/10.1016/j.rser.2012.05.022.

Prasara-A, J., and A. Bridhikitti. “Carbon footprint and cost analysis of a bicycle lane in a municipality.” *Global Journal of Environmental Science and Management* , vol. 8, no. 2, 2022, pp. 197–208, https://doi.org/10.22034/gjesm.2022.02.04.

Riebeek, Holli. “The Carbon Cycle.” *NASA*, NASA, 16 June 2011, https://earthobservatory.nasa.gov/features/CarbonCycle#:~:text=Carbon%20flows%20between%20each%20reservoir,in%20warmer%20temperatures%20on%20Earth.

Shao, Weiwei, et al. “Carbon reduction effects of Sponge City Construction: A case study of the city of Xiamen.” *Energy Procedia*, vol. 152, Oct. 2018, pp. 1145–1151, https://doi.org/10.1016/j.egypro.2018.09.145.

Spraakman, Sylvie, et al. City of Vancouver, 2022, *Vancouver Green Infrastructure Performance Monitoring Report*, https://vancouver.ca/files/cov/green-infrastructure-performance-monitoring-report.pdf., Accessed June 2024.

Srour, Nour, et al. “Quantifying carbon stocks and functional diversity of roadside ecosystems – a case study in Quebec, Canada.” *Urban Forestry & Urban Greening*, vol. 91, Jan. 2024, p. 128163, https://doi.org/10.1016/j.ufug.2023.128163.

Strohbach, Michael W., et al. “The carbon footprint of urban green space—a life cycle approach.” *Landscape and Urban Planning*, vol. 104, no. 2, Feb. 2012, pp. 220–229, https://doi.org/10.1016/j.landurbplan.2011.10.013.

Transport Canada. “Greenhouse Gas Emissions.” *Transport Canada*, Government of Canada, 27 June 2022, www.tc.canada.ca/en/corporate-services/transparency/corporate-management-reporting/transportation-canada-annual-reports/2021/greenhouse-gas-emissions.

Wang, Yupeng, and Hashem Akbari. “The effects of street tree planting on urban heat island mitigation in Montreal.” *Sustainable Cities and Society*, vol. 27, Nov. 2016, pp. 122–128, https://doi.org/10.1016/j.scs.2016.04.013.

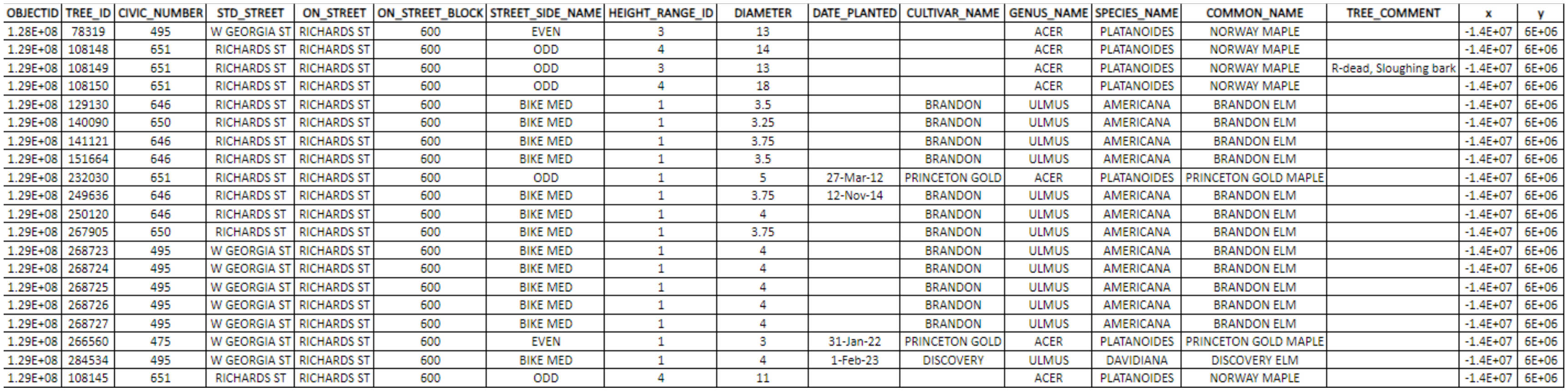
Wasko, Conrad, and Ashish Sharma. “Steeper temporal distribution of rain intensity at higher temperatures within Australian storms.” *Nature Geoscience*, vol. 8, no. 7, 8 June 2015, pp. 527–529, https://doi.org/10.1038/ngeo2456.

Zahabi, Seyed Amir, et al. “Exploring the link between the neighborhood typologies, bicycle infrastructure and commuting cycling over time and the potential impact on commuter GHG emissions.” *Transportation Research Part D: Transport and Environment*, vol. 47, Aug. 2016, pp. 89–103, https://doi.org/10.1016/j.trd.2016.05.008.

Appendix A.

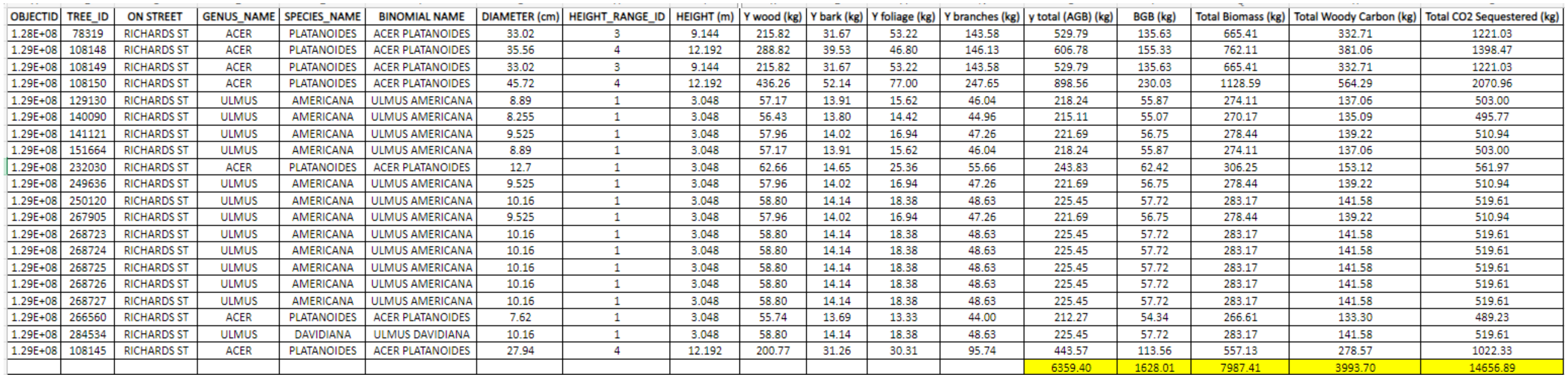
Tree Carbon Sequestration Analysis

Table 6 Raw data obtained from Vanmap for street trees along Richard Street b/w W Georgia Street and Dunsmuir Street (Source – Vanmap)



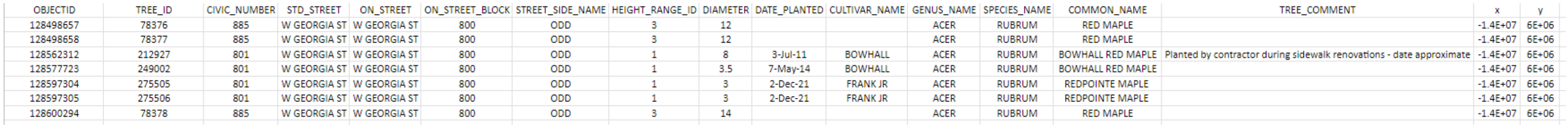
OBJECTID	TREE_ID	CIVIC_NUMBER	STD_STREET	ON_STREET	ON_STREET_BLOCK	STREET_SIDE_NAME	HEIGHT_RANGE_ID	DIAMETER	DATE_PLANTED	CULTIVAR_NAME	GENUS_NAME	SPECIES_NAME	COMMON_NAME	TREE_COMMENT	x	y
1.28E+08	78319	495	W GEORGIA ST	RICHARDS ST	600	EVEN	3	13			ACER	PLATANOIDES	NORWAY MAPLE		-1.4E+07	6E+06
1.29E+08	108148	651	RICHARDS ST	RICHARDS ST	600	ODD	4	14			ACER	PLATANOIDES	NORWAY MAPLE		-1.4E+07	6E+06
1.29E+08	108149	651	RICHARDS ST	RICHARDS ST	600	ODD	3	13			ACER	PLATANOIDES	NORWAY MAPLE	R-dead, Sloughing bark	-1.4E+07	6E+06
1.29E+08	108150	651	RICHARDS ST	RICHARDS ST	600	ODD	4	18			ACER	PLATANOIDES	NORWAY MAPLE		-1.4E+07	6E+06
1.29E+08	129130	646	RICHARDS ST	RICHARDS ST	600	BIKE MED	1	3.5		BRANDON	ULMUS	AMERICANA	BRANDON ELM		-1.4E+07	6E+06
1.29E+08	140090	650	RICHARDS ST	RICHARDS ST	600	BIKE MED	1	3.25		BRANDON	ULMUS	AMERICANA	BRANDON ELM		-1.4E+07	6E+06
1.29E+08	141121	646	RICHARDS ST	RICHARDS ST	600	BIKE MED	1	3.75		BRANDON	ULMUS	AMERICANA	BRANDON ELM		-1.4E+07	6E+06
1.29E+08	151664	646	RICHARDS ST	RICHARDS ST	600	BIKE MED	1	3.5		BRANDON	ULMUS	AMERICANA	BRANDON ELM		-1.4E+07	6E+06
1.29E+08	232030	651	RICHARDS ST	RICHARDS ST	600	ODD	1	5	27-Mar-12	PRINCETON GOLD	ACER	PLATANOIDES	PRINCETON GOLD MAPLE		-1.4E+07	6E+06
1.29E+08	249636	646	RICHARDS ST	RICHARDS ST	600	BIKE MED	1	3.75	12-Nov-14	BRANDON	ULMUS	AMERICANA	BRANDON ELM		-1.4E+07	6E+06
1.29E+08	250120	646	RICHARDS ST	RICHARDS ST	600	BIKE MED	1	4		BRANDON	ULMUS	AMERICANA	BRANDON ELM		-1.4E+07	6E+06
1.29E+08	267905	650	RICHARDS ST	RICHARDS ST	600	BIKE MED	1	3.75		BRANDON	ULMUS	AMERICANA	BRANDON ELM		-1.4E+07	6E+06
1.29E+08	268723	495	W GEORGIA ST	RICHARDS ST	600	BIKE MED	1	4		BRANDON	ULMUS	AMERICANA	BRANDON ELM		-1.4E+07	6E+06
1.29E+08	268724	495	W GEORGIA ST	RICHARDS ST	600	BIKE MED	1	4		BRANDON	ULMUS	AMERICANA	BRANDON ELM		-1.4E+07	6E+06
1.29E+08	268725	495	W GEORGIA ST	RICHARDS ST	600	BIKE MED	1	4		BRANDON	ULMUS	AMERICANA	BRANDON ELM		-1.4E+07	6E+06
1.29E+08	268726	495	W GEORGIA ST	RICHARDS ST	600	BIKE MED	1	4		BRANDON	ULMUS	AMERICANA	BRANDON ELM		-1.4E+07	6E+06
1.29E+08	268727	495	W GEORGIA ST	RICHARDS ST	600	BIKE MED	1	4		BRANDON	ULMUS	AMERICANA	BRANDON ELM		-1.4E+07	6E+06
1.29E+08	266560	475	W GEORGIA ST	RICHARDS ST	600	EVEN	1	3	31-Jan-22	PRINCETON GOLD	ACER	PLATANOIDES	PRINCETON GOLD MAPLE		-1.4E+07	6E+06
1.29E+08	284534	495	W GEORGIA ST	RICHARDS ST	600	BIKE MED	1	4	1-Feb-23	DISCOVERY	ULMUS	DAVIDIANA	DISCOVERY ELM		-1.4E+07	6E+06
1.29E+08	108145	651	RICHARDS ST	RICHARDS ST	600	ODD	4	11			ACER	PLATANOIDES	NORWAY MAPLE		-1.4E+07	6E+06

Table 7 Carbon Sequestration analysis for street trees along Richard Street b/w W Georgia Street and Dunsmuir Street



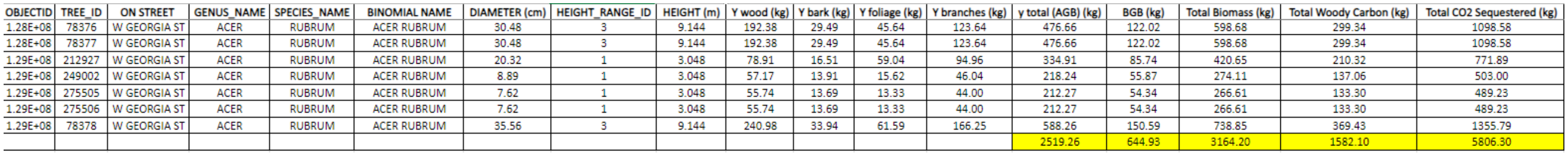
OBJECTID	TREE_ID	ON STREET	GENUS_NAME	SPECIES_NAME	BINOMIAL NAME	DIAMETER (cm)	HEIGHT_RANGE_ID	HEIGHT (m)	Y wood (kg)	Y bark (kg)	Y foliage (kg)	Y branches (kg)	y total (AGB) (kg)	BGB (kg)	Total Biomass (kg)	Total Woody Carbon (kg)	Total CO2 Sequestered (kg)
1.28E+08	78319	RICHARDS ST	ACER	PLATANOIDES	ACER PLATANOIDES	33.02	3	9.144	215.82	31.67	53.22	143.58	529.79	135.63	665.41	332.71	1221.03
1.29E+08	108148	RICHARDS ST	ACER	PLATANOIDES	ACER PLATANOIDES	35.56	4	12.192	288.82	39.53	46.80	146.13	606.78	155.33	762.11	381.06	1398.47
1.29E+08	108149	RICHARDS ST	ACER	PLATANOIDES	ACER PLATANOIDES	33.02	3	9.144	215.82	31.67	53.22	143.58	529.79	135.63	665.41	332.71	1221.03
1.29E+08	108150	RICHARDS ST	ACER	PLATANOIDES	ACER PLATANOIDES	45.72	4	12.192	436.26	52.14	77.00	247.65	898.56	230.03	1128.59	564.29	2070.96
1.29E+08	129130	RICHARDS ST	ULMUS	AMERICANA	ULMUS AMERICANA	8.89	1	3.048	57.17	13.91	15.62	46.04	218.24	55.87	274.11	137.06	503.00
1.29E+08	140090	RICHARDS ST	ULMUS	AMERICANA	ULMUS AMERICANA	8.255	1	3.048	56.43	13.80	14.42	44.96	215.11	55.07	270.17	135.09	495.77
1.29E+08	141121	RICHARDS ST	ULMUS	AMERICANA	ULMUS AMERICANA	9.525	1	3.048	57.96	14.02	16.94	47.26	221.69	56.75	278.44	139.22	510.94
1.29E+08	151664	RICHARDS ST	ULMUS	AMERICANA	ULMUS AMERICANA	8.89	1	3.048	57.17	13.91	15.62	46.04	218.24	55.87	274.11	137.06	503.00
1.29E+08	232030	RICHARDS ST	ACER	PLATANOIDES	ACER PLATANOIDES	12.7	1	3.048	62.66	14.65	25.36	55.66	243.83	62.42	306.25	153.12	561.97
1.29E+08	249636	RICHARDS ST	ULMUS	AMERICANA	ULMUS AMERICANA	9.525	1	3.048	57.96	14.02	16.94	47.26	221.69	56.75	278.44	139.22	510.94
1.29E+08	250120	RICHARDS ST	ULMUS	AMERICANA	ULMUS AMERICANA	10.16	1	3.048	58.80	14.14	18.38	48.63	225.45	57.72	283.17	141.58	519.61
1.29E+08	267905	RICHARDS ST	ULMUS	AMERICANA	ULMUS AMERICANA	9.525	1	3.048	57.96	14.02	16.94	47.26	221.69	56.75	278.44	139.22	510.94
1.29E+08	268723	RICHARDS ST	ULMUS	AMERICANA	ULMUS AMERICANA	10.16	1	3.048	58.80	14.14	18.38	48.63	225.45	57.72	283.17	141.58	519.61
1.29E+08	268724	RICHARDS ST	ULMUS	AMERICANA	ULMUS AMERICANA	10.16	1	3.048	58.80	14.14	18.38	48.63	225.45	57.72	283.17	141.58	519.61
1.29E+08	268725	RICHARDS ST	ULMUS	AMERICANA	ULMUS AMERICANA	10.16	1	3.048	58.80	14.14	18.38	48.63	225.45	57.72	283.17	141.58	519.61
1.29E+08	268726	RICHARDS ST	ULMUS	AMERICANA	ULMUS AMERICANA	10.16	1	3.048	58.80	14.14	18.38	48.63	225.45	57.72	283.17	141.58	519.61
1.29E+08	268727	RICHARDS ST	ULMUS	AMERICANA	ULMUS AMERICANA	10.16	1	3.048	58.80	14.14	18.38	48.63	225.45	57.72	283.17	141.58	519.61
1.29E+08	266560	RICHARDS ST	ACER	PLATANOIDES	ACER PLATANOIDES	7.62	1	3.048	55.74	13.69	13.33	44.00	212.27	54.34	266.61	133.30	489.23
1.29E+08	284534	RICHARDS ST	ULMUS	DAVIDIANA	ULMUS DAVIDIANA	10.16	1	3.048	58.80	14.14	18.38	48.63	225.45	57.72	283.17	141.58	519.61
1.29E+08	108145	RICHARDS ST	ACER	PLATANOIDES	ACER PLATANOIDES	27.94	4	12.192	200.77	31.26	30.31	95.74	443.57	113.56	557.13	278.57	1022.33
													6359.40	1628.01	7987.41	3993.70	14656.89

Table 8 Raw data for obtained from Vanmap for street trees along W Georgia street b/w Howe Street and Hornby Street (Source – Vanmap)



OBJECTID	TREE_ID	CIVIC_NUMBER	STD_STREET	ON_STREET	ON_STREET_BLOCK	STREET_SIDE_NAME	HEIGHT_RANGE_ID	DIAMETER	DATE_PLANTED	CULTIVAR_NAME	GENUS_NAME	SPECIES_NAME	COMMON_NAME	TREE_COMMENT	x	y
128498657	78376	885	W GEORGIA ST	W GEORGIA ST	800	ODD	3	12			ACER	RUBRUM	RED MAPLE		-1.4E+07	6E+06
128498658	78377	885	W GEORGIA ST	W GEORGIA ST	800	ODD	3	12			ACER	RUBRUM	RED MAPLE		-1.4E+07	6E+06
128562312	212927	801	W GEORGIA ST	W GEORGIA ST	800	ODD	1	8	3-Jul-11	BOWHALL	ACER	RUBRUM	BOWHALL RED MAPLE	Planted by contractor during sidewalk renovations - date approximate	-1.4E+07	6E+06
128577723	249002	801	W GEORGIA ST	W GEORGIA ST	800	ODD	1	3.5	7-May-14	BOWHALL	ACER	RUBRUM	BOWHALL RED MAPLE		-1.4E+07	6E+06
128597304	275505	801	W GEORGIA ST	W GEORGIA ST	800	ODD	1	3	2-Dec-21	FRANK JR	ACER	RUBRUM	REDPOINTE MAPLE		-1.4E+07	6E+06
128597305	275506	801	W GEORGIA ST	W GEORGIA ST	800	ODD	1	3	2-Dec-21	FRANK JR	ACER	RUBRUM	REDPOINTE MAPLE		-1.4E+07	6E+06
128600294	78378	885	W GEORGIA ST	W GEORGIA ST	800	ODD	3	14			ACER	RUBRUM	RED MAPLE		-1.4E+07	6E+06

Table 9 Carbon Sequestration analysis for Street Trees along W Georgia Street b/w Howe Street and Hornby Street

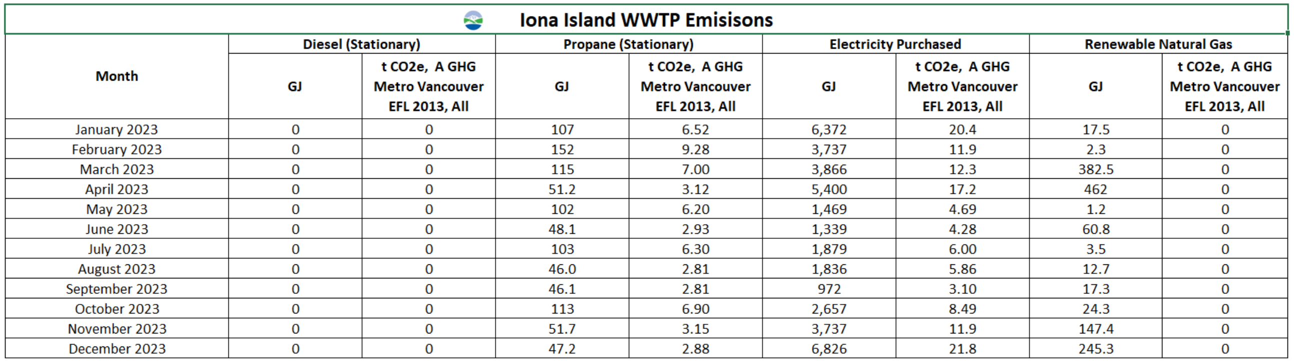


OBJECTID	TREE_ID	ON STREET	GENUS_NAME	SPECIES_NAME	BINOMIAL NAME	DIAMETER (cm)	HEIGHT_RANGE_ID	HEIGHT (m)	Y wood (kg)	Y bark (kg)	Y foliage (kg)	Y branches (kg)	y total (AGB) (kg)	BGB (kg)	Total Biomass (kg)	Total Woody Carbon (kg)	Total CO2 Sequestered (kg)
1.28E+08	78376	W GEORGIA ST	ACER	RUBRUM	ACER RUBRUM	30.48	3	9.144	192.38	29.49	45.64	123.64	476.66	122.02	598.68	299.34	1098.58
1.28E+08	78377	W GEORGIA ST	ACER	RUBRUM	ACER RUBRUM	30.48	3	9.144	192.38	29.49	45.64	123.64	476.66	122.02	598.68	299.34	1098.58
1.29E+08	212927	W GEORGIA ST	ACER	RUBRUM	ACER RUBRUM	20.32	1	3.048	78.91	16.51	59.04	94.96	334.91	85.74	420.65	210.32	771.89
1.29E+08	249002	W GEORGIA ST	ACER	RUBRUM	ACER RUBRUM	8.89	1	3.048	57.17	13.91	15.62	46.04	218.24	55.87	274.11	137.06	503.00
1.29E+08	275505	W GEORGIA ST	ACER	RUBRUM	ACER RUBRUM	7.62	1	3.048	55.74	13.69	13.33	44.00	212.27	54.34	266.61	133.30	489.23
1.29E+08	275506	W GEORGIA ST	ACER	RUBRUM	ACER RUBRUM	7.62	1	3.048	55.74	13.69	13.33	44.00	212.27	54.34	266.61	133.30	489.23
1.29E+08	78378	W GEORGIA ST	ACER	RUBRUM	ACER RUBRUM	35.56	3	9.144	240.98	33.94	61.59	166.25	588.26	150.59	738.85	369.43	1355.79
													2519.26	644.93	3164.20	1582.10	5806.30

Appendix B.

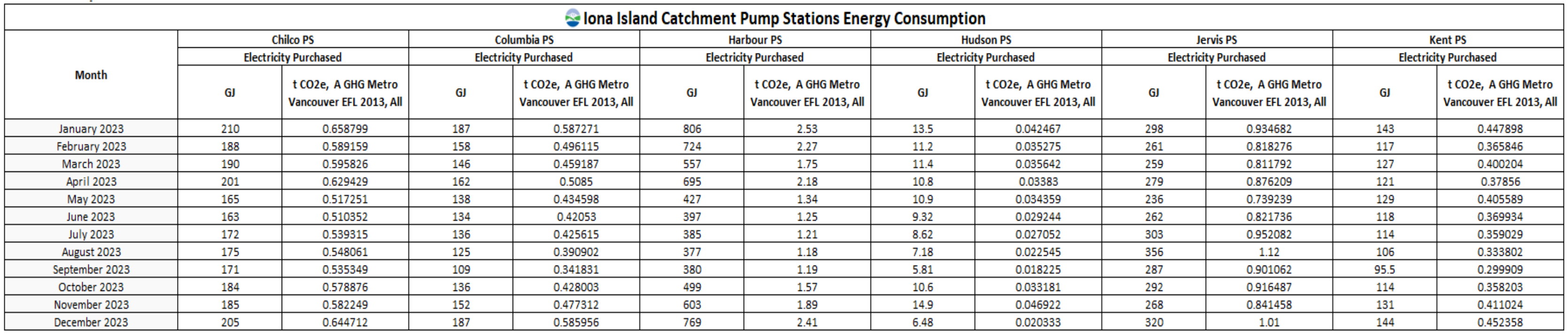
Treatment plant and pumping related emissions for Vancouver Sub region

Table 10 Iona Island WWTP emissions from energy use (Courtesy of Metro Vancouver)

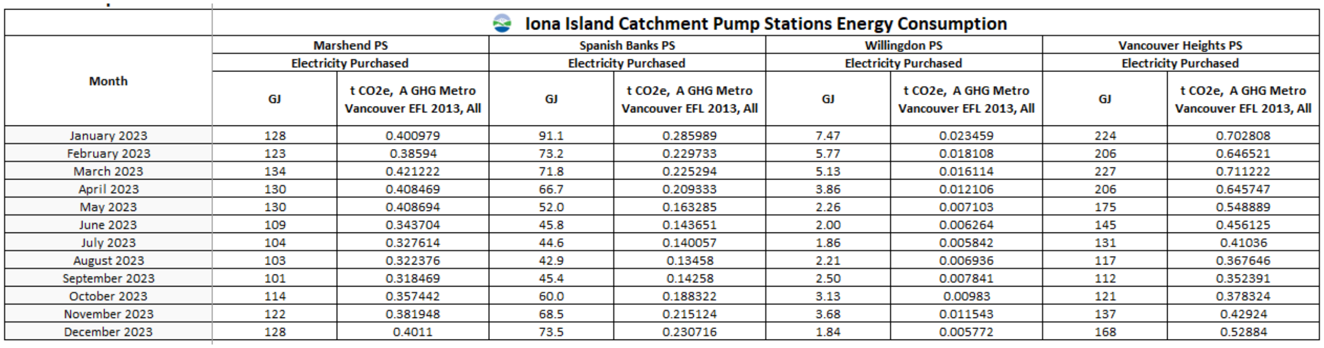


Iona Island WWTP Emisisons								
Month	Diesel (Stationary)		Propane (Stationary)		Electricity Purchased		Renewable Natural Gas	
	GJ	t CO2e, A GHG Metro Vancouver EFL 2013, All	GJ	t CO2e, A GHG Metro Vancouver EFL 2013, All	GJ	t CO2e, A GHG Metro Vancouver EFL 2013, All	GJ	t CO2e, A GHG Metro Vancouver EFL 2013, All
January 2023	0	0	107	6.52	6,372	20.4	17.5	0
February 2023	0	0	152	9.28	3,737	11.9	2.3	0
March 2023	0	0	115	7.00	3,866	12.3	382.5	0
April 2023	0	0	51.2	3.12	5,400	17.2	462	0
May 2023	0	0	102	6.20	1,469	4.69	1.2	0
June 2023	0	0	48.1	2.93	1,339	4.28	60.8	0
July 2023	0	0	103	6.30	1,879	6.00	3.5	0
August 2023	0	0	46.0	2.81	1,836	5.86	12.7	0
September 2023	0	0	46.1	2.81	972	3.10	17.3	0
October 2023	0	0	113	6.90	2,657	8.49	24.3	0
November 2023	0	0	51.7	3.15	3,737	11.9	147.4	0
December 2023	0	0	47.2	2.88	6,826	21.8	245.3	0

Table 11 Iona Island WWTP Catchment Pump station energy consumption (Courtesy of Metro Vancouver)



Iona Island Catchment Pump Stations Energy Consumption												
Month	Chilco PS		Columbia PS		Harbour PS		Hudson PS		Jervis PS		Kent PS	
	Electricity Purchased		Electricity Purchased		Electricity Purchased		Electricity Purchased		Electricity Purchased		Electricity Purchased	
	GJ	t CO2e, A GHG Metro Vancouver EFL 2013, All	GJ	t CO2e, A GHG Metro Vancouver EFL 2013, All	GJ	t CO2e, A GHG Metro Vancouver EFL 2013, All	GJ	t CO2e, A GHG Metro Vancouver EFL 2013, All	GJ	t CO2e, A GHG Metro Vancouver EFL 2013, All	GJ	t CO2e, A GHG Metro Vancouver EFL 2013, All
January 2023	210	0.658799	187	0.587271	806	2.53	13.5	0.042467	298	0.934682	143	0.447898
February 2023	188	0.589159	158	0.496115	724	2.27	11.2	0.035275	261	0.818276	117	0.365846
March 2023	190	0.595826	146	0.459187	557	1.75	11.4	0.035642	259	0.811792	127	0.400204
April 2023	201	0.629429	162	0.5085	695	2.18	10.8	0.03383	279	0.876209	121	0.37856
May 2023	165	0.517251	138	0.434598	427	1.34	10.9	0.034359	236	0.739239	129	0.405589
June 2023	163	0.510352	134	0.42053	397	1.25	9.32	0.029244	262	0.821736	118	0.369934
July 2023	172	0.539315	136	0.425615	385	1.21	8.62	0.027052	303	0.952082	114	0.359029
August 2023	175	0.548061	125	0.390902	377	1.18	7.18	0.022545	356	1.12	106	0.333802
September 2023	171	0.535349	109	0.341831	380	1.19	5.81	0.018225	287	0.901062	95.5	0.299909
October 2023	184	0.578876	136	0.428003	499	1.57	10.6	0.033181	292	0.916487	114	0.358203
November 2023	185	0.582249	152	0.477312	603	1.89	14.9	0.046922	268	0.841458	131	0.411024
December 2023	205	0.644712	187	0.585956	769	2.41	6.48	0.020333	320	1.01	144	0.452358



	Iona Island Catchment Pump Stations Energy Consumption							
Month	Marshend PS		Spanish Banks PS		Willingdon PS		Vancouver Heights PS	
	Electricity Purchased		Electricity Purchased		Electricity Purchased		Electricity Purchased	
	GJ	t CO2e, A GHG Metro Vancouver EFL 2013, All	GJ	t CO2e, A GHG Metro Vancouver EFL 2013, All	GJ	t CO2e, A GHG Metro Vancouver EFL 2013, All	GJ	t CO2e, A GHG Metro Vancouver EFL 2013, All
January 2023	128	0.400979	91.1	0.285989	7.47	0.023459	224	0.702808
February 2023	123	0.38594	73.2	0.229733	5.77	0.018108	206	0.646521
March 2023	134	0.421222	71.8	0.225294	5.13	0.016114	227	0.711222
April 2023	130	0.408469	66.7	0.209333	3.86	0.012106	206	0.645747
May 2023	130	0.408694	52.0	0.163285	2.26	0.007103	175	0.548889
June 2023	109	0.343704	45.8	0.143651	2.00	0.006264	145	0.456125
July 2023	104	0.327614	44.6	0.140057	1.86	0.005842	131	0.41036
August 2023	103	0.322376	42.9	0.13458	2.21	0.006936	117	0.367646
September 2023	101	0.318469	45.4	0.14258	2.50	0.007841	112	0.352391
October 2023	114	0.357442	60.0	0.188322	3.13	0.00983	121	0.378324
November 2023	122	0.381948	68.5	0.215124	3.68	0.011543	137	0.42924
December 2023	128	0.4011	73.5	0.230716	1.84	0.005772	168	0.52884