Effectiveness of Urban Green Infrastructure: Management Challenges in the City of Vancouver, British Columbia

LWS 548 Major Project

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Executive Summary

The accelerated climate change and the associated more intense and frequent extreme weather events have caught worldwide attention, and urban environments are significantly more vulnerable to the problem. Likewise, Metro Vancouver also encounters increased urban heat island effects, disturbed water balance, degraded ecosystem services, and other stressors from climate variabilities. In response to the current situation, the city extensively encourages the operations of green infrastructure initiatives, seeing them as mitigation solutions for future climate change due to the potential advantages. However, the challenges of incorporating them into urban landscapes have not been well explored. Also, there is currently a lack of awareness of the monitoring needs after the construction. Therefore, the project aims to determine the benefits and challenges of using urban trees and constructed wetlands as green infrastructure initiatives in the city. Meanwhile, highlight the monitoring requirements for sustaining the efforts.

Based on the systematic literature review, urban trees and constructed wetlands play a key role in sustainable water management and mitigating the leading factors and impacts of climate variabilities. However, they are also susceptible to short-term extreme weather events and long-term climate warming, which may impede their functionalities and lead to adverse environmental impacts. Consequently, a monitoring program that provides clear guidelines for relevant indicator assessments and appropriate frequency is necessary for determining the effectiveness of the green infrastructure performance and providing directions for further management. Beyond that, the collaboration between different groups, including the public, experts, local government, and non-governmental organizations, can improve the efficiencies but can be challenging. In addition to the monitoring needs, the city should raise concerns about plant susceptibility to climate change and understand the various trade-offs between broadleaf and coniferous trees, developing a more resilient species composition in the city. More research on wetland plants and their responses to heat stress and other climate variabilities is particularly needed.

1.0 Introduction

1.1 Climate change in urban environments

Rapid urban development makes cities the primary contributor to climate change due to the exponential increase in population and associated human activities, such as transportation, electricity production, and land-use change, thus increasing greenhouse gas emissions and global warming (U.S. EPA, 2020). Since the late 19th century, the average surface temperature of the earth has risen approximately 1 degree Celsius (NOAA, 2021). More significantly, highly concentrated urban environments are particularly vulnerable to climate variability (Hunt et al., 2007). Extreme events, such as heat waves, flooding, drought, and disease outbreaks, have increased frequency and severity, putting continuous pressure on the goal of sustainable water and ecosystem management. Consequently, building resilient cities has become a worldwide challenge.

1.2 Green infrastructure initiatives

Cities are the key contributor to climate change, but they are also part of the solutions for climate change mitigation. In response to the intensified risks in urban areas, several land-based planning, management, and design approaches have been implemented in developed centres to restore water balance and improve resilience. This requires a paradigm shift from sole reliance on grey infrastructure (Dolman, 2020). Green infrastructure, an emerging design applying engineered or ecosystem-based practices to absorb and filter stormwater, has been encouraged and adopted by many urban cities, supporting healthier water systems and more resilient urban environments (City of Vancouver, 2017). The benefits of green infrastructure and its flexibility in implementation allow various designs to be incorporated into the urban landscape at multiple scales, from the small backyard garden to a greenway spanning many kilometres. At a local scale, trees and vegetation cover can replace impervious grey infrastructure such as sidewalks and gutters, increasing rainwater interception and infiltration while reducing pollutant loads (City of Vancouver, 2017). When distributed throughout the watershed, even relatively small patches of green infrastructure can collectively form a network, having significant impacts on enhancing habitat and biodiversity, lowering urban heat island effects, managing flooding risks, and improving air and water quality (City of Vancouver, 2019; Metro Vancouver, 2013). Thus, green infrastructure initiatives align water management with other city-building priorities, achieving multiple-purpose infrastructure and building resiliency.

1.21 Urban trees

Urban trees are a crucial part of green infrastructure in many cities and may be observable in many applications and public locations, such as parks, streets, greenways, and parking lots. Also, some urban trees are on private property, like residential backyards. All individual trees are part of urban forests with no regard to the practice scales, fragmenting impervious surfaces with green spaces added to the landscape, playing significant roles in providing numerous ecosystem services (McGovern & Pasher, 2016). They simultaneously act as tools for climate mitigation and adaptation. Therefore, cities worldwide have set goals to plant more trees and increase the urban tree canopy, including many urban centres in Canada. For instance, the city of Montreal ambitiously plans to increase tree cover to 25 percent by 2025, while Toronto sets the goal of 40 percent by 2050 (Canadian Climate Institute, 2021). However, the success of urban trees in dense environments depends on various factors, such as tree species selection, available soil volume, appropriate soil moisture regime, and essential nutrient supply (Carlyle-Moses et al., 2020). These factors are more challenging to deal with than just planting trees.

1.22 Constructed wetlands

Constructed wetlands are categorized as large-scale green infrastructure practices that can relatively collect and manage a larger volume of surface water. However, they require complex technology, various tools, and increased land areas (Gato-Trinidad et al., 2022). The fundamental understanding of the constructed wetland technology is to mimic the natural wetland systems and enhance those naturally occurring functions, but under controlled conditions with more benefits provided (Stefanakis, 2019). For example, the engineered systems are designed for removing sediments, nutrients, and other pollutants through a series of treatment processes, thus purifying wastewater and enhancing water quality (Stefanakis, 2019). Moreover, the values of constructed wetlands have been recognized and exploited in multiple other applications during the past few decades, including the treatment of the stormwater runoff, flooding control, and habitat creation (Gato-Trinidad et al., 2022; Stefanakis, 2019).

Additionally, many forms and modifications to the operations of constructed wetland technology have been developed under exponentially growing demands over time, generally categorized by the flow path and the vegetation types (Figure 1). The free water surface and the subsurface constructed wetlands are two basic types based on the flow path (Nuamah et al., 2020). Also, the constructed wetlands can be further classified by vegetation types, including emergent, submerged, and free-floating plants (Stefanakis, 2019). The emergent vegetation is most commonly involved in the design since they have essential roles in wetland ecosystems towards contaminant removal and microbial population support (Nuamah et al., 2020). The selections of the various types of constructed wetlands are based on the performance targets, and some types of systems may show more efficiency in removing certain pollutants than others. Therefore, a single wetland facility that combines more than one type and applies hybrid wetland systems can provide more functional improvements (Nuamah et al., 2020).

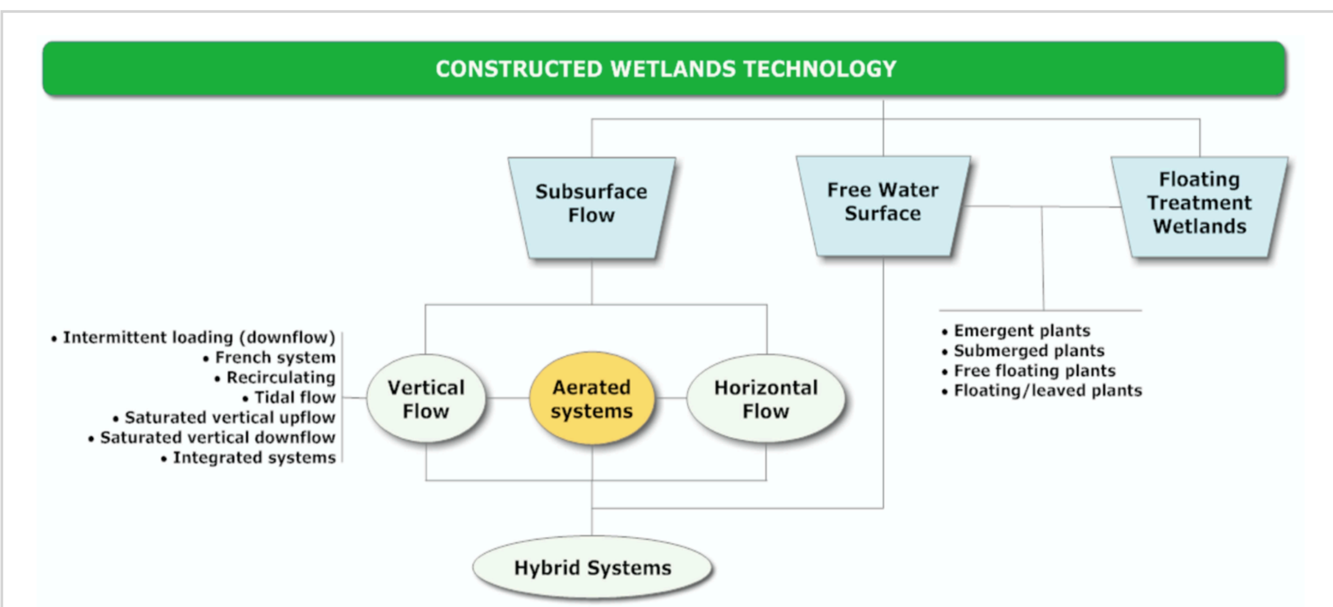


Figure 1: Classification of the various types of constructed wetlands (Stefanakis, 2019).

1.3 Knowledge gaps

The growing popularity of incorporating green infrastructure into urban landscapes for sustainable water management and climate change resiliency has been introduced, and urban trees and constructed wetlands play a key role. Also, researchers from numerous countries have increasing concerns on the topic. For instance, scientific publications related to construction wetlands exponentially increased from 21 in 1991 to 460 in 2011, and there was an expected continuous increase (Zhi & Ji, 2012). Furthermore, based on the title words and keywords analysis among 3787 published literature, the design, development, performance, and relevant benefits of different types of constructed wetlands have been well-documented (Zhi & Ji, 2012). However, this generally assumes that the infrastructure is operating under optimal conditions, and limited research has attempted to determine the susceptibility to climate variability, particularly to the internal components of wetland plants. The responses to climate change, either extreme short-term events or long-term global warming, are of concern and require further studies to reduce the uncertainties.

At present, the highlighted weakness also applies to urban trees and other types of green infrastructure initiatives, leading to failures in the performance effectiveness, and can even result in adverse environmental impacts that are opposite to the objectives (Salimi et al., 2021; Brown & Hunt, 2012). Moreover, less attention has been paid to the monitoring needs after construction, especially under enhanced climate change, which is identified as a significant threat to wetland systems and other green infrastructure initiatives (Salimi, 2021). Monitoring is the prerequisite for measuring the vulnerability of plants and facilities to climate variability and determining whether the provided benefits can be sustainable and whether there is a need for different maintenance. Conversely, a lack of monitoring programs can lead to uncertainties in the implementation efforts, challenging the subsequent maintenance.

2.0 Study Site

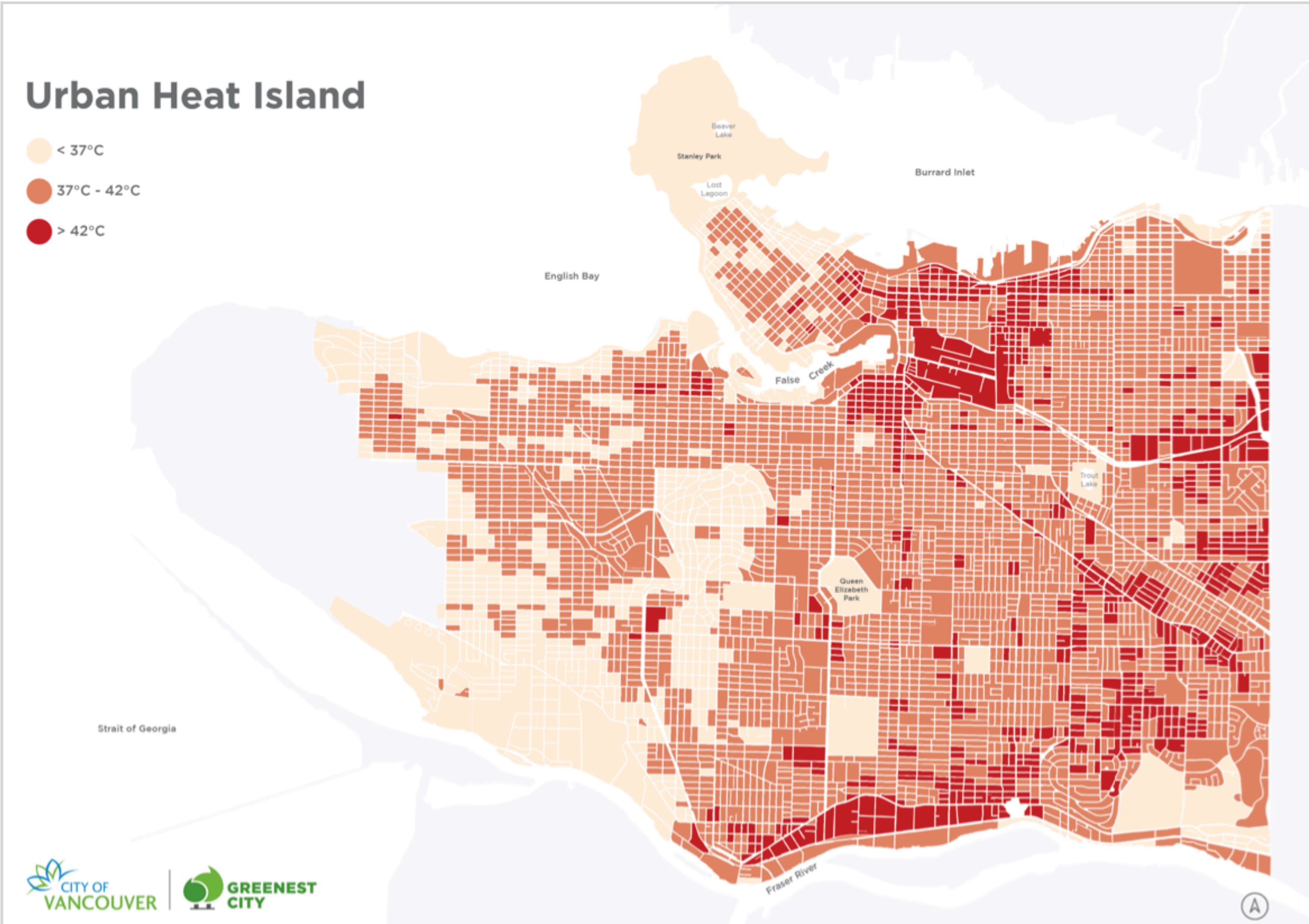


Figure 2: Urban heat island effects in the City of Vancouver, the study site of the project (2016).

Like many other urban centres, the accelerated climate changes are already noticeable in the city of Vancouver, British Columbia, the study area of the project. As one of the examples, the figure above visualizes the degree of urban heat island effects in different regions within the city (Figure 2). Temperatures in urban environments are always higher than in forests. Also, it confirms a more problematic situation in the downtown area, having the highest heat island effects with the highest density and imperviousness. More significantly, the city is predicted to face more severe climate change challenges by 2050, including changes in rainfall patterns, prolonged dry periods in summer, increased heat, rising sea levels, and impacts on water supply (City of Vancouver, 2019). In response to the current status and future trends, the city has adopted many local plans, strategies, and regulations to support the shifting from grey to green infrastructure with detailed targets for achieving climate change mitigation and adaptation goals. For example, the city of Vancouver aims to increase the urban tree canopy cover to 30 percent (Canadian Climate Institute, 2021). At the same time, the city also set targets to capture rainfall and manage urban rainwater runoff from impervious areas (City of Vancouver, 2019).

As reported by the city in 2019, more than two hundred green infrastructure assets have been implemented, and there was a projected increasing number of installations. Bioretention is the biggest category that makes up 59% of all assets, while rainwater tree trench and constructed wetlands only represent 3% and 1%, respectively. Based on the statistics, some typologies are currently given less attention, and monitoring considerations on those practices are even more occasional under the larger scenario that Metro Vancouver has initiated little monitoring until recently. Besides, there is a defined gap in water quality measurements, flow monitoring, and awareness of the elements of trees and plants based on the Vancouver Green Infrastructure Performance Monitoring Report released in 2022. Comprehensive monitoring is rare, and most measurements are conducted for water levels and only in a few selected locations and types.

Consequently, the existing assessment may not fully address the objectives of reducing stormwater contaminant load, improving water quality, and responding to future climate changes. Aligned with the city's transformative directions and action plans (City of Vancouver, 2019), it's necessary to pay more attention and dedicate resources to more practical considerations, such as continued monitoring and water quality examinations. Withal, a clear awareness of the post-construction monitoring is needed for the long-term effectiveness of urban green infrastructure under changing climate and preparing for the uncertainties of the impacts, thus sustaining the designed efforts.

3.0 Objectives

The aim of this project is to develop a targeted and comprehensive framework for green infrastructure monitoring in the City of Vancouver based on the current practices designed for their Rain City Strategy and other pursuits, mainly focusing on two types of green infrastructure initiatives: urban trees and constructed wetlands. In addition, the management framework will develop the following components, which are rarely addressed on the rationale that green infrastructure is environment-friendly with low risks: associated adverse impacts and challenges, monitoring needs and responsibilities. As a result, the framework will provide valuable and supportive information to water managers and local decision-makers by incorporating the following objectives:

1) To determine the primary benefits of using urban trees and constructed wetlands as part of green infrastructure initiatives.
2) To highlight some challenges associated with applying urban trees and constructed wetlands, specifically related to plants and susceptibility to climate variability.
3) To recognize the monitoring needs for sustaining the defined benefits and building resiliency for future climate change, including indicators, frequency, and costs for monitoring.
4) To determine groups of people that should be responsible for monitoring, such as the public, the local governments, and non-governmental organizations.

4.0 Methods

4.1 Literature review

A systematic review of peer-reviewed publications has been conducted using Google Scholar and the University of British Columbia online library to gather helpful information regarding green infrastructure initiatives, such as journal articles and book chapters. The primary sources of literature provide direct, specific, and reliable information related to the topic, building a fundamental understanding of the benefits and challenges of implementing urban trees and constructed wetlands in the city of Vancouver. Besides, relevant case studies in North America have been reviewed to determine what should be included in a good monitoring program, contributing to selecting appropriate indicators for assessing the functionality of interventions designed for different purposes. In addition to the primary literature, secondary sources published by the government, like the strategic plan and performance report, also provide summarized content regarding the development trend, the current status, and the future direction of green infrastructure initiatives in the city. Also, guiding principles for infrastructure construction can generate some ideas about monitoring criteria, sampling, and frequency, shaping the structure of the monitoring framework.

4.2 Database research

The tree species selection database, developed by Metro Vancouver as part of urban forest climate adaptation initiatives, includes an organized collection and assessment of more than 300 plant species. The database provides guidance on the tree selection considerations in the Metro Vancouver region, like canopy cover, life expectancy, suitable locations, and tree height. More significantly, the susceptibility of different trees in response to climate variability is introduced, such as drought, high temperatures, degraded air quality, and windstorms. Consequently, the tool helps the decision-makers to gain awareness of the suitability of various tree species in current and projected climates, which is a critical component in sustainable management. Similarly, a review of wetland plants is necessary for the project. The combined results of the research will be reorganized in a table, highlighting the susceptibility of trees and plants to climate change, particularly for those frequently utilized in city planning.

5.0 Results & Discussion

5.1 Key benefits of urban trees and constructed wetlands

Table 1: An overview of the benefits of urban trees.

Values of trees in the urban landscapes	
Provisioning	Food production (e.g. fruit and nut trees) (Meléndez-Ackerman et al., 2022)
Regulating	Air pollution reduction (Nowak et al., 2018)
	Carbon sequestration and storage (McGovern & Pasher, 2016)

Values of trees in the urban landscapes	
	Protection against stormwater runoff and erosion (Bartens et al., 2009; Berland et al., 2017)
	Flood alleviation (Pataki et al., 2021)
	Shading and mitigation of the Urban Heat Island effect (Long et al., 2019; Pataki et al., 2021; Sinnett, 2021)
	Bio-control of pests and diseases (Long et al., 2019)
Supporting	Habitats for urban wildlife and biodiversity (Burghardt et al., 2009)
	Nutrient cycling (Nidzgorski, 2014)
	Pollination (Daniels, 2020)
Cultural	Culture and spirituality (Westphal, 2003)
	Aesthetic values (Tyrväinen et al., 2005)
	Education (Tyrväinen et al., 2005)
	Health and recreation (Kardan et al., 2015; Mytton et al., 2012)

Table 2: An overview of the benefits of constructed wetlands (Salimi et al., 2021).

Values of constructed wetlands in the urban landscapes	
Provisioning	Water retention and storage for improved water supply
	Fish and food production
Regulating	Wastewater treatment and water purification: removal of nutrients, metals, and organics by phytoremediation
	Sediment retention and erosion regulation
	Flood controlling and natural hazard regulation
Supporting	Organic matter accumulation and soil formation; Carbon sequestration
	Nutrient cycling
	Habitats for wildlife and aquatic organisms
Cultural	Inspirational, aesthetic, recreational, and educational

The tables above (Table 1 & 2) provide an overview of various benefits of using urban trees and constructed wetlands as an alternative and complementary approach to grey infrastructure in the urban landscape, categorized in provisioning, regulating, supporting, and cultural ecosystem services. It can be determined that there are considerable similarities in their functions, such as erosion control, flooding alleviation, and other supporting opportunities. Furthermore, the values of the two focused green initiatives are not limited to environmental outcomes, the primary focus of the study, but also influence the economic and social aspects, which are the three fundamental pillars of sustainability. Following the overview, the rest of the section will specifically explore the critical roles of urban trees and constructed wetlands in sustainable water management, climate regulation, and other natural hazard regulation.

5.11 Sustainable water management

Stormwater management

Vancouver has been regarded as one of the wettest cities in British Columbia, associated with mild winter temperatures and prodigious winter rainfall (City of Vancouver, 2018). Even in the driest seasons, the amount of rainfall is still significant, although this changes since summers are becoming more parched. The considerable annual precipitation and the increased impervious surfaces increase the problem of stormwater management in the city. Thus, incorporating urban trees and constructed wetlands as green infrastructure initiatives has significant roles in sustainable stormwater management in the city. This approach also provides efficient solutions for water quality and quantity improvements and moderates rates in the urban hydrological cycle.

Urban trees planted in the urban landscape as elements of green infrastructure can alter the precipitation distribution spatially and quantitatively, thus improving stormwater control (Carlyle-Moses et al., 2020). In particular, urban tree canopies, which refer to the layers of leaves, bunches, and stems providing shelters, can intercept the rainfall before reaching the ground surfaces, resulting in canopy interception loss (Berland et al., 2017). Remarkably, this proportion of the rainfall is not relevant to runoff initiations, and it is either stored in tree canopies or evaporated into the air as a loss, controlling the water balance of a watershed. Some researchers believe that urban trees may intercept more precipitation and have higher evapotranspiration rates than the trees in natural forests due to their larger canopies (Asadian & Weiler, 2009; Zou et al., 2021). In other words, the more considerable interception loss of urban trees reduces rainwater intensity and stormwater runoff, so there is a lower potential to carry pollutants to water bodies, playing a role in protecting water quality (Asadian & Weiler, 2009). In addition to the functions in rainfall interception and evaporation, urban trees can encourage water infiltration, which is also essential in regulating runoff and soil erosion by modifying underground systems. It has been illustrated that root growth and expansion in the soil, the created macropores by root senescence and microbial activity, the enriched organic matter inputs, and stabilized soil structure may all facilitate infiltration (Berland et al., 2017). Improved infiltration can restrict the portions of rainfall that eventually reach ground surfaces from contributing to stormwater flow to some degree since the surface runoff starts from insufficient infiltration. Consequently, as more water infiltrates into the soil or counts as canopy interception loss, the achievements of urban trees in sustainable stormwater management will be more apparent in terms of water quality and quantity considerations.

Likewise, constructed wetlands also have a place in sustainable stormwater management. The application has been regarded as an ecological solution for a lower infiltration rate and limited evapotranspiration in urban areas that eventually lead to high runoff volumes, threatening water management. Aquatic plants are the main elements of the stormwater wetland, forming the macrophyte zone, having essential roles in the water treatment and other processes within the system, and improving the evapotranspiration rate (Stefanakis, 2019). Besides, the wetland plants associated with the designed shallow water-filled ponds can provide more available and sufficient infiltration areas, and reduce the runoff velocity and peak flows, thus achieving the goal of runoff volume regulation (Gato-Trinidad et al., 2022). In current practices, a sediment collection pond will be installed as a pretreatment process above the wetland, the forebay. This artificial pond captures most sediments from stormwater runoff, which can significantly enhance the efficiencies of total suspended solids removal and metals that are absorbed and carried by the sediment from urban runoff. The application requires the sediment to be removed from time to time to prevent clogging by decomposition in the wetland. The stems and root system of aquatic plants in the macrophyte zone can filter and absorb the remained soluble and particulate pollutants from the pre-treated runoff. Meanwhile, they may further contribute to nitrogen and phosphorus removal (Gato-Trinidad et al., 2022). The design of separate zones can maximize the effects of pollutant removal, better facilitating water quality and shaping sustainable stormwater management.

Wastewater treatment

The contributions of green infrastructure to sustainable water management also refers to the efficiencies in wastewater treatment, specifically under the operations of constructed wetland. The technology, seen as an environmental-friendly alternative, replaces the current practices of conventional treatment plants or technologies that consume lots of energy, have a high potential to cause adverse environmental impacts, and require large operation and maintenance expenses (Stefanakis, 2019). Also, the majority of the existing practices are still away from the goal of improved water quality and sustainable management, gone through incomplete treatment that can be left with untreated wastes and hazardous chemicals, stressing water recycling and reuse in the city (Nuamah et al., 2020). Applying constructed wetlands in urban landscapes can deal with the problems that remain with conventional methods. They collect wastewater at or near various sources rather than an extensive collection that requires further transfer through pipe networks and purifying water through a series of physical, chemical, and biological treatment processes, thus maximizing their capacities in contaminant removal and water purification (Stefanakis, 2019). The opportunities to enhance water quality and address existing stressors on wastewater management have been fully explored based on the advantages above. To improve the water purification process, building two or more wetlands in a sequence is most effective but requires more space which is often unavailable in built-up cities.

5.12 Climate regulation

Apart from the critical functions in sustainable urban water management, involving urban trees and constructed wetlands in urban green infrastructure design plays a notable role in climate regulation, such as reducing the greenhouse effects, moderating temperature patterns, and improving air quality (Zari, 2017). The climate regulations can be categorized as adaptation and mitigation strategies, managing the risks of climate change impacts, or reducing the sources that lead to climate change (Pataki et al., 2021). Those potential outcomes provide solutions for prioritized concerns in urban environments. In detail, urban trees can mitigate climate change through carbon removal and storage (McGovern & Pasher, 2016). They remove atmospheric carbon dioxide from the air, the main greenhouse gas, and they also store carbon in their tissues, enhancing carbon sequestration and reducing the sources of greenhouse gas emissions. At the same time, urban trees can absorb other gaseous pollutants such as nitrogen dioxide and ozone and intercept particulate matter on the plant surfaces to improve air quality, thus regulating local microclimates (Nowak et al., 2018).

Urban trees tend to be more promising for climate change and pollution adaptation than mitigation strategies (Pataki et al., 2021). For instance, evapotranspiration from urban trees can cool down local air temperatures by two to three degrees by converting sensible heat to latent heat (Moss et al., 2019). Also, tree canopies can intercept solar radiation, reducing heat storage (Pataki et al., 2021). Besides, wind can move more freely through urban trees, and the stimulated natural wind flow leads to cooling effects and mitigates air temperature. Therefore, dense tree planting offers an opportunity for microclimate adaptation through shading impervious surfaces and evaporative cooling, solving the problem that built-up areas absorb more heat energy than surrounding environments and reducing the city-wide urban heat island effect (Berland et al., 2017; Long et al., 2019; Moss et al., 2019).

Other than the potential adaptive and mitigative outcomes of tree planting, constructed wetlands also contribute to climate regulation in urban cities based on the applied technology and designed elements of vegetation and substrates. Similarly, the wetland system also acts as a greenhouse gas sink by absorbing carbon dioxide from the atmosphere and capturing it within the system (Kayranli, 2009). Several characteristics associated with wetlands, including high water table, high biomass productivity, and low decomposition rate under anaerobic conditions, are the dependent factors for carbon storage in soil, sediment and detritus (Stumpner et al., 2018). Moreover, lots of literature has reviewed and examined the essential roles of living plant communities in carbon sequestration (Kayranli, 2009). As illustrated, the capacity of wetlands as vital carbon sinks significantly supports climate change mitigation in urban areas.

5.13 Natural hazard regulation

Ultimately, implementing urban trees and constructed wetlands as green infrastructure initiatives can provide critical assistance to some climate-related natural hazard regulations in the city, such as flooding, windstorms, pests, disease outbreaks, and heat waves, according to their determined contributions to sustainable water management and climate regulation. For example, the discussion above has clarified that the two green infrastructure designs can provide sufficient protection against stormwater runoff and erosion while functioning as carbon sinks that prevent further global warming and associated climate change. Moreover, those outcomes are expected to be further connected to flood regulation in terms of prevention and mitigation since flooding risks are the consequences of extreme precipitation events, reduced infiltration, and increased surface runoff (Gunnell et al., 2019). Constructed wetlands, in particular, can reduce the peak flood water level, reduce the velocity of flood water, and provide flood storage, which has been recognized as a vital application for flood control (Gato-Trinidad et al., 2022). Notably, the two green initiatives are simultaneously efficient for flood management and other threats related to climate change by offering various ecosystem services, thus enhancing overall resilience in densely populated urban areas.

5.2 Key challenges of urban trees and constructed wetlands

Undoubtedly, green infrastructure initiatives of urban trees and constructed wetlands help control greenhouse gas emissions and regulate stormwater runoff and flooding, and the defined advantages are more than those. In short, they help address the leading factors and resulting impacts of climate variations, building resilience and contributing to the living environment. At the same time, however, the infrastructure may also be negatively impacted by climate change, and some critical threats include global warming and extreme weather events. Extreme events, such as heatwaves, floods, and droughts, are expected to become more challenging in terms of increased frequency and intensity as the earth warms up (U.S. EPA, 2017). These two threats are closely related, and also their durations are distinguishable. Extreme weather events are usually over short periods and do not last long, while climate warming may not come to an end without effective interventions. The clarifications of these concepts and their interconnections are necessary for further discussion on urban trees and constructed wetlands. On top of that, the section will also review the susceptibility of different types of trees and wetland plants to high temperatures, windstorms, and other climate variabilities.

5.21 Short-term extreme events

Urban trees

Urban trees experience more frequent and severe environmental stressors, including water stress resulting from flooding and drought, heatwaves, and windstorms. The altered temperature, precipitation, and wind movement patterns can generate adverse growth conditions, threatening the maintenance of photosynthesis and other functions, which ultimately induce tree health and increase mortality in urban landscapes.

The extreme precipitation events have profound potential to increase flooding stresses that can influence tree physiology, particularly tree roots and associated soil microbial community (Hailey & Percival, 2015). During flooding, macropores are water-filled and result in the limited provision of the oxygen supply, which can lead to insufficient supply to tree roots. Once the oxygen level is below the threshold, reduced photosynthesis rate and impaired activity can result in plant stress reactions (Hailey & Percival, 2015). Following, a series of symptoms of leaf chlorosis, leaf drop, and crown dieback may occur, suppressing tree health. In addition to the stressing effects on root growths and further damages, there is a decline in population for the aerobic microbial group, which also requires oxygen content for survival. Hence, their crucial roles in organic matter decomposition and nutrient cycling are affected (Macé et al., 2016). The reduced nutrient availability aligned with the destruction in soil structure during flooding can lead to undesirable tree growth. Specifically, the deposition of sediments and reduced aggregate stability may influence the soil behaviour in terms of increased bulk density and decreased soil aeration, affecting the root uptake of water and nutrients (Hailey & Percival, 2015). Tree fall is also more frequent when windstorms occur during water-saturated conditions.

In contrast, there is the potential for more frequent low precipitation events under climate change, partially contributing to water stress and droughts associated with other factors such as high temperatures and rapid evapotranspiration. Similar to flooding events, urban trees are also sensitive to the deficiencies in water availability, reflected in reduced photosynthesis and the generation of a series of processes that inhibit tree growth, such as wilting, stomatal closure, and leaf shedding (Meineke et al., 2018; Ryan, 2011). Supplementally, the direct impacts on the radial growth of trees have been examined, reflecting the decline in tree health under drought events (Nitschke et al., 2017). The situation can be even worse when drought combines with heat waves. Under the intrinsic linkage between two extreme events, the negative impacts on tree growth will be intensified, potentially leading to tree mortality (Teskey et al., 2015).

More significantly, the remaining damages from previous extreme weather events, like the disturbance to root systems, can further trigger other adverse impacts, acting as inciting factors for secondary stressors. As mentioned, flooding reduces the tree vigour, and the roots and leaves at risk are vulnerable to pathogen attack and infection, resulting in the decay of tree tissues that may eventually end with mortality (Hailey & Percival, 2015). Furthermore, the flood water encourages motile movement for pathogens and promotes the propagation rate, threatening the trees to a considerable degree (Hailey & Percival, 2015). Meanwhile, the likely root exposure after flooding events resulting from soil erosion can increase the potential for a tree fall during windstorms. Other than flooding, drought also increases the vulnerability of urban trees to pathogens and pests by weakening the defence of host plants (Nitschke et al., 2017). To summarize, urban trees are sensitive to various extreme events, and the observed impacts may be intensified by multiple weather events interacting together based on their interconnected relationship.

Constructed wetlands

Climate change has been regarded as one of the crucial challenges to the operations of constructed wetlands due to the changing water availability and temperature patterns. Likely, the alterations during hydraulic events, such as heavy precipitation and more evapotranspiration, are the driving factors for water level dynamics in the wetland systems. Furthermore, the raised or dropped water level can adversely impact the performance of wetlands in regulating greenhouse gas emissions, water quality, and biogeochemistry (Salini et al., 2021). Besides, the temperature, which refers to water and soil temperatures, is a dependent element for different microbial processes during wetland treatment (Kadlec & Reddy, 2001).

A water table drawdown that inherently relates to extreme drought events can stimulate gas emissions, shifting the role of constructed wetlands from carbon sinks to carbon sources. At the state of a low water table, the system changes from anaerobic to aerobic, promoting aerobic decomposition and increasing carbon dioxide release (Salini et al., 2021). Also, drought can inhibit the photosynthesis of plants and reduce active biomass, limiting the transformation from inorganic carbon dioxide to organic carbon (Kayranli et al., 2009). Additionally, a loss in gross primary production can be observable associated with drought events, indicating a reduced capacity in carbon dioxide sequestration (Salini et al., 2021). The failures in regulating carbon dioxide emissions and the adverse roles of global warming potentials during drought events have been illustrated. Meanwhile, the ecosystem process of gross primary production has additional influences in balancing the food web and entire ecosystem in urban landscapes by providing resources to the upper trophic levels.

By contrast, a high water table with more precipitation under flooding can maintain the role of wetlands as carbon sinks since the water-saturated conditions have higher photosynthesis, and the phenomenon of increased carbon dioxide release is reduced (Salini et al., 2021). However, unlike in aerobic conditions, the decomposition of organic matter simultaneously forms carbon dioxide and methane under aerobic conditions (Kayranli et al., 2009). Therefore, flood inundation can bring out the issue of methane gas emissions, which has a much higher global warming potential than carbon dioxide. The emissions are correlated to plants in terms of plant presence, specific species selections, and species richness (Xu et al., 2019). Other than the potential intensification of greenhouse gas emissions, flooding events may also challenge the critical function of constructed wetlands in water quality enhancement due to heavy precipitation and rapid surface runoff (Nuamah et al., 2020). As more pathogens and microbial discharge are introduced into the system, the wetland may become less effective for water purification. Beyond that, increased containment concentration has a profound relationship with flooding risk, threatening the purification efficiency of water quality (Salini et al., 2021). Thus, the excess nutrients that may be left with incomplete treatment will enter other water bodies, leading to eutrophication and other problems, disturbing the aquatic ecosystems.

Along with droughts, flooding events, and all the associated challenges mentioned above, the extreme changes in temperature patterns, like a heatwave, can have direct and critical effects on constructed wetland performances. Undoubtedly, the sudden increase in temperature can dramatically drop the water table and stimulate a series of changes, such as the photosynthesis rate, the aerobic and anaerobic state, the biogeochemical processes, and microbial activities. All those elements are responsible for a faster release of carbon dioxide and the dynamics of other greenhouse gas emissions, including methane and nitrous oxide (Nuamah et al., 2020). Beyond that, the increased temperature can further threaten the water quality by the explosion of the pathogen population (Salini et al., 2021). The discussion above has indicated the determinant role of temperature alterations in wetland operations and the interconnection with other stressors. However, the current understanding of wetland plants to heat stress is limited and more research is needed to determine the responses of different wetlands to higher water temperatures.

5.22 Long-term climate warming

Differentiating from the extreme weather events that last for a relatively short period, climate warming lasts for a more extended period with uncertainties regarding the future trend, which may take centuries to approach the end. Additionally, the influences of climate warming events are not at regional or individual levels, so it’s not about the situation that some areas worldwide can be exempt from the risky impacts, defined as a global-scale event. Moreover, the gradually-occurring climate warming changes could be irreversible but would require massive carbon dioxide reductions. It is unlikely that we will be able to reduce the greenhouse gas content in the atmosphere significantly. Hence atmospheric temperature will likely rise, hopefully at a lower rate. Even worse, global warming and the associated exposure to high solar radiation and increasing temperature are expected to be continuous (Salini et al., 2021). Thus, it's necessary to explore the impacts of global warming on the performance of urban green infrastructure, including urban trees and constructed wetlands, to determine whether the adverse consequences will eventually outweigh the provided benefits and lead to failures in operations.

Urban trees

Increasing temperatures and extended growing seasons are the direct consequences of global warming, and the combined effects are seen as an opportunity for accelerating tree growth in urban surroundings. However, the positive effects are only present under certain conditions, including a modest temperature and sufficient moisture supply (Brandt et al., 2021). Even if accelerated tree growth is observable from increased tree radial growth or aboveground expansion, there are still uncertainties in their mechanical stability, biotic resistance, and other safety and functionality concerns (Pretzsch et al., 2017). Therefore, a more rapid tree growth does not entirely stand for better performance. Reversely, acceleration may represent a faster aging and shortened lifetime, leading to management difficulties in the city (Pretzsch et al., 2017).

Apart from the potential for increased tree growth, a relatively high temperature during the growing season, accompanied by low precipitation and numerous climate stressors, can suppress the tree growth, indicating challenges in maintaining the provided environmental efforts (Brandt et al., 2021). Healthy tree conditions are the prerequisite for adapting to and mitigating climate change impacts, while stressed trees are more vulnerable to disadvantageous conditions, further intensifying the received disturbance. As frequently examined in recent case studies, long-term climate warming is a determinant factor responsible for pest and insect issues in urban centres, altering the disturbance patterns (Dale & Frank, 2014; 2017). For instance, warming temperatures allow the host plants to provide direct physiological benefits for various pests, which increase the population abundance and their potential fitness in the urban trees (Dale & Frank, 2017). More significantly, the suitability for the non-native group may also increase, leading to uncertainties in infection (Tubby & Webber, 2010). The interactive and accumulated influences from multiple climate stressors regarding climate warming can eventually generate reduced suitability of trees in urban areas and a reduced life span (McBride & Lacan, 2018). In other words, the species composition has a great potential to be altered in terms of reduced diversity, reflecting the need for more consideration of species susceptibility during tree replacement or replanting in response to the potential species loss and other threats.

Constructed wetlands

Based on the previous discussion, extreme weather events such as drought and flooding can inhibit the role of constructed wetlands in regulating greenhouse gas emissions, either shifting to carbon sources or stimulating more methane release. Nonetheless, those consequences are not permanent and may be interrupted by the subsequent changes in water availability. For example, returning the drooped water level to a critical and balanced level can help wetlands preserve their services in carbon sequestration and storage (Salimi et al., 2021). Therefore, the wetland system and its internal components of soils and sediments are still recognized as the most significant carbon sink in the world.

Unfortunately, the situation can be different under a continuously and rapidly increasing temperature under long-term climate warming. The risk of becoming an atmospheric carbon source has been pointed out in the literature (Kayranli et al., 2009). The increasing temperature can be the main driving factor for the changes in organic carbon content in the wetland system. Notably, there is a strong correlation. The decomposition rate of organic matter dramatically increases as the temperature increases, leading to decreased organic carbon content (Nuamah et al., 2020). Eventually, the wetland develops as a primary carbon source in the urban cities by releasing a considerable amount of greenhouse gases, and the emission also depends on the drainage conditions. Specifically, poor drainage under anaerobic conditions in the soil generates more gases than well-drained wetlands (Kayranli et al., 2009).

Increased methane and nitrous oxide production also results from higher temperatures (Salimi et al., 2021). On top of that, the dynamics in greenhouse gas emissions can further interact with various processes, such as photosynthesis and microbial activity, adversely impacting the ecological benefits of wetlands (Nuamah et al., 2020). Even worse, the high potential of carbon dioxide and methane for further global warming can form a vicious cycle in which the wetland system expects to be more sensitive to climate variability. As a result, the roles of wetland plants in averting increasing emissions and water treatment may fail, accompanied by a poor overall performance within the operations.

5.23 Plant susceptibility to climate change

The discussion regarding the challenges of short-term extreme weather events and long-term climate warming on green infrastructure operations in the city has brought to the attention that plants are specifically susceptible to the existing and future climate change. Therefore, a critical element for the infrastructure designs is the vulnerability of urban trees and wetland plants to climate change. This will directly decrease their contribution to climate change adaptation and mitigation, leading to a situation in which maintaining the provided ecosystem services can be incredibly challenging. Likely, plants can no longer support building resilience in the city due to the adverse climate-induced stressors. However, there is still an opportunity under this scenario since the capacity of plant adaptation and tolerance to climate variability between different species can vary (Brandt et al., 2021). In other words, certain types of plants or specific species are more susceptible to climate change than others. That being the case, it is necessary to understand the significance of species selection and explore which types of urban trees or wetland plants can provide more stability during extreme events and have adequate performance under future climate conditions. The following discussion will mainly focus on determining whether the most common plant genera in the City of Vancouver are suitable in a changing climate.

Maple and cherry trees

Table 3: Species anticipated to tolerate a broad range of sites under future climate.

VERY SUITABLE SPECIES			
Arbutus menziesii	Cupressus x leylandii	Nyssa sinensis	Quercus acutissima
Albizia julibrissin	Eucommia ulmoides	Olea europaea	Quercus agrifolia
Arbutus unedo	Ficus carica	Phellodendron amurense	Quercus alba
Calocedrus decurrens	Fraxinus ornus	Pinus banksiana	Quercus coccinea
Catalpa speciosa	Ginkgo biloba	Pinus contorta	Quercus garryana
Cedrus deodara	Gleditsia triacanthos	Pinus exilis	Quercus ilex
Celtis occidentalis	Gymnocladus dioicus	Pinus mugo	Quercus imbricaria
Celtis sinensis	Juglans major	Pinus nigra	Quercus macrocarpa
Cercis canadensis	Juniperus chinensis	Pinus pinea	Quercus shumardii
Cotinus coggygria	Juniperus virginiana	Pinus ponderosa	Quercus suber
Crataegus crus-galli	Koelreuteria bipinnata	Pinus sylvestris	Quercus virginiana
Crataegus x lavalleei	Koelreuteria paniculata	Pinus thunbergii	Rhus typhina
Crataegus x mordenensis	Lagerstroemia x 'tuscarora	Pistacia chinensis	Sorbus aria
Cupressus arizonica	Maackia amurensis	Prunus dulcis	Ulmus propinqua
Cupressus macrocarpa	Maclura pomifera	Pyrus calleryana	
Cupressus sempervirens	Notholithocarpus densiorus	Pyrus pyrifolia	

Maples (*Acer spp.*) and cherries (*Prunus spp.*) are the two dominant tree genera that have been frequently planted in Vancouver, and together they represent approximately fifty percent of all street trees in Metro Vancouver (City of Vancouver, 2018). The dependence on maple and cherry has led to further concerns on whether they are suitable for projected continuous climate change and whether their susceptibility will impact other tree species and the entire ecosystem. Referring to the urban tree list created by Metro Vancouver, which covers more than 300 species in the assessment, maple and cherry genera are not categorized as “very suitable” species that can tolerate a broad range of conditions, such as drought and excess moisture (Table 3). Conversely, maples and cherries may belong to the marginal group that can be restricted to future climate change in the research region and shows susceptibility in certain situations, which requires additional discussion on the various threats (City of Vancouver, 2019).

The rule of planting for diversity, the 10-20-30 rule-of-thumb, recommends that the tree population should not be more than 10 percent for any species, 20 percent for any genus, and 30 percent for any family (City of Vancouver, 2018). Unfortunately, maples (24%) and cherries (22%) all exceed the threshold, which may lead to increased risk from pests and other extreme events, threatening the genetic diversity in the city. In addition, as determined, many maple species are not expected to perform well under drier and warmer conditions due to their narrow range of resistance to heat and drought, such as sugar maple, big-leaf maple, and Japanese maple (Betzen et al., 2021; Zhu et al., 2019; Sjöman et al., 2015; Oswald et al., 2018). Likely, the projected increase in annual air temperature also warms the soil temperature, and the interactive effects of drought and reduced water availability can lead to insufficient water uptake of trees, which may end up in desiccation that can be reflected in various foliage responses (Harrison et al., 2020). Additionally, increased air temperature can lead to earlier bud break, extended growing seasons, and delayed lower temperatures. The adverse impacts on sugar maples have been examined as an example, including the increased vulnerability to injury from spring frosts and the depleted carbohydrate reserves from speeded leaf senescence in October, indicating the direct impacts on leaf production and crown health in the following spring (Oswald et al., 2018). Over a prolonged period, the suppression of climate change on tree growth and crown vigour may accumulate, turning into tree moralities and a decline in population in the city without any plant pathogen or insect herbivore. A case study of big-leaf maple decline in hotter urban centres has demonstrated those assumptions on the determinant role of changing climate (Betzen et al., 2021).

Likewise, the cherry genus also needs to overcome the same situation. Undoubtedly, the temperature will eventually warm beyond the range that cherry trees have not experienced during the past decades. However, the capacity for flowering cherry trees to adapt to a predictable warming climate remains uncertain due to their limited resistance to heat stress and drought conditions resulting from the alterations in precipitation and temperature patterns. Consequently, there may be a high potential for more suppressed tree growth and diminished crown vigour from now onwards (City of Vancouver, 2017). Even worse, some rare species may no longer survive in compromised growing environments, leading to a loss in species diversity. Meanwhile, those already detectable effects on flowering phenology due to a warming climate, explicitly referring to the cherry flowering time, may result in more severe and irreversible impacts on the entire ecosystem. In Japan, an earlier flowering time than any time over the past 1200 years has been documented, and the problem occurs worldwide (Primack et al., 2009). Since 1830, there has been a progressively earlier cherry blossom, and the trend expects to continue with a more rapid change as the temperature keeps increasing. Correspondingly, cherry trees may encounter various issues related to altered flowering time, including frost damage, resource competition with other species, unsynchronized flowering with pollinator activity, and pests (Primack et al., 2009). All these factors can contribute to a poor adaption of the trees, which can ultimately shift the species composition in the city and weaken the ecosystem resistance.

Interconnected with the impacts of climate warming, another posing threat to maples and cherries in the urban environment can be pest and disease outbreaks. In particular, it has been detected in Metro Vancouver that flowering cherry trees can be the targeted host plants for the gypsy moth, an introduced pest with the worst defoliation threat to deciduous trees in the city (Benoit et al., 1990; City of Vancouver, 2017). Also, the Asian longhorned beetle, which has a strong preference for the maple genus, may have a high potential to be introduced in the city based on the presented infestation and widespread tree mortality in other North American cities (Meng et al., 2015). The severe threats on maple trees are predictable, although the pest hasn't been detected yet in the city, which requires more concerns for advanced protection. Under continuous climate change, urban trees are more vulnerable to pests and diseases accompanied by suppressed tree health and other stressors, thus providing beneficial conditions for the large-scale outbreak. That being the case, the dominant maple and cherry genera are anticipated to experience widespread tree damage and even tree mortality. The relatively high percentage and dependence among all the trees make their disturbance result in more negative impacts and devastate the urban forests and environments.

Broadleaf species vs. Conifer species

Along with maples and flowering cherries, the broadleaf tree species in Metro Vancouver represent a significant number. According to the tree species diversity assessment, the most common tree genera that have been incorporated in the city planning up to date all belong to the broadleaf group, such as Ash, linden, and oak, right following the dominating maple and cherry (City of Vancouver, 2017). By contrast, conifer species have relatively restricted applications in urban centres, drawing attention to an uneven distribution in the current species composition, which may not be beneficial for shaping a resilient city. There are trade-offs between broadleaf and coniferous trees, and a combination of both is necessary for responding to future climate variabilities and disturbances.

The vulnerability of the maple and flowering cherry genera to future climate change may lead to concerns about whether those defined threats also apply to other broadleaf species, thus intensifying the adverse impacts. For instance, the Asian longhorned beetle and gypsy moth have been mentioned as disturbances for maples and cherries. Still, they also show preferences for many other broadleaf species, potentially infesting a range of urban trees under advantageous weather conditions (Meng et al., 2015). Another example can be the negative influences of earlier bud break and blossom on plants, which has been reflected in the flowering cherry trees worldwide. Recent research has claimed that the problem also applies to other flowering species in response to future warming, resulting in tree damage and suppression (Primack et al., 2009). It can be determined that there are some similarities in the disturbance patterns among various broadleaf species, revealing the hidden problem of the currently extensive practices. The detected stressors on certain species may have broader influences than expected. However, on the other side, broadleaf species are more useful in local cooling than needle-leaved species during hot temperature extremes due to their higher albedo and evapotranspiration (Schwaab et al., 2020). The ability to reflect more sunlight allows less energy conversion into heat, reducing the stress of heat storage in crowded urban environments. They can also evaporate more water due to the larger leaf surface areas, thus contributing to the cooling effects. As the fraction of the broadleaf species increases, the outcomes in temperature mitigation may be more considerable, but that does not stand for entirely positive impacts on climate adaptation and building resilience. Other factors, such as leaf shedding in fall and the susceptibility to pests and diseases, which impede the contributions or even lead to adverse effects, should be considered.

Several studies have suggested that converting from broadleaf species to conifers can bring more benefits to the warming climate. As examined in a recent study, conifers and broadleaf trees respond differently to the belowground changes. The results highlighted the remarkable plasticity of pine fine roots to climate variation by comparing the root systems of European beech and Scots pine, indicating a better capacity for conifers to adapt to the rapid environmental changes in terms of warming and drought (Förster et al., 2021). Besides, conifers can intercept more rainfall than the broadleaf species in all seasons and store more water on their plant surfaces (Berland et al., 2017). Especially in winters, their effectiveness is essential since the majority of rainfall in Vancouver is received from November to March, when the broadleaf trees have lost their leaves, resulting in reduced capacity of rainfall interception and evapotranspiration (Asadian & Weiler, 2009). Under this circumstance, planting more coniferous trees is expected in the city because their needles are retained all year round, thus becoming more effective in stormwater mitigation. In addition, the water-conserving capacity of conifers allows them to adapt to low rainfall climate by controlling water delivery and evaporation from the leaves, reducing the stress from droughts (Brodribb et al., 2014).

The discussion on whether the broadleaf group is more vulnerable to the changing climate and should be replaced by conifers is difficult to agree with due to the trade-offs between the two groups of trees. Conifer trees are essential in sustainable water management in the city, especially in the winter when the broadleaf species barely contribute and the winter storms get more intense with more rainfall events. Therefore, there is no doubt about planting more coniferous trees, but the massive replacement of broadleaf trees at the same while will also lead to problems during hot summers since they are more effective in reducing urban heat island effects. The effectiveness in different dimensions and the associated loss of other opportunities require the city to make a balance regarding species selections, thus providing resilience to thrive in forthcoming climate conditions. For instance, the Spruce that can effectively contribute to rainfall interceptions are more vulnerable to windstorms due to their shallow root systems, causing more tree falls. The trade-offs should be well noticed when incorporating the group as conifer populations. Other concerns may include but are not limited to the differences in carbon sequestration capacities, heat and drought tolerances, and disease resistances by different trees, which unfortunately have not been well explored. Above all, the city of Vancouver should raise concerns about the species diversity in enhancing resilience to future climate changes and devote more attention to selecting appropriate species.

Wetland plants

Table 4: The selection of constructed wetland plants under future climate.

FUNCTION	SUITABLE SPECIES
Phytoremediation function to depurate heavy metals and environmental contaminants (Nuamah et al., 2020)	*Scirpus* spp. (Bulrush), *Phragmites* spp. (Common reed), *Typha* spp. (Cattail), *Juncus* spp. (Rush), *Eleocharis* spp. (Spikerush), *Iris* spp. (Iridaceae), and *Carex* spp. (Sedge) *Zantedeschia aethiopica, Cyperus alternifolius, Heliconia burleana, Canna indica, Acorus calamus, Ipomoea aquatic*
Flood tolerance, reproductive ability, and prolific nature (Nuamah et al., 2020)	*Phragmites australis* and *Typha* spp.
Methane emission mitigation (Xu et al., 2019)	*Acorus calamus, Cyperus papyrus, Juncus effusu,* *Typha latifolia*

Wetland plants appear to be adversely impacted by projecting climate change variables, such as rising temperature, increased solar radiation, and more intense storms and precipitation.

The responses of the major macrophyte communities have been addressed, including submerged and emergent freshwater plants. The submerged wetland plants are especially susceptible to increasing temperatures, while emergent plants are more sensitive to climate-related hydrological alterations (Short et al., 2016). Likely, higher temperatures directly affect internal nutrient loading, which may favour macrophyte growth in low nutrient water bodies. However, warming can enhance eutrophication problems under nutrient-rich scenarios, resulting in suppressed plant growth and a chain of ecosystem reactions that negatively impact the functionality of wetlands (Short et al., 2016). Meanwhile, the changes in wind and precipitation patterns can alter the external nutrient loading by introducing more phosphorus and nitrogen content into the wetland ecosystems, intensifying the negative competition between phytoplankton and macrophyte communities. Additionally, rising air temperatures can affect the emergent groups by slowing the gas exchange and plant respiration, further influencing carbon dynamics within the systems.

The effects of climate change are not limited to those. Over an extended period, the main drivers of increasing temperatures and altered precipitation patterns, along with other variables, can reduce the habitat suitability of wetland plants (Dang et al., 2021). Therefore, there is an expected decrease in plant species richness and shifts in species composition, highlighting the need for appropriate species selection that can tolerate a wide range of environmental conditions. As indicated in the table above (table 4), some species may show more effectiveness in certain functions than others, such as phytoremediation, flood resistance, and methane emission regulations. However, the current studies have not fully explored those topics. Also, the limited understanding of the susceptibility of different species to all climate change variables can even challenge the selection of suitable wetland plants, and further research is needed.

5.3 Monitoring needs

The aggressive pursuit of planting more trees or involving more green infrastructure initiatives is inconsistent with the guiding principles in the strategic plans. It will never be the solution for sustainable management in the city, especially under a warmer climate associated with stressors in urban surroundings. The reported statistics regarding the total tree population, the tree canopy cover, or the considerable increase in green infrastructure assets are not equivalent to ensured progress in responding to climate-induced threats. Instead, the performance effectiveness of green infrastructure over time plays a more significant role in adaptation and mitigation. Based on the analysis of the challenges of incorporating urban trees and constructed wetlands in city planning, the susceptibility to short-term extreme weather events and long-term climate warming can inhibit their functionality to various degrees.

The sensitivity to changing climate and the associated adverse impacts can undoubtedly outweigh the intrinsic ability to provide benefits. The potential for sustaining the efforts to the living environment depends on various factors, such as favourable weather and site conditions and optimal adaptation capacity of the selected species. Moreover, there is a high likelihood of failure in infrastructure implementation due to the non-immediate maintenance actions in response to the threats, indicating a lack of efficient monitoring practices to be aware of the problems and to inform the subsequent efforts. Meanwhile, the current status in the city of Vancouver and the projected trend of facing more risks in frequency and severity also underline a strong demand for monitoring needs. The periodic monitoring of urban trees and constructed wetlands will determine their performance outcomes in stormwater management. The city needs to assess a range of relevant indicators, such as plant components, water, and soil. Monitoring is significant for sustainable management and for building resilience to climate variabilities and whether the operations are still effective over a long period after construction.

5.31 Monitoring indicators

Table 5: Monitoring for performance effectiveness: urban trees.

1  **Monitoring for tree performance**	• Tree species • Tree age • Crown vigour • Mortality Status • DBH Growth rate • Signs of heat/water stress (ex: chlorosis, wilting) • Pests and diseases

2 Monitoring for site conditions	• Soil structure and aggregate stability • Water infiltration rate • Hydraulic conductivity • Available water storage capacity • Growing space • Organic matter content • Microbial activity

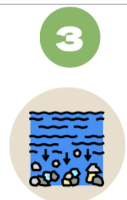
Maintaining a healthy population of urban trees has a mutual connection with their abilities to respond to the destructive effects of increased climate change (Brandt et al., 2021). Conversely, suppressed trees with inadequate functionality can not foster a safe and healthy environment to resist numerous future challenges. That being the case, monitoring tree performance can be an adequate and essential direction to determining their potential to provide beneficial influences and environmental contribution. The table above (Table 5) summarizes the various indicators that can be incorporated into the field monitoring based on the assorted research from different tree guidelines (U.S. Department of Agriculture, 2020). First of all, identifying tree species and their age can initially restrict the broad knowledge to a specific species level. Thus, providing more concise information regarding the tolerance to drought and other extreme events, requirements for soil volume, the mature size, and whether the particular tree approaches the end of its lifespan and requires replacement. Those facts allow more reliable estimations of the presence of any climate-related or urban stressors and the location suitability for planting trees by comparing with the monitored results. For instance, a decreased growth rate measured by trunk diameter or shoot extension and detectable branch loss and foliage problems help indicate the non-optimal crown vigour and suppressed conditions on the site. Besides, any signs like chlorosis, wilting, and defoliation reflect the inhibition in water regulation or the heat stress, threatening the effectiveness of tree functions. The awareness of changes in performance by monitoring, including pest and disease attacks, can inform the following maintenance practices for long-term benefits and sustainable management.

In addition to the aboveground tree performance, monitoring site conditions is significant in supporting the root systems and overall tree health, particularly for assessing the underground soil that is not visually observable. The soil structure and aggregate stability are the determinant factors for water, nutrient, and microbial movements, meanwhile related to the capacity of root penetration. Monitoring structural stability also reflects the resistance to degradation from water erosion and other threats from extreme events. Beyond that, the capability to receive, release and retain water, which is responsible for sufficient water supply and stormwater regulations, also requires monitoring practices. Likely, the water infiltration rate indicates the ability of water to move into the soil profile instead of moving along the surface, reflecting the soil health and structure. Supplementally, hydraulic conductivity measures the movement of water through the soil, and a higher value represents more optimal water pass and permeability. Other than that, the measurements of the remaining water content after a few days of free drainage, which refers to water storage capacity, can indicate the amount of soil water available for plant uptakes. Those water-related indicators can help maintain the soil water at an adequate level that provides the amount of water required for optimal tree growth and does not exceed the threshold that will lead to suppression. Additionally, whether there is enough soil volume adapted to the growing size of trees over time associated with expanding rooting depth is essential. Otherwise, the exposure of the root systems may increase the vulnerability to other threats, and a much slower growth rate may occur, declining the tree performance.

All those indicators listed above in the table help ensure more advantageous growing conditions for plants by considering the aboveground trees, the belowground soil conditions, and the aboveground-belowground interactions. Thus, progressing towards sustaining the efforts provided by trees and reducing the potential susceptibility from external forces.

Table 6: Monitoring for performance effectiveness: constructed wetlands.

1 **Monitoring for wetland plants**	• Plant species • Species richness • Mortality Status

 **Monitoring for water level**	• Inflow and outflow volumes • Loading rates
 **Monitoring for water quality**	• Physical parameters (pH, total suspended solids, dissolved oxygen, turbidity) • Chemical parameters (carbon, phosphorous, nitrogen, hazardous chemicals) • Biological (algae, bacteria)
 **Monitoring for greenhouse gas emissions**	• Carbon dioxide • Methane • Nitrous oxide

As highlighted in the previous discussion, incorporating constructed wetlands as green infrastructure initiatives in the city has multiple beneficial outcomes, such as improving water quality through a series of water purification processes, encouraging runoff storage by providing more available infiltration areas, and acting as carbon sinks. However, the technology and the treatment process have a high potential to shift the role of wetland systems to carbon sources and stimulate other greenhouse gas emissions due to climate-induced stressors, leading to extreme adverse impacts that can accelerate climate warming. Therefore, in response to the projected scenario, monitoring practices for constructed wetlands should include those considerations regarding the functionalities of the wetland system and the potential challenges in operations, mainly separated into four sections, as shown in the table above (Table 6).

Like urban tree monitoring, the optimal performance of wetland plants with vigour status is the basis for progressing the functionality of the entire system. The determinant roles of the aquatic plants in supporting contaminant removal and carbon sequestration are undoubted. If any morality or suppression symptoms of the plants are observable within the wetland system, the constructed wetland would not be effective and even result in infrastructure failure. Apart from mortality status monitoring, there is also a need to evaluate the species applied in operation and the richness since plants can influence methane flux during the treatment (Xu. 2019). Hybrid species tend to generate more methane, and the emissions increase with more species richness. Besides, plant harvesting, which may happen for plant replacement or replanting, can release the methane stored in the stem to the atmosphere and temporally bloom the emissions (Xu, 2019). Rather than the measurements on plants, the direct monitoring of greenhouse gas emissions, including carbon dioxide, methane, and nitrous oxide, also has the same effects in determining the adverse environmental impacts. The gas concentrations in the atmosphere can reflect whether the wetland still maintains its role as a sink or converting into a source.

Water level regulation and water quality improvement are the other two crucial objectives of constructed wetland application with uncertainties in effectiveness under the complex climate change, pointing out the need for monitoring practices. In detail, the assessments of inflow and outflow volume can indicate the net change in water storage within the wetland, reflecting the alterations in the water table and the capability to reduce surface runoff by providing more sufficient catchment areas. Supplementary, installing a water sensor can help maintain the water table at the most optimal level for sustaining the ecosystem services and preventing greenhouse gas emissions. Notably, a high water table can stimulate methane production, while a water table drawdown fails in carbon storage and turns into atmospheric carbon dioxide. Eventually, those situations all impede the function of climate regulation. On the other side of monitoring water quality, various physical, chemical, and biological parameters can be practical for assessments. For instance, the amount of total suspended solids and turbidity can represent the progress in removing contaminants and water purification. Meanwhile, the excessive algae population and depleted oxygen level in the water can all refer to excess nutrient content associated with the eutrophication process. Following the sample collection and analysis, the subsequent comparison with water quality guidelines can directly determine whether the result is in an acceptable range and the effectiveness of improving water quality. However, the monitoring practices for water level and quality are relatively more challenging regarding the inclusion of various parameters, the data collection and timing, and the requirements for expert knowledge and equipment.

5.32 Monitoring frequency and costs

The clarification on various indicators that can be incorporated into the monitoring practices for different objectives has shaped the foundation of a monitoring framework. However, the necessary monitoring frequency for achieving the desired outcomes and the relative costs in money and time still require further discussion. Indeed, the frequency of monitoring practices increases the cost. Expenses for continuous monitoring, which can capture more accurate and precise alterations and risks within the facility, may be much higher than single-time assessments like annual monitoring developed under the same scenario. Other suggested types of monitoring frequency that have been widely applied include daily, weekly, monthly, and seasonally (U.S. Department of Agriculture, 2020). Among all various options, the selection should be based on specific monitoring objectives aligned with supportive indicators and attributes. Meanwhile, raising concerns about the balance between the costs and potential outcomes, thus achieving a cost-effective approach.

The portions of assessment that can be completed on-site immediately by observation or use of sophisticated equipment are usually more cost-effective than those that need further experiments and analysis after sample collections. Potentially, tree diameter measurements and identifications of species and mortality status under tree performance monitoring are more straightforward than analyzing soil conditions. Experts may collect groups of soil samples from various soil depths and locations on the site to ensure a more precise and reliable result for further analysis. However, the laboratory examinations can be expensive and require much time to receive results, especially with many collected soil samples, indicating money and time-consuming. Biological monitoring like underground microbial activity can be another example that requires even higher pay and is associated with many remained uncertainties, depending on the quality and quantity of soil collections. Moreover, water quality and quantity monitoring for constructed wetlands may also be costly due to specific instruments or technology required during operations. For example, water level sensors installed to monitor the water table changes within the wetland system need high investment. This is also not a one-time payment since the sensors may require maintenance and replacements over time, adding to the total costs. Also, the pricing for specific monitoring technologies applied to trace greenhouse gas emissions can be incredible due to the complexity of data collection.

Although the discussion does not cover all the indicators, and the representative examples can not stand for all situations, there is a general assumption that monitoring costs may depend on the operation scale and the complexity of the equipment or technology being applied. That being the case, monitoring the performance effectiveness of a constructed wetland tends to require more investments than the individual tree assessments due to its larger-scale operation and more complicated design elements and function process. Furthermore, beyond the concerns on costs, the timing for data or sample collection is significant in effectively measuring the progress towards the monitoring objectives, which somehow connects to the required frequency. Continuous monitoring will be more optimal for water level monitoring to detect any rise or decrease in the water table and indicate whether it has exceeded the threshold and becomes an emission source. A good understanding of the effectiveness of regulating greenhouse gas emissions is important. The potential strategy also applies to other indicators that have been illustrated previously (Table 5,6). On top of that, subsequent monitoring of urban trees and constructed wetlands after extreme circumstances, such as heat waves and flooding, is suggested to indicate the susceptibility to climate variations and will inform the maintenance people what additional actions are needed, mitigating the impacts of similar future events.

5.4 Stakeholder participation in monitoring

If seeing the entire monitoring framework as the puzzle, another missing piece is who should be responsible for those monitoring practices designed for urban trees and constructed wetlands, which is the remaining question. City-wide monitoring requires lots of effort for the transformation from written strategies and document agreements to actual applications. The contributions behind smooth and sufficient progress towards the goal do not come from a single group of participants. Instead, multiple stakeholders with different backgrounds and skills should be involved in the heavy monitoring practices, efficiently breaking down the roles. Apart from taking charge of their responsibilities, interacting with other groups is also significant for maximizing the potential outcomes. Based on the lessons learned from green infrastructure case studies in the city, such as the Hinge Park wetland in Olympic Village development and the New Brighton Park shoreline habitat restoration project, stakeholder participation is not limited to the government level. Public engagement associated with expert guides can also lead to high-performance management. Thus, shaping the stakeholder participation into several aspects, including the public, experts, local government, and non-governmental organizations, being responsible for green infrastructure monitoring in the city of Vancouver.

5.41 Public

Although the public group usually lacks professional background in urban trees and other green infrastructure initiatives, their participation in the practices can be a significant component of the monitoring framework, especially with the assistance from experts. As suggested and applied in other case studies, expert knowledge transmissions allow the public to help complete some fundamental plant performance monitoring, such as crown vigour and mortality status, which are observable with no request for equipment. Besides, other problems may also be detectable, such as remaining wet soil conditions and high water table after a few days of free drainage, the exposed root system, and the turbidity of water bodies. The residents, as volunteers, can be organized into small groups in each community, which considerably reduces the pressure of city-wide monitoring. Once any susceptibility is observed, they can report the problems to their community or professionals to ensure the continued effectiveness of the infrastructure. Beyond the general assumption of a lack of relevant experiences in public, a small proportion of the group may have noticed some information regarding green infrastructure or have done similar assessments, like students. This group of people has the potential to be engaged in moderate-level practices, such as measuring tree growth rate and determining the signs of heat, drought, or pests, progressing the monitoring needs in the city. The significant roles of the public in working towards large-scale monitoring can be determined, responding to the climate variabilities, and achieving sustainable and resilient living environments.

5.42 Experts

As mentioned, experts play a significant role in monitoring practices in the city due to the transmission of their professional knowledge. They provide sufficient and acceptable information to all the other groups responsible for monitoring needs in the city, taking a role in sharing the required knowledge. Most participants do not have relevant knowledge and experiences, which may adversely inhibit the monitoring progress without adequate assistance. Thus, knowledge transmission is essential for ensuring high performance and can be in various forms like workshops and websites. The expert groups also play a significant role in accomplishing effective results. They are responsible for selecting the most relevant indicators, collecting data and samples, and analyzing and interpreting the results. Although the public volunteering group can contribute to some fundamental monitoring at a moderate level, they can be very effective with expert-level training. The collaboration between various groups of experts and the communities is needed and can be challenging.

5.43 Local government and NGOs

Monitoring the performance effectiveness of these green infrastructure initiatives in the city will improve if the non-governmental organizations collaborate well with the local government, the city of Vancouver. The city is responsible for funding and has a determinant role in decision-making. Hence the financial support from local government to NGOs is important in order to have an effective monitoring program in place. Without adequate resources dedicated to the practical considerations of monitoring, which depends on government decisions, the goal of sustainable stormwater management and other prioritized concerns will not be achievable. Besides, the government can also provide policy support, raising the concerns of monitoring needs and highlighting the relevant practices in the city strategies or plans.

Furthermore, non-governmental organizations like the Partnership for Water Sustainability in British Columbia also have roles in responding to the adverse environmental impacts of climate change and should participate in the monitoring practices. Their involvement can break the barriers between different stakeholders, such as the community and the local government, facilitating communications and collaboration towards the common goal. Meanwhile, NGO actors can also help deal with the pressure in funding and contribute to policy development, promoting green infrastructure monitoring in the city of Vancouver.

6.0 Conclusions & Recommendations

Under the continuous climate change, installing more green infrastructure initiatives alone but with rare attention focused on the subsequent monitoring needs can be very challenging for building a sustainable and resilient environment in response to all the concerns. Unfortunately, this is the situation that the city of Vancouver has to deal with. Undoubtedly, the development trend of incorporating more urban trees and constructed wetlands can greatly support sustainable water management, including stormwater and wastewater. The practice allows a greater capacity to intercept more rainfall, thus reducing surface runoff and erosion and enhancing water quality. Also, their contributions to climate mitigation are essential, such as regulating greenhouse gas emissions and mitigating the urban heat island effects. Nevertheless, the potential of acting as the solution for future climate change assumes the adequate performance of green infrastructure. Indeed, urban trees and constructed wetlands are susceptible to climate varieties in terms of short-term alterations in precipitation and temperature patterns, other extreme events, and long-term climate warming, leading to suppressed functionalities in climatic regulations and non-sustainable efforts to the environment. Monitoring programs that guide the assessment of relevant indicators, such as plant performance and water quality, help determine the effectiveness of the infrastructure and any signs of stressors. A clear awareness of how often and who should be involved in the monitoring practices is also necessary for sustaining long-term efforts during the post-construction. Stakeholders, including the public, experts, local government, and NGOs, have different responsibilities in the city-wide monitoring, but their collaborations are needed for smooth progress towards the goals.

The study also draws attention to the potential issue of current species composition in the city. The dominating broadleaf species of maples and cherries are susceptible to drought, heat, and pests and are not excepted to adapt well to future climate conditions. Additionally, the heavy dependence on broadleaf trees and neglecting conifer plantings may lead to species diversity loss and break the ecosystem balance, which is challenging for building the resilience to respond to climate-related risks. For the future direction of study and the progress toward sustainable green infrastructure management, the city of Vancouver should understand the many trade-offs between the broadleaf and conifer species and allocate more attention to species selections based on all different prioritized concerns. Furthermore, wetland plants are susceptible to heat stress and high water temperature. However, the current study has not fully explored the different responses of those aquatic plants frequently incorporated into the wetland systems. More research is required to determine the future climate suitability of various wetland plant species, thus allowing more adaptation and ideal performance in functionalities. The appropriate species selections and the healthy plant status are the basis of enhancing resilience to upcoming challenges in which the city should raise concerns.

7.0 References

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