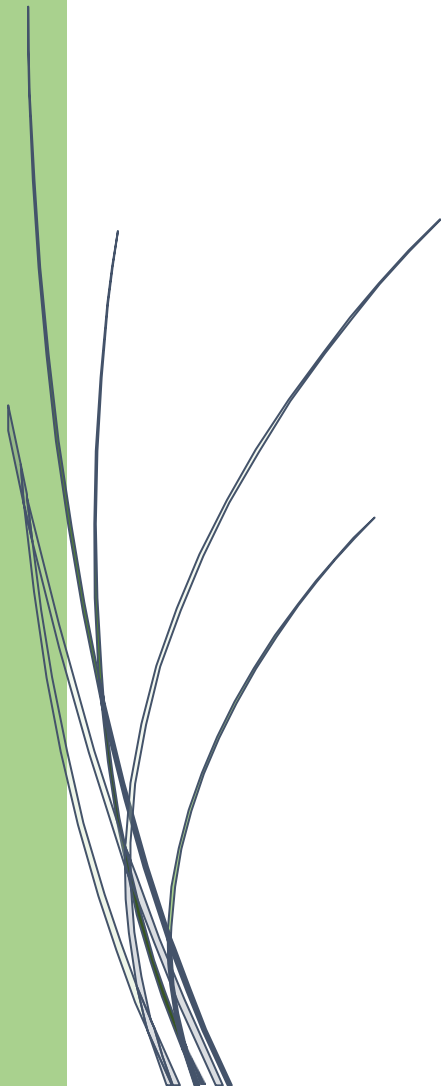




**LWS 548 Major
Project**

Greening Urban Centers: Assessment of Green Roof Garden Feasibility in Vancouver, British Columbia



Name: Mingming (Queenie) Liu

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Abstract

In the last decade, there has been a rapid increase in research on green roof gardens. Green roof gardens take advantage of Vancouver's high annual precipitation and make better use of the large impermeable areas. Green roofs have been proposed as an effective and promising practice to mitigate the adverse impacts of urbanization and adapt to changing climate while providing numerous environmental, economic, social, and health benefits. This paper reviewed the literature and case studies globally, using a systematic view to analyze the potential impacts of green roof gardens on both the natural environment and human society, especially focusing on how green roof gardens can benefit the environment, economy, society, and human health. The paper also investigated the opportunities and challenges of green roof garden construction. Numerous benefits are potentially beneficial as a feasible solution for the renovation of existing buildings, current promotional incentive policies, and a large proportion of roof areas in Vancouver.

Through an integrated assessment, the feasibility of green roof gardens construction in Vancouver, BC is considered high. However, the main challenges of green roof construction involve roof leakage, structural failure, high construction costs, and maintenance costs. In order to maximize the benefits and performance of green roofs, recommendations about improving green roof garden construction and design are provided. These challenges can be addressed by improved planning, more cost-effective design, new technology, and interdisciplinary collaboration.

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Introduction:

With the advances brought about by global economies, science and technology, the world is experiencing rapid population growth and burgeoning urbanization. It has been predicted that by 2050 the global population is expected to increase from 7 billion to 9 billion people and more than 3 billion additional people will live in cities (United Nations, 2018). These changes have created new opportunities and challenges globally, especially in developed countries where urbanization is projected to reach approximately 83% in the next decade (Shafique, Kim& Rafiq, 2018).

City sprawl has resulted in agricultural and forested land to be replaced with impermeable surfaces, environmental degradation, and food insecurity. In addition, climate change models predict that wetter winters with increased rainstorms and hotter, drier summers will become the prevalent climatic trend under global climate change in the future (McIntyre, 2018). With the increases in areas of roofs, roads, and parking lots, the urban impervious surface is expanding rapidly, which leads to increased surface runoff and decreased rainfall retention ability. Lower infiltration of stormwater has resulted in huge pressure on urban systems. For example, Vancouver's drainage systems will further face unprecedented challenges (McIntyre, 2018). More frequent urban flooding can cause a serious impact on people's living, also degrade nearby environments, damage natural landscape and property (Berndtsson, 2010). Consequently, mitigating adverse effects of urbanization, achieving urban sustainability, and maintaining the quality of people's life in Vancouver has identified a need for introducing effective green infrastructure to solve incoming challenges and green urban centers.

Green infrastructure such as rain gardens, green roofs, green walls, and bio-retention systems has attracted a lot of attention and obtained much popularity globally (Shafique et al., 2018). In recent decades, green infrastructure has proved its abilities in mitigating the adverse impacts of urbanization and improving the local environment. Green roofs, also as known as roof gardens and living roofs, are roofs, that are covered with growth medium (soil) and planted with different kind of vegetation on the top of buildings. The essential components of a green roof garden include vegetation, growth medium, filter layer, drainage layer, insulation layer, root barrier, and water proofing membranes (Shafique et al., 2018). The green roof gardens are one of the innovations that help mitigate the negative effects of the high annual precipitation in

Vancouver, as green roofs are designed to effectively absorb rainwater, thus contributing to stormwater management, and provide a convenient way for urbanites to “access” nature, satisfy present aesthetic preferences, and potentially support local food production.

As mentioned, green roof gardens are promising options that can mitigate the negative impacts of urbanization and adapt to changing climate, while providing numerous environmental, economic, social, and health benefits. However, the feasibility and environmental impacts of green roof garden applications do have some concerns. Green roof gardens can be problematic as they absorb excess water and may exceed roof bearing capacity. Lack of systematic thinking and critical considerations before construction about the outcomes, such as roof leakage and structural failure of buildings, can outweigh the potential benefits. Particularly, retrofitting or constructing green roof gardens on existing buildings requires additional considerations in planning and architectural design compared to the construction of new buildings (Li, 2019). In addition to the weight and waterproof difficulties in construction, green roof gardens face the challenge from plant selection due to the special environment of roofs. The environment of vegetation on the roof is totally different from the environment of vegetation on the ground. Green roofs are characterized by low soil depth, windy climate, and a large range of temperature and moisture. To ensure plant survival, it is very important to select suitable vegetation species for local green roof gardens (Chen et al., 2015). From a social and economic perspective, there are also challenges from high construction and maintenance costs (Shafique et al., 2018). Therefore, assessing the feasibility of green roof gardens in Vancouver, BC and identifying opportunities, challenges, and limitations are necessary to achieve co-benefits in urban centers.

Background

The study area in this project is focused on the city of Vancouver, British Columbia, (Figure 1).

The Study Site: City of Vancouver

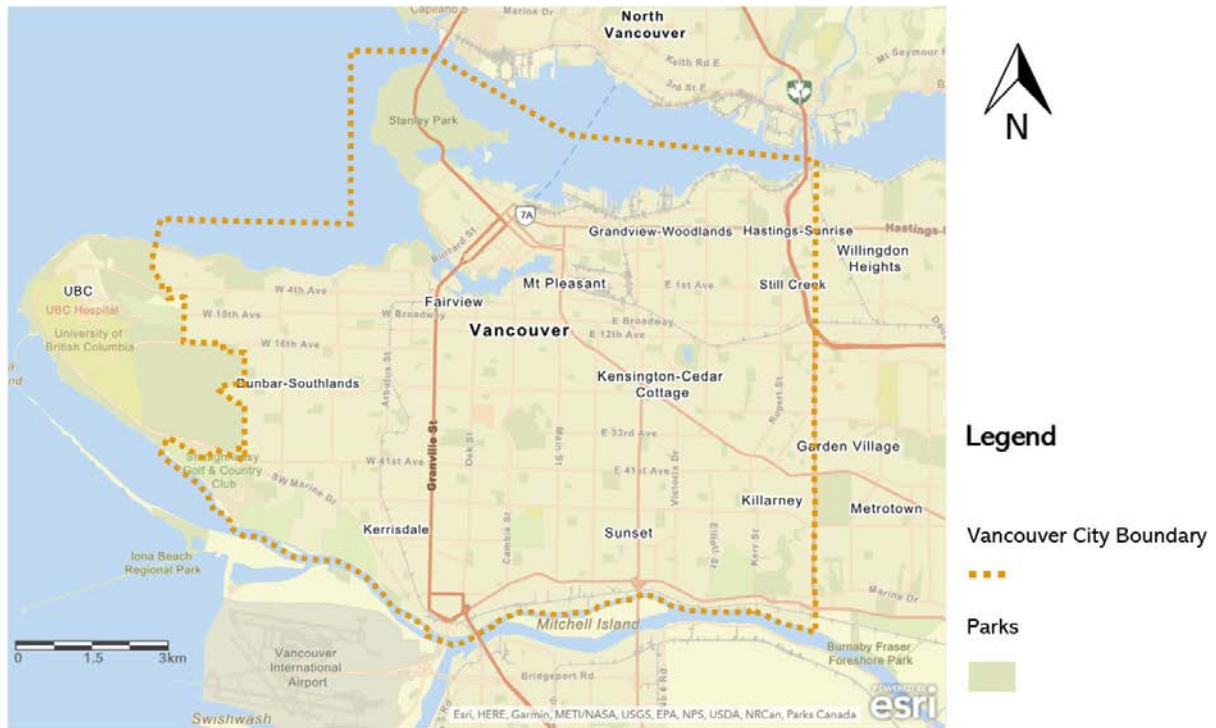


Figure 1. The study site: City of Vancouver. The orange dotted line represents the municipal boundary. The green areas on the map refer to parks, which are scattered around the city.

With the rise and prosperity of the real estate industry, buildings, pavements, roads, and driveways are gradually replacing the green space. Compared with spaces for other usage, roofs occupy a relatively large area in cities, which account for the large proportion of impervious areas in cities. Moreover, due to the chemical and corrosion products of the roofs themselves being washed by rainwater, runoff from roofs could contain a large number of pollutants (Chen et al., 2015). The pollutants along with the runoff can be infiltrated into the soil, leached to groundwater, transported, or deposited in rivers, eaten by animals, flowed into the food chain, and ultimately impacted human health and well-being.

Green urban centers reduce the impacts of urbanization and improve the local environment. Thus, the idea of constructing green space on the top of the building has the potential to suit the current needs and interests. Compared to conventional roofs with impermeable surfaces, the green roof, as a special type of land cover in urban areas, has various ecological functions (Chen

et al., 2015). Vegetation planted on the roof helps the absorption of CO₂ emission from the atmosphere. It can reduce noise and air pollution, increase urban biodiversity by providing habitat for wildlife, decrease habitat fragmentation for pollinators, reduce island heat effect, which helps to build thermal performance (CMHC, 2006). Green roof gardens also provide space for urban agriculture. This a great way to allow access to nature for everyone, especially for peoples who work and live a fast-paced lifestyle.

Project Objectives:

This paper uses a system perspective to analyze the potential impacts of green roof gardens on both the natural environment and human society to understand how green roof gardens benefit the environment, economy, society, and human health. The objective of this project is to investigate the opportunities and challenges of green roof gardens construction through an integrated impact assessment to evaluate the feasibility of green roof gardens in Vancouver, BC. This could prevent or minimize potential adverse impacts before the decision-making and achieve co-benefits. This study also analyzes some existing projects and case studies, providing recommendations for application, to incorporate improvements to future construction in Vancouver.

Methods

This paper reviewed and compared journal articles, case studies, research papers, and books from various sources. This research focused on literature and case studies that have similarities with Vancouver and BC Province, which included moderate oceanic climate, high precipitation during the winter while dry during the summer. First, informed by reviewing the literature, and a systematic approach and critical thinking were used to analyze the potential impacts of green roof gardens. Understanding each component and their interrelationships within the system are crucial. There are three main pillars of sustainable development: Environment, economy, and society (Lavkulich. M, 2019). The impact assessment of green roof gardens concentrates on

impacts from these three categories and recognize its benefits from environmental, social, and economic perspectives. Second, to identify opportunities by integrating the benefits of green roof gardens, advanced techniques, new research, and Vancouver's current situation. The "Greenest City" as a renewable initiative in the City of Vancouver, impervious roof surface occupied a large area in the city, and several new research and measures can be used to alleviate the potential problems.

Thirdly, to investigate challenges of green roof garden implementation in various urban environments, and select case studies to further explore current limitations on existing projects. Fourthly, this paper assesses the feasibility of green roof garden construction in Vancouver using five main criteria: 1) environmental benefits, 2) social benefits, 3) practicable opportunities, 4) economic viability and 5) public acceptance. Finally, this study provides recommendations to address challenges in green roof gardens construction and propose improved green roof garden designs to incorporate my findings that may be suitable for Vancouver, BC.

Environmental Benefits of Green Roof Gardens

Stormwater Management

Many research articles reveal that effective stormwater management is the most significant environmental benefit of green roof gardens (Berardi et al., 2014). As the best stormwater management practices in urban areas, green roof gardens can retain precipitation, delay peak flow, reduce stormwater runoff, and lower the risk of urban floods (Vijayaraghavan, 2016). Vegetation planted on the uppermost layer can intercept part of the rainfall that remained on the surface of plants and return to the atmosphere by evaporation (Chen et al., 2015). Plants can also absorb water from the growth substrate layer through their roots and stem into the leaves. Plants must transpire to survive, the stomata on plants release water stored in the plant tissues into the atmosphere. This process results in the leaves losing moisture and desiccating. So, the plants have to continually draw up moisture from the substrate (Martin, 2020). Precipitation infiltrates into the substrate layer and stores water in the pore spaces between soil particles, which are available for vegetation uptake. The water retained inside the green roof will evaporate through time. As for the excess water, it will flow through the filter layer, enter the drainage layer, and drain by pipes in the drainage system (Vijayaraghavan, 2016). This process

proves the retention ability and potential of reducing stormwater runoff of green roof garden. At the initial stage of rainfall, the green roof can temporarily retain rainwater to delay the runoff generation and decrease the runoff peak. After the end of rainfall, the green roof can continually store the rainwater, reduce the roof runoff volume and speed; thus, relieve the urban flood pressure (Chen et al., 2015).

Koehler proposed a formula for calculating green roof runoff: runoff from roof = precipitation – (rainwater intercepted by plants + water holding capacity of growth substrate + plants evapotranspiration + growth substrate evaporation) (Chen et al., 2015). Based on the formula, the retention ability and runoff reduction greatly depend on two essential components growth medium and plant type, and their key properties. The growth medium is responsible for water retention. Therefore, texture, type, and depth of the growth medium are crucial factors, which can influence the water holding capacity and water conductivity. Many studies from Europe and North America confirmed that there is a positive correlation between the water holding capacity and runoff retention, with the increase of water holding capacity, the retention of runoff increase as well (Vijayaraghavan, 2016). The type of plants and area of vegetation cover are two factors that impact the runoff reduction. The abilities for water interception, water retention, water uptake, and transpiration vary between different vegetation species. For example, sedum species take advantage of their high transpiration rate to retain rainwater, which accounts for up to 40% of the green roof capacity. Other studies also identify that plants in a larger size, taller height, and large roots can contribute to greater performance of reducing runoff (Vijayaraghavan, 2016).

The distinct climate conditions also affect the green roof garden performance of stormwater management. Roehr and Kong (2010), compared the runoff reduction difference in three selected case study areas: Vancouver, BC, Kelowna, BC, and Shanghai, China. By using local climate data that include precipitation, temperature, and evapotranspiration to build a soil water balance model, this model will calculate green roof runoff by using total water gain (sum of irrigation and precipitation) minus total water loss (sum of rainwater evapotranspiration and rainwater retained in plants and the growth medium). The results indicate precipitation and evaporation can strongly impact green roofs in runoff reduction. When the total annual precipitation exceeds 1200 mm, green roofs can effectively reduce runoff, especially in the

the downtown area with few green spaces that can absorb stormwater. Vancouver has the advantage of high precipitation, and calculations of evapotranspiration rates have shown that green roof gardens could potentially reduce runoff by 29% to 58% in Vancouver (Roehr & Kong, 2010).

Water Quality Improvement

Many studies believe green roof gardens have positive effects in both management of water quantity and quality in urban systems (Czemieli Berndtsson, 2010). Precipitation is an important component in the hydrologic cycle continually cycling water from the atmosphere to the earth and back to the atmosphere. Rainwater as part of nature initially is considered as non-polluted but may be polluted during its travel. Prevailing winds and local pollutant sources such as commercial farms and heavy industrial firms can cause rainwater contamination, which leads to acid rain. Rainwater may also contain large amounts of nitrates, heavy metals, pesticides, suspended solids, and residues of other pollutants (Czemieli Berndtsson, 2010). Vegetation layers and growth substrate layer of green roof gardens can naturally filter the suspended particles in the atmosphere and absorb heavy metals and pollutants from the rainwater. Through the infiltration process, pollutants are theoretically held within the growth substrate, thus runoff quality is improved (Shafique et al., 2018).

To investigate the performance of green roof gardens in runoff quality enhancement, many researchers compare the pollutant concentration in input rainwater and output runoff from green roofs or compare the pollutant concentration of conventional roof runoff and green roof runoff (Berndtsson, 2010). Berndtsson (2006) investigated the effects of an extensive vegetated roof on runoff water quality. The results revealed that the concentration of ammonia nitrogen in runoff from the green roof was decreased, lower than the inflow concentration of rainwater (Shafique et al., 2018). In 2010, Berndtsson indicated that the heavy metal concentration was related to the performance of runoff volume reduction. In general, as runoff volume decreased, the output of heavy metals decreased as well. Therefore, compared with the runoff from the green roof surfaces, the concentrations of the heavy metals in runoff from the impermeable surfaces are much higher. Berndtsson (2010) also demonstrated the usefulness of green roofs in acid rain alleviation. The pH of rainwater is normally between 5 and 6. Green roofs can buffer the acidic rain and increase the pH of runoff water to around 7 and 8. This function further

illustrates how green roofs contribute to water quality improvement. Another three-year study in Toronto evaluated green roofs for runoff quality, leachability, and retention. The study area included a shingled, modified bitumen roof (conventional roof) and a green roof planted with wildflowers on a 14 cm depth growth substrate. Rainwater samples and runoff water quality analysis were based on 21 rain events over two years and were examined for water pH, total suspended solids, metals, nutrients, bacteria, and polycyclic aromatic hydrocarbons (PAHs). This study found that the leading pollutants of roof runoff were from atmospheric deposition and roofing material leachate. The research statistics showed that runoff from conventional roofs contained a higher concentration of most pollutants. Runoff from green roofs generally has a lower level of pollutants than conventional roofs, except calcium, magnesium, and total phosphorus. These discharged constituents naturally exist in the growth substrate or are artificially added for better growth of plants. (Van Seters et al., 2009).

Nevertheless, due to the large difference of green roof construction, maintenance, growth substrates characteristics, and the current lack of relevant standards in green roof runoff quality, the impacts of a green roof on runoff water quality is still controversial (Chen et al., 2015). Some research studies have opposite opinions on runoff quality from green roofs, suggesting that leaching from green roofs will further decrease runoff water quality. The concentrations of heavy metals and nitrogen from green roof runoff depend on the growth substrate type, the input fertilizer, and the age of the green roof (Vijayaraghavan, 2016). Therefore, it is necessary to continually compare and update the research, and monitor the impacts of green roofs over the long term.

Urban Heat Island Effect Alleviation

The urban heat island effect refers to urban areas having much warmer temperatures than surrounding rural areas. The difference in temperature depends on the differences between urban surfaces and rural surfaces on absorbing and storing heat (NASA, 2020). Rural areas are mostly covered with vegetation, such as trees, shrubs, grass, and crops. The transpiration process releases water vapour from leaves into the atmosphere, which acts as a natural air conditioner to cool the rural areas (NASA, 2020). In urban areas, streets, sidewalks, parking lots, and buildings account for most of the space, which is usually impermeable material that consists of

cement, asphalt, brick, and steel. The impervious surfaces restrain water cycling and evaporation, therefore contributing to higher temperatures in urban areas (NASA, 2020).

Rapid population growth and burgeoning urbanization increase the intensity of the urban heat island effect. Many studies indicate green roofs increase the green space and have the potential to mitigate the urban heat island effect. Compared to conventional bitumen, tar, and gravel roofs that are characterized by darker surfaces, the albedo of green roofs is much higher. The albedo of green roofs ranges from 0.7 to 0.85, while bitumen, tar, and gravel roofs are generally from 0.1 to 0.2 (Berardi et al., 2014). A high albedo means the surfaces reflect a higher percentage of solar energy and absorb less heat. In contrast, low albedo means surfaces are not very reflective and absorb more solar energy. Gill (2007) reported that increasing 10% of the green space in Manchester, UK dramatically decreased ambient air temperature in the urban areas. The projected increase of 4 K of the ambient temperature over the next 80 years could be avoided (Berardi et al., 2014). Santamouris (2014) states the large-scale application of green roofs is a very promising approach to increase the albedo of cities. Existing simulation results reveal that green roofs could decrease the average ambient temperature between 0.3 and 3 K when applied on a citywide scale. Additionally, installing green roofs also provides an effective cooling effect, especially during the night, the contribution of cooling can reach the highest, to around 1.58 degrees. During 19:00–23:00, urban temperatures are expected to be 2–3 K cooler than the temperatures simulated without installing green roofs (Santamouris, 2014). Various studies compared different cities around the world and the results showed that green roofs perform the highest temperature mitigation in hot and dry regions. Thus, green roofs can significantly contribute to urban heat island effect mitigation, which has been proved by various studies. The average temperature of reduction is 2 degrees (Berardi et al., 2014). Heat island effect alleviation as an environmental benefit of green roofs can help people to better prepare and adapt to the changing climate, and reduce energy costs of air conditioners.

Noise Reduction

Sound absorption and noise insulation are other environmental benefits of green roof gardens (Berardi et al., 2014). Green roofs constructed on the top of buildings as a buffer between urban space and the indoor environment have been found to influence noise pollution from the street, vehicles, human activities, and other daily routines. The effect is reduced by

increasing insulation on the rooftop and absorbing sound (Vijayaraghavan, 2016). Sound transmission loss refers to the magnitude of sound level reduced through different mediums. Many studies show that vegetation has a high absorption coefficient that helps to decrease noises at street level in urban areas (Berardi et al., 2014). Green roofs can enhance sound transmission loss between 5 and 13 dB at low and medium frequencies, between 2 and 8 dB at high frequencies (Berardi et al., 2014). The uppermost vegetation layer of green roofs plays an essential role in noise reduction.

Connelly and Hodgson (2013) conducted experiments on the sound transmission on vegetated and non-vegetated roofs at the British Columbia Institute of Technology. This research compared non-vegetated and vegetated green roofs with different substrate depths, water content, and plant species. The results showed vegetated roofs increase the sound transmission loss of roof systems, and the noise frequency was reduced by 10 and 20 dB compared to non-vegetated reference roof, notably lessening low-frequency noise (Connelly & Hodgson, 2013). Similar research examined the green roof with a 150mm depth substrate that is more consistent than the green roof with a 75mm depth substrate. Higher depth of growth substrates has a higher ability to absorb the sound waves and to decrease the noise level (Berardi et al., 2014). Green roofs as a solution to mitigate noise pollution are more suitable to apply to low-rise buildings. Therefore, vegetation and substrate layers can be directly exposed to the urban sound field and efficiently diminish noise (Vijayaraghavan, 2016).

Air Pollution Mitigation

The negative environmental impacts of urban growth also include an increase in air pollution. Concentrated consumption of energy, food, water, and land in urban areas cause poor air quality. High pollutants concentration in urban air affects the life quality of the urban populations, also harmful to human health and the environment (Yang et al., 2008). Green roofs can mitigate air pollution and discomfort from poor air quality in urban environments in two different ways. Firstly, plants have the ability to decrease air pollution by capturing the gaseous and small pollutants through their stomata. Secondly, green roofs indirectly reduce the amount of burning fossil fuels by modifying indoor temperatures, decreasing air conditioning usage, and lowering energy consumption (Shafique et al., 2018). Research by Yang et al (2008) quantifying air pollution removal by green roofs in Chicago, applied a dry deposition model. The findings

revealed that 19.8 hectares of green roofs help to remove a total of 1675 kg of air pollutants in one year. O₃ accounts for 52% of the total pollutants, NO₂ accounts for 27%, PM₁₀ is 14%, and SO₂ is 7%. Each hectare of a green roof can capture approximately 85 Kg air pollutants per year on average. (Yang et al., 2008). Other researchers indicate that the performance of green roofs is strongly correlated to plant species. Different plant species have different properties of leaves, size, and canopy structure. For example, deciduous shrubs have the highest capability in air pollutants absorption, whereas herbs have the lowest ability to capture dust particles (Shafique et al., 2018). Considering long-term environmental benefits, installing green roofs is a practical and cost-effective practice in urban air pollution management, especially in places that lack land and public funds (Yang et al., 2008).

Ecological preservation

As lands are continuously replaced with impermeable surfaces due to population growth and urbanization, many animals lose their habitats. Green roofs can green urban centers, reduce the loss of habitats, improve biodiversity, and preserve the ecological system in urban areas (Berardi et al., 2014). The vegetation layer of green roofs naturally provides a pleasant habitat for wildlife, such as birds and insects, which reduce habitat loss in urban areas. The increasing green spaces on the rooftop also decrease habitat fragmentation for pollinators, restore biodiversity, and improve the urban ecology (CMHC, 2006).

Moreover, the green roof gardens promote smart growth and prevent city sprawl. The United States Environmental Protection Agency (2020) defines smart growth as a plan and community design that attempts to shift development patterns away from sprawl, towards more compact, mixed-use, transit-friendly, and walkable configurations. Green roof gardens locate the green space and recreational areas on the rooftop rather than exploiting adjacent rural areas that occupy large areas on the ground. Thus, green roofs, as a practical approach, convert impervious surfaces into green spaces that also provide numerous environmental and social-economic benefits in urban areas. Green roofs fit the development of smart growth, save lands, and avoid city sprawl while preserving the ecosystem and meeting future demands.

Social Benefits of Green Roof Gardens

Aesthetic Appearance Enhancement

As green roofs transform impervious surfaces on the rooftop into green spaces in urban areas, compared to conventional roofs paved with bald concrete, asphalt materials, green roofs planted with various kinds of vegetation are more aesthetically pleasing. Green roofs can be considered as an implement to improve the appearance of buildings, balance present aesthetic preference with considerations of ecological values that sustain future generations. Figure 2 shows a conceptual image of a green roof garden retrofit in the city of Philadelphia (DiStasio, 2015). There is an obvious contrast between before and after green roof construction. Trees, shrubs, flowers, and lawns create peaceful and beautiful views of the green scenery. It also creates a unique spot for urbanites to enjoy their time amongst the green roof, finds an incredible view and skyline of the city.

Green Roof Garden Retrofit in City of Philadelphia



Before



After

(DiStasio, 2015)

Figure 2. A before and after green roof construction conceptual image for the city of Philadelphia

With sophisticated design by architectural designers, green rooftops can be beautiful, sustainable, and eco-friendly. These significant environmental, architectural, or cultural meanings can make buildings to become landmarks of the city. Figure 3 displays some spectacular green roofs around the world, which further illustrates the great potential of green roofs in aesthetic appearance enhancement and greening urban centers. Well-designed planning makes the city better and better.

Moesgaard Museum, Højbjerg, Denmark



Städel Museum, Frankfurt, Germany



Rice Plant Conservation Science Center, Chicago



Chongqing Taoyuanju Community Center, Chongqing, China



California Academy of Sciences, San Francisco



Olympic Sculpture Park, Seattle



Figure 3. Spectacular green roof constructions around the world (Stamp, 2017).

Improved Mental and Physical Health

There is an inherent connection between humans and nature - biophilia. Considerable research and analysis have shown that by reinforcing and strengthening this connection, people's physical and mental health is improved, and overall well-being is also enhanced (Chomowicz, 2019). Green roofs located on the top of the building, provide a convenient way for urbanites that live in a fast-paced lifestyle to access nature. Therefore, the implementation of green roofs is a favourable option that reduces the negative impact of development, while increasing the quality of people's lives and providing numerous social benefits. Studies indicated that the green roofs help urban inhabitants generate a sense of happiness, include reducing the air and noise pollution, providing a more aesthetically pleasing and healthy environment to work and live in, also creating recreational opportunities and a place for people connection and social interactions. These all promote better mental and physical health (Shafique et al., 2018). Green roofs, as one form of urban greenspaces, not only improve mental and physical health but are related to improved attention and mood, increased productivity and creativity, and reduced improper conduct or aggressive and criminal behaviours (Williams et al., 2019).

Development of Urban Agriculture

Green roofs can attract and gather people together for roof gardening, which creates opportunities for urban agriculture and potentially support local food production (Shafique et al., 2018). Various studies believe green roofs are associated with urban agriculture enhancement, especially vegetable production (Berardi et al., 2014). Research in Michigan, USA, assessed vegetable production on extensive green roofs. Researchers chose common species in home gardens, including tomatoes, green beans, cucumbers, peppers, basil, and chives. They evaluated the production of these vegetables and herbs for over three growing seasons and found all plants from green roofs survived and produced enough yield except pepper. Findings indicate that plant selection plays a crucial role and affect food production. Choosing suitable plant species with appropriate management in an extensive green roof system provides yields of vegetables and herbs that can be very productive (Whittinghill et al., 2013). Increased food production in urban areas can help society achieve self-resilient and decrease the food desert (Berardi et al., 2014).

Educational Purpose

Green roofs create an excellent opportunity for people to access nature. The vegetation on the green roofs satisfies aesthetic preferences today while contributing to ecological sustainability and diversity. The public should know more about the ecological, economic, and socio-cultural values of vegetations, how plants impact our environment, and what kinds of ecosystem services they provide. Schools, community centers, neighbourhoods can conduct educational and recreational events on the green roofs. Thus, more people will be engaged with the environment, understand the vegetation around us, and foster harmony between humans and nature.

Economic Benefits of Green Roof Gardens

Energy Consumption Reduction

Green roofs are efficient in saving energy in buildings. As an added insulation on the rooftop, green roofs can reduce the heat flux through the roof. In warm climates, green roofs shade the rooftop layer and protect the building from direct solar radiation, which potentially reduces the indoor temperature and energy consumption of air conditioners. In cold climates, green roofs decrease heat loss through additional insulation on the rooftop and further save energy cost (Berardi et al., 2014). A study in Greece indicated that green roofs reduce that the energy used for cooling ranges between 2% and 48% depending on the area covered by the roofs. Increasing the area of shading to improve insulation and thermal performance of the roof system, can result in an indoor temperature reduction up to 4 K (Berardi et al., 2014). The British Columbia Institute of Technology reported (2020) that shading the outer surface of the building envelope has been proved to be more efficient than internal insulation. The incoming solar radiation irradiated on green roofs, resulted in 27% of the total was reflected, 60% was absorbed by the vegetation layer and the substrate surface, around 13% was transmitted into the substrate medium. Recent research in Singapore investigated the thermal benefits of green roof gardens in the tropical environment. Results showed that installing green roof gardens on a five-storey commercial building can save 1% - 15% annual energy consumption and 17% - 79% space cooling load (Vijayaraghavan, 2016). By improving building thermal performance, reducing the variation of indoor temperature, and keeping the building cooler in summer and

warmer in the winter, green roofs can markedly decrease buildings energy consumption and save energy cost (CMHC, 2006).

Longer Lifespan

Green roofs have a longer lifespan than conventional roofs. Vegetations on the green roofs facilitate the cooling effect of the membrane and the building during the summer as the plants and growing substrate act as an insulation layer (Rowe & Getter, 2010). Green roofs contain several layers and waterproofing membranes, which can protect the roof system from ultraviolet radiation and the extreme fluctuations in temperature (Rowe & Getter, 2010). This protection extends the lifespan of the waterproof membranes twice as long as the traditional roof, which means the lifespan of the green roof is longer than conventional roofs (BCIT, 2020). The waterproofing layer lasts typically between 10 and 20 years, while green roofs ensure the lifespan of the waterproofing layer is more than 50 years (Shafique et al., 2018). In the long-term, life cycle costs are competitive. Green roof application can reduce material waste from re-roofing and less the frequency of retrofitting, which decrease costs over time (BCIT, 2020).

Job Creation

Green roof gardens, as one type of green infrastructure, have huge potential to reduce the negative impact of development, while providing numerous environmental, economic, and social benefits. This new industry follows the trend of today and the significance of nature in people's daily life and culture, green roof constructions will have a steady growth trend. This new market will create various job opportunities and economic returns. For example, design and engineering professionals, landscapers, suppliers for growth substrate, light-weight soils, and plants; manufacturers for waterproof membranes, drainage systems, irrigation systems, and other specialty products such as landscaping cloth, curbs; and companies providing maintenance contracts (BCIT, 2020).

Opportunity

Feasible Solution for the Renovation of Existing Buildings

According to Life Cycle Assessments (LCA) of green roofs, green roofs are an environmentally friendly product that is considered to be the best management practice worldwide (Shafique et al., 2018).

Green roof construction is not only the best management practice for new building projects but also a feasible solution for the renovation of existing buildings (Shafique et al., 2018). In terms of retrofitting conventional roofs into green roofs in developed areas, the significant issues of concern include the increase of roof weight, additional loads, and structural collapse. A study in the UK also suggested that the mid-rise office building used reinforced concrete slabs, green roofs retrofitting do not require further modifications (Shafique et al., 2018).

Moreover, green roof implementation is recommended to improve the thermal insulation performance of existing buildings. Renovating green roofs into old buildings is more cost-effective than applying to new buildings. The reason behind this is that old buildings generally have poor insulation and use a large amount of energy for cooling and heating each year (Shafique et al., 2018). Green roofs as insulation can improve the thermal performance of existing buildings, expand the lifespan of the roofing system, and bring numerous economic and environmental benefits. The lifespan of green roofs is a crucial factor in LCA. Many studies estimated that the lifespan of green roofs is between 40 and 55 years (Shafique et al., 2018). LCA indicated that green roofs not only was a suitable option for decreasing impacts of urbanization and achieving sustainable urban development but also are a financially reasonable practice in terms of net returns. LCA results also revealed that both individuals and the social sectors obtain economic benefits during the life cycle of green roofs (Shafique et al., 2018). Overall, the various benefits from environmental, social, and economic aspects contribute to enormous opportunities and development foreground of green roofs.

The Greenest City Action Plan

The Greenest City Action Plan (GCAP) is an initiative for maintaining the leading edge of urban sustainability in the City of Vancouver, which was approved by Vancouver city council in July 2011. The objective of the Greenest City Action Plan is to ensure Vancouver will become the greenest city in the world by 2020 (City of Vancouver, 2012). City of Vancouver (2012) represents its vision: “to create opportunities today, while building a strong local economy, vibrant and inclusive neighbourhoods, and internationally recognize the city that meets the needs of generations to come.” In the GCAP, there are ten goals and fifteen measurable targets to guide Vancouver on the appropriate path toward becoming the greenest city in the world by 2020 (City

of Vancouver, 2012). Green roofs suit the GCAP perfectly. It can directly link to Goal 3 “Green

Building”, Goal 6 “Access to Nature”, and Goal 10 “Local Food”. The benefits of green roofs also facilitate Goal 1 “Green Economy”, Goal 2 “Climate Leadership”, Goal 7 “Lighter Footprint”, and Goal 9 “Clean Air”. Therefore, the green roof is the most effective choice to support this initiative and make these goals achievable. In addition, this initiative is an excellent opportunity for green roofs to show the strength and benefits, expand influence, and let the public accept these concepts and follow the trend of today.

Goal 3 “Green Buildings”, requires “all buildings constructed from 2020 onward to be carbon neutral in operations” (City of Vancouver, 2012). The Greenest city planning team developed the target for Vancouver is to reduce energy usage and greenhouse gas emission in existing buildings by 20 % over 2007 levels (City of Vancouver, 2012). Buildings are an essential part of our lives and work. Also, Canadians spend almost 90% of their time indoors. Buildings account for a massive part of Vancouver’s carbon footprint. The total consumption of electricity and natural gas in buildings constitutes 55% of Vancouver’s greenhouse gas emissions (City of Vancouver, 2012). To achieve this goal, Vancouver should improve the thermal performance of existing buildings by retrofitting and upgrading insulations and heating systems, also implement energy-efficient appliances. Green roof gardens are promising options to achieve this goal. Green roofs can improve building thermal performance and keep buildings cooler in summer and warmer in the winter, save buildings energy use, and potentially decrease greenhouse gas emission (CMHC, 2006).

According to the GCAP, Goal 6 “Access to Nature” is an important focus under the rapid development of urbanization in Vancouver. The urban planners have to expand the accessibility of urban green space and to achieve the goal that all Vancouver residents live within a five-minute walk of various types of green space (City of Vancouver, 2012). Green roofs are growing in Vancouver and are a great way to allow access to nature for everyone. It satisfies present aesthetic preferences and potentially supports local food production. Urbanites are going to plant more greeneries on communities, public and individual neighbourhoods to improve the green connection closer within a local scale in Vancouver. People can enjoy the time on rooftops, access nature conveniently, plant vegetation on the green roof as a community or educational activity. Green roof gardens will take advantage of high annual precipitation in

Vancouver, reduce the negative impact of development while providing numerous environmental, economic, and social benefits.

In Goal 10 “Local Food”, GCAP target is to increase food assets in neighbourhood and city-wide by at least 50 percent from 2010 (City of Vancouver, 2012). The concept of “local food” implies that the shorter the distance from the farm to the plate, the better outcome of the local food system. Food systems include the growing, processing, transportation, retailing, and consuming the food, which are processes from seeds to manufactured products. In fact, food is one of the most significant sources of greenhouse gas emissions (City of Vancouver, 2012). By including food-related industries, account for nearly half of the total ecological footprint. For instance, fossil fuels for transporting berries from BC Province to China and energy for cooling systems of food storage all consume resources, produce waste, and increase the ecological footprint (City of Vancouver, 2012). Strengthening the local food system can reduce the use of fossil fuel, protect the ecosystem, improve biodiversity, and further reduce the ecological footprint. Vancouver Economic Council believes local food as a growing sector strongly contributes to the green economy (City of Vancouver, 2012). As mentioned in the social benefit section, green roof gardens improve the development of urban agriculture, which creates opportunities for people to produce various vegetables conveniently and innovatively. Many studies show that vegetable and herb yields can be very high when appropriate plant species are selected and managed in the green roof system (Whittinghill et al., 2013). Increasing food production in urban areas can make the city more sustainable.

Promotional Incentive Policies for the Application of Green Roofs

Based on various environmental, social, and economic benefits brought by green roofs, many countries intend to promote the development of green roofs and have adopted corresponding policies on the application of green roofs. These policies typically include financial incentives or reductions in water or property fees (Shafique et al., 2018). For example, in Germany, Darmstadt introduced laws on the application of green roofs. Building owners can receive up to 5000 euros for installing green roofs. In Quebec, users will be reimbursed for every square metre of green roof they implemented in place. In Cologne, Mannheim and Bonn, users will be charged less for a stormwater fee when green roofs are installed. In Basel and Switzerland, the owner can be reimbursed for 20% of the total cost of the green roof construction

(Shafique et al., 2018). These incentive policies encourage residents to install green roofs, create opportunities for green roof implementation and promote green roof development, which further decreases urban footprint and achieve multiple environmental benefits.

Large Proportion of Roof Area in Vancouver

According to Vancouver Open data, I used ArcGIS to create a map about the distribution of roofs and parks in the city of Vancouver. In Figure 4, the black contour line outlines the roof of each individual building and houses. Because of the high density of buildings and houses, only large parks can be found easily on the map, such as Stanley Park and Queen Elizabeth Park. Other small parks are interspersed within the dense commercial and residential areas. It is clear to be seen that the proportion of roofs in the total area of Vancouver is as high as 50%~60%. Therefore, the amount of roof area that can potentially be retrofitted and installed with a green roof is large. Except for the golf courses and country clubs, there are 246 parks in total, regardless of the various size of the green space (City of Vancouver, 2020). Compared to commercial, residential, public, municipal, and other areas, parks only account for a small portion of the city.

Roof Areas and Park Areas in City of Vancouver

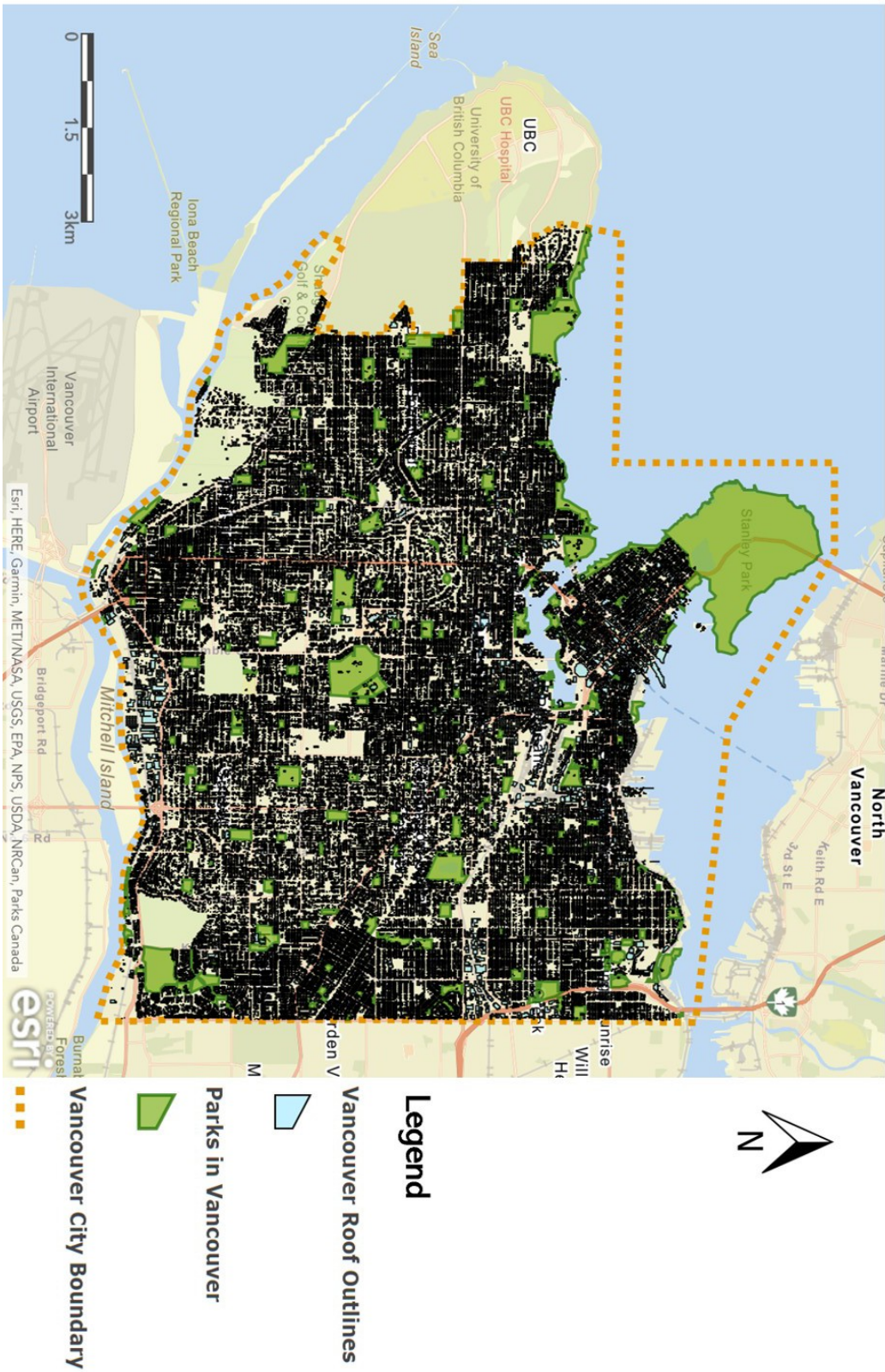


Figure 4. The distribution of roofs and parks in the city of Vancouver

Zoomed to a smaller scale, the distribution of roofs and parks in the downtown area is shown in Figure 5. Downtown is in the north-central part of the City of Vancouver and southeast of Stanley Park. As the centre of economy, finance, culture and business district of the city, downtown is the most economically advanced and prosperous region in Vancouver. Downtown is also famous for its rich history and attractions. There are numerous high-rise buildings, remaining historic buildings, and remarkable landmarks in the region.

Downtown areas always attract people and investments, which has a high density of population and buildings. Except for Stanley Park, most green spaces downtown are relatively small. There is no undeveloped land in Downtown. The value of the land becomes higher and higher, so to expand existing green space or build new parks seems impractical. Green roofs located on the top of buildings can convert impervious areas into green spaces without occupying extra land, which fits the concept of smart growth, “save the land, and preserve ecosystem”. The considerable proportion of roof area in Vancouver provides plenty of opportunities and broad prospects for green roof implementation.

Legend

- Vancouver Roof Outlines
- Parks in Vancouver
- Vancouver City Boundary

Map Labels:

- Stanley Park
- Devonian Harbour Park
- English Bay
- Hadden Park
- Sunseri Park
- CRAB Park at Potts Island
- Trillium Park
- Port Metro Vancouver-Centrum
- Burrard Inlet
- SeaBus
- 0 0.3 0.6km
- N

Figure 5. The distribution of roofs and parks in Downtown Vancouver

Challenges

Roof Leakage and Structural Failure

Although green roofs are considered a promising option that can provide numerous benefits, mitigate the negative impacts of urbanization, and adapt to changing climate, there are challenges and technical difficulties that can restrict the development of green roofs.

Green roof garden consists of a vegetation layer, growth medium, filter layer, drainage layer, insulation layer, root barrier, and water proofing membranes (Shafique et al., 2018). Since there is an increase in weight load, green roofs are heavier compared with traditional roofs. On average, adding a green roof will add 50 to 200 kg/m² to the existing rooftop (Green Roofers, 2016). Therefore, implementation of green roofs requires more structural support, especially for existing buildings, the rooftops may need to be refurbished to cope with the added weight of green roofs (Green Roofers, 2016). Besides, green roofs typically contain heavy growth substrate layers, and the precipitation infiltrates and stores in the substrate. Green roofs can be problematic as they absorb excess water and may exceed roof capacity (Li, 2009). If the green roof is not correctly implemented on the rooftop, the risks of roof leakage and structural failure become very high. Retrofitting or constructing a green roof on existing buildings requires additional considerations in planning and architectural design compared to the construction of new buildings (Li, 2019). The weight of different components and the capacity of the roofing system should be strictly and precisely examined to avoid leakage problems (Shafique et al., 2018).

Many case studies have shown that if green roofs are not well designed or maintained, they can collapse from overloading (Li, 2009). There is a case of green roof collapse in the City University of Hongkong. On May 20, 2016, a 35 × 40 m green roof on the Hu Fa Kuang Sports Centre building collapsed (Figure 6). This accident caused three people to be injured (Li, 2009). The investigation Committee investigated this collapse and found that the design of the green roof used outdated data and incorrect information, especially for the loading capacity assessment. This was most likely the main factor that caused this accident (Li, 2009). Also, the collapsed sports center was more than 20 years old. As the Chairman of the Hong Kong Project Management Exchange Centre, Yim Kin-ping believed, it is necessary to develop thorough plans and conduct accurate tests of the building's carrying capacity before decision-making, and some

roof systems may need strengthening. Otherwise, leakage problems and collapse may occur, especially during the rainy season (Li, 2009).



Figure 6. The green roof collapse at Hong Kong City University in 2016 (Li, 2009).

According to The New York Times, there is a 700×50 foot section of the green roof at a garden pond construction and supply company that collapsed in St. Charles, Ill, west of Chicago (Fountain, 2011). This incident caused \$13 million of economic damage but no serious injuries (Hitzeman 2013). The vice president of the company, Mr. Beaulieu, said the City just experienced snowfall and then the temperature rose to just below 0 degrees two weeks later. There was ice accumulation on the rooftop, and the green roof collapse occurred at the beginning of snowmelt (Fountain, 2011). The assumption from investigators indicated that ice accumulated on the roof might have blocked the drainage system and prevented meltwater from draining away from the roofing system (Fountain, 2011). Providing timely maintenance and removing the ice on the rooftop may prevent this collapse (Li, 2019).

The two disastrous collapse cases of green roofs in Hong Kong and Illinois demonstrate the significance of systematic planning and management in green roof construction (Li, 2009).

Lack of systematic thinking and critical considerations before construction, the outcomes such as roof leakage, structural failure of buildings can outweigh the potential benefits.

Structural Limitation of Buildings

Depending on the structure and material of buildings, roofs, and load-bearing walls have different capabilities to support the weight of green roofs. Some roofs and walls may not be adequate to sustain the increased weight of green roofs (Salter, 2018). For example, there are two types of green roofs: extensive green roofs and intensive green roofs. The extensive green roofs normally require a 5 to 15 cm growth substrate, which is characterized by thin and lightweight. The weight of extensive green roofs is usually less than standard gravel and tar roofs. Intensive green roofs are much heavier and thicker. The ranges of growth substrate are from 15 to 45 cm or thicker. Therefore, implementing intensive green roofs may require extra structural support (Salter, 2018). Another challenge is that green roofs can only be applied to flat or slightly sloping roofs. The maximum amount of slope allowed is around 25 degrees. The performance of green roofs could be disappointed when installed on a traditional pitched roof (Salter, 2018).

High Construction and Maintenance Costs

From a social and economic perspective, there are also challenges from high construction and maintenance costs (Shafique et al., 2018). Green roofs have high initial construction costs, which may cost twice as much as a traditional roof. An extensive green roof typically costs between \$10 and \$24 per square foot in the USA (Salter, 2018). The costs of the extensive green roof in British Columbia, Canada vary between \$12 and \$15 per square foot (Shafique et al., 2018). In terms of intensive green roofs, they are usually cost twice as much to install as extensive green roofs because they are thicker and more sophisticated (Salter, 2018).

To continually provide numerous benefits, extend lifespan, and maximize performance, green roofs need regular maintenance for long term life. The maintenance of green roofs can be expensive and laborious (Shafique et al., 2018). For the best results, green roofs require inspections at least once a year to remove unwanted weeds and wildflowers (Salter, 2018), check on the drainage system, growth substrate, and waterproofing membranes (Shafique et al., 2018). Although most green roofs system contain a root barrier layer, plant roots

sometimes can still penetrate the waterproof membranes and cause roof leakage, leading to structural damage (Salter, 2018). Under drought conditions, green roofs require watering and fertilization. Some green roof maintenance may also need to hire professional companies to manage green roofs (Salter, 2018).

Limited Plant Selection

Green roofs face the challenge of plant selection due to the special environment of roofs. The choice of suitable plants is very limited (Salter, 2018). The environment for vegetation on the roof is different from the environment on the ground, which has the characteristics of low soil depth, windy climate, and a large range of temperature and moisture (Chen et al., 2015). Compared to the extensive green roof system, intensive green roofs with relatively thick growth substrate can support the growth of a variety of plants, including shrubs and small trees. However, extensive green roof systems with thinner substrates are only appropriate for a small number of drought-tolerant plants with shallower roots depth, such as sedum plants, lichens, mosses, and low-growing grasses (Salter, 2018). The common plant species adapted to shallow soil depth are generally less lush and leafy, may not be as attractive as plants growing in deeper soil. Also, plants that are not resilient may struggle to stay robust and easy to die in the windy climate on rooftops (Salter, 2018).

The research from Roehr and Kong in 2010 analyzed how climate affects the functions of green roofs and compared green roof performances in Vancouver, BC, Kelowna, BC, and Shanghai, China (Roehr & Kong, 2010). They applied the soil water balance model to investigate the variation of soil water content in the green roof and compared the potential irrigation demands of plants in these three cities. Investigation of the soil water balance illustrated that only low water consumption plants were appropriate for planting on Vancouver's green roofs because the dry summer started from April and ended in September which meant that plants could suffer from water shortage. The green roof system in this study had a 150 mm substrate with 30 mm available water, which required irrigation of 31 mm in July and 22 mm in August for the survival of low water use plants such as Sedate (Roehr & Kong, 2010). The results demonstrated that plant selection, soil properties, and soil depth play a critical role in sustaining plant growth and reducing irrigation requirements for green roofs (Roehr & Kong, 2010). To

ensure plant survival and maximize the performance of green roofs, it is very important to select suitable vegetation species for local green roof gardens.

Feasibility of Green Roof Construction in Vancouver

A summary of the feasibility of green roofs construction is reported in Table 1. Using five main criteria to evaluate the feasibility of green roofs construction in Vancouver, including 1) environmental benefits, 2) social benefits, 3) practicable opportunities, 4) economic viability, and 5) public acceptance. Based on these benefits and opportunities, installing green roofs is the most promising option that can reduce the negative impact of development and improve the local environment, while providing access to nature for the City of Vancouver by increasing the vegetation cover on the roofs for new or existed residential and office buildings. Eventually contribute to local food production, enhance human health and well-being. Therefore, the feasibility of green roof construction in Vancouver is very high.

Feasibility of Green Roof Garden Construction in Vancouver

Main Criteria	Environmental Benefits	Social Benefits	Practicable Opportunities	Economic Viability
	Stormwater Management	Aesthetic Appearance Enhancement	Feasible Solution for the Renovation of Existing Buildings	High Economic Feasibility
	Water Quality Improvement	Improved Mental and Physical Health	Substantial Proportion of Roof Area in Vancouver	Longer Lifespan
	Urban Heat Island Effect Alleviation	Development of Urban Agriculture	Promotional Incentive Policies for the Application of Green Roofs	Energy Consumption Reduction
	Air Pollution Mitigation	Educational Purpose	The Greenest City Action Plan	Job Creation
	Ecological Preservation			
	Noise Reduction			
Public Acceptance	10	10	8	8

Table 1. Feasibility of green roof construction in Vancouver. The scores in the last row indicate the level of public acceptance, a rating scale of 1-10, where 1 is very weak public acceptance and 10 is very strong public acceptance.

By conducting a questionnaire survey of green roofs construction in Vancouver to further explore attitude and preference of green roofs construction. 101 undergraduate students at Simon Fraser University and the University of British Columbia answered this questionnaire. Before they answered the survey, the introduction section of this survey listed key points of green roofs benefits, opportunities, and challenges.

In terms of the question: “are you happy to install a green roof?” (Figure 7), Up to 64% of students are very happy to install a green roof. 24% of students want to try in the future. 7% of students hold a neutral opinion and believe they will reconsider this question after receiving more feedback from others. Only 4% of students worried about the negative impact of green roofs construction, and barely one student think the disadvantages of green roof outweigh its advantages. The score of public acceptance was obtained from question survey, environmental and social benefits are both 10, while opportunities and economic viability are both 8. The level of public acceptance for green roof construction is considered elevated, especially in environmental and social benefits sections.

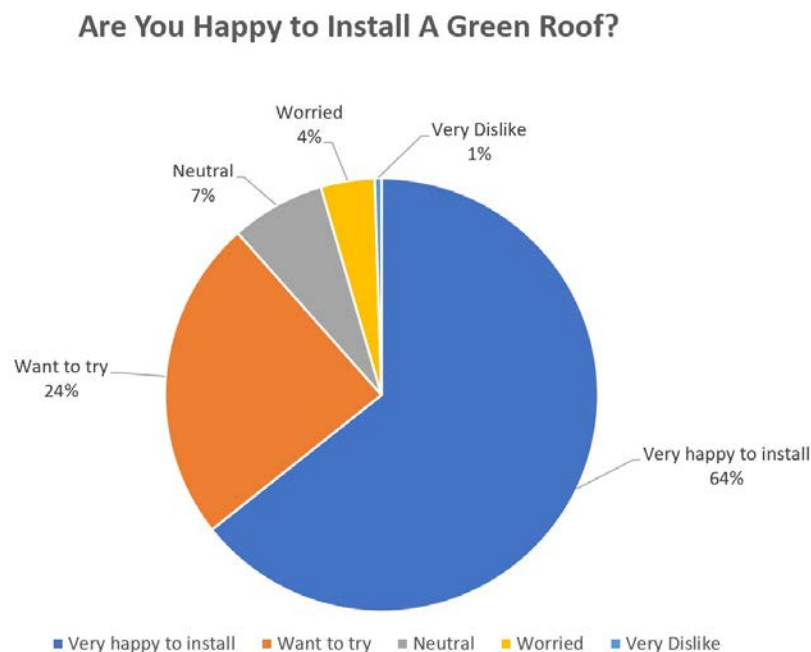


Figure 7. Survey results of question “are you happy to install a green roof” showed the attitude of green roof construction in a pie chart.

Recommendations

Through this paper, presented a better understanding of green roof gardens. Green roofs are not only beautiful, energy-efficient, and environmentally friendly, but also make better use of large impervious areas that are often neglected (Green Roofers, 2016). The green roof, as the best management practice covered with plants and vegetation, brings many environmental, social, and economic benefits to individuals, buildings, and communities. The construction of green roofs satisfies the present need, mitigates negative impacts of urbanization, and adapts to climate change. However, the lack of additional considerations in planning and architectural design before construction, the difficulty of installing and maintaining green roof systems can outweigh the potential benefits. These roofs are problematic as they absorb excess water and overweight, which may lead to leakage and house collapse. Also, the initial construction cost and regular maintenance costs are high.

To focus on the primary challenge of roof leakage and structural failure, my recommendations for improving green roof gardens construction and design include:

1. Evaluate the roof's load capacity and identify the amount of weight that the roof structure can support before green roof garden construction. Especially examine possible water storage, the weight of saturated soil, the weight of crops at maturity, weight of equipment and temporary loads such as people and snow (Lindsay, 2011).
2. Combine light expand clay aggregate and sandy loam soil by different medium prescriptions (ratio) to find the ideal combination of a light-weight substrate that is both conducive to plant growth and inexpensive (Chen, Peng, & Chen, 2016).
3. Reinvent the traditional green roof for detention by inserting a light-weight detention layer to help manage the excess rainwater runoff onsite (Aguilera & Garner, 2019).
4. Select suitable vegetation species with shallow root depth (less soil required) and broad leaves (high evapotranspiration), which will keep the weight of the roof garden light.

5. Review municipal regulations and building-code requirements for green roof gardens before design and construction (Lindsay, 2011).
6. To implement green roofs, maximize performance, and achieve successful management of green roofs introduce interdisciplinary expertise.

In support of recommendation two, there was a study in Taiwan. This study tested three combinations (mixing ratios of medium) of light expanded clay aggregate medium and sandy loam. Researchers' aim was to find an ideal combination of a light-weight medium that is both conducive to plant growth and low in cost (Chen et al., 2016). Table 2 below summarises the ratios, amount, and weight of three mediums. The prescriptions of mediums were selected by industry and research experience (Chen et al., 2016). After experimented with eight plants in three mediums, results indicated that most of the medium showing a low-alkaline environment (Chen et al., 2016). The first medium is 18.4 Kg in total weight. The ratio of light expanded clay aggregate to sandy loam is 2: 8. This medium is suitable for *Duranta repens*, *Murraya paniculata*, *Portulaca grandiflora*, and *Zoysia matrella*, which can increase the growth and coverage of these plant species (Chen et al., 2016). The second medium weighs 14.4 Kg. The ratio of light expanded clay aggregate to sandy loam is 5:5. It can facilitate the growth of *Liriope platyphylla*, *Spathoglottis plicata*. The third medium has the lowest weight, which is only 10.4 Kg in total. The ratio of light expanded clay aggregate to sandy loam is 8:2, which is suitable for *Alpinia speciosa*, *Podocarpus costalis*, and *Portulaca grandiflora* during the rainy season (Chen et al., 2016). Overall, the results of this experiment suggested that different medium prescriptions are more compatible with different plant species. Different plant species can be selected according to the local environment to create biodiversity. Finding a suitable prescription of a medium can provide a good environment for plant growth and reduce the weight of the roofing system in an inexpensive way (Chen et al., 2016).

The Amount of Three Sample Medium

Medium	Medium volume	Medium weight	Total Medium weight
*LECA 20%	0.0031 m ³	1.55 kg	18.414 kg
Sandy loam 80%	0.0124 m ³	16.864 kg	
*LECA 50%	0.00775 m ³	3.875 kg	14.415 kg
Sandy loam 50%	0.00775 m ³	10.54 kg	
*LECA 80%	0.0124 m ³	6.2 kg	10.416 kg
Sandy loam 20%	0.0031 m ³	4.216 kg	

Table 2. The volume and weight of three mixing ratios of medium (light expansive clay aggregate and sandy loam). LECA (Light Expand Clay Aggregate) (Chen et al., 2016).

For recommendation three, green roof designer Sasha Aguilera (2020) believes that the retention layer in the green roof system can facilitate the management of excessive stormwater runoff onsite by simulating friction found in nature. Natural friction examples include thick reeds in a wetland or tall grass and layers of leaves on the ground. Water takes more time to drain when it meets obstacles along the pathway (Aguilera, 2020). Sasha Aguilera (2020) states “Detention is activated by the friction-detention layer’s own large surface rather than relying on a single-flow restrictor at a roof drain (which can fail or clog).” Reinventing the traditional green roof by friction-detention technology is most suitable for projects in populated urban areas. Inserting a friction-detention layer not only has been characterized by lightweight but also provides uniformity and redundancy (Aguilera, 2020). Figure 8 provides a comparison between a traditional green roof and two innovative green roofs with friction-detention technology. Compared to the traditional green roof system, the Sponge-roof and the Purple roof both have the advantages of improving plant health, increasing the retention ability of the green roof system, and reduce the weight of the roofing system.

Comparison and Features of Traditional and Innovative Green Roof Systems

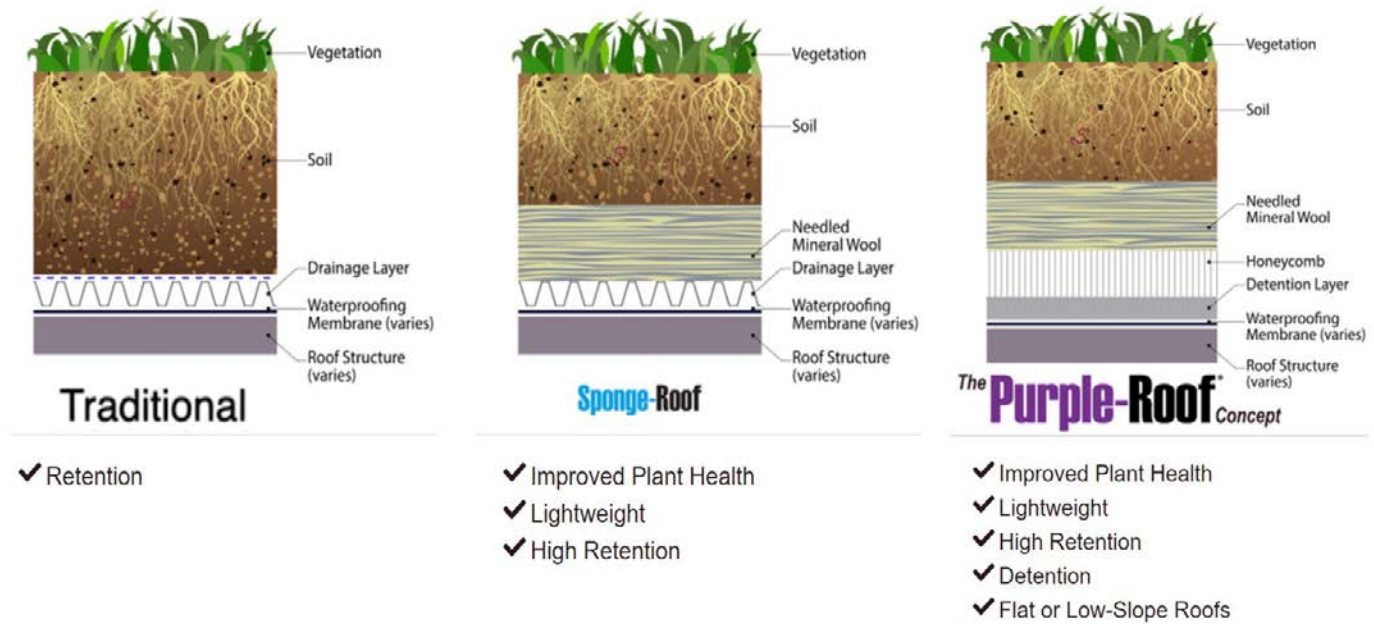


Figure 8. Comparison between a traditional green roof and two innovative green roofs with friction-detention technology (Sponge-Roof and Purple-Roof). The advantages of each green roof system are listed below (Green Roof Diagnostics, 2019).

For recommendation six, the introduction of interdisciplinary evaluations is the most feasible and effective approach. Engineers and architects can handle technical difficulties and precise architectural design to ensure the sustainability of strong and durable green roof systems with a longer life span. Biologists can identify suitable plants for the local environment, recognize the habitats for livings. Sociologists help to investigate how humans interact with the surrounding ecosystem, then design aesthetic-pleasing and environmental-friendly green roofs that meet the needs of inhabitants and balance ecosystem equilibriums. Soil scientists can provide suitable soil combinations for substrates that are appropriate for plant growth, reduce the weight of substrates and lower cost. Meteorologists forecast the weather or extreme events that may occur, such as strong wind, heavy precipitations. These weather events potentially increase the risk of adverse impacts, such as flooding and roof leakage (absorb excess precipitation). Weather forecasts theoretically can prevent more damage from extreme weather events on the economy, society, and environment. The interdisciplinary experts work together to generate an

integrated recommendation on green roof construction, minimize negative impacts before decision-making, also avoiding unintended consequences through system thinking (Lavkulich, 2019).

To deal with the challenge of high construction and maintenance costs, my recommendation is to capture companies' and investors' attention and attract business investments by increasing the value of the property as well as the aesthetic appearance of the buildings. As mentioned in the social benefits section, green roof gardens located on the rooftops create a pleasing green space for social interactions, recreational activities, and satisfying present aesthetic preference in urban environments. Supporting or financing the construction of green roofs shows the contribution that companies make to the environment. This will become an effective advertisement for enterprises in opening up markets, promoting sales, improving corporate image, and the overall competitiveness of enterprises, which can further expand the social and environmental influences of enterprises. Therefore, many convention centers, hotels, IT companies, and other commercial areas have constructed green roofs on the rooftops, for example, Vancouver Convention Centre, The Ritz-Carlton, Charlotte, Four Seasons Hotel Boston, Alibaba in China (Palmer, 2014). The investments and funds from enterprises and local governments can potentially support the high construction and maintenance costs.

Limitation

This paper reviewed the literature regarding green roof impacts, environmental, social, and economic benefits, opportunities, challenges, and existing case studies of green roof construction. Although some crucial challenges have been reported and addressed in the recommendation section, other challenges still exist. For instance, the water quality of green roofs degrades over time and increases the risks of nutrients leaching into downstream aquatic (Qiu et al., 2020). This can be caused by excessive fertilizers being used on the green roofs. Also, most components of green roofs are typically made of polymer materials, and these polymers materials can cause pollution during construction (Shafique et al., 2018). Thus, further research is needed to find suitable materials to replace these polymer materials and improve the management and collaboration between different fields.

Conclusion

Green roofs are not only beautiful, energy-efficient, and environmentally friendly, but also make better use of large impervious areas that are often neglected (Green Roofers, 2016). The green roof with best management practices covered with plants and vegetation brings many environmental, social, and economic benefits to individuals, buildings, and communities. Green roofs construction satisfies the present need, mitigates negative impacts of urbanization, and adapts to climate change. The green roof gardens are one of the innovations that take advantage of high annual precipitation in Vancouver, which is designed to effectively absorb rainwater that contributing to stormwater management, provide a convenient way for urbanites to access nature, satisfy present aesthetic preferences and potentially support local food production. Through integrated reviews and analysis, the feasibility of green roof garden construction in Vancouver, BC is considered high. However, the lack of additional considerations in planning and architectural design before construction, and the difficulty of installing and maintaining green roof systems can outweigh the potential benefits. They may be problematic as they absorb excess water and overweight, which may lead to leakage and house collapse. Also, the initial construction cost and regular maintenance costs are high. To ensure the safety of green roof garden construction and improve the design and performance of green roofs, it is necessary to assess the roof's load capacity and identify the amount of weight the roof structure can support before green roof garden constructions. Also, a proper medium prescription for the substrate must be selected, that is both conducive to plant growth and inexpensive, and transform the traditional green roof by inserting a light-weight retention layer to help manage excess stormwater runoff on-site. In addition, introduce interdisciplinary expertise to enhance cooperation and collaboration between different fields, monitor or maintain green roof systems regularly after construction. There will be more green roof garden research, investments, and interdisciplinary cooperation globally. In the future, we can expect more cost-effective green roof practices that are popularized all over the world.

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