Green Roofs in Cities: An Assessment of the Benefits and Review of Policy

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Defense Date:

4 April 2022

Abstract

Green roofs (GRs, i.e., vegetated roofs) have been increasing in popularity all over the world within the past few years but were first researched and built in Germany in the 1960s. Since then, decades of research have been done on the potential costs and benefits of green roofs: economically, environmentally, and for the mental and physical wellbeing of people living in cities. This literature synthesis will address green roof implementation in metropolitan areas and present current policy from several cities around the world. A synthesis is presented on how particular green roof aspects can be customized to given climate zones. Practices in Denver's GR industry are evaluated in view of what additional research is needed on the function of GRs, the role of plant species selection in supporting biodiversity, and how to encourage more widespread use of GRs. Economic, environmental, and public health benefits are identified, with the conclusion that these more than compensate for the initial upfront costs of GR installment, and the need for improved local and global policy work in support of mass presence of GRs and future green infrastructure.

Table of Contents

1. Introduction

In this paper, I addressed problems arising from urbanization and how green roofs (GRs, i.e., the presence of vegetation on rooftops) can mitigate many of these issues. Population growth is a driver of urbanization, which can have several negative effects on the local and global climate and the health of citizens. The UN predicts that the human population will peak just under 11 billion people (*United Nations*, 2019), and that two thirds of the global population will live in cities by 2050 (*United Nations Department of Economic and Social Affairs*, 2018).

I concluded in this paper that GR technology could improve multiple facets of human life. My research included many different angles of GRs, including their potential for improving public health, driving economic development, providing essential habitat for local species, and benefitting the global environment, while also presenting current policy and regulations in many cities around the world. This paper is a review of the current, peer reviewed, literature on GRs. It focuses on benefits and opportunities that GRs offer for the future of environmental architecture, and uses Denver, CO as an example of GR considerations in alternative climate zones. In addition, this paper summarizes current policy and practices from around the world.

While existing evaluations of GRs in the literature typically focus either on the environmental benefits or the economic costs, this literature synthesis integrates evaluation of the impact of GRs on the environment, their monetary costs and benefits, and public mental and physical health impacts. Specifically, I assessed whether a comprehensive evaluation of the diverse effects of GRs on human health, environmental health, energy-use reduction, and economic cost supports a recommendation to homeowners, architects, buildings, or any other invested party to install or lobby for the installation of GR as an alternative to conventional roofs.

2. Background

2.1 Problems Associated with Urbanization

Urbanized surfaces, such as asphalt and other impervious surfaces, prevent rainwater from being absorbed into the ground. Stormwater runoff is a considerable concern in rainier climates; city pollutants get washed into surrounding fragile aquatic ecosystems and overflow sewage pipes, compromising drinking water reservoirs (Borchers et al., 2015; Krishnan & Ahmad, 2012; Mentens et al., 2006).

City growth produces greenhouse gas (GHG) emissions through building construction, vehicular transportation, and non-renewable energy use (*EIA*, 2019). Additionally, the loss of vegetation from the transformation of natural habitat is predicted to directly contribute to 5% of global emissions (X. Q. Zhang, 2016). GHGs pollute the air and worsen air quality, but they also sit in the atmosphere, preventing heat from escaping, breaking down the ozone layer, and allowing for more solar energy to heat up the earth (NASA, 2022; PBL, 2005). This dramatic change in the earth’s climate is causing the decline of essential ecosystems, destroying habitats all over the world, and compromising human access to natural resources that we rely on for food, building materials, and clean air production (Weiskopf et al., 2020). Melting ice caps lead to rising sea levels and push people inland, further crowding cities like Denver, which has already experienced rapid growth of about 20% in the last 10 years (*Denver Population*, 2022).

Building construction requires the use of more energy, and building heating and cooling accounts for the majority of building energy use (30%-40%, depending on type of building) (Leung, 2018). Energy consumption is a major topic of interest as we face higher demand and environmental consequences of non-renewable energy use. Buildings account for 29% total annual fossil fuel emissions when emissions from electricity production are factored in (Leung, 2018) (Figure 1).

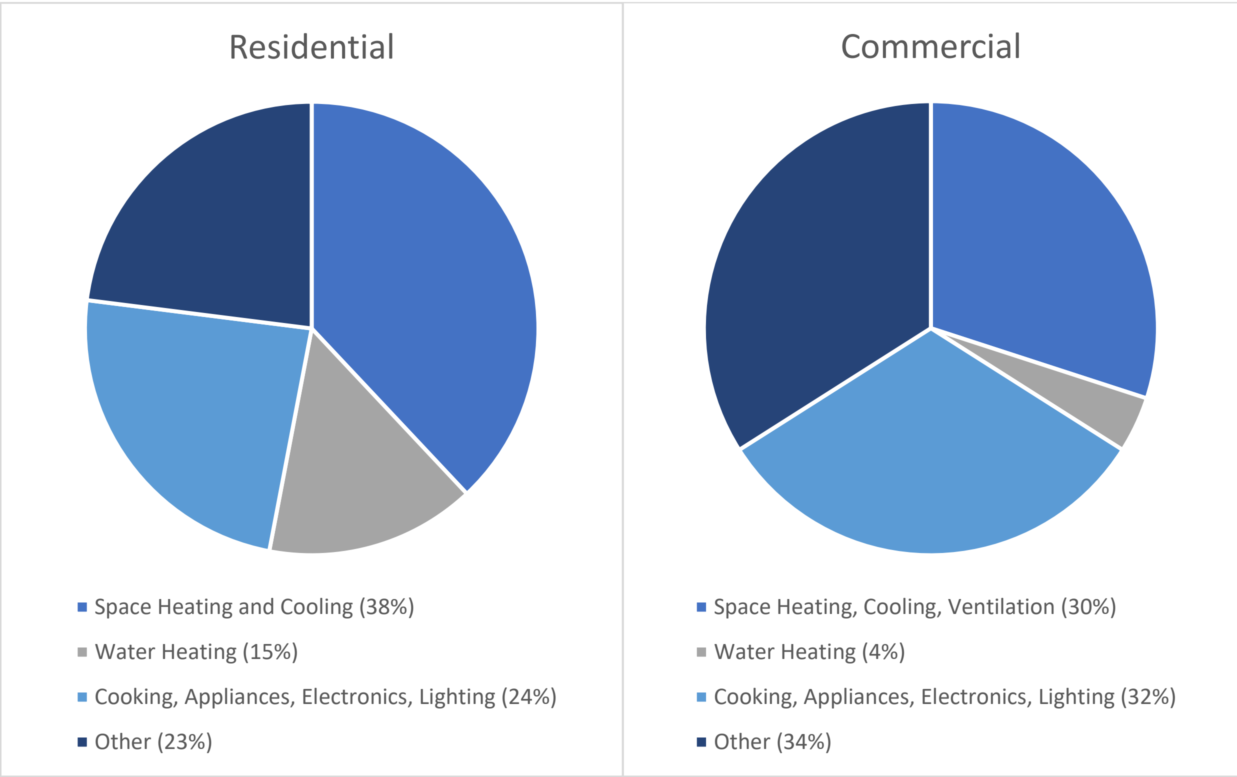


Figure 1:

Total CO_2 emissions from the residential (left) and commercial (right) sectors in the US. “Other” includes things like data servers, medical imaging equipment, ceiling fans, and pool pumps. Based on figure from Leung (2018).

Urban heat island effect (UHIE) refers to the phenomenon where urban areas are generally warmer than surrounding rural areas. UHIE is driven by the combination of heat absorbing surfaces, like dark rooftops and roads, lack of urban vegetation, and production of GHGs (Nuruzzaman, 2015). Heat stress has several human health consequences as well. Heat related mortality in the summertime is one of the highest natural hazard causes of death (Borden & Cutter, 2008). Poor air quality from these emissions can cause long term cardiovascular and respiratory problems (Heal et al., 2012), diabetes, increase risk of stroke, and increase in asthma severity (Gascon et al., 2016). Denver is a vulnerable area because of its dry arid climate, consistent sunshine, and lack of regular rainfall. Public mental health can decline in response to urbanization as well; constant noise, lack of greenery, and light pollution can cause psychological disorders like depression, anxiety, and even schizophrenia (Kuehn et al., 2021; Peen & Dekker, 2004; Vassos et al., 2012).

Biodiversity is crucial to ecosystem function (Midgley, 2012); urbanization causes the transformation of natural land to a humanized world. Habitat is lost and fragmented, causing a decline is many species populations, e.g., wild bees (Potts et al., 2010). Bees are decreasing in population size every year due to human use of pesticides, increased urban surfaces, and climatic stressors (Cardoso & Gonçalves, 2018).

2.2 What is a green roof?

Green roofs, also known as a vegetative roofs or eco-roofs, are rooftop surfaces of a building or residential home that include living and growing vegetation. There are several types of green infrastructure including vertical greenery systems, i.e., “living walls”, which are highly useful for city implementation because they require such little space – they grow up instead of out, where large horizontal plots are difficult to obtain in highly urbanized cities (Besir & Cuce, 2018). Green roofs are harder to implement because they either require the construction of new buildings, which is again difficult with the lack of space available, or they must be retrofitted onto existing ones, which requires a time and financial commitment, and other barriers like public support and permit acquisition (Zambrano-Prado et al., 2021). However, several municipalities have introduced tax deductions or partial subsidy to incentivize installation. Furthermore, green roofs are much better at carbon sequestration than vertical greenery systems, so they are better at cleaning the air (Besir & Cuce, 2018). GR layers also extend the life of the underlying rooftop and provide building insulation, which is one of the most noticeable benefits for energy and GHG reduction (*National Park Service*, n.d.), along with stormwater mitigation.

Green roofs can be classified as intensive, extensive, or a hybrid. Intensive GRs usually consist of deeper substrate materials, which allows for deeper root systems that can support larger vegetation like trees and large shrubs. Intensive green roofs provide the most variation of plant species, and the widest range of possibilities for creative design and usage (Besir & Cuce, 2018) (Figure 2). These systems can provide an array of public engagement, including community areas, rooftop gardens, or rooftop farms that may be able to grow crops locally, reducing transportation costs of produce (Harada & Whitlow, 2020). However, the high costs associated with these roofs (Besir & Cuce, 2018) make them a less likely option for the wide implementation on the majority of city buildings, either by governmental requirement or personal desire. Extensive roofs are not as thick and can only support smaller species with shallower root systems. Although they may be the less impressive model in terms of aesthetic appearance or community engagement, they still have an impressive effect on the local air quality, reduction of UHIE (Getter et al., 2009), and building insulation, and they are often the cheapest option. Hybrid versions combine aspects of both and can support medium sized species of grasses and shrubs.

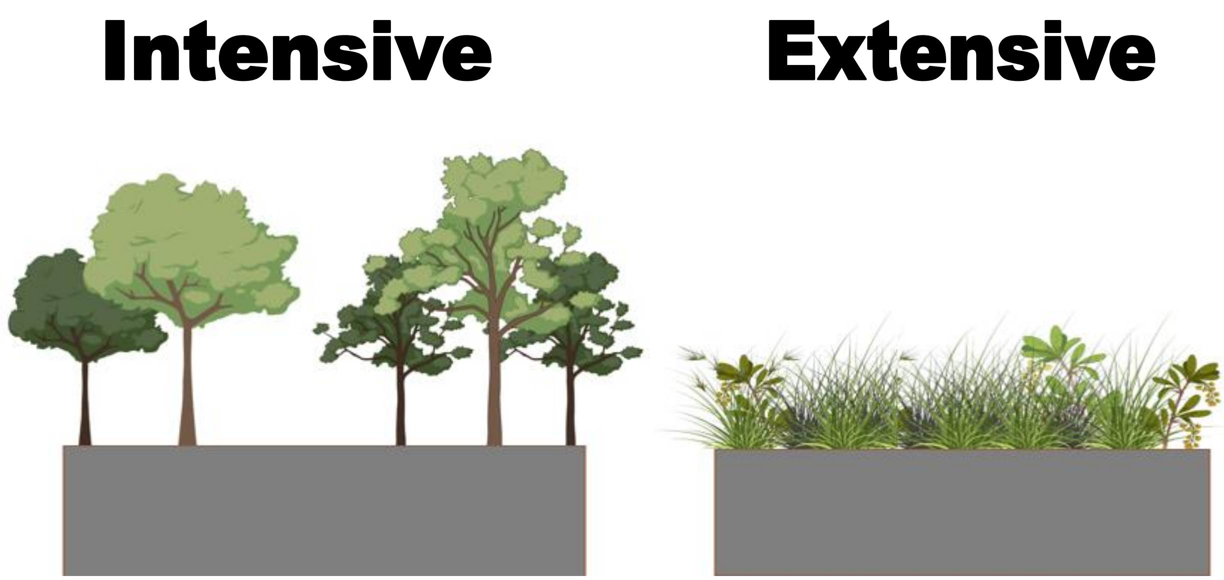


Figure 2:
Schematic depiction of intensive green roof (left) and extensive green roof (right). Created using Biorender.com

2.3 Green Roof Composition

GR makeup needs to be carefully considered depending on the conditions of the existing building roof and the substrate itself varies drastically regarding desired vegetation. GRs begin with an important waterproofing layer above the roof deck that prevents rainwater from seeping into the building structure. Above that is an insulation layer, a root barrier – so roots cannot push through the bottom of the GR and damage the roof deck -, another protection barrier, drainage layer, filtering mechanism, and then the substrate (or growing medium) which plants exist in (Figure 3) (Besir & Cuce, 2018).

The growth substrate differs in makeup and thickness depending on the type of green roof and the species makeup of the vegetative surface. Thickness of the growing substrate is an essential consideration plant health and survival and additional maintenance requirements (Durhman et al., 2007). Thicker substrates would be able to retain more water for GR in Denver; water retention is crucial because of limited annual rainfall (*Weatherbase*, n.d.). A study by VanWoert et al. (2005) found that 2-cm deep substrates required watering of Sedum species every 14 days, but that 6-cm deep growing mediums only required watering every 28 days. The study was done in Michigan, making it difficult to apply to Denver projects. However, it is useful to know that the depth of the substrate itself can have drastic effects on water retention.

Similarly, the makeup of the substrate has differing water retention properties and provides different levels of growth ability to the vegetation. Base layers for substrates can be made from several different types of construction material scraps, including broken bricks, clay, tile, compost items, and some types of plastic scraps, which can also act as fertilizers (Ampim et al., 2010). VanWoert et al. (2005) included around 5% composted yard scraps and composted poultry litter in their substrate makeup as fertilizer. A study by Young et al. (2014) tested different substrate makeups to determine the best possible composition for Sedum species. The study found that smaller pieces of brick had a significantly higher water retention capacity than large brick substrates, “green waste compost” benefited plant growth, and the presence of polyacrylamide increased water retention as well. All these aspects of green roof substrate had beneficial effects on the water retention ability of the green roofs, which is important for the application to Denver projects. Products like SwellGel, the brand of polyacrylamide used in this study, have their own environmental footprint that must be considered for future use, but could be a valuable addition to GR in Denver where water is scarce. These factors increased plant growth rate and decreased root:shoot ratio – meaning the ratio of plant biomass to root biomass is higher (Sainju et al., 2017). For artificial growing environments like green roofs and other man-made greenery projects, root depth is important because of the limited space plants have for root extension. Smaller root systems also minimize the potential for damage to GR layers or to the building roof itself. VanWoert et al. (2005) also recommends that during installation of green roofs, 100% plant cover should be attained as quickly as possible to avoid invasion of weeds and invasive species (which is also a mentioned in Portland's policy (*Portland's EcoRoof Requirements*, n.d.)).

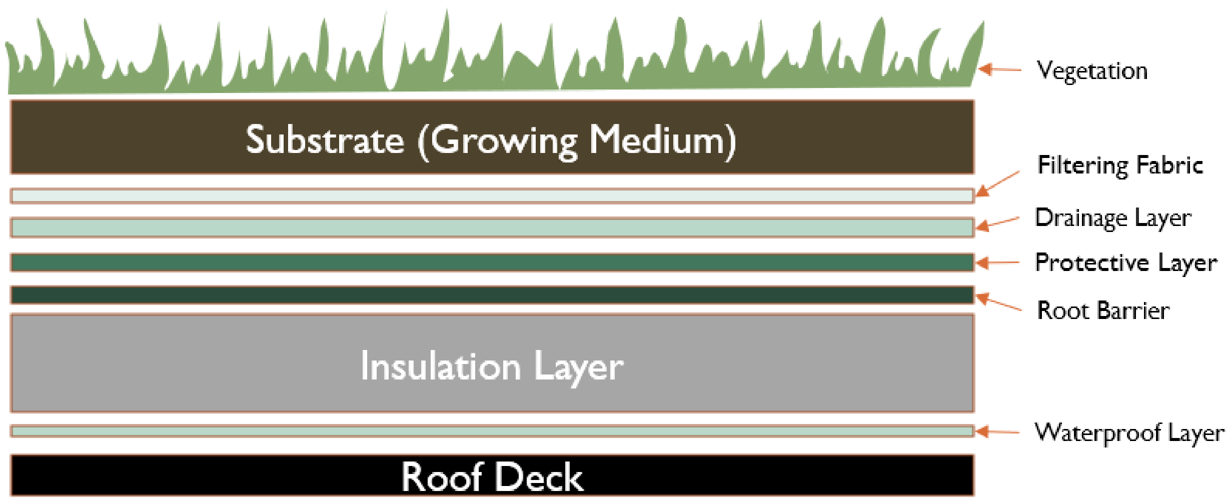


Figure 3.
Compositional makeup of green roof layers. Includes from bottom up: roof deck, water proofing membrane, insulation layer, root barrier, protection layer, drainage element, filter fabric, growth substrate, and vegetation. Growth substrate varies in thickness and makeup depending on size and species of vegetation. All other layers remain relatively consistent between greenery systems but are still dependent on climate.
Based on figure from Besir & Cuce (2018), created using Biorender.com

2.4 Barriers – Roof types

Limitations to GR design exist regarding roof angle and load-bearing capacity – a barrier to GR construction is the roof's structural ability to hold the weight of an intensive roof. Cascone et al. (2018) suggests using lightweight roofs (extensive) when retrofitting older buildings to avoid the possibility of overloading the existing building structure. Similarly, the angle of a roof may call for a more extensive and lighter weight design. Only certain species can thrive on steep angles and pitched roofs, like roofs of residential homes, naturally having smaller load-bearing capacity (Borchers et al., 2015). This makes expanding the implementation of green roofs into suburban areas difficult. It also means that slanted roofs in cityscapes need more consideration in the GR and policy design process. However, many of these difficulties can be avoided by opting for a lightweight extensive roof; Sedum and Salvia species are small enough to be suitable for the average 35 degree angle of a pitched roof (Friedman, 2012).

3. Literature Review

3.1 Environmental Impacts and Potential Species Composition

i. Species Composition

There are several options for the makeup and composition of green roofs that would yield differing amounts of energy savings and carbon capture. Intensive roofs house larger species of plants that can be as large as entire trees. While intensive roofs may have a higher capacity to take CO_2 out of the air, extensive GRs could be a more attractive option for building owners who just need to meet legal requirements, or want to keep their costs to a minimum (Peng & Jim, 2015). Even though extensive species are smaller and may have less of an impact on biodiversity and carbon storage, there is evidence showing that even small, extensive green roofs can have significant effects on energy savings, greenhouse emissions reductions, and local climate improvements. A study by Getter et al. (2009) presents the carbon sequestration of extensive roof species on two testing locations (Michigan and Maryland) representing two different climate types (Michigan being continental and Maryland temperate). The species used in this study are of the *Sedum* genus which are known to be resilient, tolerant to below zero temperatures, and suitable for dry climates, making them a valuable option for the temperate dry climate of Denver, CO (Diaz et al., 2012). Most *Sedum* plants are also an example of species that use Crassulacean acid metabolism as their photosynthetic pathway (Kluge, 1977); CAM plants can close their stomata during the hot day to limit water loss when there is no water present for them to replace water lost during the uptake of CO_2 for photosynthesis (Figure 4) (Males & Griffiths, 2017). Succulent CAM plants thus have a very high water-use efficiency and require little to no irrigation (Bousselot et al., 2011). This makes *Sedum* species an excellent option in dry climates.

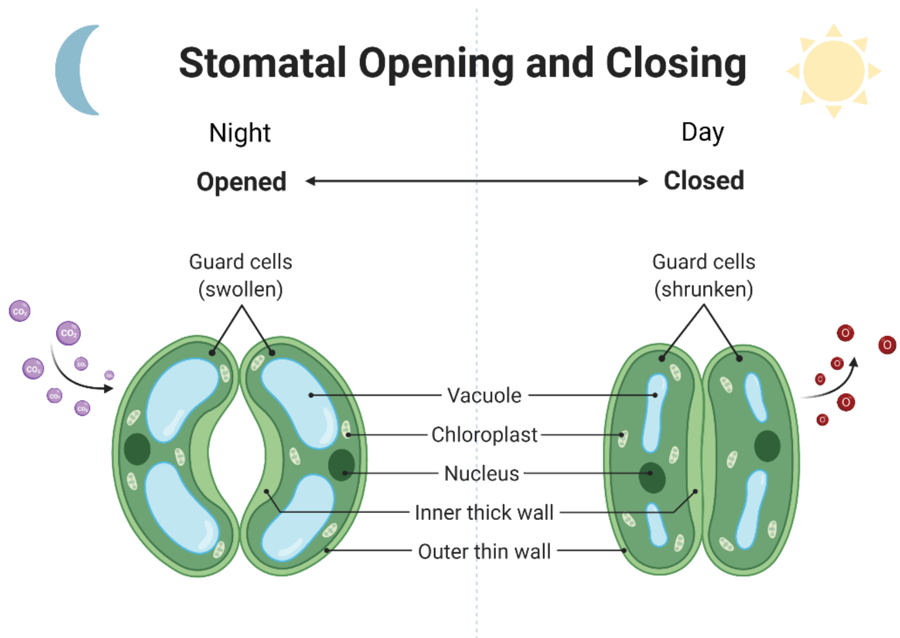


Figure 4: Simplified diagram of CAM plant stomata closed during the day and releasing oxygen as they perform photosynthesis (right) and open during the night when they take in CO_2 (left).
Created with Biorender.com

Getter et al. (2009) includes an analysis of building scale energy savings from extensive green roofs using Sedum matts. Using a building energy consumption simulation, they predicted that there could be a 2% reduction in electricity and 10% reduction in natural gas consumption.

Additionally, this simulation predicted reduced UHIE should allow for another 25% reduction of electricity because of cooler city temperatures. The results of the study concluded that, while the materials needed to install a green roof release more CO_2 than the plants took up over the course of the study (2 growing seasons), over a longer period, greenery continues to take CO_2 out of the air, thus offsetting the CO_2 produced in the production of the materials. Other studies suggest that the highest maintenance costs of GR come within the first 5 years after installation while the plants are still growing to full size (*Cost-Benefit Considerations for Green Roofs - Minnesota Stormwater Manual*, n.d.), so a two year period isn't expected to yield payoff. According to Getter et al. (2008), *Sedum album* sequestered the most CO_2 at the end of their study, but *S. kamtschaticum, S. spurium*, and *S. acre*. are also viable options for species composition.

Another study based in Italy used Sedum and Salvia species on rooftops and tested the reduction of CO_2 emissions and energy savings through GR retrofitting (Cascone et al., 2018). While the Mediterranean climate doesn't resemble that of Colorado, these species are both hardy and suitable for most climates. Salvia include commonly known sage species, which can survive cold winters, tolerate drought, and thrive in full sun (Stillman et al., 2022). The results found that retrofitting existing roofs with extensive GR systems reduced cooling energy usage by 30% and heating energy usage by 2-10% (Cascone et al., 2018). The results also show a significant amount of CO_2 and NO_2 are taken out of the air by these GR.

Figure 5:
Examples of sedum species. Left: *Sedum spurium*, Middle: Biting Stonecrop, Right: *Sedum utah*. Photo Credit: Wikimedia Commons, "I naturen" (2020), Nicholas Turland (2020), David Stang (2006), respectively.

Other US cities that experience more humid and rainy climates face a major problem with increasing "impervious" man-made surfaces. Stormwater is not absorbed by conventional roofs, asphalt, or cement buildings, and excessive rain can cause destructive flooding and push pollutants from our cities into waterways. Aquatic ecosystems are polluted by city water runoff, causing detrimental effects on their function and health (Chithra et al., 2015). Viruses can be introduced into aquatic populations, having serious effects on their population size and aquatic biodiversity (Williamson et al., 2014). GRs can reduce upwards of 60% of building stormwater runoff (Liberalesso et al., 2020).

In addition to harming aquatic and marine ecosystems, pollutants can be washed into drinking water reservoirs or overflow sewage drains, contaminating drinking water and introducing bacteria and viruses into our bodies as well (Gaffield et al., 2003). Florida, for example, focuses its policy primarily on addressing water runoff problems (Livingston et al., 2004). GRs offer a solution to this issue as they mitigate the amount of water runoff by storing it in the substrate or in the plants themselves. Some GRs have special components that act solely for the purpose of water storage for later use by the plants (SwellGel).

3.2 Biodiversity Benefits

Biodiversity is an essential aspect of ecosystem function. When native land is urbanized, species diversity normally decreases (Marzluff et al., 2012). Different species perform different tasks that are useful in the grand scheme of ecosystem health. One of the best examples of why maintaining biodiversity is crucial is the co-evolutionary mutualistic relationship between pollinators and flowers. Flowers bloom at different times during the day and different times of the year. Different species of bees and other pollinators have foraging behaviors dependent on specific plants (Lomáscolo et al., 2019). A loss in bee species leads to a loss in floral species that depend on them for pollination, and vice versa. Wild bee populations have decreased by over half in the last 50 years (Potts et al. 2010; Cardoso & Gonçalves, 2018). Cardoso et al. 2018 suggests that bee declines could be due to increased paved surfaces, presence of exotic (non-native) floral species, and increased human population.

Biodiversity provides ecosystem services to humans as well, like the conversion of sunlight, CO_2, and water into plant growth, carbon storage, and prevention of desertification (Midgley, 2012). Our agricultural industry depends on ecosystem functioning to maintain atmospheric and soil conditions, grazing land for livestock, and pollination for crops to produce high yields (Willem Erisman et al., 2016).

Green roofs can provide habitat for a lot of species experiencing population reduction and habitat loss from urbanization. In fact, bees are drawn to cities because of their warmer microclimate (Kratschmer et al., 2018). Therefore, while we aim to reduce uncomfortably hot temperatures of our cities in the summer, we can also tailor future urbanization to benefit local inhabitant animals like bees. Stillman et al. (2022) reported that bees love salvia species and MacIvor et al. (2015) showed that Sedum species provide great resources to bee species as well.

Because of the multitude of tiny flowers present on these species, bees have optimal foraging ability, which supports large population sizes. Substrates also offer suitable habitats for above ground nesting and below ground nesting bees. Kratschmer et al. (2018) concluded that species diversity and population size of wild bees were positively affected by the presence of green roofs with (Sedum) floral resources. The Vancouver Convention Center is a great example of how green roofs and bee populations work together. This system is the largest green roof in Canada and houses 400,000 plants and 60,000 bees (Stewart, 2010). Similar Sedum habitats support various bird species as well (Fernández Cañero & González Redondo, 2010).

When an ecosystem is tampered with, it's not uncommon for invasive species to dominate when local species fall short in their adaptivity to changing environments (Lepczyk et al., 2017; Grimm et al., 2008), which is why it's important to consider which plant species will reflect the natural ecosystem the best to prevent invasiveness and ecosystem instability.

i. Biodiversity Considerations

There are important considerations necessary for the ability of green roofs to serve as habitat for these species. Bees and other highly mobile insects are able to travel easily between patches of green space, meaning that green roofs can increase habitat connectivity, but there is danger to the height of buildings in respect to the bee's ability to get down. Skyscrapers and high-rise buildings have more exposure to wind and solar radiation, and without any surrounding habitat for species to find, those insects may be unable to get back to the ground (Lepczyk et al., 2017; MacIvor et al., 2015). Although not much can be done about bees getting "stuck" on rooftops, future research is needed for the prevention of population decline in response to poor design. New GR strategies can facilitate the ability to provide habitat for threatened species, allowing for coexistence with wildlife and improvement of human-animal interactions.

3.3 Public Health

i. Mental Health

Several health complications are associated with urbanization through poor air quality, UHIE, consistent noise and light pollution, and lack of greenery. Urban landscapes can cause mental health problems in many of the people who live there and can make existing disorders worse. Cases of schizophrenia, anxiety, and depression are all more common in city-dwellers (Kuehn et al., 2021, Vassos et al., 2012, Peen et al., 2010). Research also shows that the presence of greenery and green spaces can have beneficial impacts of people's mood and improve mental health, especially in the aging population (Kuehn et al., 2021). Similarly, there is a reduced risk of developing psychological disorders later in life when children grow up surrounded by greenery (Engemann et al., 2019).

Poor air quality can directly affect people's moods and overall mental health. Improved air quality is correlated with immediate mood improvement and fewer depressive episodes in Chinese citizens (X. Zhang et al., 2017). The same study reported that increased AQI (air quality index), which is a measure of how polluted the air is at a certain time, was directly responsible for 22% decline in public happiness.

UHIE can elevate levels of aggression and increase violent acts (Anderson, 1989; Levy et al., 2017). Mukherjee & Sanders (2021) found that on days with unsafe heat indexes, numbers of violent interactions between inmates in Mississippi correctional facilities increased by 20%.

Extreme heat events also increase levels of hospitalization and psychotic behavior for mental patients, having the biggest impact on dementia, mood, stress, psychotic disorders, and senility (Hansen et al., 2008).

Additionally, light pollution can disrupt the circadian rhythm that tells the body when to naturally feel tired or when to be awake, resulting in worse quality of sleep. The inability to adjust to a changing circadian rhythm can cause sleep disorders like delayed sleep phase syndrome, which causes people to only be able to fall asleep late in the night and be unable to get up early in the morning (Chepesiuk, 2009). Disruption of the circadian rhythm and other biorhythms may also have the potential to drive those with the bipolar gene to fully develop bipolar disorders, where environments with reduced light and noise pollution may have prevented those patients from ever developing the disorder (Carta et al., 2018).

Urban greenery can have beneficial effects on citizen mental health, air quality and noise, and social cohesion (Wang et al., 2019). Humans have an inherent desire for connection with nature because of our evolutionary history, as stated by the biophilia theory. The attention restoration theory also states that human immersion into nature relieves stress and allows for higher productivity when returning to work (Irvine, 2022). A Danish study of work productivity showed employees were happier and felt more productive when they had a view of outside greenery (Lottrup et al., 2015). By developing urban greening strategies, and implementing a combination of extensive and intensive GRs, large vegetation can block light and noise into people’s homes, and small vegetation can clean the air and reduce effects of UHIE.

ii. Physical Health

Both psychological and physical health seem to be positively correlated with better air quality and less extreme temperatures (Gascon et al., 2016). GRs can reduce many of the effects that urbanization has on public health.

Nowak et al. (2014) found that over 850 deaths could be avoided across the country per year with improved air quality through green infrastructure. Urban greening, in general, also brings several indirect health benefits. A study done in China found that improved air quality can reduce infant deaths by 20% (Tanaka, 2015). Other health impacts on young children include long term respiratory conditions and smaller average lung size (Beatty & Shimshack, 2014). Since GRs can reduce air pollution in cities, wide implementation of rooftop greening could potentially lead to a 15% increase in life expectancy in the US (Pope et al., 2009).

Excessive heat can be draining and even deadly for those living in hot urban centers. Although UHIE can prevent many deaths in the wintertime (Macintyre et al., 2021), it causes more deaths and will cause increasing numbers of deaths in future summers (Kovats & Hajat, 2008), especially in cities at risk of excessive warming, like Houston, TX (Marsha et al., 2018). UHIE puts additional stress on the human body and makes it difficult to maintain a stable internal temperature (homeostasis). When the body constantly works to cool itself off, it uses a considerable amount of energy, causing people to become tired faster, and puts them at risk of heat stroke, exhaustion, cramps, and syncope (dizziness or fainting) (Kovats & Hajat, 2008). Heat waves have always been causational of mass deaths. The heat wave in France in August 2003 is responsible for almost 15,000 deaths in less than a month (Kovats & Hajat, 2008), and the Chicago heat wave of 1995 lead to over 700 deaths in just 5 days (Thomas, 2015.) Extreme heat has may also lead to mortality in heart disease patients, increased heart attack and heart failure, and kidney disease from dehydration (Mücke & Litvinovitch, 2020). GRs can reduce urban air temperatures by 5 degrees C and exposed surfaces by 15-25 degrees C (Liu et al., 2021), which would significantly reduce the risk of health complications from UHIE.

Consistent exposure to light and noise pollution has detrimental impacts on public health as well. Light pollution at night can accelerate tumor growth in breast cancer patients and is correlated with cases of prostate and other types of cancer as well (Chepesiuk, 2009; Falchi et al., 2011). Disruption of the circadian rhythm can also cause cardiovascular disease (Chepesiuk, 2009). Another study also found that light pollution, or at least a combination of light and noise pollution, had a positive relationship with levels of coronary heart disease (Münzel et al., 2020). Blocking light and noise with intensive greenery systems could reduce these human induced pollutants and prevent a wide range of health complications.

Visual access to green spaces or awareness of proximity can motivate physical activity and encourage citizens to spend time outside, which can decrease stress and lead to overall improved health (Gidlöf-Gunnarsson & Öhrström, 2007). Dadvand et al. (2012) explained that even birth weight of infants can increase with maternal access to green spaces (heavier babies, to a certain degree, have higher change of survival and better health in the first 5 years of life (Ballot et al., 2010)). Elderly citizens also live longer when exposed to walkable green space (Takano et al., 2002). The intersection between human health and urban greenery is an essential understanding as cities continue to grow and urban environmental stressors become more hazardous.

3.4 Economics

Because GRs reduce energy consumption, immediate installment provides the fastest payoff for building owners and can begin reducing GHGs that would otherwise be emitted into the atmosphere. Evidence from 2019 suggests that there will be a much larger impact on human and natural systems from just 1.5 degrees Celsius of average global warming than previously thought (Nordhaus, 2019). A warming climate also means that energy consumption will increase to maintain comfortable temperature standards in residential and commercial buildings. Implementing GRs can lower energy expenses, public health costs, provide tax breaks for building owners, and could even reduce food transportation costs if rooftop farms begin to be developed.

For the city of Toronto, GR technology has been estimated to save $313 million up front, with an additional $37 million each year, including savings from storm water mitigation and sewar overflow prevention, urban heat island reduction, and building thermoregulation (Figure 6) (Banting et al., 2005; Peng & Jim, 2015). Another study from 2006 based in New York revealed that the economic benefits of 50% green coverage on all city roofs were almost 4 times higher than the costs (Acks, 2006). Similar findings have been reported by Cascone et al. (2018).

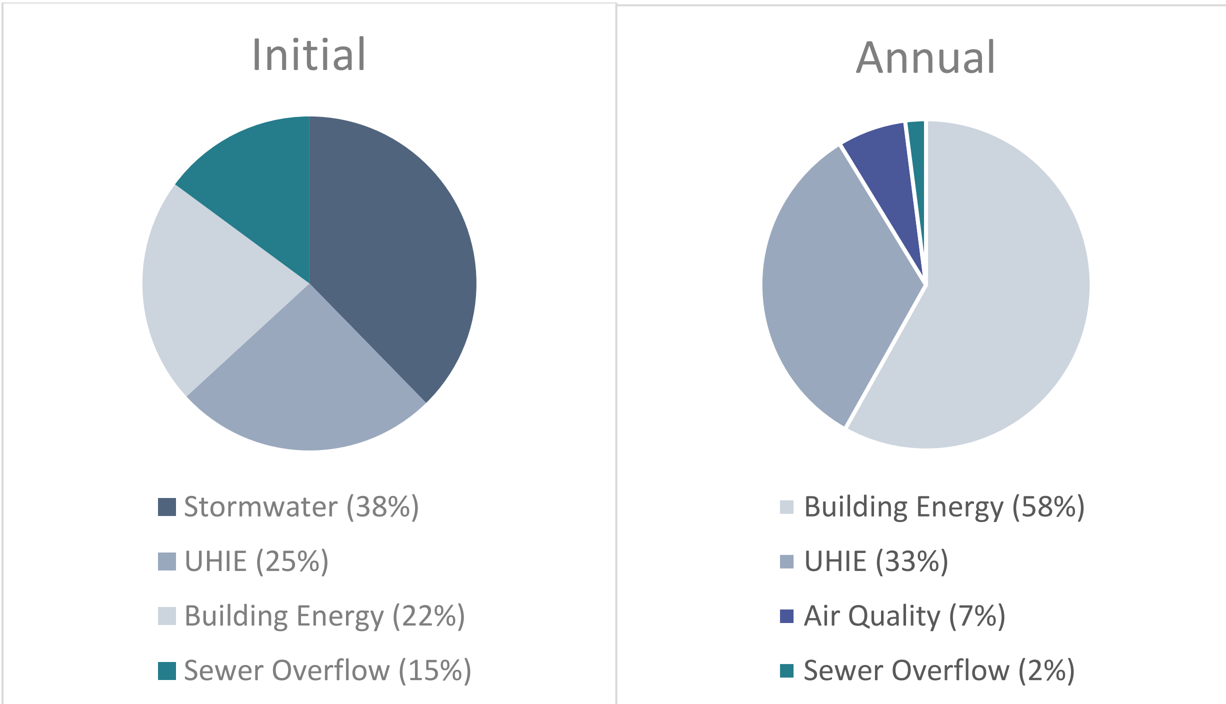


Figure 6:

Estimated breakdown of savings from Toronto study. Right: initial savings, Left: annual savings. Based off of diagram from Banting et al., 2005.

i. *Energy Savings*

Although the initial upfront costs on green roof installation is high, it compares similarly to projects like solar panels that have high upfront costs but pay themselves through longevity and energy savings. Solar panels typically cost around $10,000 - $40,000 to install, but save the client an average of $35,000 over 20 years (Photon Brothers, 2022). This is comparable with GRs because it takes a while to see the payoff, around 13-18 years (Cascone et al., 2018), but once they pay themselves off, it saves money for the client every year after.

Although GRs provide a wide array of benefits and economic savings, a study by Clark et al. (2008) showed the net present value (NPV) of a green roof is considerably less than that of a conventional roof, which is one of the reasons why they are undesirable. Net present value refers to how much your money is worth to you at that time. Since it is presently spendable, the NPV matters more than the value of the money at a different time; in other words, it's always more favorable to save money in that moment. However, after 40 years, when a conventional roof needs replacement, a GR will still be in great condition, saving the building owner somewhere around $8,000 (Perry, 2021). According to RocketMortgage.com, the average mortgage on a house is 30 years (Rocket Mortgage, n.d.), so homeowners may not want a financial commitment longer than their mortgage. A quick estimate of green roof installment costs in the Denver area can be between $12,000 and $40,000, using HomeAdvisor (*Learn How Much It Costs to Install a Green Roof.*, n.d.). Another company based in Boston estimates that an extensive roof should cost between $10-$50 per square foot (*Green Roof Cost Breakdown*, 2022), while the average cost for a conventional, black, shingled roof ranges between 20 to 30 cents per square foot (GSA, 2011). However, the lifespan of a green roofs can be 3 times longer than that of a conventional roof (*Green Roof Cost Breakdown*, 2022). Another great aspect of GRs for their implementation in cities is that the cost per square foot goes down as the size of the roof goes up (*The Benefits and Challenges of Green Roofs on Public and Commercial Buildings*, 2011) (Figure 7). Therefore, larger projects on larger rooftops, should provide some discount in terms of cost per square foot.

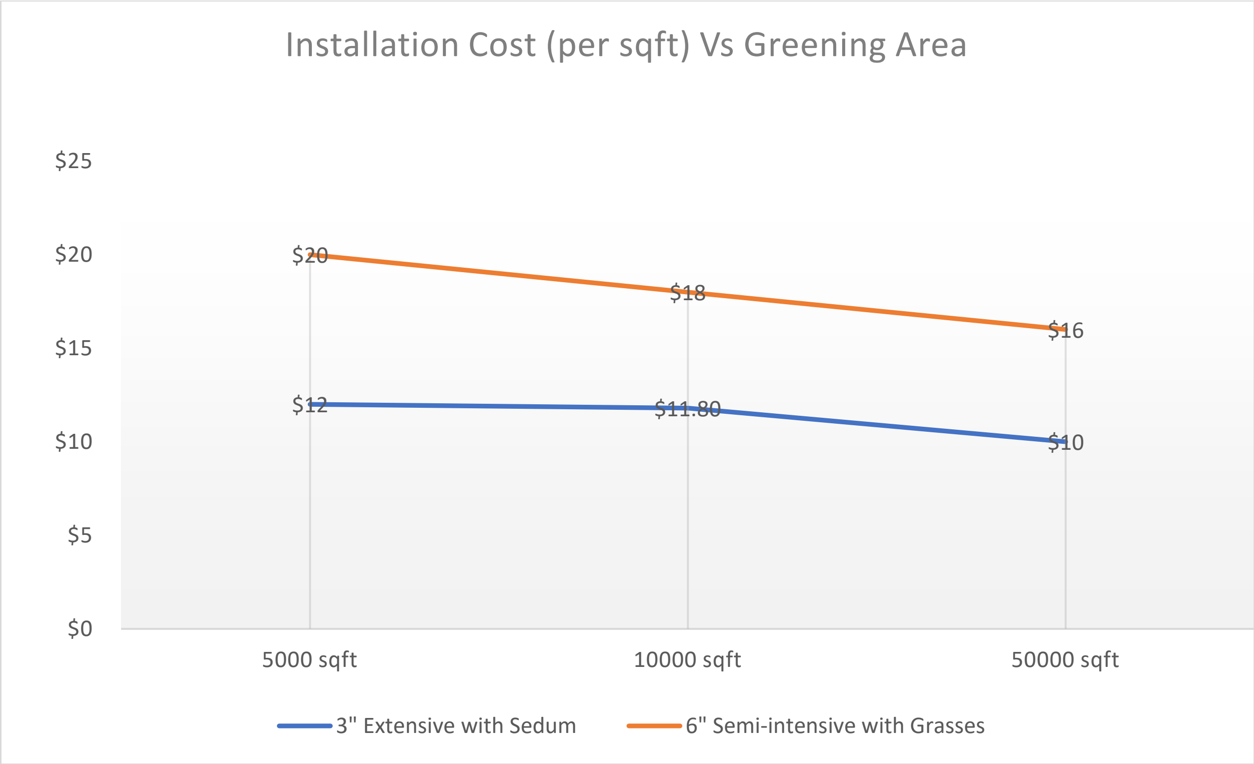


Figure 7:

GR installation cost per square foot of greening area as the total size of the GR increases. Higher costs per square foot are associated with smaller greening projects, larger projects see the most discounts. Based on a graph from GSA Green Roof Benefits and Challenges report (GSA, 2011).

Economic benefits exist for the building owners by installing green roofs through subsidies and tax breaks. Many cities, e.g., New York, have policies that reward tax breaks to buildings with environmentally friendly practices, green roofs being one of those options (Clark et al., 2008; Peng & Jim, 2015; Savarani, 2019). More information on these economic benefits will be covered in a future section titled "Policy".

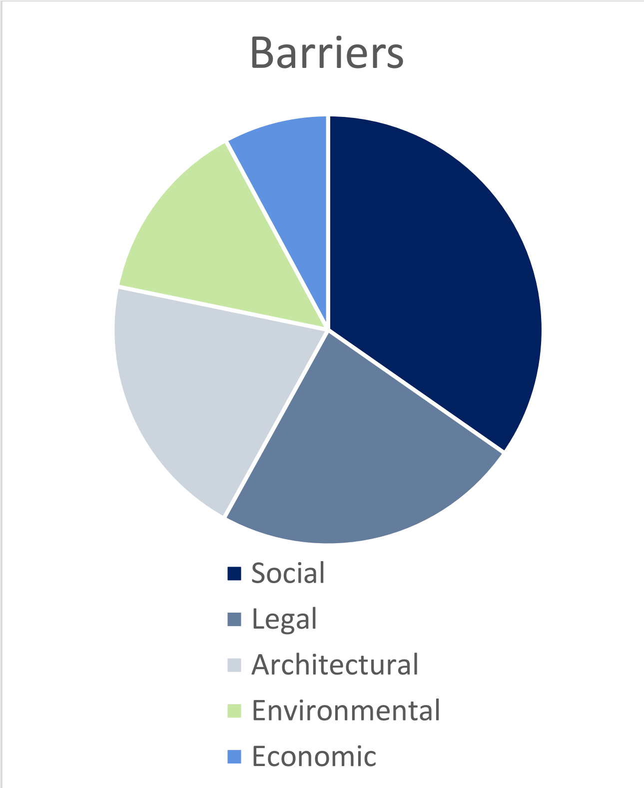
ii. Public Health Costs

Several areas of economic loss in response to climate change have been estimated in recent studies, from agricultural downfall to welfare costs. Poorer countries will suffer more than wealthier countries in their fight for food, water, and shelter, and even slight increases in warming temperatures can negatively affect economic growth in poor countries (Dell et al., 2012). Agriculture, for example, will be heavily impacted by warming climates and more extreme weather. Crops are adapted to a certain climate and warming weather and increased drought will significantly decrease crop yield and worker productivity (Dell et al., 2012; Sterner, 2015). With a growing population, food scarcity is a major concern for the future. Obesity and malnutrition could become the most apparent public health issues and could significantly increase health care expenditures (Dietz, 2020). Projections of unmitigated climate change put the costs of maintaining current welfare standards at over 28 trillion by the end of the 21st century (a 30% increase from the cost today) (Barrage, 2020). Pediatric health costs attributed to poor air quality are estimated on the order of billions of US dollars annually (Beatty & Shimshack, 2014).

3.5 Social Perceptions and Barriers

There are several barriers as to why green roofs have not yet been widely accepted and implemented – most notably the overall lack of information. Many people don't know what the term "green roof" means, which is in part why I chose this topic to research. If most of the public isn't aware of GRs, there's not a lot of public support and the decision is left to builders, architects, city planners, etc. Other people who do understand their benefits may not want to spend the money or take the time to install one. Zambrano-Prado et al. 2021) conducted an interview and survey-based study of public perception of green roof projects. The study found that the main barriers to public support included lack of information or specifics of projects, little apparent support by municipal governments, few ongoing projects to connect with, and the general feeling that the projects will bring more harm than good (Figure 8).

Other barriers include the belief that homeowners associations (HOAs) would not allow green roofs (Borchers et al., 2015), and in some cases, this is true (McGreevy, 2009). Colorado is taking steps to promote the construction of green roofs, breaking down HOA restrictions (Rodriguez & Communications, 2021). Even for those living in apartments or condos, if the rent increases due to installment of a green roof, it will lower their electric bill in time (Opatowski, n.d.). From the same article, homeowners also feared judgement from neighbors and didn’t want to be the first to install such an obviously different style roof.



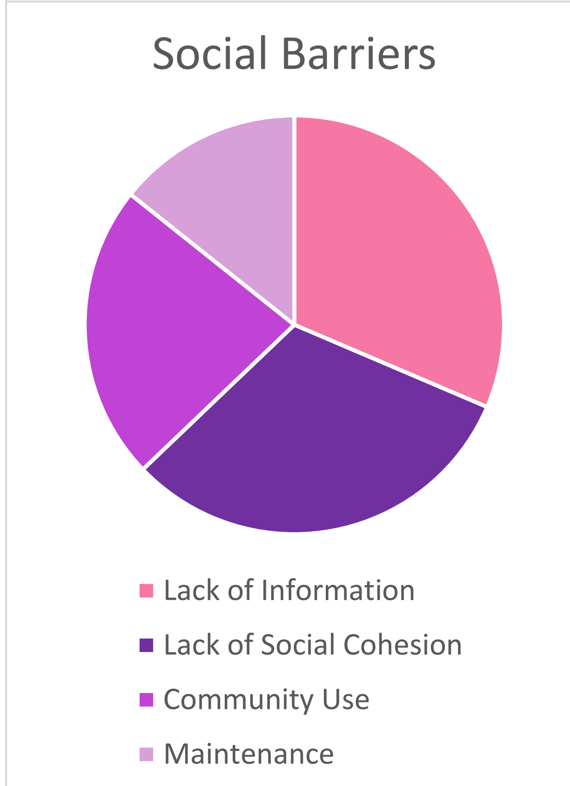


Figure 8:

Breakdown of perceived barriers (left) and specified social barriers (right) of green roof projects, including stakeholders (those involved in current projects), those not involved in current projects but have knowledge in the field, and citizens. Based on figure from Zambrano-Prado et al. (2021).

3.6 Policy

i. Gaining Public Support

Considering the public doesn't know much about what GRs are or what they can provide for public health and the climate crisis (Zambrano-Prado et al., 2021), these projects could benefit from proposal in terms of direct benefits they can bring for the citizens (without forcing the climate change terminology). Climate change issues often get pushed down because of over sensitization to those terms. They've also become politicized and polarized through the media, and end up being detached from scientific fact all together (Marshall, 2015). Focusing on benefits such as psychological wellbeing, aesthetic feel, improved air quality, monetary savings, etc., could have more impact on gaining public support if they are presented simply and clearly as to not deter citizens without environmental science backgrounds. The benefit of using green roofs to aid in the climate crisis is that they are passive solutions (Castleton et al., 2010; Kumar et al., 2019; Pearlmutter & Rosenfeld, 2008) and don't require a long-term, everyday commitment by the public. Steg (2016) states that people are less likely to act on "pro-environmental" values if they are outside the context or have other values competing for action. Shutting off the lights, driving cars without excessive acceleration, turning off the faucet while brushing teeth all require consistent attention and energy to change those behaviors. GRs and other types of green infrastructure are one-time installments that can be left to earn energy savings and provide a multitude of secondary benefits. Further education on the topic of GRs and the focus on direct public benefits could help drive further implementation of GRs all over the world, and clear benefits from local projects can drive the advancement of GR policies (James & Metternicht, 2013).

ii. Existing Policy

Several cities around the world have implemented some form of green roof ordinance. Most municipalities require some type of eco-roofing, either by greening or installation of renewable energy sources, or reflective or cooling surfaces.

Foreign Policy

Germany

In Germany, green roofs are standard procedure for new construction sites (Philippi, 2002). Germany was the first to begin research on green roofs and to actually construct them (Figure 9) (Shafique et al., 2018). The FFL (in English: The German Landscape Research, Development and Construction Society) provides standardized requirements for new green roof developments, which have also been extensively researched and tested (Philippi, 2002). In the US, private companies develop their own substrate compositions with less research attributed to them than the German standard. This creates more room for failure or complication because each company is fighting for the cheapest product to obtain the most largest clientele (Philippi, 2002). Munich's ordinance requires that all buildings with roofs larger than 100 m^2 have GRs, and Hamburg's Green Roof and Solar Tax Abatement Program required that the city and state provide tax credit of $5.23/ft^2 up to $100,000, until 2018 (Savarani, 2019).

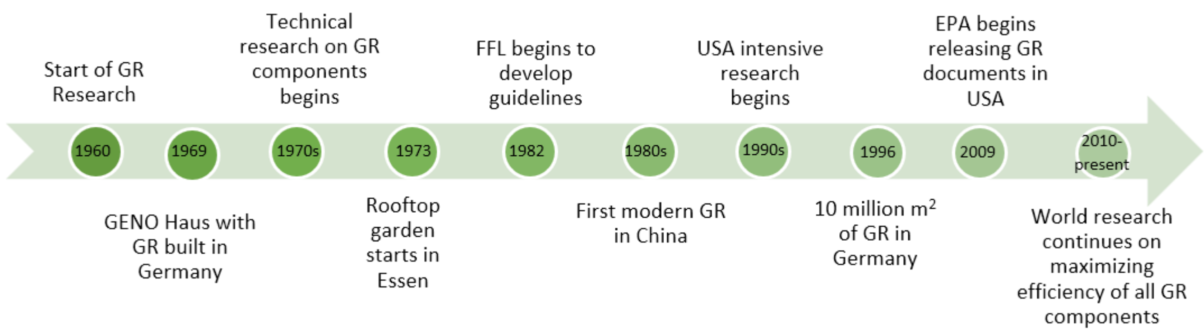


Figure 9:
Timeline of Green Roof Technology research and project construction in various countries, 1960-now. Based on Shafique et al. (2018).

Since the FFL was developed in 1975, they are by far the first organization to develop standardized guidelines and they have over 40 years of experience. German standards can be used as a backbone for advancing US policy (Philippi, 2002).

Switzerland

Similarly, Switzerland has had laws in place since 1991 that state that all new or renovated flat roofs that are not considered rooftop terraces must install GRs (Savarani, 2019). Because of Switzerland's regulations, 15% of roofs were transformed with vegetation by 2017, leading to annual energy savings of 4GW/yr (Besir & Cuce 2017). To put an image to this number: Switzerland saves 4 billion watts of energy a year which is equivalent to the power generated by over 3 million solar panels, or similarly, 364 wind turbines (*How Much Power Is 1 Gigawatt?*, n.d.). Basel, Switzerland's Green Rood Installation Subsidies Program also incentivized green roofs with additional governmental funds for one year in the 90's and one year in the 2000's.

Domestic Policy

Portland, OR

Portland, OR requires new buildings over 20,000 ft^2 to have their entire rooftop area be greened, excluding certain specific alternate uses for rooftop area, ie. community areas, solar panels or other sustainable energy structures (*Portland's EcoRoof Requirements*, n.d.). They also have specific regulations on which species need to be included (at least 50% evergreen) and how fast the roof needs to grow into 90% (within 2 years of installation). Because of Portland's policy, 70% of buildings are required to have GRs.

Denver, CO

In 2018, Denver, CO began requiring buildings over a certain size to have “reflective, light colored surfaces, and to also have either solar panels or GRs, achieve LEED gold status, purchase renewable energy, or pay a per square foot fee (Savarani, 2019).

New York City, NY

NY’s government has raised tax breaks for building owners who install green roofs in some areas by about 300%, from $5.23/sqft to $15/sqft, and recently decided to continue offering until 2024 (*Green Roof Legislation & Policy*, 2018). Additionally, in 2011, they included a grant program that offered funds for green infrastructure projects (Savarani, 2019).

A lot of governmental policies allow for the presence of either a green roof or other environmental infrastructure, i.e., solar panels. However, some eco roofs feature part green roof and part solar energy panels (Photovoltaic or PV panels) because they seem to work together. PV panels function best at cooler temperatures, and green roofs can cool the air around them through evapotranspiration (Vijayaraghavan, 2016). This means that green roofs paired with PV panels can provide more efficient energy savings than either mechanism on its own.

4. Synthesis and Conclusions

For future urban designs, efficient technologies are needed that support a growing population, while mitigating negative environmental consequences associated with urbanization. The present integrative literature evaluation indicates that green roofs combine multiple benefits, including public health and happiness, energy savings, better air quality, and reduced urban heat island effect.

The two major components of GR include living vegetation and the substrate that roots exist in. Both the substrate and the vegetation have carbon sequestration abilities, preventing CO_2 from being released into the atmosphere (Getter et al., 2009). Because around 30%-40% of all urban surfaces is rooftop (Besir & Cuce, 2018; Friedman, 2012), greening all urban roofs would have a noticeable impact on the local air quality, summertime UHIE, and could work towards improving global reduction of GHGs. GRs can have several other benefits including energy savings through building insulation, improving the visual landscape of a city, psychological wellbeing and physical wellbeing through incentives to exercise, community engagement, biodiversity conservation, and secondary economic improvement through eco-tourism, reduced produce transportation costs, and avoidance of habitat restoration expenses. Because of their economic appeal, projects can be pitched focusing on the client's personal economic savings as the main goal, while also allowing them to feel productive in improving the environment.

The future of green infrastructure has so much potential. Ecological projects like the animal bridges in Germany represent some of the most innovative ways to coexist with non-human co-inhabitants. These bridges give highly mobile and migratory species the ability to safely cross large highways that fragment natural habitats (Meeteren & Smit, 2015; Nuwer, 2012) (Figure 10).

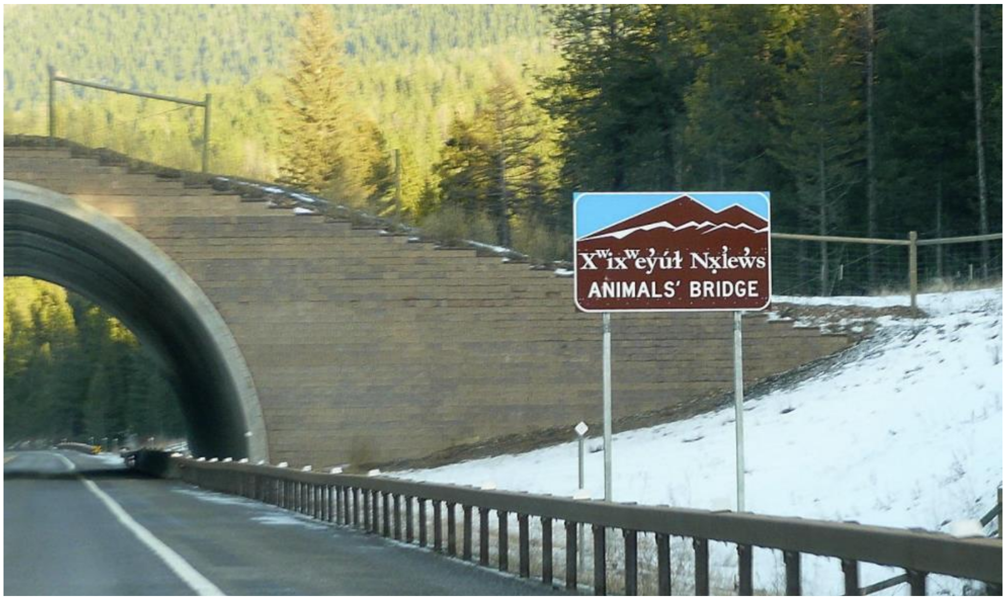


Figure 10:

Animal bridge near Evaro, Montana. Animals are provided with a safe passage over highways to avoid collision with cars and to travel between fragmented habitats. Credit: Wikimedia commons, Djembayz (2012).

Land needed for agriculture is becoming increasingly scarce as our population grows. Most of our agricultural land is used not to feed us but to feed livestock. Rooftop gardens have to potential to provide restaurants with “rooftop-to-table” services. At first, it may act as an exclusive dining experience aiding to the tourism industry, but as they become more prevalent, it can help reduce the cost of food by reducing transportation costs, trucking spillage, packaging, etc. (*FAO*, 2019; Qin & Horvath, 2022). Transforming rooftops into local farms can increase public involvement and social cohesion by providing volunteer harvesting and education opportunities, decreasing emissions due to crop transport, and developing healthier cities on their way to becoming environmentally sustainable (Harada & Whitlow, 2020). Figure 11 below shows the Umbrella House Garden in New York City, which serves as a way for residents to grow their own produce on their apartment building’s roof.

Figure 11:

Example of an intensive rooftop garden. This 820 sq foot garden is located in NYC built in 2012 and first grew produce in 2015 (“Umbrella House Garden,” 2015). Photo credit: Wikimedia Commons, Ru-Shin Shieh (2018).

Other related projects, like creative green architecture, have the potential to draw tourists, who may be seeking impressive architectural designs or connection with the natural environment while also providing downtown city exploration (Scerri et al., 2019; Straupe & Liepa, 2018). Tourism thus raises municipal funds to subsidize more projects like this (Scerri et al., 2019). Intensive greenery systems, like those designed by Stefano Boeri in Milan, are impressive combinations of art and environmental design, which draw people from all over the world to experience the site. He presents incredible directions for the future of green cities and drives the movement towards environmentally conscious urbanization (Figure 12).

Figure 12:

Twin greenery structures designed by Stefano Boeri in Milan, Italy. A beautiful combination of environmental design and creative architecture. The project was finished in 2014. ("Vertical Forest," 2014). Photo Credit: Wikimedia Commons, Thomas Ledl (2016).

Although this literature synthesis is meant to reiterate and present the benefits of green roofs, there is some discussion about their potential to drive gentrification and further separate socio-economic classes (Anguelovski et al., 2019). Climate injustice is a serious consideration in the development of greenery projects as people of color and migrant communities have historically contributed the least to climate change, yet are effected by it the most and have the least access to green space (Anguelovski et al., 2019). Green roofs, like all other environmental urban infrastructure, therefore, require further research and governmental subsidy to be implemented in all parts of a city, providing access and benefits to all ethnicities and people from all cultural backgrounds to mitigate future climate gentrification.

Acknowledgments

Many thanks go out to those who helped me in the Honors Program process: Dr. Roger Pielke Jr., Dr. Barbara Demmig-Adams, Dr. Rebecca Safran, and all my friends, family members, and peers who helped me in any way they could or were there for much needed support. Special thanks to my advisor Dr. Roger Pielke Jr., who coached me along the way, gave me weekly feedback, and was the reason why I was able to participate in the University of Colorado, EBIO Honors Program. Dr. Barbara Demmig-Adams also helped me so much with her guidance during our Honors Seminar meetings, last minute feedback, and her amazing attitude towards the Honors Program. Dr. Rebecca Safran has always been a mentor to me ever since I took her general biology classes as a freshman and has inspired me to pursue biology.

Thank you.

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