Elevating Urban Landscapes: How Green Roofs Enhance Biodiversity and Address Climate Change in California

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This Master’s Project

Elevating Urban Landscapes: How Green Roofs Enhance Biodiversity and Address Climate Change in California

by

Jeff Beaudoin

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Submitted: 

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Jeff Beaudoin, Date

Stephanie Siehr, Ph.D. Date
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<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>ASTM</td>
<td>American Society for Testing Materials</td>
</tr>
<tr>
<td>AR</td>
<td>Atmospheric River</td>
</tr>
<tr>
<td>CAM</td>
<td>Crassulacean acid metabolism</td>
</tr>
<tr>
<td>DACH</td>
<td>Germany, Austria, Switzerland</td>
</tr>
<tr>
<td>FLL</td>
<td>German Landscape Research, Development, and Construction Society</td>
</tr>
<tr>
<td>GR</td>
<td>Green Roofs</td>
</tr>
<tr>
<td>IPCC</td>
<td>Intergovernmental Panel on Climate Change</td>
</tr>
<tr>
<td>PV</td>
<td>Photovoltaic</td>
</tr>
<tr>
<td>UHI</td>
<td>Urban Heat Island Effect</td>
</tr>
<tr>
<td>WGIN</td>
<td>World Green Infrastructure Network</td>
</tr>
</tbody>
</table>
ABSTRACT

Green roofs are increasingly valued for mitigating the Urban Heat Island effect, providing thermal comfort amidst rising temperatures of climate change, enhancing hydrological properties, and improving urban biodiversity. In this report, I explore the environmental benefits and practical challenges of green roofs, with a specific focus on California. My study evaluates the effectiveness of green roofs in enhancing environmental sustainability using a weighted rating system. I categorize the benefits of green roofs into key areas: thermal performance, stormwater management, ecological support, mental health benefits, noise reduction, air quality improvement, and water quality enhancement. Green roofs have shown the potential for city-wide adoption, decreasing electricity demands by 25%. The implementation of green roofs comes with significant installation and maintenance costs, yet there are long-term economic gains, including increased durability of roofing materials and reduced energy costs due to their insulative properties. Moreover, innovative technologies such as modular systems and integrating green roofs with solar photovoltaics offer promising avenues for boosting their functionality and expanding adoption. This report found successful green roof implementation across different global regions, supported by proactive policies and community engagement, and gathered lessons for Mediterranean climates like those in California. My recommendations include establishing statewide California green roof policies to ensure consistent standards, equitable incentives, and widespread adoption. Also, to prioritize green roof development on commercial real estate due to cost-effectiveness while investing in educational campaigns to raise public awareness and encourage policy support. Lastly, the standardizing of training for skilled labor and development of guidelines for plant selection based on specific climate biomes, especially Mediterranean climates, to optimize the ecological and functional benefits of green roofs in tandem with integrating modular and bio-solar innovations.
I. INTRODUCTION

The IPCC predicts that by 2100, a significant portion of the global population - ranging from half to three-fourths - will be impacted by life-threatening heat and humidity. This issue will be particularly acute in urban areas, which are already home to over half of the world's population and will see a further increase of 2.5 billion people by 2050. Those living in cities will be exposed to double the level of heat stress compared to their rural counterparts, and many urban areas will experience almost six months of extreme temperatures. As global temperatures rise, the number of cities experiencing 150 or more days a year of temperatures exceeding 35°C will increase from 67 to 197 (Dodman et al., 2022).

Global population growth has fueled a surge of new construction projects, with the number of megacities projected to reach 43 by 2030. This increase correlates to a 3% increase in greenhouse gas emissions (Abass et al., 2020). In 2021 alone, the construction industry's value skyrocketed to approximately $7.3 trillion, with projections foreseeing a substantial increase of about $14.41 trillion by 2030. This sector alone accounts for nearly 40% of global resource consumption, 28% of which is from solely powering the building, generates 40% of waste worldwide, and shoulders almost 40% of annual CO₂ emissions. This underscores the urgent need to integrate sustainability practices within the construction domain to mitigate resource depletion and waste generation (Tighnavard Balasbaneh et al., 2024).

Given that building roof surfaces cover 20–25% of urban areas, they present an opportunity to reduce surface and air temperatures in cities effectively (Abass et al., 2020). By embracing climate-conscious and energy-efficient urban designs, cities can effectively confront issues of urban sustainability and global climate change. In this context, the adoption of green roof construction has gained significant traction as a potent design strategy owing to its myriad environmental benefits (Tighnavard Balasbaneh et al., 2024).

The adoption of green roofs aligns with organizational sustainability objectives by bolstering energy conservation through building insulation and the mitigation of thermal heat gain. Crucially, the reduction in building energy consumption facilitated by green roofs can substantially decrease CO₂ emissions, thereby mitigating pollution and curbing energy usage. Furthermore, green roofs play a pivotal role in mitigating the heat island effect and facilitating natural water dynamics modulation (Tighnavard Balasbaneh et al., 2024).
1.1. Green Roofs

A GR is a human-made structure installed on the roof of a building (Jim, 2017). The roof is partially or entirely covered with vegetation and a growth medium (substrate), which serves both as a functional roof and a habitat for vegetation (Yu et al., 2017). GRs are made up of several components, including plants, a substrate for nutrient supply, a water system to support root growth, and a drainage layer to manage excess water, as seen in Figure 1. These components create an environment that is conducive to plant growth (Abass et al., 2020). GRs may also be called “living roofs”, “eco-roofs”, “vegetated roofs”, and “rooftop gardens”.

![Diagram of Green Roof Components](image)

**Figure 1: Components of a green roof (Source: Le Trung et al., 2018).**

GRs are categorized into four types: intensive, semi-intensive, single-course extensive, and multi-course extensive. Intensive green roofs have a substrate thickness of over 12 inches and accommodate diverse plant life, including trees and shrubs. They require significant maintenance, irrigation, and structural support due to their weight. Semi-intensive green roofs have a substrate thickness of 6-12 inches and contain smaller plants and shrubs, requiring regular maintenance. Intensive GRs require a higher capital investment than extensive GRs. Single-course extensive roofs have a substrate thickness of 3-4 inches, typically featuring sedum vegetation and requiring minimal irrigation and maintenance. Multi-course extensive roofs, with a substrate thickness of 4-6 inches, are lightweight and commonly used in the USA,
offering low maintenance and capital costs (Shafique et al., 2018). Figure 2 visualizes the difference between extensive and intensive GRs, while Table 1 sums up the characteristics and differences.

![Figure 2: High-level overview of the different depths and vegetation support between extensive and intensive GRs (Source: The Purple Roof System, 2019)](image)

<table>
<thead>
<tr>
<th>Growing Conditions</th>
<th>Extensive &amp; Multi-Course GR</th>
<th>Intensive &amp; Semi-Intensive GR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Substrate</td>
<td>3-6 inches</td>
<td>6-48 inches</td>
</tr>
<tr>
<td>Irrigation</td>
<td>Minimal</td>
<td>Significant</td>
</tr>
<tr>
<td>Upkeep</td>
<td>Minimal</td>
<td>Significant</td>
</tr>
</tbody>
</table>

| Structural Intensity | Weight | Structural Engineer | Ideal Scale | |
|----------------------|--------|--------------------|-------------|
| Lightweight          | Not Required | Required | Large Areas | Smaller Areas |

<table>
<thead>
<tr>
<th>Vegetation</th>
<th>Extensive &amp; Multi-Course GR</th>
<th>Intensive &amp; Semi-Intensive GR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plant Support</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Range of Species</td>
<td>Limited</td>
<td>Diverse</td>
</tr>
<tr>
<td>Support for Trees</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>

The substrate, or growth medium, is essential to the vegetation on GRs. The ideal substrate proportions vary based on the climate of the region, vegetation type, and maintenance support. For example, lightweight substrates with low organic content may require extra watering and supplements to support plant growth, while thicker substrates retain more water, reducing watering requirements but adding...
significant weight. Most available substrates adhere to either the American Society for Testing Materials (ASTM) or German Landscape Research, Development, and Construction Society (FLL) guidelines. Optimal substrates have a pH value closest to 7.0, reducing the need for additional soil amendments. Electric conductivity (EC) and total dissolved solids (TDS) are two other important factors to consider when selecting GR substrates (Kader et al., 2022).

1.2. Problem Statement

According to recently published 2020 Census data, California has the highest urban population density and urbanization in the United States. California's urban population density is 4,790 per square mile, higher than the second-highest New York's 4,645. Impressively, 94.2% of California residents live in urban areas, narrowly surpassing Nevada's 94.1%, the second-highest percentage. California contains 70 of the 100 densest urban areas in the nation and 35 out of the 43 urban areas (81%) with population densities exceeding 5,000 per square mile. It also has the three densest urban areas with more than 500,000 population (Cox, 2023). Therefore, California requires environmental solutions tailored to dense urban areas.

California has also seen a significant increase in the cost of electricity. Costs rose 78% from 2013 to 2021, followed by an additional 16% in 2022 and 14% in 2023. They are scheduled to continue to increase 17.6% in 2024, 10.5% in 2025, 9.2% in 2026, and 7.7% in 2027. The California Public Utilities Commission (CPUC) reports that the average electricity cost per month has increased exponentially since 2014. Three major electricity providers across the state have corroborated the Commission’s findings (Baker Home Energy, 2024). Based on this trend, California is going to require solutions that promote thermal efficiency and energy reduction in buildings.

In addition to the urbanization and rising cost of energy, California is already experiencing the effects of climate change, with summer temperatures 1.8°C higher than 1896. These effects have a significant impact on human health. In 2006, a heat wave caused over 600 deaths, 16,000 emergency department visits, and nearly $5.4 billion in damages. Studies show that by the 2090s, the risk of mortality could increase ten-fold for those aged 65 and above due to climate change. If global greenhouse gas emissions continue at their current rate, the state's average temperature is expected to rise by over 2°Fahrenheit by 2040, over 4°Fahrenheit by 2070, and over 6°Fahrenheit by 2100. The most significant impacts of this warming will be felt during short periods of heat events, such as days exceeding 106.6 degrees Fahrenheit (Cayan et al., 2024). Recent research has shown that some heat waves have become more humid, leading
to warmer nighttime temperatures - a pattern consistent with climate change projections. Additionally, coastal areas that were previously cooler are now experiencing stronger mid-summer heat waves.

In California, the annual water supply is mainly determined by the presence or absence of a few large winter storms. These storms come in the form of long, narrow bands of water vapor known as atmospheric rivers (ARs). While ARs are the source of the West Coast's heaviest rains and snow, they also pose a significant risk of flooding, causing over $1 billion in damages each year. As with hurricanes, the damage caused by atmospheric rivers increases with their strength, and scientists expect their intensity to increase further with global warming trends (Cayan et al., 2024). Cities require a solution that mitigates stormwater load on the sewer system during these periods of intense rain.

Climate change is causing habitat degradation in California, impacting diverse ecosystems. Rising temperatures and prolonged droughts are altering landscapes, leading to habitat loss for many species. This affects both wildlife and human communities that rely on these ecosystems for resources and recreation. Insects and birds, crucial components of the state's biodiversity, are particularly affected. Insects are struggling to find suitable environments due to climate change-induced alterations, while birds are facing challenges such as habitat destruction and reduced breeding success. Conservation efforts are urgently needed to protect these crucial species and their habitats.

Effective January 1st, 2017, San Francisco became the first U.S. city to require solar or GRs on 15-30% of new constructions. However, this mandate allows for an ‘opt-out’ fee, essentially negating the intent. Despite this local progress, no comprehensive state or federal law currently encourages the adoption of GRs (San Francisco Planning, 2024).

1.3 Research Questions and Design

This study aims to evaluate the feasibility and benefits of implementing large-scale GRs in California and identify the factors that hinder their adoption.

With the above problem in mind, my main question is:

**Main Question**

*How can green roofs be utilized more widely for environmental benefit in California?*

- **Sub-Question 1**
What are the environmental benefits of green roofs and under what conditions are they significant?

Objective: In evaluating the advantages, it is crucial to determine which are most effective in promoting environmental sustainability. I will employ a weighted rating system that properly assesses each benefit to accomplish this.

- **Sub-Question 2**
  What are the challenges and opportunities of green roofs, and under what conditions are they significant?

Objective: I want to understand the main factors slowing and preventing the widespread adoption of GRs. In this section, I will examine those factors and identify opportunities for mitigation.

- **Sub-Question 3**
  What technological developments and innovations for green roofs enhance the benefits and address challenges?

Objective: I assess the most pertinent technologies and innovations that could promote wider adoption of GRs.

- **Sub-Question 4**
  Where are green roofs being utilized successfully, and why?

Objective: I research international and domestic GR policies, market trends, and citizen engagement to understand why other countries are more effective in promoting adoption.

- **Sub-Question 5**
  What are the lessons learned from and for California?

Objective: I analyze the best practices for GRS in Mediterranean climates and examine successful green roof implementations in California cities.

II. LITERATURE REVIEW

2.1 Historical Development and Geographical Distribution of Green Roof Studies

GR research has witnessed significant developments since the late 1960s, with a notable increase in scholarly publications beginning in 1992. By the early 1990s, the field had expanded rapidly, culminating in 74 studies by 2012, predominantly from the USA and the European Union, which collectively contributed about two-thirds of all publications. Asian countries accounted for around 20%, with minimal input from African nations, highlighting a geographical disparity in GR research (Blank et al., 2013).
2.2 Shift in Research Focus and Interdisciplinary Contributions

Over time, the focus of GR research has evolved from basic architectural designs to more complex ecological concerns, as detailed by Blank et al. (2013). This shift has been driven by increased global environmental awareness and the recognized potential of GRs to address such issues. Notably, studies have emphasized the ecological benefits of GRs, such as promoting local biodiversity, mitigating urban heat islands (Prado & Ferreira, 2005), and managing stormwater runoff (Stovin, 2010).

The role of GRs in supporting diverse biotic communities, including invertebrates (Brenneisen, 2006; Kadas, 2006) and bird species (Baumann, 2006), has been well-established. These ecosystems have been studied from the perspective of reconciliation ecology, with contributions like Francis and Lorimer (2011) discussing the importance of varied architectural designs to maximize biodiversity potential. Meaning how can buildings aid in increasing biodiversity as opposed to hindering it?

2.3 Historical Context and Evolutionary Aspects

GR technology traces back to traditional sod roofs in Northern Scandinavia (van Hoof & van Dijken, 2008), evolving through the 20th century into sophisticated designs across Europe and North America (Dvorak & Volder, 2010). Studies like those by Boivin et al. (2001) and Lundholm et al. (2010) explore factors critical for the performance of GRs, such as soil depth, and their implications for plant survival, aesthetics, energy savings, and stormwater management.

2.4 Broadening Research Themes and Future Directions

Recent decades have seen GR research broaden to include thermal performance, hydrology, energy impacts, and ecosystem services. Noteworthy contributions include Sailor (2008), Peng and Jim (2013), and Berardi et al. (2014), who have explored a vast range of topics from thermal dynamics to policy formulation. Research has particularly focused on the interactions between water and plant systems, examining moisture retention, drought resilience, water quality enhancement, and thermal regulation (Berndtsson et al., 2010; Castleton et al., 2010; Vijayaraghavan and Raja, 2014).

Further studies have emphasized creating biodiverse habitats and modeling energy use to enhance both ecological and energy efficiencies of GRs in urban landscapes (Lundholm et al., 2010; Nagase and Dunnett, 2012; Rowe et al., 2012). Additionally, the mitigation of UHIs and the role of GRs in reducing building energy consumption have been further areas of study (Takebayashi and Moriyama, 2007; Santamouris, 2014; Akbari et al., 2016).
Recent contributions from North America, Europe, Asia, and Australia (Xie et al., 2024) underscore the essential functions of GRs in cooling urban environments, augmenting stormwater capture, and enhancing urban biodiversity (Sadineni et al., 2011; Mentens et al., 2006; Oberndorfer et al., 2007; Norton et al., 2015). The intersection of GRs with renewable energy technologies represents a burgeoning area of research, with ongoing studies into the synergistic benefits of integrating GRs with building-applied photovoltaics (solar panels)(Manso et al., 2021; Liu et al., 2023).

2.5 Selection of Vegetation Based on Climate and Resource Availability

Research into the ideal plant species and planting methods for GRs suggests localized solutions tailored to the environment and design aspirations. One study by Pianella et al. (2017) suggests three species that can withstand thermal radiation common in some geographies, while others suggest using seeds and plant remains (Nagase & Dunnett (2010); Lundholm et al. (2010). These studies demonstrate a flexible approach to vegetation selection based on environmental adaptability and design aspirations.

2.6 Economic Evaluation Techniques in Green Roof Implementation

The literature extensively covers the methodologies for the economic evaluation of GRs, including both tangible and intangible benefits. Sproul et al. (2014), Teotónio et al. (2018), and Clark et al. (2008) attempt to quantify the energy savings, air quality improvements, stormwater management, and roof longevity driven by GRs. Many of these papers tried to utilize a net present value for these benefits in order to establish a total cost for GRs. However, challenges remain in valuing intangible benefits such as well-being and noise reduction, as explored by Bertram & Rehdanz (2015) and Van Renterghem & Botteldooren (2011).

Further expanding on economic evaluations, the literature includes discussions on Cost-Benefit Analysis by Liu et al. (2014), Life-Cycle Assessment by Maiolo et al. (2018), Cost-Effectiveness by Kousky (2014), Multicriteria Decision Analysis by Alves et al. (2018), and Energy Analysis by He et al. (2020). Clark et al. (2008) These studies provide a range of tools for assessing the economic viability and broader impact of GRs, supporting decision-making processes with a blend of quantitative and qualitative analyses.

2.7 Vegetation Impact on Environmental Performance

Significant research has also been conducted on the environmental impacts of selected vegetation types on GRs. Studies by Clark et al. (2008) and Speak et al. (2013) delve into how different plant forms and
taxa contribute to air pollution reduction through physical trapping and absorption. The thermal and water retention capabilities of specific plants are further discussed in research by MacIvor et al. (2011) and Foustalieraki et al. (2017), illustrating how plant selection can enhance the ecological and functional performance of green roofs.

2.8 Biodiversity and Sustainability Through Native Planting
The role of native plants in enhancing biodiversity and sustainability on GRs is emphasized in studies by Brenneisen (2006) and Mihalakakou et al. (2023). These sources advocate for the conservation of local plant communities and wildlife, highlighting the ecological benefits of integrating native vegetation into urban greening projects.

2.9 Technological Research
Various experimental and modeling studies have assessed the performance of bio-solar roofs relative to conventional solar setups, yielding mixed results. Pilot-scale experiments by Alshayeb and Chang (2018) found a 1.4% increase in energy production for model bio-solar roofs, while Chemisana and Lamnatou (2014) noted increases of 1.29% and 3.33% in energy production from five-day pilot-scale experiments on Gazania sp. and sedum plots, respectively. Despite numerous pilot-scale studies supporting these findings, there is a notable gap in the employment of commercial or full-scale GRs for extended energy assessments. However, one of the limited full-scale studies on bio-solar roofs by Fleck et al. (2022) noted a prior study where only a 2% performance increase compared to a conventional system occupying the same roof space.

III. ENVIRONMENTAL BENEFITS ASSESSMENT

Addressing Sub-Question 1: What are the environmental benefits of green roofs, and under what conditions are they significant?

In this section, I will comprehensively analyze and assess the advantages of environmentally sustainable roofing systems. The objective is to examine the implications & importance of these advantages.

GRs present benefits across economic, social, and environmental dimensions. These include enhanced stormwater management, decreased energy demands, alleviation of urban heat island effects improved air
and water quality, noise attenuation, extended durability of roof structures, and expansion of green spaces within urban settings. Recognizing these benefits, numerous nations and municipalities have enacted policies to encourage or mandate the adoption of green roofs (Vijayaraghavan, 2016).

3.1 Stormwater Management

Urbanization in developed countries is increasing rapidly, replacing croplands, grasslands, and forests with impervious surfaces, thus exacerbating stormwater runoff, groundwater recharge reduction, and stream erosion. GRs are a promising, practical, and cost-effective mitigating strategy for the impacts of urbanization on stormwater management. Specifically, GRs can substantially decrease the peak runoff during rainfall by retaining a portion of the rainfall within the GR, and slowly releasing excess water stored in the substrate's pores over time, called evapotranspiration. Their impact expands with targeted plant selection. Figure 2 shows the basic concept of a GR on an urban building and its impact during a storm event.

The United States has 772 communities with combined sewer and stormwater systems (Rowe, 2011). In these areas, heavy rain events can lead to Combined Sewage Overflow (CSO) incidents when runoff volume surpasses the stormwater system's capacity, where untreated sewage is discharged into rivers. Even in urban settings with separate stormwater management systems, stormwater contamination occurs when pollutants like oil, heavy metals, salts, pesticides, and animal wastes are washed into waterways. GRs play a crucial role in mitigating these issues by retaining stormwater, thereby reducing the likelihood of CSO events in combined systems and reducing the costs of large separate stormwater systems (Rowe, 2011).
3.1.1 Runoff Reduction and Retention

In 2006, Mentens et al. conducted a study in Brussels, Belgium to investigate the impact of green roofs on reducing runoff. The study found that traditional non-green roofs release up to 91% runoff, while intensive GRs can reduce runoff to as low as 15% (Figure 2). Variables such as roof type, number of layers, substrate depth, slope angle, and annual precipitation significantly affect runoff reduction, while roof age and length have no significant correlation. Figure 3 clearly shows the substantial difference in

Figure 3: A simplified example of drainage for an urban building (Source: City of Melbourne (2024))

Green roofs can reduce stormwater volumes by up to 85%

Plants soak up water and release it as clean air

Rainwater is retained in the soil and drainage layer

Excess water flows to drain
roof type runoff reduction. We can see clearly that intensive roofs vastly outperform traditional roofs.

![Box plot of annual runoff for various roof types](image)

**Figure 4: Annual runoff for various roof types as a percentage of total annual rainfall (Source: Author, based on Mentens et al. (2006))**

The research suggests that using extensive GRs on only 10% of roofs within a moderately green urban environment, such as Brussels, could reduce annual runoff by 2.7%. The impact would be larger in denser areas compared to suburban regions and using intensive GRs compared to extensive GRs. However, increasing the substrate layer's depth may lead to additional maintenance costs, including watering during dry periods and structural adjustments to support the weight.

The layers of vegetation and substrate on a GR can store a significant amount of rainwater and increase evapotranspiration. The scale of the reduction in runoff varies depending on factors, like the type of vegetation, thickness of the substrate, drainage material, rainfall intensity, and slope of the green roof.
The substrate of a GR is the most crucial aspect. A study conducted by Mickovski et al. (2013) compared the performance of three types of vegetation (sedum, long and short grass) for surface runoff during different rainfall events, and sedum was found to produce a more significant surface runoff volume than other vegetation types (Shafique et al., 2018).

Numerous studies have explored the hydrological performance of GRs, indicating that they are effective in mitigating stormwater runoff. Retention rates from GRs range from 55% to 88% (Shafique et al., 2018). Please note that the percentages when discussing retention vs. reduction are flipped. A retention value in this case is saying 55% to 85% of a specific rainfall event is either completely contained within the GR or time delayed. Time delay refers to slowing down the rain as it works its way through the plants, substrate, and other various layers before entering the sewer system. For instance, Bengtsson (2005) studied 3cm thick sedum-moss roofs for the runoff analysis and found that the GRs can reduce the runoff and control it in urban areas. Similarly, Carter & Jackson (2007) indicated that GR runoff retention is higher compared to conventional roof runoff retention, and peak outflows also reduce with the use of GRs. Zhang et al. (2015) examined the stormwater retention capacity by using GRs in Chongqing, China, and found that they retained 77.2% of the runoff at an average rate, suggesting their usefulness for stormwater management in urban areas. A similar result was found by Speak et al. (2013) when they conducted an experiment on an aged intensive GR in Manchester, UK. They analyzed 69 rainfall events and found that GRs retained 65.7% of the runoff. Other researchers also noted uniform results for water retention using GRs (Shafique et al., 2018).

One study conducted by Razzaghmanesh & Beecham (2014) revealed that extensive and intensive GRs retain significant amounts of stormwater runoff, with average retention rates of 74.0% and 88.6%, respectively. Moreover, GRs have the ability to delay runoff, as extensive roofs delay runoff for approximately 3 hours on average, while intensive roofs can delay runoff for up to 17 hours, indicating their effectiveness in reducing peak runoff flows. The study emphasizes the importance of proper design considerations in green roof retention performance, taking into account factors such as rainfall duration, depth, intensity, and antecedent dry weather period. Figure 5 shows the time delay effectiveness of a GR for a storm event.
Another experiment by Villarreal and Bengtsson (2005) tested the retention of consistent precipitation levels. They found that runoff initiation typically occurred after 6 to 12 mm of rainfall. Retention was largely influenced by rainfall intensity and the angle of the green roof, with lower intensity and shallower slopes resulting in higher retention. In extremely dry scenarios, a horizontal GR could retain up to 15 mm of rain, while sloped roofs achieved a maximum retention of 10 mm.

3.1.2 What Plant Types are Most Effective for Runoff Reduction?

GR vegetation plays a crucial role in water retention and transpiration capacity (Razzaghmanesh & Beecham, 2014). Taller plants intercept more rain due to their larger surface area, while plants with dense fibrous roots capture less water runoff from GRs, reducing the growing medium’s porosity and water retention volume (Clark, 1937; MacIvor & Lundholm, 2011). There is no single consensus on specific plant species to optimize water retention – all plants will achieve this to some effect. But there are two consistent guidelines: to consider native plants and to include a diversity of plants with complementary systems. Some studies promote the use of sedum specifically in dry climates.

Plants are classified into three types based on their photosynthetic mechanism: C3 (majority), C4 (grasses), and Crassulacean acid metabolism (CAM) (succulents) (Nagase & Dunnett, 2012). C4 plants exhibit high transpiration rates and faster growth compared to C3 and CAM plants, while CAM plants have higher water-use efficiency due to closed stomata during the day, reducing transpirational water loss (Gravatt & Martin, 1992). It was previously thought that C3 and C4 plants are more effective in reducing
water runoff from green roofs than CAM plants due to their higher water usage (Nagase & Dunnett, 2012). However, sedum, a CAM plant, has become the leading plant used for stormwater reduction due to its water-storing leaves (drought tolerance) and ability to act as an effective ground cover. Table 2 provides an overview of the three plant categories and their characteristics.

Sedum facilitates neighboring plant growth during water stress but acts as a competitor when water is abundant (Butler & Orians, 2011). Certain mixtures of GR systems outperform the best monocultures in terms of water capture and evapotranspiration (Lundholm et al., 2010). The impact of vegetation composition on water retention and release from GR requires further investigation. (Nagase & Dunnett, 2012).

Table 2: Characteristics of C3, C4, and CAM plants (Source: Author, based on BYJU’s, 2024)

<table>
<thead>
<tr>
<th></th>
<th>C3</th>
<th>C4</th>
<th>CAM</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Environment</strong></td>
<td>Cool and wet</td>
<td>Tropical and dry</td>
<td>Semi-dry</td>
</tr>
<tr>
<td><strong>% of Plants</strong></td>
<td>95%</td>
<td>5%</td>
<td>5%-10%</td>
</tr>
<tr>
<td><strong>Examples</strong></td>
<td>• Rice</td>
<td>• Maize</td>
<td>• Agave</td>
</tr>
<tr>
<td></td>
<td>• Wheat</td>
<td>• Sugarcane</td>
<td>• Cacti</td>
</tr>
<tr>
<td></td>
<td>• Oats</td>
<td>• Pearl millet</td>
<td>• Pineapple</td>
</tr>
<tr>
<td></td>
<td>• Barley</td>
<td>• Sorghum</td>
<td>• Quillwort</td>
</tr>
<tr>
<td></td>
<td>• Cotton</td>
<td>• Indiana grass</td>
<td>• Jade</td>
</tr>
<tr>
<td></td>
<td>• Peanuts</td>
<td>• Big Bluestem</td>
<td>• Bryophyllum</td>
</tr>
<tr>
<td></td>
<td>• Tobacco</td>
<td>• Bermudagrass</td>
<td>• Sedum</td>
</tr>
<tr>
<td></td>
<td>• Sugar beets</td>
<td></td>
<td>• Spanish Moss</td>
</tr>
<tr>
<td></td>
<td>• Soybeans</td>
<td></td>
<td>• Orchids</td>
</tr>
<tr>
<td></td>
<td>• Spinach</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Temperature for photosynthesis</strong></td>
<td>Low (59°F – 77°F)</td>
<td>Medium (86°F - 104°F)</td>
<td>High (104°F &gt;)</td>
</tr>
<tr>
<td><strong>Photosynthesis</strong></td>
<td>Only when stomata are open during the day</td>
<td>Leaf anatomy allows CO2 to concentrate in ‘bundle sheath’ cells around Rubisco (enzyme)</td>
<td>Photosynthesize during the day with closed stomata and exchange CO2 at night</td>
</tr>
</tbody>
</table>
Diversity in plant species and structural types may lead to a reduction in water runoff. (Rixen & Mulder, 2005) Species with contrasting growth forms utilize soil water differently, enabling differential exploitation of the soil profile (Lamont & Bergl, 1991).

Plant structural attributes play a pivotal role in rainwater interception, with shorter plants shedding more runoff and taller ones intercepting and retaining more. Additionally, root growth contributes to water capture in the substrate. However, studies suggest that the water use efficiency of plants, particularly evapotranspiration rates, may impact runoff. Further research is warranted to explore the impact of plant species mixtures on runoff and to conduct experiments under field conditions over both short and long terms. Ultimately, grasses and forbs with tall heights, large diameters, and substantial biomass are recommended for reducing water runoff in GR installations (Nagase & Dunnett, 2012).

3.2 Water Quality Enhancement

Beyond their role in water retention and runoff management, GRs contribute to enhancing water quality (Shafique et al., 2018). The composition of the substrate and vegetation layers in GRs is pivotal for absorbing pollutants from rainwater. Various factors, including the type of plant, substrate composition, rainfall intensity, local environmental conditions, GR type and age, drainage layer type, fertilizer composition, and the presence of organic material in the substrate, collectively determine the effectiveness of GRs in improving runoff water quality (Shafique et al., 2018).

The influence of plants and growing substrates on runoff quality, whether they filter pollutants or introduce additional contaminants, such as heavy metals and nutrients, remains a subject of debate. Berndtsson et al. (2006) initiated a series of studies to determine whether GRs act as sources or sinks of pollutants and how the age of such roofs affects runoff quality. Berndtsson compared runoff quality from green roofs with that from non-vegetated ones in the study areas, investigating various metals and nutrients, including Cd, Cr, Cu, Fe, K, Mn, Pb, and Zn. Figure 6 is an illustrated example of metals in a GR substrate.
Figure 6: Illustration of metals existing in the substrate (Source: Abuseif, 2023)

Findings reveal that, except for nitrogen, GRs generally act as sources of contaminants. Though metal concentrations are lower than typical urban runoff, some reach levels comparable to moderately polluted natural water bodies. Nitrate is retained, while most GR except the oldest ones, contribute phosphate to runoff. Maintenance of vegetation systems must be carefully managed to prevent storm-water contamination, avoiding easily soluble fertilizers (Berndtsson et al., 2006). Teemusk and Mander (2009) conducted a study in Estonia, which found that GRs reduce nitrogen levels in runoff. It should be noted that this is one study in 2006.

Changes in physicochemical parameters, such as pH, can influence heavy metal adsorption, potentially causing their release into storm runoff. Evapotranspiration can cause water-soluble substances to precipitate within GRs, reducing pollution loads, but subsequent rainfall may release them. Fertilization during construction and every few years is necessary to maintain dense plant cover, but easily soluble fertilizers exacerbate water quality issues. Controlled-release fertilizers offer a more sustainable alternative (Berndtsson et al., 2006). Furthermore, diverse GR communities may reduce the need for fertilizer, which can contribute to nitrogen pollution in urban areas (Cook-Patton & Bauerle, 2012).
Studies from Germany indicate nutrient and heavy metal removal by GRs, suggesting plants retain or take up contaminants. Retention rates for heavy metals depend on water retention capability. The first flush effect - initially, a broad spectrum of pollutants exhibits higher concentrations in the first runoff, gradually decreasing as the rainfall continues, observed in urban runoff, also occurs in GR runoff, possibly due to drainage material. While rainwater generally contains fewer contaminants than GR runoff, overall runoff quality regarding metals is good (Berndtsson et al., 2006).

Substrate research has risen in the past decade, but I found it important to note the complexity of this issue. With so many factors in play to determine the effectiveness of GRs on water quality, it is reasonable to assume that best practices will not always be adhered to. GR improvement for water quality has vast potential but is less consistent in its environmental benefit than others noted in this section.

### 3.3 Air Quality

In urban settings, high levels of pollutants can create unhealthy conditions and significant health risks for residents, as Yang et al. (2008) highlighted. The American Lung Association's research has found that even a small increase of 10 parts per billion (ppb) in ozone (O₃) levels can result in over 3700 premature deaths annually in the United States. Similarly, the World Health Organization estimates that urban air pollution in developing nations causes over 1 million premature deaths globally each year. As the urban population is projected to grow from 3.3 billion in 2008 to 5 billion by 2030, vulnerable groups such as children and the elderly will be disproportionately affected (Yang et al., 2008). Conventional methods for mitigating air pollution typically address the sources of pollutants, with the goal of minimizing the emission of new contaminants. Although effective in reducing the release of additional pollutants, this approach does not address the problem of pollutants that are already present in the atmosphere (Yang et al., 2008). GRs offer a promising solution by capturing harmful fine dust particles from the air, providing relief to residents in densely populated urban areas where airborne particulate matter often compromises environmental quality and human well-being (Shafique et al., 2018).

Urban vegetation is a promising tool for mitigating the impact of air pollutants in densely populated areas. Their surface area and rough texture, provided by branches, twigs, and foliage, make them an effective sink for air pollutants, facilitating dry deposition processes. Furthermore, vegetation contributes indirectly to pollution reduction by modifying microclimates. By providing shade, plants can lower indoor air temperatures (as noted in Section 4.4), which, in turn, reduces the energy consumption required to power air conditioning systems, leading to reduced emissions from power plants. Additionally, vegetation plays a crucial role in reducing ambient air temperatures by changing the albedos of urban surfaces and
facilitating evapotranspiration cooling. This reduction in ambient temperature can also slow down photochemical reactions, resulting in fewer secondary air pollutants, such as ozone (Yang et al., 2008).

Studies support the potential of trees to significantly reduce air pollution in urban areas (Yang et al., 2008). Nowak et al. (2006) estimated that urban trees in the United States remove approximately 711,000 metric tons of pollutants annually. These findings prompted the EPA to include tree planting as a state implementation strategy for improving air quality in 2004 (Yang et al., 2008). However, planting trees in densely populated cities can be challenging. For instance, in New York City, impervious areas constitute as much as 64% of the land, and in districts like Mid-Manhattan, it can reach up to 94%. Green roofs offer a solution to this challenge by utilizing rooftops, which typically constitute 40–50% of the impervious area in a city (different than the urban area statistic mentioned in the introduction) (Yang et al., 2008).

In 2008, Yang et al. conducted a study in Chicago to evaluate the effectiveness of GRs in removing air pollutants. The study utilized a dry deposition model to quantify the extent of air pollution removal by GRs. The results showed that 19.8 hectares of GRs removed a total of 1675 kilograms of air pollutants in one year. Ozone (O₃) comprised 52% of the total, followed by nitrogen dioxide (NO₂) at 27%, particulate matter (PM10) at 14%, and sulfur dioxide (SO₂) at 7%. The highest removal of air pollutants was observed in May, while the lowest was observed in February. Each hectare of green roof removed 85 kilograms of pollutants annually. The study also estimated that if all rooftops in Chicago were covered with intensive GRs, the total amount of pollutants removed would increase to approximately 2046.89 metric tons. Despite the initial costs involved in installing GRs, the study suggests that their long-term environmental benefits could justify the investment (Yang et al., 2008).

GRs have been proven to be effective in mitigating air pollutants. However, the diversity of species on GRs can potentially optimize their capacity to mitigate such pollutants. Research indicates that tall herbaceous plants are more effective at removing ozone, nitrogen dioxide (NO₂), sulfur dioxide (SO₂), and small particulates compared to short grasses. Thus, increasing the biomass on GRs through efficient resource utilization could enhance pollution removal (Cook-Patton & Bauerle, 2012).

Different species exhibit variations in nutrient absorption methods and timing, suggesting that diverse GR communities might collectively absorb more nutrient pollution than monocultures. Studies comparing various GR communities, such as prairie, algal, and seaweed, have shown higher nitrogen uptake in diverse mixtures than in monocultures. However, this pattern needs empirical validation.
To understand the impact of diversity on GRs’ capacity to mitigate air pollutants, future research should explore how different plant species differ in pollutant uptake and how pollutant absorption rates change in diverse mixtures. The total uptake of pollutants could either be additive or non-additive, depending on the collective absorption by a mixture aligning with the sum of each individual species’ uptake. It is essential to note that GRs have the potential to mitigate various pollutants from the air and water, and the effect of diversity may vary depending on the type of pollutant. For example, different nitrogenous compounds have distinct chemical forms, impacting uptake based on species presence and nitrogen preference. In contrast, carbon sequestration primarily depends on plant biomass (Cook-Patton & Bauerle, 2012).

Several studies have been conducted in China to explore the benefits of GRs. Shafique et al. (2018) discussed these studies and revealed that a 1000 m² GR can capture approximately 160–220 kg of dust per year, significantly enhancing the local environment. Additionally, research conducted in a city found that GRs reduced dust deposition in the city by 100 mg/m². Plant species possess unique abilities to capture dust, attributed to variations in leaf properties and canopy structure.

Deciduous shrubs exhibit the highest capability for dust particle absorption, whereas herbs demonstrate the lowest. Trees are highly effective in capturing airborne dust particles and have been shown to possess a greater capacity to mitigate air pollutants. In Zhengzhou, China, a study highlighted that tree species accounted for 87.0% of airborne dust capture, followed by shrubs at 11.3% and lawns at 1.7% (Shafique et al., 2018).

Similar to their effect on water quality, many factors can play into GRs’ effectiveness on air quality. When best practices, primarily consisting of large plant growth, are adhered to, the positive effects can be far-reaching. This benefit, along with water, depends on scalability. The more GRs exist in an urban area, the more pronounced the effect. As buy-in on GRs continues to grow and increase adoption rates (Section 6), GRs' effect on air quality will become more pronounced.

3.4 Thermal Effects
In recent years, California has experienced a significant hike in electric rates, with a staggering 78% increase from 2013 to 2021 and projections for continued escalation up until 2027. This surge in energy expenditure coincides with the escalating temperatures caused by climate change, resulting in more intense and humid heat waves across the state. Since 1896, summer temperatures have increased by approximately 3°F, a trend that is expected to persist, with an anticipated rise of over 6°F by 2100. This
temperature rise has significant implications for public health and infrastructure, emphasizing the need for sustainable solutions like GRs to mitigate urban heat and reduce energy consumption. The following section will explore the thermal contributions of GRs.

3.4.1 The Urban Heat Island Effect

The UHI is caused by man-made structures with higher thermal capacity than natural landscapes. This leads to elevated temperatures in densely populated urban areas, with daytime temperature increases of 1°F - 7°F and nighttime temperature rises of 2°F - 5°F, as demonstrated in Figure 7 (USA EPA, 2024). Reduced natural landscapes in urban areas, hard surfaces like roofs and roads, and urban building materials contribute further to elevated temperatures. Heat emissions from vehicles, building heating, and cooling systems exacerbate the UHI effect (Jabbar et al., 2023).

![Heat Islands Diagram]

*Figure 7: Example of temperature fluctuation with the UHI on different terrains (Source: Climate Central, 2012)*

UHIs have adverse impacts on human health and comfort, leading to increased mortality rates in cities. Replacing natural land cover with heat-absorbing materials is crucial for mitigating UHIs and their contribution to air pollution and global warming (Jabbar et al., 2023).
Two distinct types of UHIs exist: atmospheric urban heat islands (AUHI) and surface urban heat islands (SUHI). SUHIs entail dry, exposed urban surfaces like roofs and pavement reaching temperatures of 80°F to 122°F on hot summer days. Conversely, shaded or damp rural surfaces tend to maintain closer ambient temperatures. These disparities are most pronounced during daylight hours but can occur at any time (Jabbar et al., 2023). Table 3 shows the ranges of AUHI and SUHI temperature fluctuation (increase) during certain time periods. It is amazing how much surface temperature can increase.

<table>
<thead>
<tr>
<th>Intensity of Temporal Variation</th>
<th>Atmospheric UHI</th>
<th>Surface UHI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day</td>
<td>Low/Non-existent 1°F to 7°F</td>
<td>High 50°F to 60°F</td>
</tr>
<tr>
<td>Night</td>
<td>High 2°F to 5°F</td>
<td>Medium 41°F to 50°F</td>
</tr>
<tr>
<td>Peak Season</td>
<td>Winter</td>
<td>Summer</td>
</tr>
</tbody>
</table>

### 3.4.2 Thermal Performance of Green Roofs

The thermal benefits of GRs are widely acknowledged within the architectural sphere. GRs serve as effective thermal shields, alleviating the thermal load imposed on buildings while simultaneously enhancing the microclimate. The exploration of GRs' thermal impacts has become a focal point for numerous researchers, who employ various methodologies ranging from field measurements to experimental and computational analyses (Wong et al., 2003). Reduction of surface temperature and thermal comfort are the two important functions of the GR in urban areas. GRs add thermal resistance to the building and can cool the building in summer (Shafique et al., 2018).

Delving deeper into the thermal behavior of GRs, Barrio (1998) conducted a mathematical analysis, concluding that GRs primarily function as insulation devices rather than direct coolants for rooftops. Likewise, Eumorfopoulou (1998) conducted calculations to evaluate the thermal performance of GRs, asserting that while they enhance the thermal performance of buildings, they cannot replace traditional insulation layers.

Field measurements under tropical conditions revealed significant reductions in surface temperatures due to shade from plants, with maximum temperature decreases of up to 86°F observed (Wong et al., 2003).
GRs exhibited superior heat transfer resistance compared to bare roofs, owing to the combined effects of soil insulation and vegetation shading. Plants' cooling effect was evident through ambient air temperature differentials. Plants achieve heat reduction through evaporation and transpiration. Notably, GRs mitigated the urban heat island effect by emitting less long-wave radiation and reflecting solar heat, thus contributing to a cooler urban environment, as illustrated in Figure 8 (Wong et al., 2003).

![Figure 8](image)

**Figure 8:** In Celsius, showing the stark temperature difference between asphalt and vegetation (Source: Richards, 2019)

He et al. (2017) analyzed the seasonal thermal performance of GRs and corresponding traditional roofs for a non-insulated building in the Shanghai area, based on a validated model and measured data of plants and substrate. The analysis reveals that, across different seasons, the heat flux through GR is consistently lower than that through traditional roofs at the same indoor temperature. Comparing the performance curves of GR and traditional roofs, it is evident that the slope for GR is smaller, indicating a more gradual response to changes in indoor temperature.

Analyzing the heat transfer direction between GRs and corresponding traditional roofs, three scenarios emerge: when indoor temperature exceeds the critical temperature for traditional roofs, GR prevents heat loss from the room; when indoor temperature is below the critical temperature for GR, GR prevents heat...
gain into the room; and when indoor temperature falls between the critical temperatures for GR and traditional roof, GR absorbs heat from the indoor space (He et al., 2017).

Morakinyo et al. (2017) assessed the thermal effects of GRs by conducting a comprehensive analysis of pedestrian air temperature differences at both nighttime (00:00 h) and daytime (15:00 h) across various climate conditions and urban densities. Their findings reveal both positive (warming effect) and negative (cooling effect) air temperature differences associated with GR implementation. Although the cooling effect is more spatially pronounced, it's important to note that even a subtle reduction in extreme heat, by as little as 2°F, has been correlated with lower human mortality rates and a 50% decrease in warm spell durations, particularly in tropical regions (Morakinyo et al., 2017).

The daytime cooling performance of GRs varies significantly across different climate zones and GR types. Notably, full-intensive GRs exhibit the most pronounced cooling effect, following a distinct order across climates: hot-dry (Cairo), hot-humid (Hong Kong), warm-humid (Tokyo), and temperate (Paris). This variability can be attributed to the interplay between these regions' solar intensity, air temperature, and relative humidity (Morakinyo et al., 2017).

Shafique et al. (2018) says research findings indicate that GRs have the most pronounced impact in the hottest and densest urban areas, where the cooling effect is most needed.

3.4.3 Green Roofs Effect on Energy Consumption

It has been observed that regions with dense, dark green vegetation tend to have lower temperatures, whereas those with sparse, red vegetation or only soil tend to have higher temperatures. This trend can also be observed in buildings with and without GRs. Interior spaces in buildings with GRs are found to have significantly lower air temperatures than those without (Niachou et al., 2001).

Studies have shown that non-insulated buildings can experience energy savings of up to 37% over a year, which can be further increased to 48% with the addition of night ventilation (Akbari et al., 2001). Moderately insulated buildings also enjoy energy savings ranging from 4% to 7%, depending on the type of ventilation employed. Although the impact of GRs on energy savings in well-insulated buildings is less significant, generally accounting for less than 2% (Niachou et al., 2001). This does not diminish the importance of GRs in insulating buildings, given the numerous other benefits, but more shows that GRs will dramatically increase efficiency for an inefficient building. As mentioned earlier, GRs are not a replacement for insulation but can serve as a bolster for insulation’s performance or partially compensate
for its’ absence. The extrapolation of energy savings in buildings with GRs in Thessaloniki, Northern Greece, has shown a reduction in heating and cooling consumption by up to 5% and 16%, respectively, on an urban scale (Karteris et al., 2016).

It is worth noting the positive impact of GRs on building energy performance is more evident in buildings with fewer stories. Studies have demonstrated that the installation of GRs in commercial buildings can result in significant savings in annual energy consumption, space cooling load, and peak space load (Wong et al., 2003). GRs with shrubs and clay soil have been identified as the most efficient types of GRs, with the former achieving savings of up to 15% in annual energy consumption, 79% in space cooling load, and 79% in peak space load, and the latter achieving savings of up to 3% in annual energy consumption, 64% in space cooling load, and 71% in peak space load (Wong et al., 2003). The installation of GRs can yield substantial cost savings, with potential savings of up to US$3,625 per year in the total consumption cost of a five-story commercial building. (Wong et al., 2003).

Sailor (2008) conducted a study examining the integration between the energy balance of GRs and Energy Plus, a building energy simulation model supported by the U.S. Department of Energy. His simulations revealed that GRs could lead to a reduction of 2% in electricity consumption and 9-11% in natural gas consumption. Moreover, his model of a generic building with a 2000m² GR showed that annual savings could range from 27.2 to 30.7 GJ of electricity and 9.5 to 38.6 GJ of natural gas, monetarily represented as $965 - $1,144, subject to the climate and design of the GR. A study conducted by Akbari & Konopacki (2005) proposed that the widespread adoption of large-scale GRs across urban areas could lead to an indirect mitigation of heat islands, resulting in a further 25% decrease in electricity consumption.

This section strived to demonstrate the far-reaching thermal effects of GRs. In my mind, this is the single most important area a GR affects. Based on all of my research, city dwellings will drastically benefit from GR implementation. Scorching summer days can instead be inconveniently hot as opposed to deadly.

3.5 Noise Reduction

In a study conducted by Connelly & Hodgson (2013), it was found that GRs can increase the transmission loss of roof systems. The study utilized a combination of measurements from an indoor-to-outdoor sound transmission lab and field evaluations of GRs with varying substrate depths, water content, and plant species. The results of the study indicated that the transmission loss of GRs was greater than that of non-
GRs by up to 10 and 20 dB in the low and mid-frequency ranges, respectively. It is important to note that the transmission loss measurements of GRs were not in agreement with mass law. Mass law means the higher the density of a material the more unlikely it vibrates when influenced by a sound wave (Stahl & Wakili, 2021). This can be attributed to the porosity of the substrate and the vegetated layer, which reduces the effective mass. However, as the plant community establishes, root masses significantly increase the porosity of the vegetated layer, reducing transmission loss.

Furthermore, Yang et al. (2012) explained that GR systems have been regarded as an effective structure to reduce noise pollution in urban spaces arising from road, rail, and air traffic. The use of sustainable materials that utilize natural means can contribute to the reduction of environmental impact as well as the improvement of soundscapes. GRs act as absorbers, especially for diffracted sound waves between parallel streets, and can increase the sound insulation of lightweight roof structures. Parametric studies have shown that GRs effectively mitigate noise, creating quiet sides in street canyons and courtyards. Similarly, Shafique et al. (2018) discussed how papers in China have shown that vegetation has a high absorption coefficient that helps reduce noise.

Van Renterghem & Botteldooren (2011) conducted a study that measured sound propagation over flat, extensive GRs in five case studies with single or double diffraction (a modification which sound undergoes especially in passing by the edges of opaque bodies or through narrow openings and in which the waves appear to be deflected). The measurements were taken before and after placing the GRs in dry conditions, and they showed consistent and significant sound reduction in locations with diffracted sound waves. Single diffraction cases showed acoustic improvements exceeding 10 dB over a wide frequency range, while double diffraction cases showed positive effects over the full frequency range. The presence of shearing waves and sufficient substrate thickness were important factors in achieving positive effects. The study also noted that water on the green roof can improve its sound-absorbing capabilities.

3.6 Ecological Support

In recent years, there has been a growing interest in GRs as a potential solution for mitigating urban habitat degradation. There is a need to investigate how GRs can be optimized ecologically to increase urban habitat value and movement of wild species. GRs have been found to support a variety of insect species, which play a vital role in many ecological processes, including pollination, pest control, and decomposition (MacIvor & Lundholm, 2011).
Insects are essential components of urban ecosystems, and the abundance and diversity of niches occupied by insects indicate the essential role they play in many ecological processes. GRs have the potential to provide habitat for a wide range of insect species, and studies have shown that they can support insect diversity. The potential for GRs to support insect diversity has been investigated in several countries, including Germany, Switzerland, England, the United States, and Canada (MacIvor & Lundholm, 2011).

Several strategies have been undertaken to provide habitat for functionally valuable insect species, including GRs in their design. For example, the California Academy of Science building in San Francisco has a 2.5-acre green roof that provides habitat for the rare Bay Checkerspot butterfly (*Euphydryas editha bayensis*). In Basel, Switzerland, GRs are mandatory on all flat-roofed buildings and must meet plant and growing medium design criteria to maximize their habitat value for local flora and fauna (MacIvor & Lundholm, 2011).

The vegetation community on a GR attracts a diverse invertebrate community. The presence of pollinators like European honeybee and blue banded bee have been noted, thanks to vegetation like *Dianella caerulea* and *Viola hederacea*. Studies have shown that invertebrates present on GRs were urban-adapted species. A study by Wooster et al. (2022) showed that the vegetative community was dynamic throughout the study period, with changes primarily dominated by the growth of *M. cordifolium*. Shaded areas can become dominated by a few select species, while open areas of vegetation remain relatively stable. Future GR locations may benefit from being located closer to the ground to allow for the establishment of more arthropod and avian species (Wooster et al., 2022).

GRs have the ability to connect fragmented green spaces in cities to facilitate species dispersal within the urban landscape. Habitat fragmentation can compromise the conservation of insect biodiversity in urban areas, and it is thought that GRs might serve to connect fragmented green spaces in cities to facilitate species dispersal within the urban landscape (MacIvor & Lundholm, 2011).

A study conducted by Wooster et al. (2022) in Sydney, Australia, found that GRs support a higher avian diversity than conventional roofs. The study's results suggest that GRs play a vital role in supporting urban avian biodiversity, aligning with previous research highlighting the significant conservation value of urban green spaces. All avian species present on the GR were urban-adapted and relatively common throughout Sydney. GRs tend to provide habitat and foraging opportunities to urban species rather than attracting new ones. Figure 9 provides an example of a seagull’s nest on top of a convention center in
Manhattan. The study also detected evidence of intraguild predation on the GR. A deceased noisy miner was found beneath the PV panels, with its head removed and most of its organs consumed, indicating the presence of an avian predator or scavenger. The widespread implementation of GRs may facilitate the urban recolonization of birds of prey (Wooster et al., 2022).

*Figure 9: Gull nest on the roof of a convention center in Manhattan, NY (Source: Rapp Learn, 2022)*

The GR in Wooster’s study was young, established only months before the study began. Previous work has shown that GRs reach peak biodiversity approximately two years after their establishment. It is also important to note that biodiversity atop roofs may have been higher than recorded within the study. The study used non-lethal methods to assess diversity to avoid interfering with, harming, or reducing the diversity of rooftop inhabitants. While regular insect surveys and camera traps were sufficient to quantify the benefits of GR implementation, diversity is likely to have been greater than estimated (Wooster et al., 2022). Plant species not initially planted have also been observed establishing on GRs, likely as a result of avian and wind dispersal.
3.7 Mental Health and City Use

A recent study by Manso et al. (2021) highlighted the positive impact of urban green spaces on mental and physical health. According to their findings, greenery has a calming effect on the mind and helps to alleviate stress, thereby enhancing the well-being of citizens. The study also suggests that even the mere sight of green spaces can have a positive psychological effect on people. Therefore, integrating GRs into urban spaces can be an effective tool to promote the health and well-being of citizens.

GRs not only add to the beauty of buildings and urban spaces but also provide recreational opportunities for citizens, thereby improving their quality of life. These systems can even be used for urban agriculture, promoting sustainable local food production and reducing the community's ecological footprint.

The visual impact of these solutions depends on the characteristics of the system and the surrounding environment. GRs may be more valued in densely populated urban areas with limited green and leisure spaces, and solutions with a wider variety of plants may be more appealing. Therefore, GRs should be designed and installed according to the local context and citizens' preferences.

A survey conducted by Safayet et al. (2019) in Dhaka, Bangladesh, found that citizens are willing to practice rooftop farming and provide at least 50% of roof space for it. This highlights the potential of GRs to promote ecological sustainability and citizens' interest in sustainable local production of food.

3.8 Weighted Evaluation of the Benefits

Table 4 is meant to be a synthesis of the benefits I have quantified above. I tried to be consistent with the following criteria:

- Do the benefits have far reach, large-scale impact, and tangible results
- Do they address the most dire issues urban areas are facing (e.g. UHI, flooding, etc.)
- Will their impacts increase with scalability to a significant degree

All of the benefits have merit. The rating system below is not meant to diminish the importance of any one area but instead appreciate the exceptional benefits GRs offer. It is also meant to be a visually appealing way to synthesize the data and provide a quick takeaway for the viewer.
Table 4: Star ratings for environmental benefits (Source: Author)

<table>
<thead>
<tr>
<th>Benefit</th>
<th>Rating (out of 5)</th>
<th>Rationale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stormwater Management</td>
<td>★★★★</td>
<td>Quantified results for reduction and retention of stormwater that can reduce flooding and strain on sewer systems during periods of intense rain</td>
</tr>
<tr>
<td>Water Quality Enhancement</td>
<td>★★★</td>
<td>Results are debated. Heavy metals and Nitrate are shown to be removed by plants and substrate but could be added back with heavy rain. More research is needed</td>
</tr>
<tr>
<td>Thermal Effects</td>
<td>★★★★★</td>
<td>Reduction of UHI is of vital importance for urban dwelling. Proven to improve building energy efficiency and reduce overall urban temperatures</td>
</tr>
<tr>
<td>Air Quality</td>
<td>★★★★</td>
<td>Plants and trees have been proven to reduce and remove dust and airborne particles</td>
</tr>
<tr>
<td>Noise Reduction</td>
<td>★★★</td>
<td>Shown to diminish by 10-20dB and particularly in downtown areas reduce ‘canyon effect’</td>
</tr>
<tr>
<td>Ecological Support</td>
<td>★★★★</td>
<td>Provides green space for insects and birds to establish nests, cross through urban areas, and reintroduce previously removed populations back to urban environments</td>
</tr>
<tr>
<td>Mental Health and City Use</td>
<td>★★★</td>
<td>Least tangible of all the benefits, greenery has proven to promote mental well being</td>
</tr>
</tbody>
</table>

IV. CHALLENGES AND OPPORTUNITIES

ASSESSMENT

Addressing Sub-Question 2: What are the challenges and opportunities of green roofs, and under what conditions are they significant?

GRs are widely recognized as a useful solution to combat pollution and restore natural hydrology in urban areas. However, despite the numerous environmental, social, and economic benefits that GRs offer, their adoption is still limited due to several challenges. Some of the main challenges are the high initial cost of construction, lack of state and Federal policy support, deficiency in public and professional awareness regarding their benefits and construction, and inconsistent knowledge of best plant usage (Shafique et al., 2018).
Another significant challenge is designing GRs that can work in all climates and locations. Most of the current research in this field has been conducted in cold regions, which makes plant selection a crucial unexplored factor for successful implementation in other areas. For instance, in hot regions, selecting plants that will provide insulation in summer is necessary for the successful implementation of GRs (Shafique et al., 2018).

However, with every challenge, there exists opportunity. Rebate and incentive programs can help citizens shoulder the cost of construction. Education and training programs can help inform citizens and contractors of the importance of GRs and the best practices for them. The following section is segmented into a challenge issue followed by a discussion of the opportunities that exist to address these challenges.

4.1 Cost and Economic Review

**Challenge:**
The cost of installing a GR can vary widely based on the type, size, and location of the roof. On average, prices start around $10 per square foot for a simple extensive GR and can go up to about $30 per square foot for more complex intensive systems. For large projects exceeding 10,000 square feet, costs per square foot may be reduced by up to 50%, making them more economically viable on a larger scale. This is particularly important to emphasize for commercial installation. Large commercial real estate like Costco, Target, etc. typically have large, flat roofs. The largest cost for installation on these surfaces would typically be for load-bearing purposes. Commercial real estate is prime for GR development. Annual maintenance costs are typically between $0.75 and $1.50 per square foot (Home Advisor, 2022).

A root barrier covering an average home might cost between $170 and $1,400 or more. Labor costs for installing a GR typically range from $5 to $10 per square foot, which means labor could cost between $8,500 and $17,000 for a 1,700-square-foot roof. Additionally, if the existing roof requires removal, this could add $1 to $5 per square foot to the total cost (Home Advisor, 2022). All this is to say that the estimation of a complete GR project is hard. Material costs and availability fluctuate constantly and vary by area. What we can determine from the above numbers though, is the cost for an average homeowner to bear is in the tens of thousands, if not hundreds of thousands of dollars.

GRs necessitate consistent maintenance to ensure their long-term effectiveness. Yet, there is a notable scarcity of research on the optimal maintenance practices for GRs. Common misconceptions suggest that these installations require little in the way of regular watering or fertilization. In reality, to maintain their health and functionality, especially during drought conditions, periodic watering and fertilization are
essential. Additionally, GRs benefit from systematic maintenance routines including regular inspections of the plants, drainage systems, and substrate. These proactive measures are crucial to prolong the lifespan and enhance the performance of GRs (Shafique et al., 2018).

Given the challenges in quantifying the average value of a green roof, numerous studies have employed cost-benefit analyses (CBAs) to calculate net-present values (NPV) for the various benefits attributed to GRs. These benefits are then prioritized, with thermal advantages often receiving the highest weight and air quality benefits the lowest (though I happen to disagree with it being the lowest). The findings from these studies consistently show that GRs are economically viable over their expected lifespans, reinforcing the notion that GRs are worthwhile investments. Moreover, they often merit subsidy support due to their broad environmental and economic benefits. A comparison of CBA methodologies reveals that, although similar methods are used to evaluate the costs and benefits of GRs, the results can vary significantly—by approximately 13% to 106%—depending on the specific approach taken in each case study (Hekrle et al., 2023).

**Opportunity:**
A study conducted by Teotonio et al. in 2018 investigates the feasibility of installing GRs on residential and commercial buildings in highly urbanized areas like Lisbon even with high initial costs. The research indicates potential gains from both extensive and intensive GRs, ranging between $76 and $545 per square meter, respectively. The study recommends policy development and financial incentives to attract private investment in green infrastructure. It suggests balancing the installation of extensive and intensive GRs with semi-intensive options as economically favorable, particularly for flat roofs and in building rehabilitations where thermal insulation is absent. This brings me back to my point about commercial roof development. The real estate per cost of these projects would be overall cheaper to implement due to the favorable sloping, large square footage, and already flat nature of the roofs.

Numerous industry groups advocate that GRs can more than double the lifespan of the waterproofing membrane beneath them and more than double the lifespan of a conventional roof, a claim attributed to the protective layer of vegetation and growing media that shields the membrane from damaging ultraviolet radiation and physical wear. Although GRs have only been utilized in the United States for the past two decades—with limited domestic examples to substantiate these benefits—data from Europe demonstrates that GRs can indeed last more than twice as long as traditional roofing systems. Despite the higher initial costs associated with GRs compared to traditional shingle roofs, the potential long-term advantages—such as lower energy expenditures, increased durability of roofing materials due to
elemental protection, and eligibility for tax rebates and credits—position GRs as a valuable investment. These benefits, particularly the significant reduction in energy costs and enhanced durability over conventional roofs, support the case for GRs as a sustainable option that can yield substantial economic returns over time (Carter & Keeler, 2008).

Cities in the United States are beginning to incentivize the implementation of GRs. For example, according to Olson (2018) Washington, D.C. offers financial support ranging from $10 to $15 per square foot, depending on the type of sewer system serving the proposed site. Philadelphia provides a 25% credit against all expenses, up to a limit of $100,000. Meanwhile, the Milwaukee Metropolitan Sewerage District offers a subsidy of $5 per square foot, while Chicago provides grants covering 50% of the costs, up to $100,000.

Some cities have introduced innovative approaches to encourage the adoption of GRs, such as seeding credits for stormwater management fees. Cincinnati, for example, offers up to a 50% credit toward stormwater management fees. Additionally, some municipalities, like Austin, TX, offer density bonuses, allowing developers to build an additional 8 square feet of floor space for each square foot of GR installed. Moreover, initiatives like the Illinois Green Infrastructure Grant and Tennessee’s Green Development Grant Program provide funding opportunities for local government units and others to install water runoff control infrastructure (Olson, 2018).

It is important to reiterate that commercial properties generally incur lower installation costs for GRs, while residential buildings experience greater increases in property value, especially with intensive GR installations. Additionally, GRs confer immediate property value enhancements, with studies indicating potential value increments ranging from 7 to 11 percent upon installation (Olson, 2018).

### 4.2 Social Barriers

**Challenge:**
The implementation of GRs in the U.S. faces significant challenges, in some part due to a widespread lack of awareness. For instance, a 2023 study by Meyer & Trandafir revealed that a mere 45% of Americans surveyed were familiar with GRs, a stark contrast to more informed European and Asian populations. This educational deficit hinders the adoption of such sustainable practices, which promise enhanced urban life quality but remain underutilized and misunderstood.
Surveys have repeatedly highlighted that while interest in eco-friendly solutions exists, the broader public remains uninformed about the specifics, including the benefits and the required investments for GRs. This lack of detailed knowledge results in ambiguous perceptions and undefined willingness to pay (WTP) for the installation and upkeep of these nature-based solutions. For example, research by Yuen, Belinda, and Wong Nyuk Hien (2005) demonstrated that although some people recognize GRs on public buildings, they seldom use them as intended, such as for public gardens.

The attractiveness and acceptance of GRs are influenced by several factors, including the level of public awareness about GR technology, amendments in building regulations, environmental consciousness, and cost considerations. Studies such as those by Sarwar and Alsaggaf (2020) in Lahore and Vanstockem et al. (2018) in Flanders have shown how these elements impact public attitudes towards GRs. Moreover, aesthetic preferences, such as those studied by Fernandez-Cañero et al. (2013) in Spain, reveal a preference for well-designed roofs with diverse vegetation and colors, underlining the importance of aesthetic appeal alongside functionality.

However, the economic feasibility of GRs varies widely. For example, a study in South Korea by Ji et al. (2022) found an average WTP of $3.77 total per household per year, indicating that large-scale GR projects are likely only viable in densely populated areas. This is echoed in findings from China, with $3.50 WTP in Guangzhou (Cristiano et al., 2023), yet in Beijing, a much higher WTP suggests a more substantial economic viability for extensive GR installations, largely due to the high concern over urban heat islands. The intent of this data is to highlight that not every citizen will value green infrastructure despite natural assumptions that it would be universally accepted. It is impossible to survey every global resident, but understanding that there will always be resistance to pay is an important consideration for governments when promoting policy.

Despite these interests, challenges such as gentrification present additional complexities. Studies from Berlin and New York City highlight how green projects can inadvertently drive inequality and gentrification, showcasing the paradoxical nature of urban greening efforts (Cristiano et al., 2023). These findings underscore the multifaceted challenges facing GRs: while they offer considerable environmental and aesthetic benefits, their adoption and sustainable integration into urban landscapes remain hindered by their direct reduction of public expenditures for affordable housing and inconsistent equitable access.

**Equity Concern:**
According to Razzaghi Asl (2023), the uneven distribution of GRs poses a significant challenge, particularly as these beneficial systems are less accessible to low-income populations. This disparity
creates environmental justice concerns since these communities often lack the resources to implement green infrastructure that can mitigate flood risks and enhance urban resilience, issues exacerbated by climate change.

In various U.S. cities, policies and incentives for GRs differ markedly, with wealthier areas often benefiting from more substantial green infrastructure. For instance, in New York City, laws now require new buildings or those undergoing major renovations to install GRs or solar panels. However, the mandatory laws permit a five-year exemption for low-income communities, which may delay the benefits that GRs could provide. Furthermore, the city's incentive of a tax abatement of only $4.50 per square foot of GR, covering roughly one-fourth of the total cost, has seen limited uptake, particularly among affluent property owners who do not face the financial barriers experienced by less wealthy citizens as the tax break is viewed as not robust enough. New York’s tax abatement policy is simultaneously not large enough to help lower income individuals or pique the interest of higher income households.

Chicago and Philadelphia offer contrasting approaches. Chicago's policies, the Green Elements Permit and the Sustainable Development Policy, incentivize GR installation through financial mechanisms that cater to different income groups, including residents in low-income housing. However, these policies primarily focus on distributional justice within commercial and public buildings and do not fully address the broader scope of private and public installations or the procedural aspects of environmental justice.

Philadelphia, with its Green Roof Tax Credit and expedited permit review processes under the Green City Clean Waters program, encourages the installation of GRs by offering financial incentives and streamlined procedures. These initiatives aim to increase urban canopy coverage and manage stormwater more effectively, particularly in lower-density residential and commercial areas.

Despite these efforts, the policies often do not adequately address the need for broader recognition of justice, where a co-production of knowledge among all stakeholders, including marginalized communities, is essential for fair and equitable GR implementation. This lack of engagement results in policies that do not fully consider the diverse needs and capabilities of all city residents.

**Opportunity:**
Surveys indicate a robust general interest in adopting GRs, particularly on public buildings, highlighting an opportunity for widespread implementation. However, the enthusiasm wanes when considering private structures, primarily due to high installation and maintenance costs, and strong competition from solar panels. Although many citizens recognize the economic returns of solar panels, these systems offer only
energy savings and lack the broader community and environmental benefits provided by GRs (Cristiano et al., 2023).

The juxtaposition of photovoltaic systems and GRs suggests a compelling case for combined installations, which should be actively promoted through policy incentives and integrated into urban planning. This approach would not only harness the financial appeal of solar energy but also capitalize on the environmental advantages of green roofs (Cristiano et al., 2023). This is further elaborated on in section 5.

In Western contexts, such as Portland, USA, Netusil et al. (2022) explored GR benefits and public WTP, estimating potential city-wide investments could be substantial, ranging from $54.4 to $116.8 million, with $202 to $442 WTP for each household. Similarly, in Portugal, Teotónio et al. (2020) found a significant preference for accessible GRs, with a willingness to allocate around 3% of rent or mortgage payments towards such initiatives.

The WTP for maintaining GRs on public buildings further underscores the feasibility of large-scale urban or regional GR projects. Survey data suggest a minimum WTP of approximately $37 per person per year, aggregated by Cristiano et al. (2023). This figure aligns with findings from Beijing by Zhang et al. (2019), where residents are willing to pay $22 per year. This value, predominantly derived from a demographic with higher education—who traditionally show greater WTP for nature-based solutions (NBSs) as per Chui and Ngai (2016)—suggests a significant potential revenue stream for GR projects.

For instance, in a city like Cagliari, Italy with nearly 150,000 residents and about 42% holding at least a high school diploma, an annual collection of approximately $2.31 million from this demographic alone could fund the implementation and maintenance of GRs on a substantial scale. Assuming a 25-year project with a unit cost of $162/m² for installation and $11/m² per year for maintenance, it would be feasible to cover approximately 126,000 m². This strategy could extend regionally, encompassing up to 1.5 km² of green roofs sustained over a quarter-century. The benefits of such an extensive installation, including flood mitigation, reduction of urban heat islands, enhanced biodiversity, and CO2 sequestration, would be considerable. These outcomes would support resilient urban development in line with the Sustainable Development Goals of the United Nations 2030 Agenda (Cristiano et al., 2023).

In the Sarwar 2022 study, they found that 92% of the respondents felt that governments had to advertise GRs. Governments must, therefore, assume a central role in promoting and facilitating the installation of GRs, enhancing public awareness, and outlining the multifaceted benefits these structures offer. Public opinion already acknowledges the value of green spaces in enhancing quality of life, with nearly half of
the population agreeing that a lack of greenery adversely affects urban living (Sarwar & Alsaggaf, 2020). This public sentiment, combined with structured governmental support, could greatly accelerate the adoption and successful integration of GRs into urban landscapes.

4.3 Policy and Legislation

GR legislation encompasses laws and regulations designed to mandate or incentivize the installation of GRs on new and existing buildings. In response to growing environmental concerns, governments globally are increasingly adopting GR legislation to promote their installation and ensure compliance with established quality and sustainability criteria.

Challenge:
A significant challenge in implementing GRs is providing the necessary support and resources by local and regional governments to ensure these systems are installed correctly. Moreover, there is a pervasive lack of awareness regarding GR legislation. Many individuals remain uninformed about the benefits of GRs and the laws and regulations that govern their installation, which complicates efforts to ensure these systems meet required standards. GR legislation often mandates or encourages the installation of GRs on new constructions or the retrofitting of existing buildings. Such regulations may also specify requirements concerning the vegetation types suitable for GRs, soil depth, water conservation measures, and other relevant standards (Holmes, 2023).

Holmes (2023) highlights that although GRs are well-regarded for their capacity to manage stormwater, enhance resilience, and support green infrastructure, many developers still opt for alternative practices, especially in locales lacking targeted policies and incentives for GRs. These alternatives most commonly are solar panels or traditional roof installation. This reluctance forms a considerable obstacle to GR broad adoption.

In the U.S., the landscape of policies and incentives for GRs shows significant regional variability, contrasting sharply with the more uniform and extensive policies for clean and renewable energy that typically offer immediate financial advantages. As a result, property owners and design teams often prefer rooftop solar installations over GRs, even though combining these technologies could enhance solar efficiency (covered in section 5). This disparity highlights the need for integrated policies that advocate for the simultaneous implementation of GRs and solar systems (Holmes, 2023).
In places like Cambridge, Massachusetts, regulations now mandate that developers consider both GR and solar installations on new developments. However, in areas lacking specific incentives for GR, developers frequently prioritize conventional site-based stormwater management strategies during the early design phases to facilitate permit approvals, often to the detriment of GR integration. Once a project is approved, there tends to be little incentive to revisit or optimize GR designs, despite their proven benefits in stormwater management (Holmes, 2023).

GR policies range from mandatory compliance regulations to voluntary incentive programs designed to encourage the adoption of green roofing technologies. These programs are often managed by different agencies with aligned goals to promote the implementation of such environmentally beneficial systems (Stern et al., 2019). The construction specifications for mandated and incentivized GRs differ significantly. They can include basic requirements such as the extent of roof coverage and substrate depth, or more stringent construction criteria, including leak detection systems and stipulations for ongoing maintenance (Stern et al., 2019).

In instances where such policies and regulations have been enacted, the initial costs associated with installing GRs have consistently presented a political hurdle. Stakeholders often focus on the immediate financial outlays, reacting to upfront costs rather than evaluating the potential long-term savings and benefits associated with the GR's life cycle. This shortsightedness in financial considerations remains a significant barrier to the broader acceptance and implementation of GR policies (Stern et al., 2019).

**Opportunity:**

Since 2014, Green Roofs for Healthy Cities and the Green Infrastructure Foundation have developed the Living Architecture Performance Tool (LAPT), a comprehensive performance rating system for GRs. Designed to provide municipalities with a uniform standard, the LAPT covers design, construction, maintenance, and performance criteria across various markets, geographies, and bioclimates. This tool has demonstrated the robust life cycle value and financial return of GRs, prompting an increasing number of cities to implement mandatory GR requirements (Stern et al., 2019).

Such regulations have stimulated the growth of mature markets for GRs, facilitating the rapid development of local providers and dramatically reducing installation costs. Cities like New York, Seattle, Toronto, San Francisco, and Washington, DC, have adopted combinations of GR regulations and incentives that effectively integrate GRs into new developments, enhancing urban environments and achieving various public policy objectives (Stern et al., 2019).
GR policies not only address environmental and health issues but also accelerate economic development and advance social equity. By leveraging underutilized roof spaces these policies promote substantial municipal benefits and encourage private sector investment in building development and redevelopment (Stern et al., 2019).

In the United States, the Environmental Protection Agency (EPA) has instituted a range of grants and incentives to promote the installation of GRs. The EPA offers comprehensive guidance on the design and installation of GRs, coupled with recommendations on optimizing their environmental and functional benefits.

The innovation phase for GRs has lessened and their technical and economic viability has been established across diverse economic and bioclimatic conditions. However, to overcome barriers to widespread adoption, further public policy initiatives and awareness campaigns are essential. In cities with high rates of GR installation, public policies have catalyzed the market by educating stakeholders and offering financial incentives or regulatory mandates (Stern et al., 2019).

4.4 Skilled Labor

**Challenge:**

GR construction projects typically involve a diverse team of professionals. This team includes the client, building architect, landscape architect, structural engineer, civil engineer, mechanical engineer, electrical engineer, roofing consultant, cost estimator, irrigation specialist, regulatory bodies, and a green roof professional (Minnesota Pollution Control Agency, 2023). To assemble this team will take time, money, and coordination.

When it comes to selecting plants for a GR, ecological considerations must be taken into account. Factors such as whether to use only native plants, drought-resistant species, or tall herbaceous plants must be evaluated. Native plants are generally preferable as they require less irrigation, are less likely to become invasive, and provide habitat for local wildlife, thus enhancing area biodiversity. Ideally, the landscape architect would make these determinations.

One of the primary challenges in GR adoption is managing the system post-construction. This is often hampered by inadequate cooperation among the involved disciplines, such as architects, engineers, and residents. The key issue is determining who is responsible for maintenance since neglecting this can result in the loss of the initial investment.
Globally, this underscores the necessity for stakeholders to clearly assign responsibilities for construction and maintenance costs. Enhanced collaboration among architects and civil and environmental engineers is crucial for effectively implementing GRs in urban environments (Shafique et al., 2018).

A notable issue is the division of labor in designing drainage and stormwater management systems. These are typically under the purview of civil engineers but often are excluded from the initial phases of GR design. Civil engineers usually handle elements like roof drain overflow and external conveyance, which might not encompass the integrated design of GRs included in architectural, structural, landscape, and plumbing plans (Holmes, 2023). They need to work closely with the design team to ensure the GR meets the project’s stormwater management goals and are responsible for the hydrologic stormwater calculations that document the GR’s performance (Holmes, 2023).

**Opportunity:**
In 2009, Green Roofs for Healthy Cities (GRHC) initiated the Green Roof Professional (GRP) Training & Accreditation program to address the industry's significant knowledge gap in training and best practices. Prior to this initiative, there was no comprehensive training program that encompassed all the critical competencies required for effective GR implementation, such as building science, horticulture, irrigation, waterproofing, plant physiology, and structural engineering. Since the program’s inception, more than 750 individuals have successfully passed the GRP Accreditation Exam and obtained the GRP designation (Green Roofs for Healthy Cities, 2024).

The GRP Training program is structured around three primary courses: Green Roof Design & Installation, Green Roof Waterproofing & Drainage, and Green Roof Plants & Growing Media. Each course is designed to provide in-depth knowledge and practical skills essential for specialists in the field, ensuring that they meet the high standards required for successful GR projects.

### 4.5 Native vs. Non-Native Plant Usage

**Challenge:**
Debates persist concerning the use of native plants on GRs across the world. Many studies have demonstrated that numerous award-winning GRs have incorporated native plants, highlighting their significance in green infrastructure. Various non-profit, governmental, and commercial organizations in the United States, such as the Ladybird Johnson Wildflower Center and the City of Toronto's Green Roof
Pilot Program, actively promote the usage of native plants because of their environmental advantages (Li & Yeung, 2014).

Implementing native plants on GRs involves challenges. Concerns include the threat of invasive species and the difficulty of maintaining native plant communities, which could lead to higher costs and management complexities. Additionally, the survival rate of native plants from non-local seed sources can be uncertain, prompting suggestions to use seeds from local plants to enhance establishment success (Li & Yeung, 2014). The debate also extends to the practicality of planting rare or native species that may be vulnerable to genetic alteration from other similar plants, coupled with their specific habitat requirements which could complicate long-term success (Li & Yeung, 2014).

When the California Academy of Sciences in San Francisco reopened in August 2008, it featured a unique “living roof” planted with selected native species intended to demonstrate sustainability. Despite initial plans, only nine species proved capable of self-sowing sustainably. Over the next 2.5 years, ongoing monitoring revealed mixed results: two-thirds of the predominant species remained native, but non-native species began to outnumber natives in half of the roof’s quadrants that were left unweeded. Despite efforts to sustain them, native plants required intensive gardening, including irrigation, contradicting the notion of their natural sustainability in urban settings. This experience highlighted the challenges of maintaining native plant ecosystems in urban environments, underscoring the need for realistic approaches to urban vegetation that consider both ecological function and cultural values (Del Tredici, 2011).

**Opportunity:**
Native plants are preferred because they are well-adapted to local conditions and, once established, usually require no additional watering, fertilizers, or pesticides. They play a critical role in restoring healthy ecosystems by attracting diverse wildlife such as birds and butterflies. Studies have shown that GRs with native vegetation can support richer biodiversity compared to those planted with non-native species (Li & Yeung, 2014).

The potential ecological and aesthetic advantages drive the interest in native plant use on GRs. Research indicates varied growth and survival rates of native plants under different green roof conditions, underscoring the need for careful plant selection and management to ensure successful outcomes. Ultimately, the effectiveness of GRs in terms of aesthetics and ecological function can significantly influence public acceptance and the broader adoption of green roofing practices (Li & Yeung, 2014).
V. TECHNOLOGY ASSESSMENT

Addressing Sub-Question 3: What technological developments and innovations for green roofs enhance the benefits and address challenges?

In this section, I will examine the developments and innovations in GR technology. These developments are direct responses to the challenges highlighted earlier. Mainly to allow for cheaper installation and maintenance, integration with solar panels, and improved substrate research aimed at sustainability and decreased chemical load.

5.1 Modular Technology

Modular GR technology offers a dynamic and energy-efficient alternative to traditional GR structures, addressing concerns around the cost of installation and maintenance while retaining the core benefits of GR. Modular designs reduce the cost of installation because they are prefabricated and pre-assembled with easy interlocking connectors. Maintenance of the modules is easier relative to traditional GRs, as single modules can be removed to access underlying cables and piping, or replaced as needed. Modular technology is ideal for flat roofs and could be the solution for large commercial real estate. However, they can go on sloped roofs. Furthermore, these systems typically employ ecological and recyclable materials and integrate additional energy-saving devices like solar panels and automatic watering systems, enhancing their impact. The design flexibility and aesthetic customization potential of modular systems cater to a variety of architectural needs, reducing labor and waste during construction and expanding the accessibility & desirability of GRs (Korol & Shushunova, 2016). Figure 10 provides an example of what a modular design can look like. Figure 11 provides an actual image of a modular roof. Modular technology is currently not a patented technology and can range in design.

Modular GRs have convenient pre-vegetated trays with slotted sidewalls to encourage root integration and create a natural meadow appearance. The slotted flat bottoms enhance water circulation, and the underlying capillary mat ensures even moisture distribution. The system includes built-in drainage channels for stormwater management in wet seasons and automatic drip irrigation in dry seasons. Such designs can be instrumental in urban areas, optimizing limited space and enhancing urban aesthetics with the potential for extensive landscaping (Korol & Shushunova, 2016).
Figure 10: An example of a modular design (Source: Baciu, 2020)
5.2 Bio-Solar

GRs and solar photovoltaic (PV) systems are increasingly recognized as critical technologies for sustainable building development and reduction of greenhouse gas emissions. Integrating these systems atop buildings can significantly enhance their functionality and effectiveness through mutual cooling and shading effects. Rooftop solar PV systems play a pivotal role in generating renewable power and supporting sustainable energy frameworks (Parida et al., 2011).
Although GRs and solar panels might initially seem to compete for limited rooftop space, their combined implementation can amplify the benefits of each, significantly enhancing overall building sustainability. Evapotranspiration from GRs cools PV panels, improving their electrical efficiency, while the panels' shade reduces excessive sunlight exposure and water evaporation, benefiting the vegetation (Hui & Chan, 2011).

Research has indicated that the electrical efficiency of PV cells, primarily affected by the amount of solar irradiation received, is compromised under high temperatures due to increased conductivity in the crystalline semiconductor of the panel, which inhibits charge separation and lowers voltage output. Such conditions can reduce PV panel productivity by up to 25% and affect efficiency by -0.45% per degree Celsius (Hui & Chan, 2011). Because GRs have been shown to reduce the roof surface temperature and thus the operating temperature of the PV surface, thermal degradation rates can be mitigated and power generation maintained (Meral and Dinçer, 2011).

Integrated systems have also been observed to enhance the GR biodiversity and ecosystem viability, increasing both the number and health of plant species under the partial shade of PV panels (Hui & Chan, 2011).

Year-round simulations have shown that integrated systems consume less energy for air conditioning compared to standalone PV panels. This is due to the thermal performance of GRs discussed in section 3. The integrated approach also generated 8.3% more electricity than systems without GRs. The degree of these benefits varies based on the system design and the specific architectural and environmental conditions of the building site (Fleck et al., 2022).

One significant study by Fleck et al. (2022) presents the largest known commercial Bio-Solar Green Roof (BSGR) study to date, performed in summer months in a warm climate. It reports that the BSGR achieves an average energy output 4.5% greater than conventional solar roofs (CSR) and boosts the total energy output by 23.83%. This setup not only offsets the fossil fuel energy consumption by an additional 11.55 metric tons of CO₂ but also has the potential to mitigate up to 1.55 metric tons more CO₂ through the vegetation on the roof. The monetary value of the increased energy output amounts to $2,990.86 and is equivalent to planting 192.49 trees over ten years in an urban setting. Furthermore, placing a GR over a conventional solar array increased the system's energy output by 23.88 kWh, decreased GHG emissions by 0.019 metric tons of CO₂, and generated an additional $5.04 per square meter of solar panels throughout the study period. The performance of the BSGR during winter months remains undetermined,
prompting recommendations for future long-term monitoring studies in colder climates like the Eastern Australian coastline.

Practically, solar panels should be installed above the level of vegetation for shading, using lightweight frames that enable optimal sun exposure while allowing for the growth of shade-tolerant vegetation underneath, see Figure 12. These systems are often designed with structural considerations to enhance roof integrity and utilize GR layers as ballast, thus reducing the need to penetrate the roof structure in solar panel installation (Hui & Chan, 2011).

![Figure 12: Bio-solar example integrated into an urban environment (Source: Greenwood, 2018)](image)

5.3 Substrate Materials

GR substrates are engineered to provide water and nutrients to plants while ensuring good drainage, lighter weight, and stability over time. These substrates are typically shallow, less than 8 inches deep on extensive GRs, and vary with design goals, climatic conditions, and intended uses. Therefore, there is no one-size-fits-all substrate suitable for all GRs (Xue & Farrell, 2020).

Substrates consist mainly of lightweight inorganic materials like crushed brick, pumice, heat-expanded shale, and scoria, which make up 80-90% of the volume. These materials provide a stable structure and create necessary pore space for drainage and oxygen supply to plant roots. Organic components, which make up the remaining 10-20% by volume, enhance water retention crucial for stormwater management and plant survival, reduce the weight of the substrate, improve cation exchange capacity, and supply nutrients to the vegetation (Xue & Farrell, 2020).
The selection of the type of organic matter and the rate at which it is added require careful consideration to optimize substrate composition. Recent discussions on GR materials have focused on their environmental impact, including the use of recycled materials and alternatives to synthetic materials. Studies have explored the production and recycling potential of synthetic materials. Meanwhile, research has highlighted environmental concerns with materials like expanded clay, rock wool, and high-impact polystyrene (Tams et al., 2022).

This section will explore the potential of organic waste, recycled materials, and materials for weight reduction and better performance as alternative substrate components to enhance sustainability and reduce the environmental impact of GR construction.

5.3.1 Organic Waste

Organic waste materials have the potential to improve the quality of scoria-based GR substrates, but their impact on plant growth varies depending on the type of material used and the rate at which it is added. The incorporation of organic matter in substrate mixes should not exceed 20% by volume, consistent with FLL guidelines. Studies have shown that adding 15-20% coarse or fine coconut coir and composted green waste can make substrates lighter and increase the amount of water available to plants. However, specific types of green waste, like pistachio shells and almond hulls, should not be used due to their phytotoxicity. (Xue & Farrell, 2020).

Other organic materials, such as peat, coconut coir, composted green waste, composted pine bark, mushroom compost, olive mill residue, and grape marc compost, have been tested and proven effective in supporting vegetation and enhancing water retention. However, their availability varies by region, emphasizing the need for local substrate development and evaluation to reduce transportation costs and energy consumption. Using local waste materials can transform low-value resources into valuable ones and promote the adoption of GRs (Xue & Farrell, 2020).

When selecting organic components for substrates, it is essential to consider the desired ecosystem services of the GR. In arid climates, substrates must have a high-water retention capacity for effective stormwater management and must ensure that a significant portion of this water remains available to plants. Research has addressed how different organic components and application rates affect water retention in GR substrates, but their impact on plant water availability has received less attention. In regions where GRs are uncommon, evaluating the effects of various rates and types of organic matter,
particularly when mixed with locally available mineral components, is crucial, as the interactive effects cannot be predicted solely based on the physical properties of individual components (Xue & Farrell, 2020).

The intended use of the GR can also dictate the substrate mix. While ornamental GRs are limited by the FLL guidelines to less than 20% organic matter in the substrate mix, rooftop agriculture requires a higher proportion of organic matter. A study (Eksi et al., 2015) on GR substrates for cucumbers and peppers found that adding municipal yard waste compost at rates of 60% or 80% significantly improves plant growth and fruit yield. This outperformed ground-level gardens of the same composition.

5.3.2 Recycled Materials

To promote sustainable GR systems and lessen the negative environmental impacts of construction, it is essential to use recycled or locally sourced materials. Using recycled materials diverts waste from landfills. Eski et al. (2020) conducted a study to assess the viability of four recycled materials (crushed concrete, crushed bricks, sawdust, and municipal waste compost) and five materials that are local to Istanbul (lava rock, pumice, zeolite, perlite, and sheep manure) as GR substrates over the span of a year. Twelve substrate mixtures were prepared by combining the inorganic components (crushed concrete, crushed bricks, lava rock, pumice, zeolite, perlite) with the organic amendments (municipal waste compost and a sawdust-sheep manure mixture) in an 8:2 volume ratio.

The study evaluated several metrics, including plant growth index, chlorophyll fluorescence, plant coverage ratio, and survival rates of plant taxa, for five native species: *Allium schoenoprasum*, *Helichrysum italicum*, *Sedum lydium*, *Stachys thirkei*, and *Thymus vulgaris*. Substrates composed of pumice and perlite, amended with municipal compost, demonstrated superior performance in terms of plant growth, stress response, and chemical and physical properties, comparable to commercial substrates that are more resource-intensive to obtain. Substrates made of concrete, crushed bricks, lava rock, and zeolite, amended with the sawdust-manure mixture, showed satisfactory performance in certain metrics, indicating their potential suitability for specific GR applications. For example, lava rock’s thermal conductivity created unfavorable conditions for species dependent on stable substrate temperatures (Eksi et al. 2020). The study highlighted the significant impact of using recycled or locally available materials on plant growth. The substrates showed considerable decreases in carbon and nitrogen content as well as electrical conductivity from their initial values. Water retention, infiltration, and plant survival during dry periods were strongly influenced by the porosity and particle size distribution of the substrate mixtures. It
is important to note that this study was not attempting to compare local to non-local material effectiveness but was just demonstrating the viability of using local materials.

Jiang et al. conducted research in 2024 to explore the benefits of using recycled construction waste materials as substrates for GRs. They created six composite substrates using crushed bricks and concrete mixed with peat. The crushed brick substrates showed better results than crushed concrete. The medium-sized brick particles provided the best growth environment, outperforming traditional substrates. The findings suggest medium-particle-size brick substrates as a viable option for sustainable green roofing.

Several studies have explored the use of recycled materials as a drainage layer rather than a substrate in GRs. Recycled rubber, bamboo, polyethylene, and cork panels have demonstrated comparable or better performance than conventional materials. Recycled granular aggregates and urban waste aggregates have also been tested, both showing promising results regarding thermal resistance and water drainage (Cascone, 2022).

5.3.3 Substrate Optimization

Researchers are optimizing substrate composition to support diverse vegetation and meet ecological and structural requirements, hoping to promote standardization and, thus, easier adoption.

A recent study by Fei et al. (2023) assessed three lightweight substrate materials commonly used in GRs—peat soil, vermiculite, and pumice—across four mixes. Through laboratory tests and simulated rainfall experiments, twelve substrate modules were installed and evaluated for properties like lightness, water retention, nutrient retention, and rainwater runoff mitigation. The study revealed that mixes of peat soil and vermiculite, particularly the PV-40 mix (40% peat soil, 60% vermiculite), displayed superior lightness and water-holding capabilities compared to pumice alone, achieving the highest multifunction index. Research shows vermiculite's lightness and moisture retention make it most effective during heavy rainfall and a practical choice for GR applications. However, pumice mitigates nutrient leaching during rainfall.

Although higher nutrient substrate ratios can boost performance, the quality of substrate materials often outweighs the benefits of their combinations or proportions. Ongoing research is needed to refine GR substrate designs. To progress GR development in urban areas, a proposed assessment model could incorporate a wider range of functional indicators to tailor substrate designs to specific needs and conditions of the specific urban environment.
VI. CASE STUDIES ON GREEN ROOF SUCCESS

Addressing Sub-Question 4: Where are green roofs being utilized successfully, and why?

GRs are increasingly recognized for their ecological and urban benefits, leading to the establishment of various guidelines and standards in Europe and North America to ensure consistent performance and promote best practices. Notably, the German FLL Guidelines for GRs provide comprehensive directives on material selection, plant weights, substrate properties, and water flow characteristics.

However, the adoption of GRs varies globally. This section aims to explore how specific cities and countries have successfully integrated GRs into their urban landscapes. It will examine market trends and the momentum towards more sustainable urban development strategies.

6.1 Green Roof Market Potential and Trends

Currently, GRs account for only 1% of all global roof area, approximately 17 billion square meters, as calculated by Project Drawdown. The total addressable market is expected to more than double, a range of 45 to 70 billion square meters, by 2050. This could translate to a reduction of 0.53-0.99 gigatons of carbon dioxide emissions. Two scenarios were considered to estimate the impact of increased adoption of GRs from 2020 to 2050. In Scenario 1, the adoption of GRs at a 9% rate, resulting in a total adoption of 44.71 billion square meters of residential and commercial roof space. In Scenario 2, the adoption of GRs grew at an 11% rate, resulting in a total adoption of 69.06 billion square meters of residential and commercial roof space (Metz et al., 2024).

According to Market Research (2024) the GR market saw a significant surge in value in 2023, reaching $12.4 billion, and is projected to reach $35.2 billion by 2033, with a Compound Annual Growth Rate (CAGR) of 11.3% from 2024 to 2033. This growth – similar to that in Scenario 2 - is driven by several factors, including the increasing demand for residential constructions, heightened environmental awareness, and increased industrialization worldwide.

The German, Austria, and Switzerland (DACH) region in Europe dominates the GR market with a remarkable 32.3% share. The Asia Pacific region emerges as a rapidly growing market propelled by urbanization, population growth, and a mounting emphasis on environmental conservation. Governments across the region are incentivizing green infrastructure projects, spurring demand for GRs. China and Japan are among the frontrunners in adopting sustainable building practices.
While currently a smaller segment in terms of GR adoption, the Middle East and Africa are witnessing a gradual uptake of GRs, driven by a growing recognition of their benefits in mitigating UHI effects and enhancing energy efficiency. Initiatives promoting sustainable development and green building certifications are expected to fuel market growth in the region.

Latin America, characterized by diverse climatic conditions, presents opportunities for GR adoption, particularly in densely populated urban areas. Governments are introducing policies to promote sustainable construction practices, fostering market growth in countries like Brazil, Mexico, and Colombia.

The market's upward trajectory is attributed to heightened environmental consciousness, with individuals and organizations actively seeking ways to contribute to a greener future. Moreover, regulatory initiatives mandating environmentally friendly construction practices further propel market expansion.

Extensive GRs dominated new GR construction in 2023, offering lighter-weight, low-maintenance vegetation favored by both commercial and residential property owners. Their cost-effectiveness and eco-friendly nature, particularly in urban areas, where space constraints and environmental concerns prevail, contributed to their widespread adoption. Technological advancements, such as modular systems and improved stormwater management capabilities, further bolster the market penetration of extensive GRs.

Commercial buildings emerged as the dominant market segment for GR construction in 2023. The commercial building sector, including hospitality, healthcare, and education, drove significant growth. Financial incentives, such as tax credits and grants, offered by government agencies and environmental organizations, facilitated the widespread adoption of GRs in commercial settings.

Residential and industrial segments also exhibited promising growth opportunities. Increasing homeowner interest in sustainable living and urban gardening drove the adoption of GRs in residential buildings, while environmental impact mitigation and regulatory compliance drove GR adoption in industrial settings.

Government initiatives promoting eco-friendly practices and regulations mandating sustainable building practices are pivotal drivers for this burgeoning market. With a focus on mitigating environmental impact and fostering sustainable urban development, governments incentivize the adoption of GRs through tax breaks, subsidies, and regulatory frameworks, stimulating innovation and investment in the sector.
6.2 Green Roofs in Europe

6.2.1 Switzerland

According to a study conducted by Brenneisen & Baumann in 2024, Basel, Switzerland achieved the highest per capita GR coverage globally in 2019, with 5.71 square meters per inhabitant. Figure 10 shows an example of a GR in Basel. This statistic is highlighted in the 2019 report "Living Roofs and Walls: From Policy to Practice." Basel's initiatives, initially spurred by energy-saving measures, have evolved to focus on biodiversity conservation.

The city of Basel has actively promoted GRs through subsidy programs initiated in 1996, offering up to 90 CHF per square meter, and a subsequent program from 2005 to 2007 offering 30-40 CHF per square meter for retrofitting. These subsidies were financed by the Energy Saving Fund, sourced from 5% of all local energy bills.

Legislative support in Basel began with a 2002 amendment to the Building and Construction Law, mandating GRs on all new and renovated flat roofs, reinforced by a 2010 regulation. These measures aim to mitigate UHI and manage stormwater runoff more effectively. Future climate projections for Basel anticipate significant increases in both heat extremes and changes in precipitation patterns, underscoring the importance of GRs in urban climate adaptation.

The city's approach combines financial incentives and regulatory mandates to expand GR coverage. It was originally motivated by energy conservation and biodiversity protection. Initial funding in the mid-1990s aimed to raise awareness, followed by further investment in biodiversity studies. The 2005-2007 funding phase included specific ecological and safety standards for eligible projects. Basel's commitment to GRs has established a solid foundation for ongoing urban greening efforts, demonstrating that dedicated funding and regulatory support can effectively enhance urban sustainability.
6.2.2 Germany

Jan Davidse and Bornholdt's 2024 study highlighted Hamburg, Germany, as a leading city in GR implementation. In 2015, Hamburg introduced a GR policy to promote GRs on new and renovated buildings to accommodate population growth and climate adaptation, backed by the Ministry for Urban Development and Environment. The policy allocated €3 million to this initiative. Owners of projects over 20m² with at least 3 inches of soil depth can receive subsidies up to €100,000 via the Hamburg Investment and Development Bank (IFB) bank. However, completed projects are ineligible for this funding retroactively.

Hamburg's comprehensive Green Roof Strategy is the first of its kind in Germany and aims to develop 100 hectares of GRs by 2024. Unfortunately, finding a current update on this progress has been difficult. The program covers up to 60% of installation costs and subsidizes 50% in rainwater reduction fees due to the GRs’ retention capabilities. The city's broader strategy is to enhance open spaces, with 70% of new or renovated flat roofs targeted for greening.

The strategy is supported by a €3 million fund managed by IFB, and funded by various governmental budgets. In 2020, the strategy expanded to include green facades, with an additional €0.5 million allocated. Over six years, Hamburg & its residents have invested €13.5 million in GRs, with significant
public funding underpinning these efforts. This initiative represents Hamburg's commitment to integrating nature-based solutions into urban planning, enhancing the quality of life and environmental sustainability through innovative green infrastructure.

6.2.3 France
In 2015, France implemented a law to combat the UHI, requiring all new commercial buildings to have at least 30% of their rooftops covered with vegetation or solar panels (Biggs, 2024). Paris had already mandated GRs on new buildings or renovations exceeding 5000 m² since 2008, and this requirement was extended nationally (Rousset-Rouviere, 2022).

The Climate and Resilience Act of 2022, effective July 1, 2023, expanded these regulations. It now applies to new constructions and significant renovations of commercial, industrial, or artisanal facilities, as well as warehouses, hangars, and covered parking accessible to the public. The law also newly includes office buildings exceeding 1,000 square meters of ground rights-of-way and substantial office renovations, as well as shade houses over parking areas (Rousset-Rouviere, 2022). Exemptions may be granted by planning authorities if technical, security, architectural, or heritage constraints make installation infeasible, risky, or prohibitively expensive (Rousset-Rouviere, 2022).

6.2.4 Portugal
The Portuguese government established the Environmental Fund in 2020 to promote the requalification of buildings for improved energy efficiency. The Environmental Fund's "More Sustainable Buildings" support program offers a 70% subsidy, up to €3,000, for retrofits that include GRs following guidelines from the Portuguese National Association for Green Roofs (ANCV). The program aims to finance measures that promote rehabilitation, decarbonization, energy, and water efficiency in existing residential buildings (Palha & Fogeiro, 2021).

Barreiro was the first Portuguese municipality to offer a financial incentive for the construction of GR, as per Article 7 of their "Regulamento Municipal de Concessão de Incentivos ao Investimento." The regulation supports the efficient use of energy, including the construction of GRs (Palha & Fogeiro, 2021).

The Fifth Façade Project (PQAP) is a collaboration between the ANCV and the Porto City Council. Its objective is to include GRs in the environmental and urban strategy of Porto’s city. The project has been ongoing since August 2016 and involves various departments of Porto City Council, universities, foreign
municipalities, the European Federation of Green Roofs and Walls Associations, and the World Green Infrastructure Network. The PQAP is a significant step for the GRs movement in Portugal, as it is the first time a city council has included GRs in its urban planning documents. The PQAP also increases ANCV's executive capacity and visibility and highlights the interdisciplinary nature of the association (Palha & Fogeiro, 2021).

6.2.5 Denmark

The Municipality of Copenhagen began creating a GR policy program with the development of the Waste Water Plan in 2008. This was the first time the Municipality considered alternative ways for handling rainwater, establishing the framework for local rainwater management. Then, in 2009, the Climate Plan integrated the establishment of GRs as one of the adaptation measures intended to combat increased rainfall and rising temperatures (ENVS, 2015).

In May 2010, the City Representation decided that GRs would be mandatory for all new buildings with a slope below 30°. This strategy was incorporated into the 2011 Municipality Plan and the Climate Plan 2025. Based on these plans, the obligation to establish GRs on new buildings was included to require the establishment be in line with the architecture of already existing buildings (ENVS, 2015).

6.2.6 European Commission

Europe is set to experience significant changes in 2024, as European elections are scheduled for June 6-9. The outcome of these elections will reshape the European Commission, which will, in turn, have an impact on GRs in four recently passed policies (Petito, 2023).

A major policy milestone in 2023 was the Nature Restoration Law, which includes mandatory urban green targets. EU member states are required to submit National Restoration Plans to the European Commission, outlining their strategies to achieve targets and monitor progress. These plans will cover the period until June 2032, with reviews every ten years until 2050 (Petito, 2023). Another important policy development was the European Parliament's adoption of a report on revising the Urban Wastewater Treatment Directive (UWWTD). This report promotes green and blue infrastructure solutions for stormwater management (Petito, 2023).

The recent resolution on a revised Pollinators Initiative emphasizes the importance of incorporating biodiversity conservation and ecosystem services into urban planning, specifically to protect pollinator
populations. Lastly, co-legislators successfully agreed upon the revision of the Energy Performance of Buildings Directive (EPBD) in 2023. The directive now includes language conducive to fostering the widespread adoption of green infrastructure (Petito, 2023).

The following is from a report issued by the World Green Infrastructure Network (WGIN) (Guidi, 2021). On February 24th, 2021, the European Commission adopted a new EU Strategy for Adaptation to Climate Change. This strategy outlines a plan to prepare for the inevitable impacts of climate change. Of note, the strategy places importance on GRs as they provide multiple benefits for climate adaptation.

According to the strategy, blue-green infrastructures are versatile solutions that offer environmental, social, and economic benefits while building climate resilience. The strategy suggests investing in nature-based solutions to generate gains for adaptation, mitigation, disaster risk reduction, biodiversity, and health. Additionally, the Commission aims to make adaptation actions "systemic" across the EU by integrating adaptation into macro-fiscal policy and local action.

The strategy also calls for strengthened action to prepare Europe's building stock to withstand the impacts of climate change. GRs are essential to ensuring that buildings can contribute to large-scale adaptation, such as local water retention that reduces the UHI effect. The Commission has announced that it will support the integration of climate resilience considerations into the criteria applicable to the construction and renovation of buildings and critical infrastructure.

6.3 Green Roofs in Asia

6.3.1 China

GRs are gaining traction in China due to advancements in construction technology and government support, albeit more slowly than in other developed countries, largely due to overall lower levels of infrastructure investment, construction techniques and materials, and environmental regulations. Significant development has been noted in cities like Beijing, Shanghai, Guangdong, Chongqing, and regions like Sichuan and Zhejiang (Xiao et al., 2014).

China’s approach to GR development is marked by two distinct phases. The early phase up until the late 20th century saw gradual, spontaneous growth, primarily consisting of roof gardens without supporting policies or technical standards. The second phase, commencing in the early 21st century, represents a period of rapid expansion in the scope and quality of GRs, with diverse buildings like government offices, hotels, and hospitals leading the construction efforts (Xiao et al., 2014).
As of 2011, notable achievements include Beijing’s 1.5 million square meters and Shanghai’s 1.45 million square meters of GR areas. These cities, along with others like Chengdu, which boasts over 3 million square meters of GRs built by more than 500 companies, illustrate widespread adoption across various building types. However, residential GR development lags behind, especially in older areas (Xiao et al., 2014).

Plant suitability studies for GRs in China have highlighted species like Sedum and Dianthus as particularly effective. Innovations such as the Shanghai Academy of Agricultural Sciences' light flat roof greening technology have contributed to the field, although detailed, recent data on China's GRs remains scarce (Xiao et al., 2014).

In Beijing, strategies to develop sustainable, low-maintenance GRs without irrigation are being explored, particularly to address the city’s water scarcity issues (Zhang et al., 2021). Concurrently, to mitigate the UHI, Beijing aimed to increase GR coverage by 100,000–120,000 m² annually from 2015 to 2020, complementing broader urban greening efforts through the "urban vertical greening project" started in 2011, which added a million square meters by 2017 (Zhang et al., 2019).

Conversely, Guangzhou has struggled with its GR implementation. A report from the Guangzhou Institute of Landscape Gardening indicates that GRs only constitute 0.5% of the city's area, much lower than other major Chinese cities. Challenges such as water seepage and heightened management costs have hindered broader adoption despite regulations mandating GRs on new large public buildings since 1997 (The Global Grid, 2017).

6.3.2 Japan

The Tokyo government's Nature Conservation Ordinance mandates that new, repaired, or extended buildings with significant flat roof areas incorporate at least 20% green coverage, a figure that increases to 25% for roofs over 5000 m². This initiative has led to the installation of over 250 hectares of green roofs and walls in Tokyo (Jim et al., 2022).

Efforts to promote this policy included widespread media outreach, resulting in over 5,700 buildings in Tokyo adopting approximately 180 hectares of GRs to comply with local regulations (Doi & Okano, 2015). The city aimed to install 1,000 hectares of greenery by 2016, fostering biodiversity and mitigating UHI through strategic greening of roofs and ground-level spaces.
According to 2017 data, in Tokyo's Sumida ward alone, potential GR space after adjustments for architectural constraints amounts to about 1.18 km², representing 25% of the ward's total roof surface area, with current GR coverage at just 0.46% (Aleksejeva et al., 2022).

Launched in 2023, the Tokyo Green Biz project is a century-long initiative aimed at enhancing green infrastructure across the city. This project promotes GRs, water-friendly seawalls, and nature-based solutions for climate resilience, with over 2.7 million square meters of GRs already established. It also focuses on conserving local green spaces and expanding urban parks, with the total green area reaching 2,063 hectares by 2023 and plans for further expansion by 2030 (Tokyo Metropolitan Government & Tokyo Green Biz, 2024).

6.3.3 South Korea

South Korea has actively pursued GR projects since the mid-1990s, particularly in Seoul, where urbanized areas cover 364 km², accounting for 60% of the city's total area, with rooftops comprising 46% of this urbanized zone. Since 2002, the Seoul Metropolitan Government has invested about KRW 71 billion, creating 315,532 m² of GRs across 758 sites. In 2021, subsidies for GRs increased from 50% to 70% for construction costs, underscoring a continued commitment to these initiatives (Ji et al., 2022).

The building sector in South Korea contributes to roughly a quarter of the country's indirect greenhouse gas emissions. GRs are seen as a strategic response, with the public showing willingness to pay for such projects, estimating their total annual economic value at KRW 90.5 billion (US $76.7 million). However, a cost-benefit analysis indicates that such projects are economically viable primarily in major cities like Seoul (Ji et al., 2022).

As part of the Green K-New Deal (launched in July 2020), South Korea plans to invest significantly in green technologies, including GRs. The government proposed an investment of $135 billion, combining federal, local, and private funds. This initiative aims to create 659,000 jobs by 2025 and strengthen urban resilience against climate change (Thurbon et al., 2022; Shafique et al., 2018).

My aim for this section was to emphasize the robust policy support many countries give to greening efforts. These policies clearly speed GR adoption and allow for best practices through standards being put in place. I found this section inspirational, and it gives me hope that GR momentum is there.
VII. ANALYSIS FOR CALIFORNIA AND THE MEDITERRANEAN BIOME

Addressing Sub-Question 5: What are the lessons learned from and for California?

The majority of regions with Mediterranean climates have mild winters and warm summers. According to the Köppen climate classification (National Geographic, 2024), "hot dry-summer" climates with temperatures above 72°F (classified as Csa) and "cool dry-summer" climates with temperatures below 72°F (classified as Csb) are often referred to as "Mediterranean". In many areas with this climate, temperatures have a strong diurnal character during the warm summer months, due to strong heating during the day and rapid cooling at night. As a result, these areas receive almost all of their precipitation during winter and spring and may go three to six months in the summer and early fall without significant precipitation (Cascone, 2019).

These dry months make it difficult for plants to grow and survive. Unfortunately, summer water shortages, a recurring problem in the Mediterranean region, are expected to increase due to climate change. While irrigation is an option, it is not economically or ecologically satisfactory long-term solution. High summer temperatures and prolonged seasonal drought in Mediterranean regions also make it difficult to install efficient and fully functional GRs. Therefore, new considerations about substrate characteristics and plant species are emerging in an adaptive approach to green roof construction in these areas (Cascone, 2019).

California's climate ranges from hot desert to alpine tundra, shaped by latitude, elevation, and proximity to the Pacific Coast. The Mediterranean climate can be found in California's coastal regions, the Sierra Nevada foothills, and much of the Central Valley. Therefore, California must explore the optimal GR specifications for the Mediterranean climate. This section aims to examine how GRs have performed in Mediterranean climates, delve into successful implementations in specific Californian cities, and make a case to state-level policymakers about the adoption of GRs across California.

7.1 Optimization for the California Climate

In Mediterranean climates, an ideal green roof should prioritize sustainable materials, water retention, and renewable energy through the use of PV panels. An innovative GR solution has been proposed by Cascone (2022) for Mediterranean climate areas. It uses recycled polyethylene granules for the drainage
layer and a substrate with more organic matter to sustain vegetation during drought. The recycled polyethylene granule drainage layer is designed to retain excess water. The high ratio of organic material in the substrate better sustains vegetation during prolonged periods of droughts in the Mediterranean area. When compared to two commercial GRs, this solution reduced surface temperatures and the building’s energy consumption for cooling.

Chenot et al. (2017) conducted a study on the thickness and composition of substrates required to maintain adequate moisture for vegetation cover. They combined fine elements, such as clays and silts, with coarse elements, such as pebbles, to support Mediterranean vegetation communities without human intervention. The results showed that a substrate thickness of 6 inches, composed primarily of clays and silt (75%) and pebble-sand (25%), was the optimal level for GRs in a Mediterranean climate (Cascone, 2019).

Ondoño et al. (2015) studied the germination capacity and development of five Mediterranean plant species on three different recycled substrates. The result showed that crushed bricks and expanded clay substrates were more appropriate for Mediterranean plant growth than a clay-loam soil mixture. The authors recommended the use of lightweight and highly porous substrates for Mediterranean plant growth and the combined use of perennial and annual species (Cascone, 2019).

7.1.1 Irrigation

In Mediterranean countries with long and dry summers, irrigation is necessary to sustain vegetation during extended dry periods. The success of a GRs depends on several variables like the average annual rainfall, distribution of rains, temperature trends, and relative humidity. The type of irrigation system used also matters. The Rain Irrigation System, the oldest type, simulates rainfall through high-pressure water sprayers, making it ideal for both large and small GRs. However, some water is lost due to wind and heat before it reaches the ground and root apparatus. The Micro-irrigation System is a more modern approach based on frequently providing small amounts of water near the plant roots. This system reduces water losses due to wind and evaporation (Cascone, 2019).

Azeñas et al. (2018) quantified the effect of irrigation water volume on the thermal capacity of a GR system in a Mediterranean area. They found that modules with limited irrigation reported lower heat fluctuation than well-irrigated modules. On the other hand, Schweitzer & Erell (2014) revealed that the water requirements of different plant species ranged from 2.6 to 9.0 L/m² per day. *Aptenia cordifolia* was the most water-efficient plant species providing the highest cooling benefit per unit of water required for
irrigation (Cascone, 2019). Borràs et al. (2023) examined irrigation schedules. Installing a daily irrigation system throughout the year yielded significant cooling savings of 26.52% for extensive GRs and 36.04% for intensive GRs compared to a reference model. These savings surpassed those of other models with less frequent or no irrigation. A daily irrigation schedule limited to the warmer months (June to September), with no irrigation for the rest of the year, optimized the system by increasing energy savings and reducing water use. This schedule minimized unnecessary water use during cooler months, aligning better with seasonal energy needs and avoiding the reductions in heating savings seen with year-round irrigation.

While increased irrigation can enhance cooling effects in intensive GRs, it does not significantly affect extensive roofs where water simply exceeds storage capacity without additional heat loss benefits. Optimizing irrigation schedules according to seasonal energy demands in regions with high year-round solar radiation, such as the Mediterranean, can enhance overall energy savings without increasing water consumption.

Reducing soil temperature while keeping air temperature relatively high has been found to improve the growth and survival of plants (Leotta et al., 2023). This is a challenge when balancing the need to reduce substrate depth to limit weight and installation costs. Research by Savi et al. (2015) on two drought-adapted shrubs (Cotinus coggygria Scop. and Prunus mahaleb L.) in shallow substrates of 4 or 5 inches depth showed less water stress than expected. This suggests that even with reduced plant biomass leading to lower water consumption, shrubs could thrive on green roofs in Mediterranean areas with only a 4 inch deep substrate.

7.1.2 Factors for Plant Selection

The following is synthesized from Leotta et al. (2023): plant survival is a crucial factor in selecting the appropriate plant species for GRs and affects maintenance costs. Succulent plants that have the CAM photosynthetic cycle are commonly used on GRs and suit xeric environments, which are typical conditions of GRs. Forbs and grasses generally have a lower survival rate than drought-resistant succulent plants. Plant species with C4 photosynthesis, which are better adapted to thermal and water stress, ensure greater survival on roofs in hot and dry climates. The height and coverage of herbaceous plants can influence both the interactions between plant species mixtures and the positive ecosystem functions. Positive interactions can be observed between plant species, and a greater sward (upper layer of soil) height can increase the survival rate of plants on green roofs.
In the absence of irrigation, the selection and survival of plants depend mainly on the substrate depth of the GR system. In semi-arid regions, roofs with higher substrate depths may be required, ranging from 6 inches for succulents to over 12 inches for grasses and herbs, but a compromise must be found between substrate depth and weight because building structures often cannot support excessive weight loads. The inclusion of a water retention layer, which stores water available to plants for a longer period, could be a viable solution. Placing the GR in a more sheltered position reduces the rate of evapotranspiration and helps keep the substrate moist longer. Meaning shade will increase the overall health of these plants.

To identify plants capable of surviving on extensive GRs in a Mediterranean environment, the inclusion of native plants has been tested with positive results. However, the choice of native plants should not be based solely on their adaptation to the climatic conditions of the site because the conditions in which they evolved, and above all the depth and characteristics of the soils, are very different from those of the substrate used in GRs, which are generally shallow and well-drained. It is necessary to pay attention to plants originating from habitats characterized by shallow and well-drained substrates, such as rocky or ruderal habitats, as these communities may have plant species suitable for extensive GRs. Finally, the seeds of native plant species must be able to bud on GRs in order to sustain vegetation.

Identifying several complementary plants with characteristics and physiology suitable for the conditions of a GR in a dry climate can significantly reduce irrigation needs and related maintenance costs. Monoculture increases the risk of parasitic attack, so multiple plant species improve the chances of success.

Raimondo et al. (2015) provided insights into the importance of species-specific drought resistance strategies and hydraulic properties for selecting Mediterranean native species best suited for specific technical functions and ecological requirements of GRs. The study used two Mediterranean shrub species, *Arbutus unedo* and *Salvia officinalis*, and found that both were suitable for use in GRs in the Mediterranean area (Cascone, 2019).
Figure 14: Arbutus unedo, also known as the Strawberry Tree, is native to the Mediterranean climate and has strong adaptability in California (Image Source: SRJC)
Savi et al. (2015) investigated the performance of two Mediterranean shrubs, *Cotinus coggygria* and *Prunus mahaleb*, grown over GRs with extremely shallow substrate depths. They identified the impact of substrate thickness on shrubs' water status, survival, and growth in a sub-Mediterranean climate. The results confirmed that installing extensive GRs vegetated with stress-tolerant shrubs in sub-Mediterranean areas is possible using a 4-inch deep substrate (Cascone, 2019).

Van Mechelen et al. (2014) provided an overview of plant traits crucial for plant survival in areas with prominent dry periods, especially in the Mediterranean climate. They incorporated the most critical plant traits into an easy-to-handle screening tool and applied it to a species list of a vegetation survey in Mediterranean southern France. The study found that Sedum album and Sedum acre were the highest-scoring species, both of which are already frequently used on GRs. The authors highlighted that 35% of the species in the new potential species group recommended in the Mediterranean region are therophytes (Cascone, 2019).

As noted, plant selection for GRs involves several factors such as habitat template, plant characteristics, canopy structure, growth rate, nutrient requirements, and sensitivity to pollution. Ideal plants should be drought, heat, and wind tolerant, pest resistant, light-loving, have low height, good coverage, and shallow root system. Succulents, geophytes, perennial grasses, and herbaceous flowers are suitable for extensive GRs. Species with slow rates of water use under water deficit conditions are more tolerant to drought (Leotta et al., 2023).

Two approaches can be used to select plant species for GRs. First, the "habitat template" approach aims to create conditions similar to natural habitats to help plants adapt. Secondly, selecting plants with certain strategic characteristics such as aesthetic value, resistance to abiotic stress, and canopy structure can be effective. Plants with mostly horizontal leaf distribution and extensive foliage are preferred to reduce solar radiation. Succulents like Sedum and Delosperma are reliable options due to their shallow root systems and high drought tolerance. Geophytes and therophytes are also promising choices. To reduce urban stormwater runoff, plants must use water when available and reduce transpiration when water is limited (Leotta et al., 2023).

Azenas et al. (2018) analyzed five Mediterranean plant species grown in conditions similar to those found on a GR. All species survived and exhibited suitable aesthetic performance and vegetation coverage.
*Sedum sediforme* recorded the highest biomass production and the least changes in appearance. *Brachypodium phoenicoides* appears to be an interesting alternative due to its valuable aesthetic characteristics and water consumption during the rainy season.

The suitability of four native plant species in Portugal - *Antirrhinum linkianum Boiss. & Reut.*, *Asphodelus fistulosus L.*, *Centranthus ruber (L.) DC.* and *Sedum sediforme (Jacq.) Pau* - was evaluated based on resilience and drought tolerance. *Asphodelus fistulosus L* was found to be the most suitable for use due to its high number of flowers, longest seed production duration, and highest area coverage. The level of irrigation did not significantly affect flowering and green coverage for any of the species, and irrigation costs could be reduced by adopting deficit irrigation (Esfahani et al., 2022).

Attention has been given to therophyte species; these annual plants are significant in the Mediterranean basin's vegetation but are underrepresented on GRs due to their short lifecycle, difficulty in regenerating, and lower competitiveness compared to perennials. Their absence in summer limits GRs’ cooling effects during hot months (Leotta et al., 2023). Van Mechelen et al. (2014) studied plants in natural habitats in southern France with conditions akin to green roofs, identifying 372 potential species, 35% of which are therophytes. These annuals are noteworthy for their brief flowering periods and high seed production. Their conservation value is also significant, as many are threatened in Mediterranean regions.

Several species of sage that are native to Greece were evaluated for their potential use in an extensive green roof in a Mediterranean climate during the summer period. The species evaluated were *Salvia fruticosa Mill.*, *S. officinalis L.*, *S. pomifera ssp. pomifera*, *S. ringens Sm.*, *S. tomentosa Mill.*, and interspecific hybrids. The evaluation was conducted with regular or reduced irrigation, with substrate humidity of 16-22% every 2-3 days and 7-11% every 4-5 days. The results showed that regardless of the irrigation frequency, *S. pomifera ssp. pomifera x S. ringens* and *S. officinalis x S. pomifera ssp. pomifera* had the highest survival rate among all hybrids and species, as well as satisfactory growth. On the other hand, *S. fruticosa* had the lowest survival rate. These findings suggest that numerous Salvia species could be used in extensive green roofing in arid regions (Leotta et al., 2023).

A study looked into the use of two Mediterranean shrubs, *Arbutus unedo L.* and *Salvia officinalis L.*, for GRs. The first shrub, *Arbutus unedo L.*, can quickly reduce its stomatal opening at the first signs of stress, helping to prevent too much water loss. The second shrub, *Salvia officinalis L.*, tolerates big changes in water levels by only partly closing its stomata. Both plants are suitable for Mediterranean GRs, although the *Salvia officinalis L.* is more sensitive to the type of soil it's planted in (Leotta et al., 2023).
I created Table 5 below to summarize the above information into a solution-oriented checklist for optimization and standardization in a Mediterranean climate.

Table 5: Standardization and optimization checklist for a Mediterranean environment (Source: Author)

<table>
<thead>
<tr>
<th>Mediterranean Climate Characteristics</th>
<th>Plant Selection</th>
<th>Substrate Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Summers are long, warm, and dry</td>
<td>✓ Native plants from shallow, well-drained habitats</td>
<td>✓ Combination of clays, silts, and coarse elements like pebbles</td>
</tr>
<tr>
<td>• Strong diurnal temperature variation</td>
<td>✓ High tolerance for heat &amp; wind</td>
<td>✓ High organic matter substrates to support vegetation during droughts</td>
</tr>
<tr>
<td>• Precipitation in winter &amp; spring</td>
<td>✓ Drought-resistant species with CAM photosynthetic cycles</td>
<td>✓ 6-12in. deep to balance water retention, weight, and plant support.</td>
</tr>
<tr>
<td>• Mild winters</td>
<td>✓ Succulents, geophytes, and perennial grasses</td>
<td>✓ Recycled polyethylene granules for drainage</td>
</tr>
<tr>
<td></td>
<td>✓ Mixed species to reduce parasitic attacks</td>
<td></td>
</tr>
</tbody>
</table>

7.2 Successful Green Roof Implementation in California Cities

There is a concerning lack of both incentives and mandates for GRs in California, at both state and city levels. Currently, San Francisco is the only city in California that has a requirement for a portion (15-30%) of a new construction's roof to be designated for solar and/or GRs. While cities such as Los Angeles, Berkeley, and Bakersfield are promoting GRs, they do not yet have mandates for them. Most cities pursuing initiatives are focusing on solar and cool roofs. Those technologies have significant merit and are worthy of promotion. Even absence of strong government support, GRs have proven long-term viability and deserve more consideration from California governments alongside solar and cool roofs. I wanted to show these examples to demonstrate the viability of GRs in California and also demonstrate the impacts they have, even on a small scale. With more Government support the benefits of GRs could be felt to a much larger degree.

7.2.1 Sonoma Academy High School, Sonoma

The following case studies are obtained from Dvorak & Drennan (2021).
Sonoma Academy, shown in Figure 15, completed in September 2017, boasts an intensive GR designed by Rana Creek. The project was designed by Mar Structural Design and installed by SYMBIOS across an area of 6,074 ft². The GR is inspired by Garry oak ecosystems and features a diverse array of plant species with substrate depths ranging from 8 inches to 12 inches. The roof is designed to create a habitat for local and migrating birds and insects.

The vegetation on the green roof comprises grasses such as Deer grass (*Muhlenbergia rigens*) and Purple needlegrass (*Nassella pulchra*), herbaceous perennials such as California fuchsia (*Epilobium canum* ‘Everett’s choice’) and Hummingbird sage (*Salvia spathacea*), as well as shrubs like Cleveland sage (*Salvia clevelandii* ‘Pozo Blue’). The GR also includes succulents like Stonecrop (*Sedum spathulifolium*) and a selection of plants specifically for the photo-voltaic understory, like Foothill sedge (*Carex tumulicola*) and Yerba buena (*Clinopodium douglasii*), strategically placed to cool solar panels and enhance the roof’s ecological function.

The GR has an irrigation system that draws water from a 19 m³ (5000-gal) cistern connected to other cisterns on campus. The irrigation system is meticulously zoned to meet the specific water needs of the varied plant life and is monitored by a weather tracking system. This system also supports 88% of the building’s non-potable water needs, including flushing toilets and watering plants.
Figure 15: Sonoma Academy is an example of a North Bay Area GR that has used native plants to successfully offer habitats for local animals (Image Source: Symbios, 2021)

7.2.2 Slide Ranch Nature Center, Muir Beach

This GR project, shown in Figure 16, was completed in 2017. It covers an area of 740 ft² and was created with the aim of highlighting native plants that grow in the coastal meadows found on the property. The GR enhances stormwater retention and supports local wildlife. The substrate, which is 6 inches deep, consists of locally sourced materials and supports a variety of plant life, including small-flowered needlegrass, California aster, coast buckwheat, seaside daisy, wild strawberry, yarrow, yerba buena, and bluff lettuce. All plants were grown from seeds collected on-site. The roof has successfully attracted a range of pollinators, including butterflies, bees, and birds, demonstrating its ecological value. All planted species have been successfully established, indicating the effectiveness of the chosen native vegetation in this controlled environment.
The GR is equipped with an overhead spray irrigation system that is utilized as necessary to maintain plant health. For the first two years, the ranch staff managed the roof maintenance monthly, after which it was outsourced due to the specialized nature of the work required.

*Figure 16: This roof of Slide Ranch is sloped, showing that GR design can incorporate more than just flat surfaces (Image Source: Symbios, 2021)*

7.2.3 One South Van Ness Avenue, San Francisco

In 2010, San Francisco launched its first pilot project for GRs (pictured in *Figure 17*), covering an area of 9,579 square feet. The project aimed to demonstrate the potential of GR technology and provide a learning opportunity for interested parties. The objective was to create a self-sustaining, low-maintenance, and resilient GR that supported urban wildlife and utilized no potable water.

The GR consists of a biodegradable Biotray system and a monolithic (layered) system, with a combined substrate depth of 6 in. The Biotrays were made of coconut coir, organic latex, and wood chips, resting on top of an additional 3 inches substrate made from scoria (volcanic rock), sand, compost, and fir bark enriched with essential macronutrients and micronutrients. This substrate was inoculated with mycorrhizal fungi to enhance plant growth.

The plant palette comprises species native to California's coastal ecoregions, such as Coast poppy (*Eschscholzia californica ssp. maritima*), California polypody fern (*Polypodium californicum*), and Little
Sur manzanita (*Arctostaphylos edmundii*). These plants were chosen for their compatibility with the local climate and ability to thrive in the rooftop's unique conditions.

Irrigation is managed through a 25.6 cubic meter (6,500 gallon) cistern and pump system that feeds a drip irrigation system embedded in the growing medium. The irrigation schedule varies seasonally, with reduced or no watering during the rainy season and weekly watering during the drier months.

The City of San Francisco is responsible for maintaining the GR. They employ no pesticides or herbicides in its upkeep. Observations have noted that hummingbirds, bees, dragonflies, and butterflies are frequent visitors, contributing to the roof's biodiversity. Over time, certain plant species have naturally migrated within the roof to their preferred microclimates, demonstrating the ecosystem's adaptability and dynamic nature.

*Figure 17: One portion of the One South Van Ness GR (Image Source: Greenroofs.com, 2024)*
7.2.4 California Academy of Sciences, San Francisco

In 2008, a project featuring a substantial GR spanning 1 hectare was completed, as shown in Figure 18. This living roof was designed to exhibit both resistance and resilience. Its 6 inch-deep custom-blended substrate incorporates local materials and microbes to foster robust vegetation growth. The roof facilitates research, with logs placed to observe how woody debris influences the development of microflora in GR substrates. Notably, the rooftop also serves as a secure location for the solarization of bones from archaeological digs before their inclusion in exhibits or storage at the museum. Additionally, the south-facing top of the roof was developed as a xeric habitat, supporting plants adapted to drier, warmer conditions.

Initially, the California Academy of Sciences introduced nine pre-tested plant species to the GR, quickly expanding to 70 taxa to enrich the diversity of California coastal meadow species. This GR serves as a dynamic platform for ongoing botanical trials and educational outreach. The Academy's website lists nearly a hundred taxa trialed on the roof, ranging from annuals and ferns to shrubs and succulents. Furthermore, the roof’s irrigation system utilizes harvested rainwater, distributed via subsurface drip lines activated by moisture sensors during the drier months, illustrating a sustainable approach to plant maintenance.

The rooftop has also become a vibrant habitat for various wildlife, observed and documented through the iNaturalist.org project managed by the Academy. This includes diverse insect species and birds, highlighting the roof's role in urban biodiversity. Moreover, Pacific Horticulture has recognized the roof's best-performing native vegetation, adapted to the unique rooftop microclimates affected by elements like salt spray and high winds. These insights underscore the ecological and educational significance of the GR, demonstrating its successful integration into the urban landscape and its contribution to environmental sustainability and biodiversity.
Figure 18: The incredible and 1 hectacre roof of the Cal Academy is home to many insects and plants (Image Source: Sheber, 2015)

7.2.5 Sutter Hospital at Van Ness and Geary, San Francisco

The project, completed in March 2019, boasts a GR of 26,791 square feet that is both visually appealing and easy to maintain, partially seen in Figure 19. The design team prioritized the use of native vegetation to create simple garden beds that provide easy access to nature for patients without the complexity of formal gardens. The main objective was to cultivate a stable and long-lasting plant community that reduces the chances of infestations and supports local wildlife. This approach has favored the growth of fibrous-rooted herbaceous plants, which have attracted native pollinators.

The GR contains different plants such as annuals, ferns, grasses, and herbaceous perennials, all of which are native to the region. Among the selected species are hedge nettle, deer fern, western sword fern, California fescue, ‘Siskiyou blue’ Idaho blue fescue, and purple needle grass. These plants contribute to the area's ecological health and help retain and purify stormwater. The roof also features a central visitor area that extends indoor space to an outdoor seating area surrounded by colorful native grasses and plants that attract hummingbirds, butterflies, and other pollinators.

To support this green infrastructure, the project includes an advanced irrigation system that collects approximately 1400 cubic meters of precipitation annually. This water is stored in a 340 cubic meter
cistern located in the hospital’s parking level and reused to irrigate the green roofs, ensuring sustainable management of water resources and fostering a thriving rooftop ecosystem.

Figure 19: The Sutter building is a great example of utilizing GRs for mental health improvement and habitat creation (Image Source: USGBC, 2024)

7.2.6 Salesforce Transit Center, San Francisco

In 2018, a project was completed which created a 1.82-hectare green roof. The GR was designed as a didactic park to educate visitors about California's native ecoregions and other regions worldwide with Mediterranean-like climates. The park is structured in a way that features a thematic gradient that extends from east to west, from wet to dry areas. The park includes diverse plant collections ranging from wetlands, shrublands, and forest communities to desert plants. The plant communities are thoughtfully arranged to cover various habitats such as coastal meadows, chaparral, oak woodlands, desert scrub, and succulent plant communities.

The Salesforce Transit Center rooftop park, shown in Figure 20, is not just a botanical garden but also a conservation effort. It showcases over 55 species of trees, 208 species of understory plants, and 23 species of groundcovers. These collections are meticulously curated to attract endangered species like the Bay checkerspot butterfly and are abundant with pollinator plants to support local ecosystem needs.
Noteworthy plant selections include the Dwarf horsetail, native to Canada and the northern U.S., and the Mexican grass tree from northeastern Mexico.

The project's innovative irrigation system is a hallmark of its sustainability features. Rainwater and greywater from the transit center are collected and purified in the rooftop Wetland Garden. This recycled water is then used for irrigation and in restroom facilities throughout the transit center, optimizing water use. The system uses multiple irrigation zones and moisture sensors to regulate water flow based on the weather, soil moisture levels, and the specific needs of the plant collections.

This GR has become a hub for biodiversity, with citizen scientists on iNaturalist.org recording frequent sightings of hummingbirds, bees, and other wildlife. This illustrates the vibrant life supported by this urban ecosystem.

![Salesforce Park](Image)

Figure 20: Salesforce Park stands as a prime example for how a downtown urban environment can coexist with nature (Image Source: Pershan, 2024)

7.2.7 Other Successful Green Roof Projects In California

**Ecocenter at Heron’s Head Park, San Francisco**: The EcoCenter, built in 2010, has two small GRs that share space with solar panels and skylights for a total of 1,100 sq ft. The plant life includes a mix of pre-
grown and re-seeded species, ranging from ferns and grasses to shrubs and succulents. An overhead irrigation system, supported by harvested rainwater stored in tanks, ensures that the plants receive adequate water. The GRs have become a haven for birds, butterflies, bees, and other insects, contributing to the overall biodiversity of the park.

**Los Angeles Museum of the Holocaust, Los Angeles:** The GR, completed in 2010, covers an area of 12,701 square feet and serves as both a park and a garden for the museum. The vegetation is resilient and durable, with plants selected to withstand temperature fluctuations and create a visual effect appropriate for the museum's sloped facade. The roof is irrigated from rainwater collected in cisterns, and bees, sparrows, doves, and pigeons have been observed. The three grasses selected for the garden have performed well since 2010.

**Palomar Medical Center, Escondido:** The GR project, which covers 60,000 square feet, was completed in 2012. It was designed to be water and energy-efficient and built with recycled and renewable materials. The plant community of the green roof was inspired by a coastal meadow to attract wildlife and provide views of greenspace. The vegetation was established through hydroseeding and irrigated with harvested rainwater. The GR has observed butterflies, bees, hummingbirds, and migratory birds. All of the vegetation planted has adapted to the roof.

**NOAA Southwest Fisheries Science Center, La Jolla:** The GR project was completed in 2013, covering about 30% of the roof space (27,000 sq. ft.) with plants and the rest with photo-voltaic panels. The GR was designed to manage stormwater, conserve energy, and enhance biodiversity. Native plants were chosen to showcase their diversity and were grouped in mosaic drift patterns. The irrigation system includes multiple irrigation zones that make use of harvested rainwater. The vegetation provides a habitat for bees, hummingbirds, and many insects.

**Good Earth Plants Building #1, San Diego:** Completed in 2007, this extensive GR covers an area of 1,700 square feet and features California and southwest native plants, including cacti, succulents, grasses, sun rose, desert marigold, and beach primrose. It has two substrate designs, one with a 4–5 inch deep built-up GR system and the other with 24 modular units. The roof is irrigated by a subsurface drip system operating for 20 minutes three times per week during the summer. The roof is home to various wildlife, including crows, ravens, spiders, bees, Monarch butterflies, aphids, and ladybugs. The best-performing plants on the roof include agave, grasses, milkweeds, onion grass, prickly pear, and yarrow. Coyote brush,
a California native woody shrub, has established itself on the roof and is retained for its benefit to pollinator insects and wildlife.

**Takeaway**: There is a growing interest in implementing GRs in California, especially using native vegetation. Despite California's coastal region's dry and hot summers, many successful GR projects have been implemented, particularly in the slightly cooler and wetter northern California. GRs with native plants are less common in southern California, especially the Los Angeles area. The existing GRs in southern California often rely on harvested rainwater or greywater to supplement natural rainfall, reflecting a viable but underutilized approach to GR design in drier regions.

GRs in California typically feature a minimum substrate depth of 6 inches, accommodating a diverse mix of native grasses, annuals, and herbaceous perennials. Some roofs thrive with even shallower substrates through careful design and maintenance. These roofs often have irrigation systems that utilize collected rainwater, promoting the sustainability goals of the projects. Native plants, occasionally supplemented with non-native species, dominate these roofs, enhancing local ecosystems and biodiversity.

The design, implementation, and maintenance of these green roofs involve meticulous planning and often partnership with firms experienced in ecoregional designs. These projects serve as critical models for future development, offering insights into the benefits and challenges of integrating green infrastructure within urban environments.

**VIII. DISCUSSION AND CONCLUSION**

In this section, I will revisit the questions and objectives presented in Section 1.3. Then, I will discuss the most significant findings and synthesize them in the conclusion to answer the study's main question.

### 8.1 Environmental Benefits

**Sub-Question 1**

*What are the environmental benefits of green roofs, and under what conditions are they significant?*

**Objective**: In evaluating the advantages, it is crucial to determine which are most effective in promoting environmental sustainability. I will employ a weighted rating system that properly assesses each benefit to accomplish this.
A vast amount of literature is available on the benefits of GRs for ecosystems, their hydrological properties, and their addressing of thermal issues such as the UHI. Green roofs serve multiple purposes; their benefits can be extensive or specialized. However, based on my analysis, I believe there is a clear ranking of the environmental effects that GRs have.

1. **Thermal Performance: 5 stars** GRs offer excellent insulation, reduce heat absorption, mitigate UHI, and cool surrounding air, resulting in improved local climate and reduced energy consumption for cooling buildings in hot weather.

2. **Stormwater Management: 4.5 stars** GRs help manage urban runoff by retaining rainwater, reducing peak flows, and lowering the risk of flooding. Studies have shown that even a small percentage of GRs in a city can significantly reduce annual runoff.

3. **Ecological Support: 4 stars** GRs help increase local biodiversity by providing habitats for pollinators and birds, connecting fragmented habitats, and supporting urban wildlife.

4. **Air quality: 4 stars** GRs filter pollutants from the air, reducing harmful particulates and gases. This contributes to cleaner and healthier urban environments.

5. **Noise Reduction: 3.5 stars** GRs reduce noise pollution by acting as natural sound barriers, making them ideal for urban areas.

6. **Mental Health: 3 stars** GRs have been linked to enhanced mental health by providing urban dwellers a place to relax and connect with nature, reducing stress levels and improving overall well-being. However, there is a concern about equitable access and gentrification.

7. **Water Quality: 2.5 stars** GRs filter pollutants from rainwater and improve water quality. This reduces pollution in natural water bodies and minimizes harmful runoff events in urban water systems. Many factors determine whether this is successful, such as substrate materials, pollutants on plants, rain quality, and air quality.

### 8.2 Challenges and Opportunities

**Sub-Question 2**

*What are the challenges and opportunities of green roofs, and under what conditions are they significant?*

**Objective:** I want to understand the main factors slowing and preventing the widespread adoption of GRs. In this section, I will examine those factors and identify opportunities for mitigation.
GRs can be costly to install and maintain, but they offer long-term economic and environmental benefits such as increased durability of roofing materials. Maintenance practices are critical to ensure their effectiveness and longevity. GRs can be economically viable over their lifespans, and some cities in the United States offer incentives to promote their adoption. GRs can significantly contribute to sustainable building development and greenhouse gas reduction by maintaining cooler operating temperatures and increasing power generation when integrated with solar photovoltaic systems. However, careful consideration is necessary for their installation and maintenance.

GRs face significant US adoption barriers due to a lack of public awareness and economic feasibility. While there is interest in GRs, enthusiasm declines for private structures due to high costs and competition from solar panels. Governments can play a central role in promoting GRs by providing financial incentives and enhancing public awareness. GR legislation sets specific requirements for vegetation types, soil depth, and water conservation practices, but a lack of awareness can hinder compliance. Policies and incentives for GRs vary greatly across regions, but initiatives like the Living Architecture Performance Tool provide a standardized rating system to support best practices that maximize the impact of GRs.

Commercial real estate serves as a perfect foundation for GRs. They offer a flat, large surface that would require minimal roof adjustments. GRs on commercial properties are proportionally cheaper for companies as opposed to residential development.

8.3 Technologies and Innovations

**Sub-Question 3**

*What technological developments and innovations for green roofs enhance the benefits and address challenges?*

**Objective:** I assess the most pertinent technologies and innovations that could promote wider adoption of GRs.

Modular GRs are sustainable systems that combine environmental restoration with modern design flexibility and stormwater management capabilities. They have pre-vegetated trays with slotted sidewalls and flat bottoms that facilitate root integration and water circulation. These trays are made from recycled polypropylene, making them durable and eco-friendly. They are designed to be interlocked, simplifying
assembly and disassembly, allowing for easy installation and maintenance without the need to dismantle the entire system. Modular GRs offer a dynamic alternative to traditional GRs and reduce labor and waste during construction. They allow for aesthetic customization to fit various architectural styles and needs, supporting extensive landscaping that can transform urban spaces.

GRs and solar PV systems, when integrated, create a synergy that improves overall sustainability. The evapotranspiration from GRs cools the PV panels, enhancing their electrical efficiency, while the panels provide necessary shade that reduces water evaporation and protects the vegetation from excessive sunlight. Integrated systems generate more electricity than conventional setups, boosting total energy output by 23.83%, and reducing CO₂ emissions more effectively than conventional roofs. However, installation and maintenance require careful consideration, including structural considerations to ensure roof integrity.

Innovation in GR substrates has allowed us to maximize water and nutrients to plants while ensuring good drainage, lightweight, and stability. The ideal type of organic matter incorporated into the substrate varies depending on factors such as local availability, suitability, and personal preference. Using organic waste and recycled materials in substrates can enhance sustainability and reduce the environmental impact of green roof construction.

8.4 Where Green Roofs are Successful

Sub-Question 4

Where are green roofs being utilized successfully, and why?

Objective: I research international and domestic GR policies, market trends, and citizen engagement to understand why other countries are more effective in promoting adoption.

GRs are gaining recognition for their ecological and urban benefits, with guidelines and standards established in Europe and North America to promote best practices. Some cities like Basel, Copenhagen, and Munich require GRs on new and renovated buildings. Financial and zoning incentives, along with stormwater management credits, promote the integration of GRs into development projects. The global market for GRs is projected to reach $35.2 billion by 2033, with a Compound Annual Growth Rate of 11.3%. The DACH region in Europe leads this market expansion, while the Asia Pacific region is rapidly
8.5 California and the Mediterranean Climate

**Sub-Question 5**

*What are the lessons learned from and for California?*

**Objective:** I analyze the best practices for GRs in Mediterranean climates and examine successful GR implementations in California cities.

The Mediterranean climate is characterized by mild winters and warm dry summers. Water shortages during summer are a recurring problem in these areas, making it challenging for plants to grow and survive. GRs can help reduce the need for irrigation and generate electricity through renewable sources, such as solar power. Several studies have suggested optimal GR specifications for Mediterranean climates, including the use of sustainable materials, water storage ability, and specific substrate characteristics and plant species. Successful GR implementations have been reported in specific Californian cities.

Plant selection for GR depends on several factors, including the plant's ability to survive and its effect on maintenance costs. Succulents with CAM photosynthetic cycles are commonly used on GR due to their drought resistance. Plants with C4 photosynthesis are better adapted to hot and dry climates. The ideal plant species should be drought, heat, wind-tolerant, pest-resistant, light-loving, low height, good coverage, and have a shallow root system. Native plant species are suitable, but care should be taken in their selection, given a shallow substrate. Plants with extensive foliage and mostly horizontal leaf distribution are preferred. Sedum and Delosperma are reliable options due to their shallow root systems and high drought tolerance.

California has a lack of incentives and mandates for GRs. Even San Francisco only currently requires 15-30% of a new construction's roof to be designated for solar and/or GRs. However, there are successful independent GR implementations in California, such as the Sonoma Academy High School, Slide Ranch Nature Center, and One South Van Ness Avenue in San Francisco. These GRs feature diverse plant species, irrigation systems and support local wildlife.
8.6 Conclusions

GRs are continuing to find their place in the world market as research into ideal substrates, species, and irrigation proliferates and translates into standards that can drive faster adoption. Their environmental benefits, including mitigation of the UHI, stormwater reduction, and promotion of biodiversity, are more than enough to validate GR support. However, the financial burden of installation and maintenance is too much for the average citizen. This is why governments should begin with policies aimed at commercial real estate development. We see in Europe and Asia that robust government support in the form of incentives, rebates, and mandates, all lead to widespread adoption.

We continue to see development in technologies and research in the GR field. Modular technology reduces the cost of GR installation by being an ‘out of the box’ type solution, making it more accessible. Further research into substrate materials benefits plant health and reduces the need for chemicals and maintenance. GRs can also contribute to the circular economy by diverting landfill waste to be reused as substrates. This continued research has also seen optimization to the more challenging drier Mediterranean environment. As the world continues to warm, such adaptability is key. GRs have shown they can be resilient and optimized for these drier environments.

IX. RECOMMENDATIONS

9.1 State Government Policy

I propose the establishment of statewide California GR policies instead of individual city policies due to the varied benefits and challenges associated with green roof implementation. A unified statewide policy would ensure consistency in standards, provide equitable incentives and access, and potentially lead to more widespread adoption across diverse municipalities. By doing so, we can overcome the piecemeal adoption and variability in success rates seen in cities that implement their own policies in isolation.

I also recommend conducting comprehensive research into the formulation of these policies. This research should examine the economic, environmental, and social impacts of GRs. The research should also consider the integration of GR with other sustainable building practices and technologies, aiming to create a holistic model of urban sustainability that can be adapted and implemented throughout the state. Finally, the research should explore which type of government intervention is the most effective at
spurring successful GRs – whether mandates, subsidies, or training programs and which industries and customer segments to target.

Section 6 shows the success of government policies throughout the world. We can also see successful California implementation without policies in Section 7 that demonstrate feasibility throughout the state. My research highlights the significant role that government support and incentives have played in fostering the adoption of GRs in residential, commercial, and industrial areas. Given the environmental, economic, and social benefits of GRs, it is essential for governments at various levels to actively promote their implementation through targeted incentives that include tax rebates, subsidies, reduced permit fees, or grants specifically designed for homeowners willing to invest in GR technology. Section 4 goes into more detail about the challenge of education for GRs and costs. Moreover, educational campaigns funded by the government could help increase homeowner awareness and interest in the benefits of green roofing. Therefore, it is recommended that policymakers implement comprehensive incentive programs and support mechanisms that make GR adoption more attractive and financially feasible for residential property owners. Such initiatives would accelerate the uptake of GRs and contribute to urban sustainability and environmental resilience.

9.2 Commercial Real Estate Implementation

According to my research, it is recommended that efforts to promote GR development should prioritize commercial real estate properties. This is because commercial buildings usually have larger, flat roofs that are more suitable for GR installations. Additionally, commercial buildings generally have greater access to capital for such investments. Finally, implementing GRs on commercial properties is more cost-effective than on residential buildings, as discussed in section 4. Therefore, focusing on commercial real estate can leverage these economic benefits while also maximizing the environmental and social impacts of green roofs in urban areas. Future policies and incentives should be tailored to encourage GR projects in the commercial sector, which could potentially transform urban sustainability practices on a significant scale.

9.3 Increasing Educational Awareness

This research highlights the urgent need for increased educational efforts to raise awareness about the benefits of GRs as discussed in Section 4. Studies have shown that the general public lacks sufficient knowledge about GR technology, which can limit policy support and widespread adoption of this
technology. By drawing from successful models in Europe and Asia, it is clear that raising public awareness can strongly encourage citizen buy-in and support for GR initiatives, which in turn can spur more progressive public policies and faster adoption. I recommend that governments and stakeholders invest in comprehensive education and outreach programs to disseminate information on GRs’ environmental, economic, and social advantages. Such programs will help to foster a well-informed public and generate the necessary support to implement effective green roof policies and projects, leading to more sustainable urban environments.

9.4 Training Programs

My research underscores the critical need to enhance and standardize training for skilled labor and contractors to boost the efficiency and effectiveness of GR construction, as discussed in section 4. Developing and enforcing standardized training programs is essential to ensure that GRs are constructed to maximize performance in specific environments. Standardization also promises to streamline construction and maintenance processes, thus lowering costs and making GRs more accessible. The imposition of legal mandates could be instrumental in ensuring compliance with these standards, promoting industry uniformity. It is imperative for policymakers to enact regulations mandating standardized training and certification for all professionals involved in the design, construction, and maintenance of green roofs. Implementing such measures would guarantee the quality and sustainability of GR projects and facilitate their widespread adoption as a norm in urban development.

9.5 Standardize Plant Selection for Specific Climates

I tried to emphasize with my research the importance of having standardized guidelines for selecting plants for GRs based on specific climate biomes, to optimize their ecological and functional benefits. This is discussed in sections 3, 4, and 7. For regions with Mediterranean climates, like California, it is crucial to establish such guidelines for plant species and practices that are best suited to the local environmental conditions. This standardization will ensure that GRs provide maximum environmental benefits, including enhanced biodiversity, improved building insulation, and effective stormwater management. To achieve this, policymakers and industry professionals should collaborate to develop and implement a standardized framework for plant selection and green roof practices in Mediterranean environments based on scientific research. This framework should be tailored to these climates' unique challenges and opportunities, promoting more sustainable and effective GR installations across the region.
9.6 Standardize Bio-Solar and Modular Technologies

To maximize the environmental and economic benefits of GRs in California, it is recommended that bio-solar and modular GRs be integrated into standard practice, particularly suited to the state’s Mediterranean climate. Adopting bio-solar roofs, which combine the advantages of biotic components with photovoltaic technology, can enhance solar efficiency by reducing rooftop temperatures and thereby increasing the efficiency of solar panels. Meanwhile, modular GRs offer flexibility and ease of installation, which can significantly reduce construction and maintenance costs. Modular roofs can also come preassembled with optimized plant and substrate for the Mediterranean biome. Standardizing these innovative roofing solutions can lead to widespread adoption, fostering a more sustainable urban environment across California.
X. REFERENCES


Talbot, H. (2021, Jul 12,). Switzerland: How this swiss city is using green roofs to combat climate change. Asia News Monitor Retrieved from https://search.proquest.com/docview/2550057318


USA EPA. (2024). Heat island effect.


