A Comparative Analysis of Rooftop Garden Systems

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Preface

In the summer of 2014, I took a six-week course on 19th century Art History in Paris, France. I had just completed an associate's degree in Interior Design, and was transitioning into the Environmental Studies major. I first recognized the significance of city design as we studied Haussmann's renovation of Paris. While walking around the city I could identify the wide avenues, parks, trees, and lighting that were constructed over 100 years before. I fell in love with the distinct boulevards, centers, parks, and the ease of public transportation. I was most fascinated by the vast amount of vegetation embedded between and on top of the buildings. The greenery delicately juxtaposed the old, white facades. I remember looking out from the Arch de Triumph in awe by the symmetry and green space that composed the city. Since my time abroad, I have been curious as to why cities in the United States are designed so differently.

The CU Environmental Studies and Environmental Design programs have allowed me to collectively pursue my interests in design, environment, and city planning. The research, interviews, and mentorships I conducted in creation of this thesis have been very significant to my undergraduate experience.

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Introduction

The built environment makes significant contributions to environmental issues such as green house gas emissions, global climate change, and pollution. Additionally, global urbanization is occurring at an unprecedented rate. Increased environmental impacts arise with the acceleration of urbanization including: area of impermeable surfaces, air and water pollution, heat island effect, pluvial flooding, and loss of biodiversity and habitats. Urbanization disconnects humans from natural systems, an integral component of our evolution. The adoption of green roof technology will help to unify the natural and built environment. The integration of vegetative systems into the urban fabric has the capacity to reduce negative environmental impacts and increase economic and social well being. This honors thesis is a qualitative analysis of green infrastructure in urban settings. I will emphasize the environmental assets of low impact design but will also discuss economic and social influences. I provide evidence that green infrastructure has the capacity to mitigate environmental stresses and rejuvenate the built environment. I conduct a case-study analysis of four living roof systems that emulate green-infrastructure functions through distinctive designs. I begin this study with the history and progression of man's relationship with nature. I then examine a selection of urban design theories that describe the built environment as a functioning ecosystem. Next, I analyse low impact design, city storm water management and green infrastructure systems. My focus is on rooftop garden systems, or green roofs, as storm water management techniques. My research questions have lead to the explanation of the ecosystem services provided by green roof technology and how these outputs vary between design models. My thesis proposes that green roofs are a viable and preferable alternative to cities' conventional storm-water management systems by the provision of multiple ecosystem services.

Not all living roofs perform equally and functional output varies between design models. I compare four green roof models with contrasting objectives in different climatic regions. I conclude by proposing living roof parameters for future Boulder developments and the Alpine Balsam site. I have derived these proposed parameters from my case studies and conclusions about design efficiencies as well as local climatic conditions.

Background

Green roof technology has appeared throughout history. Green roofs are recorded as early as the hanging gardens of Babylon in 500 B.C, one of the seven wonders of the ancient world. In the early 20th century Le Corbusier, a pioneer of modern design, included roof gardens in his *Five Points Towards a New Architecture*. He explains that roof gardens can serve a "domestic purpose" while providing essential protection to the roof. He states, "Roof gardens mean to a city the recovery of all the built-up area" (Corbusier 1926).

History of Cities and Nature

Between 500 B.C and the 20th century, human approaches to nature and the built environment changed substantially. An Urban Parks movement arose in the late 1800s in response to industrialization and pollution. These parks provide essential green space and filtration for a city and are still widely used today. For example, Frederick Law Olmsted designed Central Park in New York City, built in 1858, and Golden Gate Park in San Francisco built in the 1870s. Ebenezer Howard proposed the Garden City in 1898 that would allow city dwellers to escape the pollution and overcrowding of the city and live closer to nature by moving to the outskirts of the city or the countryside. This movement was a response of the need to improve the quality of urban life during the Industrial Revolution. The Garden City movement caught on post WWII, as the economy was growing and much of the nation experienced prosperity. Many urbanites fled cities in seek of a suburban lifestyle. Suburban areas became home to one third of the nation's population by 1960 (Boundless). In modern times, we are experiencing a movement of people back into the city. The proportion of the population living in cities is growing rapidly; in 2014, 54 percent of the world's population resided in cities. It is predicted that 66 percent of the world population will be urban by 2050 (United Nations 2014). The conventional urban drainage systems are not equipped to accommodate higher quantities of runoff from increased urbanization (French, 2011). Green infrastructure increases infiltration surface area, reducing the amount of runoff entering city drainage systems.

Cities as a Mass Polluter

According to the United Nations, cities produce 70 percent of the world's greenhouse gas emissions and consume approximately 75 percent of the world's energy. Yet, cities occupy approximately 2% of the Earth's surface (AAAS). Storm water runoff is one of the leading causes of polluted waterways (EPA 2016). Industrialization and urbanization have increased the percentage of impervious land cover. Impervious surfaces correlated with urban sprawl can significantly change natural river flow patterns and groundwater recharge. Increased impervious surface area also causes excessive runoff during storms that can oversaturate urban drainage systems, a phenomenon known as pluvial flooding. Flooding and sewer overflows caused by pluvial flooding pollute urban waterways and the watershed. In cities and developed areas storm water runoff collects pollutants such as fertilizer, pesticides and petroleum residues. The increased level of nutrients entering streams, rivers and oceans cause eutrophication disrupts ecosystems and contaminates drinking water. About 40 percent of the rivers and lakes in the U.S. surveyed by the EPA are too polluted for swimming or fishing (The Nature Conservancy). It is essential that we protect our watersheds by developing urban stormwater infrastructure that reduces both the quantity and pollutant load of runoff.

Future of Cities

The load on urban stormwater systems will continue to increase because of general population growth and the influx of individuals to cities. Urbanization is a global occurrence; simultaneously the world population is exponentially increasing. The increase of population marks the beginning of "megacities", a city with a population of 10 million or more residents. Some contemporary megacities include Cairo, Los Angeles, Bangkok, Moscow, Kyoto, Mumbai, Mexico City, and New York City (Cox). The majority of urban population growth is concentrated in the less developed regions of the world. The United Nations estimates that China alone will need to build new cities accommodating over 350 million people in the next 20 years (McKinsey 2009). Over the same period, 250 million will migrate into the cities of India (McKinsey 2010) and 380 million in Africa (United Nations 2008). How can we address the challenges of meeting the needs for more people with fewer resources and increased weather variability? Sustainable development will increase urban resilience and is necessary to meet the needs of the growing urban population. Green infrastructure is more commonly used in Western Nations. However, China is an emerging new leader in sustainable development and incorporates innovative designs such as 'vertical forests', which is to be built in Nanjing Providence. The ecosystem services provided by green infrastructure and green roofs have the capacity to improve urban conditions in developing nations. The greatest obstacle is the cost of implementation and maintenance of this technology.

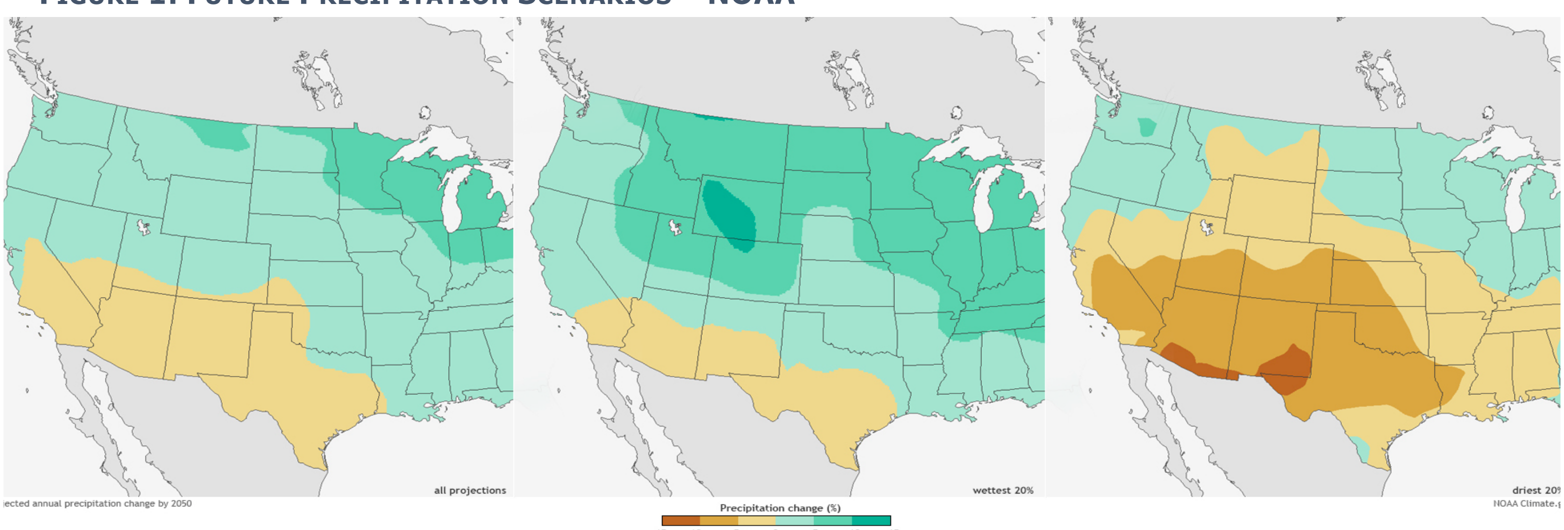
Future of Boulder

According to U.S Climate Data, the average annual precipitation in Boulder County is 20.66 inches and the average annual snowfall is 89 inches. With increasing temperatures in Colorado, the state is expected to face significant challenges to managing water resources according to the Water Western Report (NOAA). Report authors write:

"We have high confidence in continued warming, and the warming alone will have impacts on hydrology and water resources, especially the likely continuation of the ongoing shift to earlier timing of snowmelt and runoff. The more uncertain projections of annual precipitation and streamflow for Colorado—which in many cases show little or no average change—should not be construed as a 'no change' scenario, but rather as a broadening of the range of possible water futures, some of which present serious challenges to the state's water systems."

The map below illustrates three scenarios of future precipitation change based on weather models. NOAA predicts either a 5-10% increase in precipitation, or a 10% reduction as shown in Figure 1. Regardless of a drier or wetter future, a more functional approach to water-management is necessary. Green infrastructure supports both dry and wet climates as it reduces runoff by retention and storage properties. The captured water is stored and used by the plants when needed.

FIGURE 1: FUTURE PRECIPITATION SCENARIOS – NOAA



Sustainable Development

The term "sustainability" has several connotations and has become quite cliché. I refer to green infrastructure as "sustainable" systems that construct "sustainable" cities. When I use the term sustainable, I refer to systems that do not have negative long-term repercussions associated with performance. Sustainable practices do not deplete the resource base for future generations while *active* sustainability satisfies human needs while enhancing environmental quality and the natural resource base upon which human activity depends. This is the definition I will refer to when using the term "sustainable".

The 1987 report, *Our Common Future* by the UN sponsored by World Commission on Environment and Development defines the concept of sustainable development:

> "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs. The concept of 'needs', in particular is the essential needs of the world's poor, to which overriding priority should be given; and the idea of limitations imposed by the state of technology and social organization on the environment's ability to meet present and future needs."

Sustainable development is most often defined as economic growth achieved through cleaner industrial and energy production, the green economy (Mollison 1994). Yet, the way in which *cities* are organized and operated has an enormous impact on economic growth, energy requirements, natural systems, and quality of life. The average 20th century western city is designed to accommodate the automobile, which promotes sprawl and large amounts of land dedicated to roadways and parking lots. This model consumes massive amounts of resources and has proven to be unprecedentedly inefficient. Therefore, it should not be replicated in the developing urban models. A new approach to urban design must be developed in order to harness cities' potential as the new engines of sustainable growth. If more sustainable forms of development are utilized, such as the integration of green roofs, cities will gain environmental, economic, and social benefits.


PHOTO FROM *FRIENDS OF THE HIGH LINE*

Urban Resilience

Urban Resilience is the ability of a city to bounce back from external shocks and to quickly recover to its normal state in the presence of a disturbance or disaster. In order to adapt to change we must transform our infrastructure so it is capable to function as *preventative* and *prescriptive*. Green infrastructure, including green roof technology, increases urban resilience within a city at both the building and regional scale and helps cities adapt to future environmental disturbances (Wilkinson).

Review of Literature

In this section I review models of urban design that present theories of development, which integrates nature into the built environment. Green infrastructure technology is a supporting component in the framework of these models.

Bioliphic Cities

The Biophilic City is a concept that puts nature at the core of its design, planning, and management (Beatley 2011). The design concept, developed by Timothy Beatley, is based on the studies of Harvard Biologist E.O Wilson. Wilson's Biophilia hypothesis suggests that humans have an innate tendency to seek connections with the natural world. Thus, the Bioliphic City is more than a sustainable city; it includes human well-being as a part of the environmental conservation agenda. The emphasis is on imagining places we want to live that are full of nature, not just energy efficient buildings or public transit. This model fosters the city dwellers' need for daily natural interactions. "It is a place that learns from nature and emulates natural systems, incorporates natural forms and images into its buildings and cityscapes, and designs and plans with nature" (Beatley 2011). Beatley suggests that tree planting, forests, and rooftop gardens are all assets that engage citizens with nature while simultaneously reducing urban temperatures and pluvial flooding. He also argues that these influences will impact public health. For example, trails along streams and rivers promote exercise. Beatley uses Boulder, Colorado, as an example of a Bioliphic City, yet there is no perfect model of a Biophilic City, although it is important to move cities closer to an *immersive* experience. He states that conventional parks are an important aspect of this experience, but they are not the whole solution. In the Biophilic city one feels that one is living in a park; the city dweller should not have to go to visit nature for nature is all around.

Janine Benyus's Biomimicracy design model is another innovative approach that seeks sustainable solutions to human challenges by emulating nature's patterns. Similar to Biomimicracy, Biophilic cities understand the wisdom of natural systems and the need to model design and planning after them (Beatley 2011). This concept is also reflected in architect Bill McDonough's work to design "buildings like trees, cities like forests." An example of his work is the environmental studies building at Oberlin College.

Ecological Urbanism

The Ecological Urbanism Model is based on the idea that adaptation is the key to human survival. Ecological Urbanism is based in the principles of ecology, the study of an organism's relationships with its environment, and applies this study to urban design and planning. The combination of these two disciplines will help us to design places that are functional, sustainable, and meaningful (Spirn). The city is viewed as habitat in an ecosystem, and all ecosystems are connected. The city is a system in which energy, resources, and information are flowing through. Humans are constantly interacting with each other and their built environment. The more inefficiently resources are used, the more waste and pollution is produced. Patrick Geddes, a biologist who refuted the "Garden City" model was among those scientists who saw the city as an ecosystem and advocated for surveys that would gather information about the regional evolution of the city; climate, geology, hydrology, soils, wildlife, and vegetation. Ecological Urbanism provides a framework for global challenges such as sea level rise, increasing energy demands, and environmental justice. Urban Planner Jane Jacobs also believed that cities should be considered part of the natural world; she argued, "Cities are problems of organized complexity, similar to living organisms". Anne Spirn recognizes that all cities transform their natural recourses similarly resulting in more frequent floods and polluted air and water. Cities are dysfunctional, inefficient, and prone to natural disasters. By recognizing there is no separating agent from natural forces and the urban world, design and management of cities will be transformed. This model argues that infrastructure, buildings, and parks within the city should be designed with long-term maintenance in mind. They should be designed like a "closed-ecosystem" with minimum inputs of energy and resources to sustain it. Green roof technology helps to establish this goal by providing multiple regulating services from a single origin. It also works to densely integrate the built and natural environment. Similar to Biophila and Ecological Urbanism, *New Urbanism* seeks to create dense, mix-use, sustainable communities as a response to industrialization and sprawl. The sustainable city not only views nature as an aesthetic and recreational pleasure, yet as a functional system.

The Permaculture City

Dense, mixed-use cities may support a more sustainable lifestyle than suburban and rural homes. Urban dwellers often use energy more efficiently, occupy smaller living spaces, and rely more heavily on public transportation and walking as they are in closer proximity to their daily needs (Hemenway 2015). Additionally, cities provide unique benefits that only occur at the larger urban scale including more frequent social interactions, employment opportunities and diversity. Physiscist Geoffery West conducted research that found a city that is ten times the size of another generated seventeen times more patents or start-ups (Hemenway 2015). This suggests a "superlinear" relationship between innovation and population size of a city. Interacting and being influenced by other people stimulates creativity leading to original works, performances, publications, or innovative products. Cities are the economic powerhouses of the world. Urban activist Jane Jacobs acknowledged "great cities are not like towns only larger" (Roy). The density, diversity, mixed-use, interactions and relationships are what sets towns apart from cities. Additionally, cities have a multitude of functions; the major categories include gathering places, security, and trade. However, when these functions of the city fail, urbanities flee to the suburbs or a more functional city. Those who cannot leave may occupy or be forced into ghettos and enclaves (Hemenway 2015).

In present-time, the world is experiencing a movement back into the cities. This is significant economically and socially because of the increased innovation and relationships developed within cities. Yet how can we design our cities to be more functional and livable? How can we design to decrease the ecological footprint of these economic powerhouses? Should water purification and mitigation be an essential function of cities? Low Impact Design offers a tangible practice by which cities can implement components of the design models previously discussed.

Low Impact Design

The integration of vegetation within a dense urban environment (as discussed in the design models) can be applied through Low Impact Design. Conventional drainage systems are designed to collect and transport water runoff from urban areas by sewer networks and water treatment facilities. The main goal is to manage water volume in order to avoid urban flooding in city areas. The act of managing stormwater via green infrastructure is collectively known as low-impact development (LID) (City of San Francisco 2015). LID reduces the capacity of treatment facilities by utilizing the natural infiltration process of plants and soil. Vegetation absorbs and filters water, slowing and reducing the amount of runoff in treatment plants. The EPA uses the term ‘green infrastructure’ (GI) to refer to the management of water by a variety of natural areas that provide habitat, flood protection, cleaner air and cleaner water within a city (EPA 2017). LID objectives are to preserve, restore and create green space by use of vegetation and rainwater harvesting. LID applies principles such as preserving or recreating natural features and minimizing imperviousness to create aesthetic site drainage that “treats stormwater as a resource rather than a waste product” (EPA 2017). There are many GI systems that are used to perform these principles such as bioswales, rain gardens, vegetated rooftops, rain barrels and permeable pavements.

Green Infrastructure

Green Infrastructure (GI) characterizes several practices that use and mimic natural systems to provide ecosystem services. Green infrastructure and green roofs performs multiple functions that contribute to urban resilience when integrated into the city framework. National Planning Policy Framework (NPPF) defines GI as a network of multi-functional green space capable of delivering a wide range of environmental and social benefits for local communities (NPPF 2012). These functions help to alleviate environmental problems by reducing buildings' energy consumption, the volume of stormwater into infrastructure and waterways, and the urban heat-island effect. Green infrastructure increases sound insulation, longevity of the roof membrane, air quality, and habitat area within a city. Vegetated systems are also known to improve health, reduce postoperative recovery times, increase employee satisfaction, and reduce stress (Oberndorfer, 823). Green infrastructure impacts the overall "livability" of cities and is implemented as Sustainable Urban Drainage Systems (SUDS). SUDS are designed to capture water and store it, gradually release it into the ground, or allow it to be evaporated. The main objective of SUDS is to drastically decrease the drainage water leaving the property (Oudolf). Therefore, SUDS prevent water pollution, slow run-off, reduce flooding, and in some cases can recharge groundwater. These systems add green spaces in urban areas for people and habitats for wildlife. Bioswales, rain gardens, and green roofs are a few GI systems that are integrated into sustainable urban drainage schemes. Table 1 describes different types of GI and their functions.

TABLE 1: GREEN INFRASTRUCTURE SYSTEMS

Type	Description	Function
Bio swale	A planted area in the sidewalk that serves as a bio retention facility by collecting and filtering water. Consists of inlet layer above a low depression, layered with soil or rock used to slow, collect, infiltrate, and filter storm water before entering connecting drain.	Capture & Mitigate Storm water Habitat Creation Filter Pollutants (small scale)
Rain Garden	Vegetated depressions designed with a soil layer that promotes infiltration of stormwater runoff into the underlying soil. In addition to direct rainfall, stormwater runoff from surrounding impervious surfaces can be directed in to the rain garden so it can be absorbed into the ground.	Capture & Mitigate Storm water Habitat Creation Filter Pollutants (small scale)
Rain Barrel/Cistern	Watertight receptacles designed to catch and store stormwater off of roofs and other impervious surfaces. Usually connected to the existing downspout of a roof and reuse the stormwater for watering plants and other landscaping uses. Cisterns are often larger than rain barrels and can be located underground, at ground level, or on an elevated stand.	Capture & Mitigate Storm water
Green Roof	Top vegetative layer that grows in an engineered soil, which sits on top of a drainage layer. A green roof can be intensive, with thicker soils that support a wide variety of plants, or extensive, covered in only a light layer of soil and minimal vegetation.	Capture & Mitigate Storm water Habitat Creation Mitigate Heat Island Effect Filter Pollutants
Permeable Paving	Porous concrete that allow water to seep in between the paving materials and be absorbed into the ground. This can be used instead of traditional impermeable concrete or asphalt.	Capture & Mitigate Storm water
Creek Daylight	Physically uncovering and restoring buried waterways and streams to restore watershed and reduce potential for flooding.	Capture & Mitigate Storm water Habitat Creation Filter Pollutants

Green or Living Roofs

Living or green roofs insert vegetated spaces in otherwise unvegitated urban areas and serve as multifunctional systems that provide ecological, economic, and social services (Table 2). Green roofs make use of dead space, an advantage compared to other stormwater management systems, as space within cities are very limited. In addition, GR have the potential to convert between 40 and 50% of the impervious areas in cities into vegetated, functioning spaces (Villar-real 2004). Green roof services are site-specific and vary with design.

Table 2: Green Roof Assets

Function	*Ecological*	*Economical*	*Social*
Mitigate storm water	✓		
Filter pollution	✓		✓
Mitigate Urban Heat Island	✓	✓	✓
Roof Protection		✓	
Building Insulation	✓	✓	
Green Space Creation	✓	✓	✓
Habitat Creation	✓		
Biodiversity Conservation	✓	✓	
Food Production			✓

Green Roof Typology and Design

There are three main green roof design categories; extensive, semi-intensive, and intensive. Extensive roofs have a shallow substrate, less than 6 inches, and support up to 30 lbs. per square feet of *saturated weight*. These systems are lightweight and suitable for retrofit, although the shallow substrate is limiting for many plant species. Intensive roof substrates are greater than 8 inches and can support up to 100 lbs. per square feet of saturated weight. The deep substrate of an intensive roof can support a wider range of plant diversity, yet requires more irrigation and maintenance. Semi-intensive roofs encompass benefits of both systems as they are made up of substrate between 6-8 inches and can support 25-40 lb. per square feet.

TABLE 3: GREEN ROOF CATEGORIES

	Extensive Green Roof	Semi-Intensive Green Roof	Intensive Green Roof
Maintenance	Low	Periodically	High
Irrigation	Rare	Periodically	Regularly
Plant communities	Moss-Sedum-Herbs and Grasses	Grass-Herbs and Shrubs	Lawn or Perennials, Shrubs and Trees
Weight	60 - 150 kg/m² 13 -30 lb/sqft	120 - 200 kg/m² 25 - 40 lb/sqft	180 - 500 kg/m² 35 - 100 lb/sqft
Costs	Low	Middle	High
Use	Ecological protection layer	Designed Green Roof	Park like garden

FIGURE 2: GREEN ROOF LAYERS

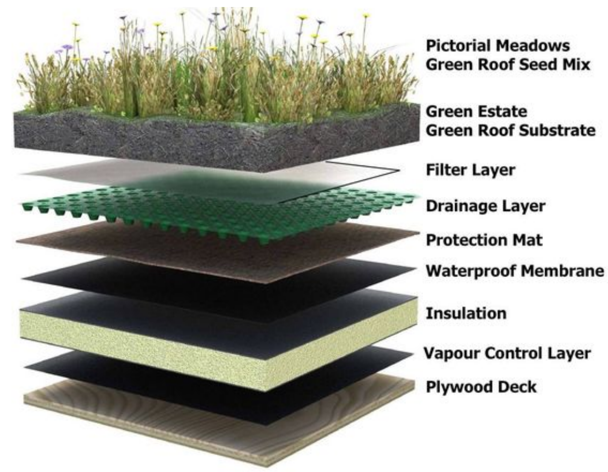
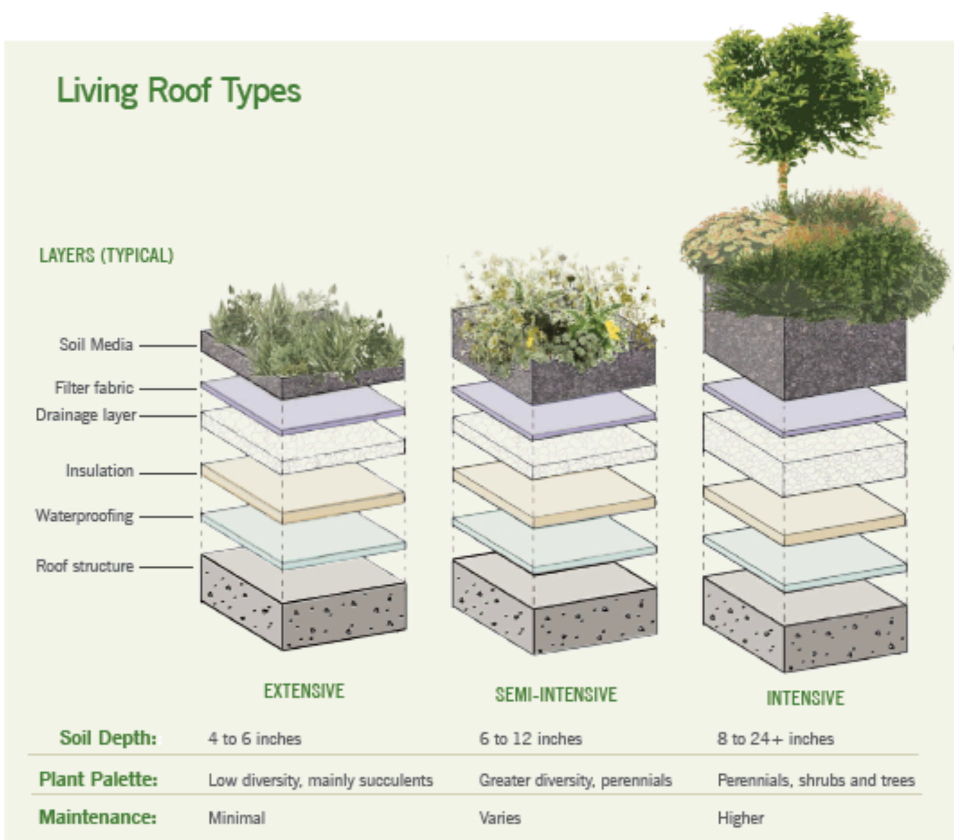


PHOTO BY BOB VILLA

Green Roof Systems

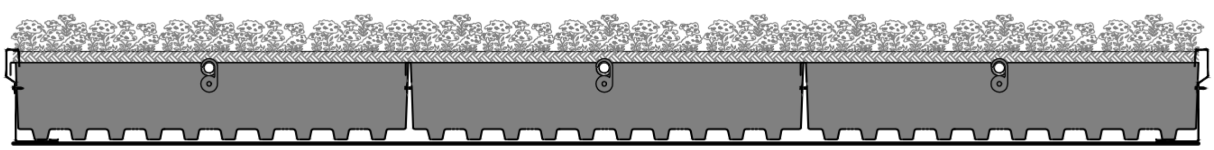
A traditional planted roof consists of a series of layers above the structural support. They are usually installed all at once. The layers include a waterproof roof membrane, root barrier, insulation, drainage layer, retention layer, filter cloth, growing medium, and plants (Figure 2). The layer materials and design vary with designer and roof type.

FIGURE 3: LIVING ROOF SYSTEMS



In addition to the traditional built up green roof, modular systems can be used on extensive and semi-intensive green roofs. These are self-contained trays that prevent excessive growth, protect the roof membrane, and use less material (Figure 3). Modular systems are easier to install, which minimizes construction and labor costs (Snodgrass). They come either pre-planted or can be planted after the trays are installed on the roof. Modular systems require the same water-proofing methods of the roof membrane and consist of a similar layer structure. These systems are still designed for rainwater capture, are low maintenance, and can create an instant grown-in look. However, the modular system further limits plants on a green roof. They are restricted in growth and not able to communicate with plants outside their module. This creates several small communities versus one cohesive plant community.

FIGURE 4: MODULAR SYSTEM



Another method for extensive roofing is the mat system, which is laid like sod. These are considered continuous systems consisting of shallow- root plants and layer of substrate held together by a thin material.

Growing Medium

Organic material or soil does not account for the total substrate used on green roofs because of its heavy weight and decomposition properties. The substrate used on green roofs is engineered for stability and longevity. The mixture is usually composed of 30-95% expanded aggregate, 5-30% organic material, and up to 35% of additional minerals. The aggregate is lightweight, stable, absorbent and supports drainage. It is usually pumice or expanded clay or shale. Its size ranges from 2-20 mm (Bousselot). The organic material is ideal for roots, increased water, and nutrients for the plants. The organic material generally used is compost, back, peat moss, or coir. As decomposition occurs over years, eventually the green roof substrate is comprised of just 3-6% organic matter (Bousselot). In some cases, up to 35% of other material is used for increased drainage, water, and nutrients. Vermiculite, perlite, and zeolite are usually the absorbent minerals used.

Green Roof Plant Species

Dependent on the climate, green roof plants commonly consist of ground covers, shallow and fibrous rooted (not tap rooted), and drought tolerant species. Extensive and semi-intensive roofs tend to be planted with plant communities, a collection of plants that co-exist well, that survive with minimal maintenance. These are often species from dry meadow habitats because the vegetation is tolerant of dry, thin and infertile soil (Oudolf). These species are categorized as herbaceous perennials, forbs, and grasses. Sedum is also one of the most common genuses used on extensive and semi-intensive roofs. Sedum establishes quickly, is drought resistant and low maintenance because of their water retention properties.

Ecosystem Services

Ecosystem services are collectively defined as the benefits that humans derive from ecosystems (Tietenberg 2014). These services include aquifer recharge and water filtration by wetlands, oxygen filtration by vegetation, nitrogen fixation in soil, climate regulation through carbon sequestration and pollination by bees. Ecosystems also provide aesthetic and recreational activities. Ecosystem services are considered *flows* or actions that are generated from *stocks* or reservoirs of natural assets that support human life.

Ecosystem services are divided into four categories:

1. *Provisioning services:* direct benefits such as water, timber, food, and fiber provided.
2. *Regulating services:* flood control, water quality, disease prevention, and climate.
3. *Supporting services:* photosynthesis, nutrient cycling, and soil formation.
4. *Cultural Services:* recreational, aesthetic, and spiritual benefits.

In 2001, the Millennium Ecosystem Assessment (MA) was initiated with the goal to assess "the consequences of ecosystem change for human well-being and to establish the scientific basis for actions needed to enhance the conservation and sustainable use of ecosystems and their contribution to human well-being" (Tietenberg 2014). The report states that ecosystems have changed at a higher rate in the last 50 years than any other time period. The assessment also suggests that reversing the degradation will require significant changes in institutions, infrastructure, and policies. Economic implementation can play an important role in such transformation by assigning a monetary value to ecological performance. Placing monetary value on an ecological function provides a measurement of reference by which to compare. The cost of lost ecological services is then compared to infrastructure or policy cost that may preserve or enhance such service. A cost benefit analysis will provide evidence that indicates which systems are in economic interest to conserve or prevent further destruction. Methods used to place economic value on the environment include the willingness to pay by humans, the production function, and the evaluation of damage costs avoided by ecosystem services.

Green roofs offer all four ecosystem services to the city, but the primary service green roofs (and infrastructure) provide are *regulating* services. Green roofs regulate pluvial flooding by increasing surface area for water to infiltrate which reduces water quantity in sewer systems. Captured water is stored in the substrate, taken up by the plants, and transpired back into the atmosphere. Green roofs regulate water quality by filtration and the urban temperature by transpiration. Green roofs offer supporting services for pollinators by providing habitat. Green roofs also provide cultural services by increasing recreational space within a city.

Methodology

I use a qualitative approach to assess the ecosystem services provided by three distinct green roofs. I conduct a case study analysis of three projects that vary by climatic regions, size, type, and design. First, I will outline the green roof function. I then discuss their assets pertaining to ecosystem services. I compare their function by building structure, materials, vegetation, and the purpose of the design. I discuss the trade-offs associated with the primary design goal and green roof assets. There is an emphasis placed on the stormwater mitigation properties provided by green roofs. Finally, I will propose parameters of a green roof for the Alpine Balsam redevelopment project and other future developments in Boulder, Colorado. Based on my a summary of the strengths and weaknesses outlined in these case studies, I will also describe a green roof framework that is suitable for Boulder given the climatic conditions and policies of the city. I present my formed perceptions of an efficient, actively sustainable design based on flaws and successes I have identified in my case studies.

Green Roof Functions

Green roofs provide numerous ecosystem services to an urban environment including air quality improvement, reduced energy requirements, habitat provision, extended roof lifetime, stormwater runoff reduction, and water quality improvement (EPA 2010). Each green roof is designed to fulfil a range of primary functions or purposes based on the need of the site. Thus green roofs are not created the same and the performance of ecosystem services vary. Below I discuss each case study roof's primary design goal and compare the output and trade-offs.

Stormwater Mitigation

Conventional stormwater management techniques include reservoirs, retention ponds, and constructed wetlands, yet these technologies are difficult to implement in dense urban areas. Green roofs are ideal for urban storm-water management because they make use of existing roof space.

Green roofs are designed to capture and retain stormwater by the absorbance of the substrate and initial uptake from plants. Additionally, the drainage layer is comprised of depressions that store water to be later used by the plants. Green roofs can reduce annual total building runoff by as much as 60% to 79% (Kohler 2006). In the same study, estimates based on a 10% green-roof coverage within a city can reduce the overall regional runoff by about 2.7%. (Oberndorfer 2007).

Filtration

Plants improve air and water quality by converting polluting compounds to nutrients, thus reducing the overall pollutant load. Green infrastructure, especially green roofs, is effective in trapping pollutants. The vegetation collects particulate matter, filter noxious gases, and break down complex hydrocarbons (VOCS) into carbon dioxide and water (Refahi 2015). Studies show evidence for green roof systems in dense urban areas to remove tonnes of air pollutants annually (Rowe 2011).

Membrane Longevity

Ultraviolet (UV) light penetrating roof surfaces cause quick degradation of the membrane material. In Ottawa, Canada, Liu (2004) found that an unvegetated control roof reached temperatures higher than 70 degrees Celsius (°C) in summer months, while the surface temperature of the green roof only reached 30°C (Oberndorfer 2007). The material layers add physical barriers from solar radiation while the vegetation collectively cools the system. Green roofs can extend the lifetime of a roof membrane by more than 20 years (EPA 2000).

Energy Efficiency

Green roofs reduce heat flows through the roof by promoting evapotranspiration, physically shading the roof, and increasing the insulation and thermal mass. During warm weather, green roofs reduce the amount of heat transferred through the roof, thereby lowering the energy demands of the building's cooling system (Oberndorfer 2007).

Urban Heat Island Mitigation

Urban surfaces have a low albedo (reflectivity), high heat capacities and conductivities therefore the amount of solar radiation absorbed is increased (Osmond 2016: 38). Urban areas can be much warmer than the surrounding rural land because there is less evapotranspirative cooling from vegetation, soil, and water. Additionally, there is a high input of generated anthropogenic heat within cities. There are three urban heat island types: surface**,** urban canopy, and boundary. The urban canopy layer, the layer of air beneath the height of the buildings and trees, averages 1-3 Celsius temperature increase (Osmand 2016: 39). As building density increases, so too does the proportion of reflection and emission of solar radiation occurring on building roofs (Bruse 1999). Plants absorb solar energy for photosynthesis but they reflect the excess; this latent heat-release through evaporation. Green roofs are most associated with and mitigate the *surface* urban heat island.

Habitat and Biodiversity Creation

The built environment reduces habitat area and connectivity. Green infrastructure and living roofs increase habitat area for insects, pollinators, and birds. Green infrastructure integrated throughout the city provides connecting corridors to city parks and the surrounding rural land. This supports small animals by providing a connecting, cohesive ecosystem throughout the built environment. According to garden designer Piet Oudolf, the most important aspect of planting design for animal diversity is a range and connection of habitats. Such is provided by a combination of trees, shrubs, perennials and ground-cover vegetation (Oudolf 62).

Case Study Analyses

I am comparing three distinct green roof systems; the California Academy of Sciences the Denver Botanical Gardens, and the New York Highline. The typologies of these green roofs range from extensive, semi-intensive, and intensive systems. They are very different from one another in size, climatic region, and primary purpose of design.

California Academy of Sciences (CAS)

Renzo Piano combines technology and ecology to create a cutting-edge model for the future of sustainable design. The new Academy building was designed to mimic the mission of the CAS, a "commitment to energy efficiency, reducing our carbon footprint, and preserving natural resources" (California 2017). The Living Roof sits 35 feet above the ground and is organically shaped by small rolling hills, inspired by the seven major hills in San Francisco. These mounds are nearly 60 degrees in slope creating two dome-like structures above exhibitions that allow natural light to penetrate into the museum (Green 2008). Photovoltaic cells are implemented into a glass trellis overhang, providing shade and capturing sunlight. This duel-functioning system provides the building with 5% of its energy, preventing the release of over 450,000 pounds of greenhouse gas emissions each year (Designing Our Future).

PHOTO FROM CALIFORNIA ACADEMY OF SCIENCE

The vegetated roof provides additional energy reducing properties by means of insulation and thermal inertia. On average, the vegetation layer lowers the interior by 10 degrees Fahrenheit during the summer months (Designing Our Future). The Living Roof is an "extensive" system with an average substrate depth of six-inches. The roof was installed using a modular planting system with biodegradable coconut husk trays. According to the landscape-architecture firm SWA Group, Piano wanted a consistent, clean look to the roof (Lanks 2008). Thus the plants selected for the roof are predominately drought tolerant, low growing, and have vast "green" seasons. The roof was initially planted with nine different California native species, both annual and perennial. According to Jessica Van Den Berg, SF State Grad Student, Golden Gate Park is comprised of mainly non-native species, thus, the roof acts like an "island". Her research has found that more native insect species inhabit the roof than the below garden (Living Roof 2017). The roof landscape acts as a habitat for insects, butterflies, and birds. Today, 1.7 million native California plants occupy the CAS roofscape (Living Roof 2017). The vegetation is adapted to the local ecosystem requiring little irrigation, fertilization, and maintenance. The underlying drainage system is made up of 24-by-24-foot wire basket grids. These "gabions" are filled with over 30,000 lbs. of lava rocks to support water retention and drainage (Lanks 2008). In addition to allowing for drainage and holding the substrate in place, the gabions are used as footpaths. According to multiple sources, this system absorbs over 90 percent of stormwater that falls on the roof, preventing as much as 3.6 million gallons of runoff each year (Jacobs 2009).

Lastly, the museum has been designed to reduce the urban heat island effect. The large roof overhang and plant design ensures that 30% of all hard surfaces are shaded (Designing our Future). The roofs main regulating services include native conservation, habitat creation, water filtration, and cooling.

California Academy of Sciences (CAS) Living Roof

Education/Research

Completed: 2007
Owner: California Academy of Sciences
Location: San Francisco, CA, USA
Size: 2.5 acres
Design: Extensive
System: Biodegradable Tray
Type: Education/Research
Cost: $17 per sq. ft.
Maintenance: Low
Storm Water Retention Rate: 98%
Team: Renzo Piano Building Workshop, Rana Creek Design, SWA Group, ARUP

Photo by Rana Creek

Project Description:

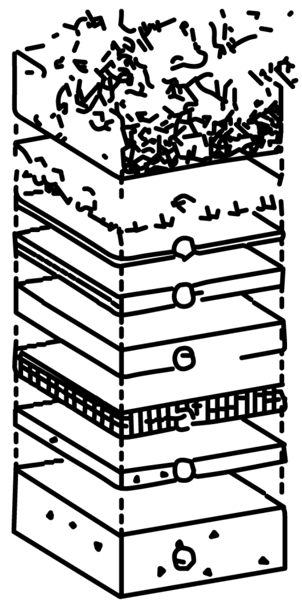
The CAS Living Roof is the largest green roof in California. The system does not require **fertilization** or extensive irrigation after plant establishment. The CAS Living roof absorbs about 98% of all storm water, mitigating as much as 3.6 million gallons of runoff each year (Jacobs). The underlying drainage system is comprised of 24x24 foot grids of rock-filled wire baskets. The gabions collect water flow, keep the soil in place, and are used as footpaths for maintenance crews.

Research Conducted:

Wildlife Quantity & Diversity
Energy Efficiency

Structural Design:

1. Vegetation
2. Biodegradable Trays
3. Additional Soil
4. Polypropylene Filter Sheet
5. Plastic Drainage Layer
6. Polystyrene Insulation
7. Vinyl Protection Layer
8. Building Concrete
9. Thermal Plastic Waterproofing



Vegetation:

The regionally native flora on the roof acts like an island to the surrounding vegetation in Golden Gate Park (mainly nonnative species). **More native insect species are found on roof** versus the garden below (Van Den Berg). Species chosen are low-growing, thrive in a limited environment, and attract wildlife.

Plant Taxa:

Originally planted with nine native species (annuals and perennials):

Fragaria chiloensis (beach strawberries)
Prunella vulgaris (self heal)
Armeria maritime (sea pink)
Sedum spathulitholium (stonecrop)
Layia platyglossa (tidy tips)
Lupinus bicolor (miniature lupine)
Eschscholzia (California poppies)
Plantago erecta (California plantain)
Lasthenia californica (goldfield plants)

Photo by Rana Creek

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Denver Botanic Gardens Green Roof (DBG), Denver, Colorado

The Denver Botanic Gardens is home to two living roof systems. The original Green Roof at the Botanic Gardens, designed by Civatas, was completed in 2007 and is the first publicly accessible green roof in Denver. It is designed to be informative and educational by demonstrating the benefits of green roofs to communities and the environment. It also serves as a testing ground for low maintenance green roof plant species. The planted portion of this roof is quite small, spaning 11,000 sq. ft., and is retrofitted over the café. The roof is an *intensive* system with substrate 18-20 inches deep composed of 80% expanded shale, 10% compost and 10% mulch. There are two low points with drains on opposing sides of the garden. No fertilizers or pesticides are used on this roof. Plant species are selected for environmental tolerances, rate of establishment, propagation potential, aesthetic value and wildlife habitat value (Schneider 2011). The plants used are predominately native to Colorado and the Southwest regions in order to evaluate the suitability of species for a rooftop environment in a semi-arid climate. The research conducted on this roof tests for species' tolerance of minimal irrigation and survival rate. Lead DBG horticulturist Amy Schnieder rarely waters the plants, and recalled, "In 10 years I have watered the roof only 31 inches". Schnieder monitors the specie survival rate and total rainfall hitting the roof each year. She prefers a diverse plant palate to the traditional sedum monoculture to potentially provide a greater variety of species for green roof use. However, if a sedum plant takes root on the roof, she will let it establish and intermingle with the plant community. Schnieder acknowledges the harsh microclimate of the roof, and observes smaller growth rate and plant sizes are minimal compared to the same species on the ground. She states the roof environment is similar to that of an Alpine climate. Because roof environments are prone to more extreme weather, the plants concentrate their energy on making seeds because they prioritize reproduction. There are 82 taxa on the roof from several families including Plantain, Cactus, Thyme, Mint, Iris, Grass, and Rose. The plant habits include succulent, herbaceous, sub-shrub, shrub and tree. The combination of woody and herbaceous species creates a plant community.

In the 2007-2009 growing season, 4 to 6 inches of monthly establishment watering took place. After the three-year establishment period, irrigation was reduced significantly (Schneider 2011). Since 2011, the annual irrigation amount is recorded; amounts vary in relation to the local precipitation.

TABLE 4: ANNUAL GR IRRIGATION

Year	Amount Irrigated (inches)	Local Precipitation (inches)
2016	8.0	12.86
2015	0	29.012013
2014	1.0	17.51
2013	2.0	19.3
2012	8.0	12.3
2011	3.5	22.04
2010	8.0	12.45

Mordecai Children's Garden in the Botanic Gardens, Denver, Colorado

The Mordecai Children's garden is a 1-acre semi-intensive system constructed over a parking structure. The substrate depth ranges from 6-18 inches consisting of a light, porous, expanded shale and compost mix. Underlying styrofoam berms create varying topographic forms, which allow roots to penetrate deeper over a greater area. This design by Tryba Architects, allows for a more diverse planting scheme. The garden's peripheral drainage system leads to a central drain. The captured storm water volume is monitored by the city's Urban Drainage & Flood Control (UDFC) unity Urban Drainage & Flood Control (UDFC) unit. According to three-year study conducted by the UDFC, the Mordecai roof reduces storm water runoff volume by 65 to 80 percent per year (Piza 2015). Results are compared to a control roof in central Denver and a commercial parking lot. The UDFC also tests the quality of the captured water. Below is a water quality comparison made between the Mordecai Roof to a control roof and the Mordecai Roof to a commercial parking lot.

Pollutant Load Comparison (Roof)

UDFCD Summary Report 2015

Analyte	DBG Green Roof		Control Roof		Load Reduction
	Concentration (mg/L)	Load (g/yr)	Concentration (mg/L)	Load (g/yr)	
Total Kjeldahl Nitrogen	2.08	118	1.93	220	46%
Nitrate Plus Nitrite	3.95	225	2.79	318	29%
Phosphorus, Total	0.4	23	0.21	24	5%
Phosphorus, Dissolved	0.37	21	0.14	16	-32%
Phosphorus, Ortho-P	0.42	24	0.17	19	-24%
TSS	15	854	33	3,758	77%
COD	67	3,815	46	5,238	27%
DOC	19	1,082	29	3,302	67%
TOC	22	1,253	14	1,594	21%
Copper, Total	0.146	8	0.025	3	-192%

Pollutant Load Comparison (Lot)

Analyte	DBG Green Roof		Commercial		Load Reduction
	Concentration (mg/L)	Load (g/yr)	Concentration (mg/L)	Load (g/yr)	
Total Kjeldahl Nitrogen	2.08	118	2.8	472	75%
Nitrate Plus Nitrite	3.95	225	0.89	150	-50%
Phosphorus, Total	0.4	23	0.35	59	61%
Phosphorus, Dissolved	0.37	21	0.13	22	4%
Phosphorus, Ortho-P	0.42	24	0.15	25	5%
TSS	15	854	219	36,947	98%
COD	67	3,815	187	31,548	88%
DOC	19	1,082	35	5,905	82%
TOC	22	1,253	36	6,073	79%
Copper, Total	0.146	8	0.027	5	-83%

The gardens within the DBG connect two of Denver's parks, serving as a green space corridor within the city.

Denver Botanic Garden's Green Roof & Mordecai Children's Garden

Park and Education/Research

Completed: 2007 **Mordecai:** 2010
Owner: Denver Botanic Gardens (City)
Location: Denver, CO USA
Size: 1,180 sq. ft **Mordecai**: 1 acre
Design: Semi-Intensive
System: Continuous
Type: Education & Test/Research
Cost: 30,000 (water monitoring system)
Maintenance: Low
Water Retention Rate: 65-80% annually
Team: Civitas Inc., Mark Fusco,

Green Roof (GR) Photo by DBG

Project Description:

The Botanic Gardens is home to two living roofs. The original Green Roof is the first publicly accessible green roof in Denver. All of the plants used on the GR are native to the Southwest and Colorado region to test their potential for use on green roofs. The Mordecai Children's garden serves as an educational park situated over the parking garage.

Research Conducted:

Mordecai Children's Garden:

- Storm-water retention
- Storm-water filtration

Green Roof (GR):

- GR species suitability for semi-arid climate

Mordecai Garden Photo by DBG

Structural Design

Substrate: 70-80% Expanded Shale, 10% compost, 10% mulch

Retrofit roofs: Designed for existing structures

Green Roof (GR) Photo by DBG

(GR) Vegetation:

This roof monitors plant survival and growth rates. It serves as a testing ground for the use of a wider range of GR suitable species. All taxa selected are native to the Southwest and Colorado region. The Green Roof is composed of over 100 native, drought tolerant species. Species are also selected for rate of establishment, ease of propagation, aesthetic and potential habitat value.

Plant Taxa:

Chrysanthemum weyrichii
Delosperma nubiginum
Thymus neiceffi
Veronica thymoides
Hesperaloe parviflora*
Nolina microcarpa*
Arctostaphylos*
Amorpha nana*
Chilopsis linearis*
Penstemon angustifolius
Penstemon cyananthus
Ephedra minuta
Ipomopsis aggregata
Scutellaria prostrata

*Slow growers

New York City High Line, Manhatten New York

The New York City Highline is a 1.5 mile elevated park structured similar to that of a green roof and designed by a collaboration of James Corner Field Operations, Diller Scofidio + Renfro, and planting designer Piet Oudolf. It is considered an intensive design; the soil depth ranges from 8 to 36 inches with an average depth of about 18 inches (Harvey 2012). The High-line Park is a renovation of an abandoned railway that has been idle since the 1930s. Unique plant communities often form on abandoned grounds. Many of the spontaneous, pioneer species that inhabited the prior railway are included in the renovation and over half of the species used are native to the New York region. Instead of the typical green roof substrate, topsoil is used as the initial layer. Just beneath the topsoil is a thick layer of specially mixed coarser, clay-based subsoil followed by the filter fabric and drainage mat. The drainage mat utilizes the egg carton shape and is filled with crushed gravel to reduce flow of excess water. Plants can use the re-tained water when needed. The underlying concrete pathway system is designed to retain storm water runoff and reduce irrigation. The paths are made of open-jointed pre-cast concrete planks that allow rainwater to drain between planks and into adjacent planting beds (Harvey 2012). Centralized drains are placed at low points in the planting beds to prevent water soil oversatura-tion. Regulating ecosystem services provided by the Highline include: a reduction of storm-water runoff by up to 80% and mitigation of the "heat island" effect (Harvey 2012). The vegeta-tion that creates shade, oxygen, and habitat for insects and birds provides supporting services. However, the cultural eco-system services provided are perhaps the primary design goal of reno-vation. The Highline Park is one of the most visited attractions in New York City, as of July 2014; there have been over 20 million visitors (High Line fact sheet).

The New York HighLine Park

Elevated Parkway

Completed: Phase I: 2009 Phase II: 2011
Owner: City of New York
Location: New York, New York USA
Size: 1.5 miles
Design: Semi-Intense/Intensive
System: Continuous Layers
Type: Elevated Park
Cost: 238.5 million
(672,000 Annual operating cost)
Maintenance: High
Landscape Architect: James Corner Field Operations
Architect: Diller Scofidio + Renfro
Planting Design: Piet Oudolf

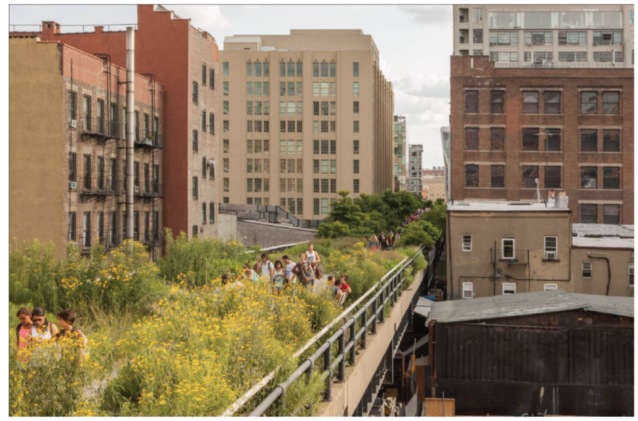


Photo by NYC & Company

Project Description:

An abandoned elevated railroad track reconstructed into a linear park has quickly become one of the most visited sites in Manhattan. The Highline is a model of contemporary ecological design. The concrete pathway system is designed to capture rainwater to reduce runoff and irrigation. The paths are made of open-jointed concrete planks that allow rainwater to drain into adjacent planting beds. Location of drains at low points in the planting beds allow water to be absorbed into the beds when it's needed, or drained when soil is over saturated.

Green roof benefits:

- Storm water Mitigation: up to 80%
- UHI Mediation
- Habitat Creation

Research Conducted:

- Plant taxonomy: native vs. nonnative
- Social Effects (gentrification)
- Financial & Maintenance

Structural Design:

1) Initial topsoil depth: 8 -36 in. (18 Inch average)
2) Layer of coarser, clay-based subsoil
3) Filter fabric
4) Drainage mat filled with crushed gravel when needed. This egg-carton shaped layer acts as a water reserve. Stored water is used by plants reducing the flow of excess water into the sewer

Harvey, E. (2012)

Vegetation:

Plant Species for the Highline was selected by designer Piet Oudlof. Oudlof suggests that contemporary expectations for planting should **support some part of the web of nature**. The most important aspects of planting design for animal diversity are a range of habitats that are *connected*. Habitats are created by a combination of trees, shrubs, perennials and ground-cover vegetation. Species from the prior plant community that established on the abandoned rail line are included in the plant list. Over half

Plant Taxa:

Trees & Shrubs
Aesculus parviflora
Amelanchier arborea
Perennials
Asclepias tuberosa
Nepeta sibirica
Salvia azurea
Grasses
Briza media
Vines
Clematis tibetana
Bulbs
Eremurus himalaicus
Wetland Plants

Discussion

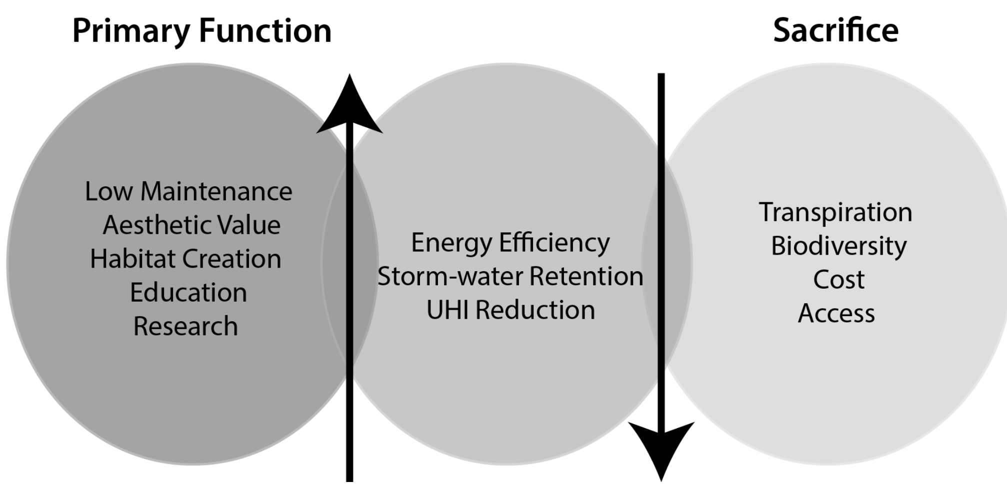
A green roof has the potential to not only impact the building but also the surrounding region. Yet not all green roofs are designed for the same function and green roof outputs vary widely depending on their primary design objective. Designers must often compromise ecosystem service functions for aesthetic goals.

California Academy of Sciences GR

This CAS roof's vegetation is composed of many drought tolerant plants. However, plant resilience is often a compromise of storm water retention as has been observed in the sedum genus. A variety of sedum genus (stonecrop) is the most widely used plants on green roofs because of its adaptability and year-round aesthetic quality. As an adaptation to dry conditions, sedum stores water in the leaves and stem, reducing its transpiration during the day to minimize water loss (Wolf 180). Transpiration is the process by which moisture is carried through plants from roots to the leaves, and then evaporates into the atmosphere. Water uptake and transpiration increase the ability of a roof to retain water from heavy rain events (Villarreal 2004). Maximizing transpiration rates within green roof vegetation will reduce the total amount of runoff from the roof. Sedum does not absorb stormwater as efficiently as other species because it stores water in its fleshy leaves and limits transpiration. Thus, a trade-off exists between transpiration cooling and plant survival in dry conditions (Durhman 2006). The degree of slopes also has the potential to reduce storm water retention because water retention diminishes as slope increases (Villarreal 2004). The CAS roof has seven miniature hills ranging from 40-60 degrees. The mounds are visually interesting and provide natural lighting, however the design again reduces the quantity of storm water retained.

The materials that compose each green roof layer should also be considered when designing a green roof. Green roof insulation and water proofing layers are widely made from petroleum-based materials. However, the CAS uses non-traditional materials such as recycled blue jeans for insulation and biodegradable coconut husk modules instead of plastic trays.

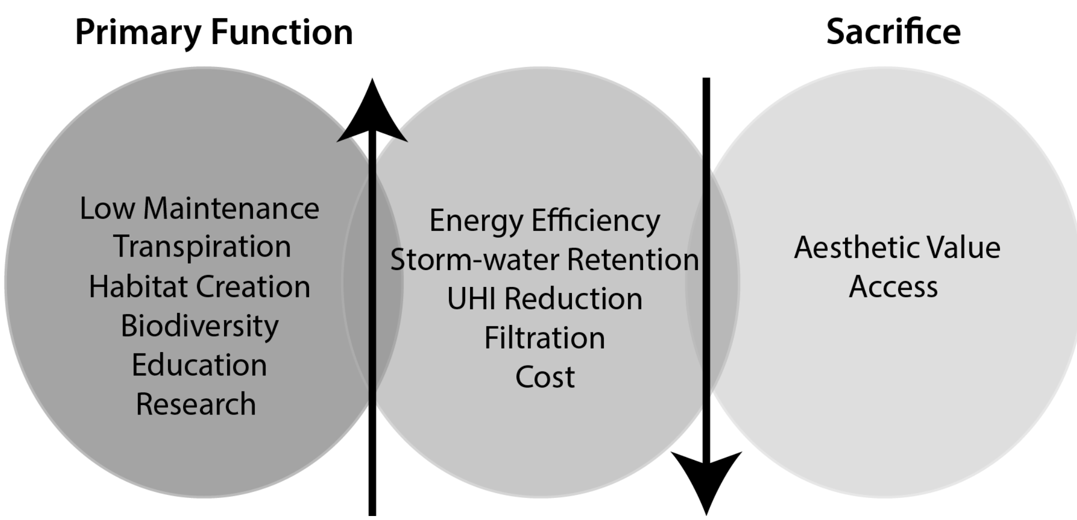
The roof provides visual appeal from the extensive green periods through out the year. The trade off is between the amount of water retention of the roof and the biodiversity of a mixed plant community. However the depth of an extensive green roof is not able to support a diverse plant community. This roof displays higher plant diversity than the traditional extensive green roof. The over-arching success of this roof is the use of the innovative materials, self-sustaining vegetation, support of biodiversity and education.



Denver 'Green Roof'

Similar to the CAS roof, the DBG Green Roof specifically uses drought tolerant plants. However, the species used are not the fleshy ground cover Sedum. To provide a wider range of ecological benefits, a more diverse group of plants is being considered for green roofs. The DGB Green Roof serves as a "testing ground" for a larger selection of species capable of surviving on roofs in Colorado. Native species have been shown to provide more benefits over traditional Sedum monocultures including higher transpiration and water mitigation (Dunnett and

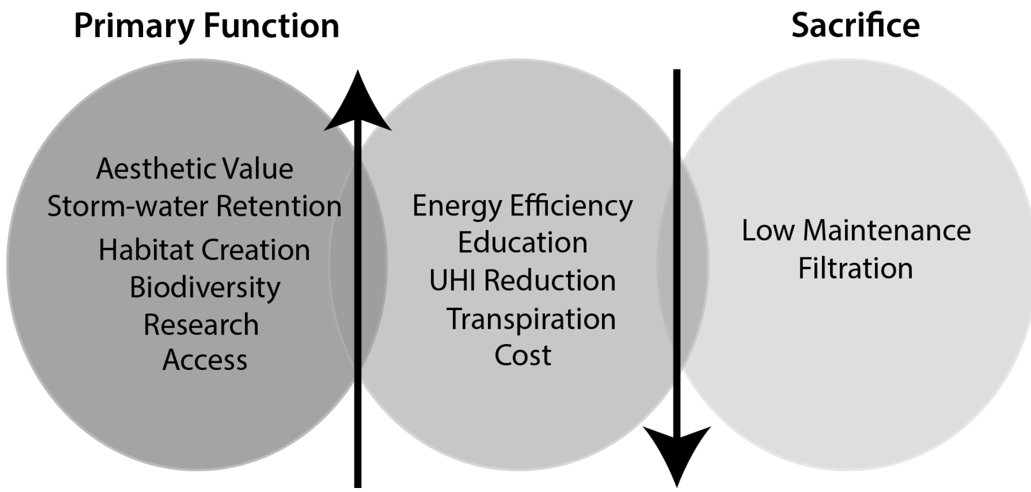
Kingsbury, 2004). Rather than using traditional green roof plants, this roof aims to identify a wider palette of plants that may be feasible for Colorado green roofs. This test roof benefits other designers in the Southwest region who wish to use a more diverse palate then traditional sedum roofs. The plants on this roof are underdeveloped and dormant for long periods of the year. The primary goal of this roof is a low maintenance, drought tolerant, and diverse plant community. The compromise is the aesthetic appeal of a densely planted and extensively in-bloom roof plant community.



Denver Children's Garden

The runoff water is tested for quantity and quality by a third party. The amount of water that flows from the roof is considerably lower than the test roof (65 to 80% annually) (UDFCD). Most of the polluting agents tested for are significantly reduced in the runoff from the Mordecai roof. However there is a 32% increase of dissolved Phosphorus, 24% increase of Orthophosphates, and 192% increase of Copper in runoff from Mordecai compared to the control roof runoff. When compared to a control commercial lot, a 50% increase of Nitrogen is observed.
This is most likely due to the fertilization necessary for the annuals on the roof. Increased phosphorus and nitrogen are the main contributing nutrients to eutrophication zones. Excess nutrients

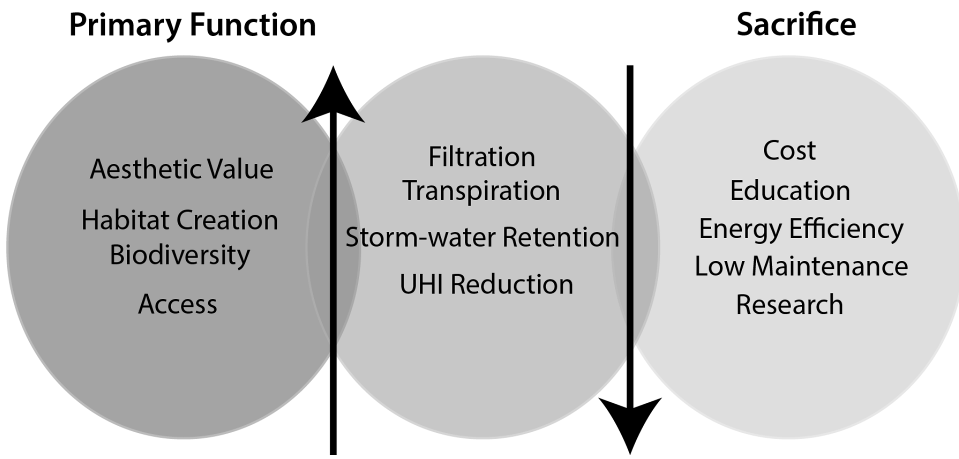
are detrimental to the hydraulic system. Fertilization is often necessary for a diverse mix of annual and perennial plants; the cost is the increase amount of nutrients that are collected in the runoff. Research and education are the major successes of both DBG green roofs.



The New York High Line

The High Line's maintenance is both ecologically and financially costly. A diverse plant community is apparent on the High Line, although it is not self-sustaining and the plants must be replaced often. Instead of a consistent soil depth of 18 inches, the gradient varies creating several narrow, shallow plant beds. It is difficult to maintain homeostasis in the High Line's limited environment as the soil easily becomes too saturated or dry out. Additionally, there have been many reports of gentrification repercussions since the remodel of the Highline Park (Birge-Liberman). Green roof systems are expensive to build and maintain; the High Line's initial construction cost was $238 million and the total annual operating cost is roughly $672,000 (Birge-Liberman). In comparison, the annual operating cost of Central Park is $32,000. Although owned by the City of New York, a group known as "The Friends of the Highline" made large donations for the initial construction ($44 million) and continues to make donations for maintenance and replanting. These large financial contributions illustrate the how much people value green space within a city. However, this design can only be sustained by a group of wealthy elites.

The Highline has become one of the most visited sites in New York City. This social and cultural attraction is the most successful element of this design.



Yet high operating costs and the inaccessibly of the planted beds creates a sense of "muesemification" or "organicism" of nature. Organicism is the belief that everything in nature has an organic basis or is part of an organic whole (Birge-Liberman). When construction began on Central Park in the 1800s, the site was essentially devoid of any vegetation. The park was a human-made construction within the city. It is not a remnant of nature that the city is built around, as many people believe. Human recreation of the natural environment may be perceived as "organicism" yet it has a functional role within the city. Man-made vegetated space within the urban environment provides ecological, economic, and social assets in the form of ecosystem services. Varying magnitudes of regulating, supporting, and cultural services are apparent as in all three case studies. A variation of the 19^{th} century Urban Park movement is currently being revitalized by the construction of green infrastructure into cities. The contrasting element is that green spaces are no longer created in one centralized area, but incorporated on top of and in between buildings creating a sense of “Urban Wilderness” (Baker 113). The urban wilderness characteristic of roof top gardens is perceived through all three case studies. The CAS roof acts as an extension of the surrounding Golden Gate Park. The DBG roofs connect two major parks within the city, creating a habitat corridor. Finally, the High Line serves as an alternative walkway to the streets below.

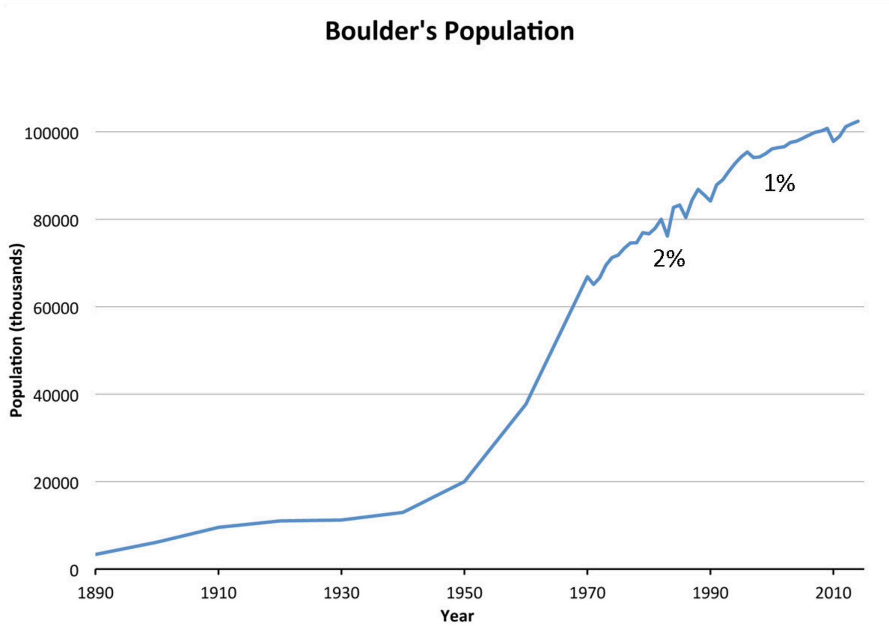
City's Role of Implementation

The CAS and DBG services benefit the community, yet they are privately owned green roofs and citizens must pay to use these facilities. In contrast, city buildings and infrastructure are accessible to citizens without cost, such as the New York Highline. City owned buildings and infrastructure are viable sites for green infrastructure implantation because the longevity of building ownership and the desire to increase livability of a city. City planners have a large influence on the construction of green infrastructure into their community. European cities are leading the in the application of green roof technology, especially in the UK and Germany. The NPFF in England requires local authorities to implement GI networks into their planning strategies (Carter 2015). This mandate may exist because the recognition of green infrastructure to reduce the risks posed by climate change is more widely validated in Europe. A comprehensive Green Roof guideline is used throughout Europe, created by The German Landscape Research, Development and Construction Society (FLL). The FLL guidelines provide parameters to building owners, designers and installers for proper materials of the different green roof systems (extensive, semi-intensive, or intensive). It also contains guidelines that help designers and users understand green roof technology given different green roof solutions, components, and functions (Breuning 2017). There are various green roof guidelines used in North America, however none as comprehensive as the FLL guidelines exists. Many U.S. green roof manufacturers and designers choose to use the FLL guidelines for base composition and structure; yet some experts in the field think the guidelines are inadequate for the U.S. However, green roof design components are specific to each site and regional climate. Bruce Dvorak, a professor of landscape architecture and urban planning at Texas A&M University, has stated, "various regions of the U.S. require modifications to FLL guidelines to accommodate greater drainage capacity or more water retention" (Maddox 2014).

Green infrastructure is not as integrated into United States' cities as they are in Europe. The U.S is lacking urban resilience strategies to prevent and mitigate potential damage accrued by extreme weather events. Yet, several U.S cities are emerging as leaders in the adoption of green roof technology including Chicago, New York, Portland, and Washington D.C (Maddox 2014). In 2013, the D.C region implemented 1.3 million square feet of rooftop vegetation, the city aims to achieve 20% green roof coverage by 2020 (Maddox 2014). New York City, Portland, and D.C offer tax incentives for green roof installations. Green roof technology is in its infancy in Colorado, the potential for policy adoption and installations is high.

Application: Boulder Growth & Future Development

Stormwater runoff in Boulder is released directly into Boulder Creek, affecting the entire downstream watershed. High impervious surface coverage in Boulder, as in other cities, increases the volume of runoff that impact vulnerable waterways, reduce the quality of runoff, and raise the risk of pluvial flooding. Many cities have similar watershed management plans, so it is imperative to limit impervious surface area in new development and renovation projects to reduce water pollution. The incorporation of vegetative storm water management systems will reduce the quantity and quality of runoff. A holistic, integrative, and functional design is necessary for the future of Boulder as it densifies. The Boulder County Comprehensive Plan, adopted in 1978, centralizes urban development around the municipalities. Its overarching goal is to reinforce distinction between rural and urban areas by limiting and directing growth. Under this plan, Boulder has preserved over 85,000 acres of open space land from development (Boulder County). This land is permanently protected. Boulder's population has grown significantly since the 1950s and continues to increase.



SOURCE: LIVABLE BOULDER

New developments in Boulder include Alpine Balsam, CU Boulder South, and Google. The Alpine-Balsam project is a remodel of the old Boulder Hospital location in North Boulder. The nine-acre site will be reconstructed for affordable housing units and a new centralized city-office campus. An existing 64,000 sq. ft. building will be renovated to accommodate city office space. Google is building a new campus in Boulder near 30th and Pearl St. The campus will include 330,000 square feet of office space between 3 four-story buildings. The campus will house up to 1,500 workers. The influx of Google will have repercussions of companies, business, and workers moving into the region. This continues growth will increase impervious area and the resources used within Boulder. The current challenge Boulder faces is how to live sustainably within the defined municipal limits while supporting a growing population.

The conventional urban drainage systems are not equipped to accommodate higher quantities of runoff from increased urbanization (French, 2011). Expanding and retrofitting the piped drainage systems is a large financial investment. Therefore, increasing infiltration and evapotranspiration offers an alternative, cost-benefit option. The indispensable appeal of roof top garden systems is the ability for one structure to provide several functions.

Energy Reduction in a Changing Climate

There are currently 6,000 non-residential buildings located across municipal Boulder County. According to 40% of the model projections conducted by Boulder County, buildings will experience increased damage from increased precipitation. The projections are $1.6 million by 2030 and $3.2 million cumulative by 2050 (Boulder County). Additionally, buildings in Boulder County are projected to experience a cumulative increase in cooling costs by 23% ($23 million) by 2030 and 32% ($72 million) by 2050. That is an estimated total cost of $75.2 million by 2050 from increased energy use and storm water damage alone.

Within the city of Boulder, 53% of total GHG come from commercial and industrial buildings (Boulder County). The Boulder Building Performance Ordinance (BBP) was adopted in 2015 to improve the quality of Boulder's commercial building stock. The BBP affects privately owned commercial, industrial and city-owned buildings. Additional goals include reducing GHG, increase awareness of building energy metrics, and driving market transformation and to inform design of future programs and services (City of Boulder). Building owners must rate and report building energy use and implement energy efficiency measures by 2025. Every ten years, owners must attain assessments that meet or exceed the requirements provided by ASHRAE. A cost estimation tool is provided by the city for required energy assessments and retro commissioning. Retrofit green roofs can serve as an insulation barrier to buildings needing to lower their energy consumption.

Parameters for Green Roofs in Boulder, Colorado

Efficient green roof design is specific to each site and climatic region. Boulder (USDA Hardiness Zone 5b, 6a) receives an annual average rainfall of 20.66 inches and 89 inches of snowfall is considered a cold-semi arid climate (U.S Climate Data). Green roofs in Boulder should be designed to retain water for extensive periods of drought. Plant taxa used in Boulder must also be able to thrive in a cold, semi-arid climate and the harsh microclimate on rooftops. I organize parameters of an efficient green roof in Boulder based on the primary function of each green roof. A list of those functions is presented in the following tables (1-4).

1. Energy Efficiecy Roof (retrofit)

If the primary goal is energy efficiency, the green roof will most likely be a retrofit roof. New buildings use advanced insulating technology that reduces energy consumption, and while green roofs may complement this insulating technology, they are not the primary technological component. The Academy of Science claims their extensive green roof reduces interior temperatures by about 10 degrees during the warmest months, eliminating the need for air-conditioning (Wels 2008, 70). A retrofit green roof can help a commercial, industrial or city owned buildings reduce energy consumption to meet the Boulder Building Performance Ordinance requirements.

Energy Efficiecy Parameters

Retrofit roofs designed for energy efficiency can be extensive or semi-intensive (5-12 inches of substrate). One must first identify the slope of the roof when planning to retrofit. The maximum pitch (slope) of a retrofit is about 30 degrees (Dixon 16). Existing structures must have the capacity to bear the additional load of a roof top garden. A semi-intensive roof is preferred for energy efficiency because depth maximizes transpiration and insulation. However, if the load bearing capacity is limited, an extensive roof will also increase energy efficiency. Selected plant species will have a high rate of transpiration. The process of latent heat loss (phase change to vapor) reduces the energy available to be dissipated as sensible heat. Thus a higher transpiration rate is correlated with reduced heat. The range of transpiration varies with plant taxa. Determining factors include leaf shape, size, pores (stomata), and soil moisture conditions. For example, Salvia was found to transpire 3x as much as Sedum (Vaz Monteiro, 2015). A study conducted in temperate England found that herbaceous plants are the best insulators because they offer more substrate shading, had lower leaf temperatures, and higher transpiration rates (Blanusa). This study compares the temperature of bare substrate with the temperature of substrate below vegetation. *Sedum* reduced temperature of the underlying substrate by 3C and *Stachy* by 15C compared to the control (Blanusa 2013). Stachy and salvia are uunlikely to thrive in the limited extensive systems. They are drought tolerant species and capable of survival in deeper substrate provided by semi-extensive roofs. Plants in the Cassulacea family (sedum) do not offer optimal transpiration because of their water-conserving properties. When water is limited, their stomata closes during the day, reducing the amount of water lost to the atmosphere. Sedum is able to thrive in limiting and dry environments such as extensive roofs, though sedum does not cool roofs as efficiently as other herbaceous genus' (Blanusa 2013). Sustainable watering methods of the energy efficient green roof are required for reduction of temperatures because drought conditions will lessen the plants' transpiration.

Plants act as insulation in winter months. In the same study conducted by Blanusa, Stachy genus warmed substrate by 1.8 C compared to bare surface, Sedum warmed substrate by 1.4C. This suggests that plants vary in transpiration rate yet act similarly as insulation in the colder months.

A similar study found that a 21-37% reduction in winter heating could be achieved via extensive or semi-intensive roofs (Cameron 2015).

ENERGY EFFICIENCY PARAMETERS (TABLE 1)

	Parameter	Description
Function	*Energy Efficiency for retrofit buildings*	Provide insulation and increased transpiration to reduce/increase interior temperatures and reduce overall energy consumption
Type	*Extensive* *Semi Intensive*	13-30 lb./sq. ft. 25-40 lb./sq. ft.
System	*Biodegradable Tray* *Drainage Board*	Low cost and maintenance installation Retrofit, Non-accessible
Ecosystem Service	*Regulating*	Climate regulation
Substrate	*Expanded-shale aggregate*	10% compost, irregular shape, small granular on top layer
Irrigation	*Low to Moderate*	Energy efficient roofs require moisture for high transpiration rate
Plant Species	*Herbs, Grass, Shrubs*	Salvia, Heuchera, Stachy

2. Storm water mitigation roof (retrofit or new):

Living roofs alleviate flooding by delaying and reducing the volume of runoff that reaches storm water drainage systems. Several studies have found that substrate alone accounts for the majority of rainwater retention (Boone 2012). However, the vegetation absorbs water from the substrate, which restores the substrate's retention capacity. Water taken up by plants may be stored in plant tissue or transpired back into the atmosphere (Vaz Monterio). Semi-intensive and intensive roofs with greater than six-inches of substrate improve anchorage of roots and water storage. Extensive roofs also mitigate storm water runoff, although the shallower substrate has a lower saturation capacity. Similar to cooling function, the rate of transpiration is directly related to storm water retention. Thus, plant taxa still accounts for maximum water mitigation. A study conducted by Nagase and Dunnett in 2012 tested forbes, grasses, and sedum on extensive green roofs. They found that grasses reduced the most runoff because their larger canopy and root systems correlated with efficient water retention (Nagase and Dunnett 2012). Another study led by Tijana Blanusa in the UK measured substrate (not identified) moisture and transpiration volumes for species in the following genus: Heuchera (Obsidian), Salvia, Sedum, and Stachy. Blanusa measured the saturation of the substrate after three days of initial watering. They found that sedum lost the least amount of water (127.3 ml) via transpiration. Heuchera lost 249 ml, Salvia 262 ml and Stachys lost 217ml. The saturation of substrate at capacity was .24 m3/m3. After three days the bare substrate saturation reduced to .175, sedum .18, the remaining three plants reduced saturation to about .10. Thus, the sedum genus retained more moisture than the unvegetated substrate. The ability of plants to quickly transpire water retained in the substrate allows for greater retention capacity of future rainfall events. The Alpine-Balsam site in North Boulder lies within the Goose-Creek floodplain. Incorporating water mitigating green roofs will reduce the amount of runoff on the site, decreasing the overall load on the drainage system. This will help to alleviate potential flooding on the Alpine-Balsam site. Because green roofs retain water, they support the drainage network by mitigating potential pluvial flooding events.

Runoff Mitigation Parameters (Table 2)

	Variable	Description
Function	*Water Mitigation*	Provide water retention to reduce quantity and quality of runoff, decreasing overall load on surrounding drainage system
Type	*Semi Intensive* *Intensive*	25-40 lb./sq. ft. 35-100 lb./sq. ft.
System	*Continuous* *Granular Drainage System*	Diverse plant community Maximum water retention
Ecosystem Service	*Regulating*	Water treatment
Substrate	*Expanded-shale aggregate*	10% compost, 10% mulch
Irrigation	*Low*	Water storage capacity for dry periods
Plant Species	*Herbs, Grass, Shrubs, Woody perennials*	Salvia, Heuchera, Stachy

3. Habitat creation roof (new):

Green roofs can serve as corridors for wildlife between the open space and urban areas. Greater plant variety, such as long-lived perennials in conjunction with woody plants, enhances biodiversity and improves sustainability (Oudlof). Semi-intensive and intensive roofs have the ability to support a range of plant taxa. Plant communities are relatively stable groups of plants from multiple species, which can be managed as a unit. The described "zeitgeist of contemporary planting design" is a move away from precise individual plant placement to combinations of species. Rather than planting a mass of individuals, this approach creates a community*,* in which the sum is greater than the parts. This also means that there is more interaction between plants, and so more competition.

HABITAT CREATION PARAMETERS (TABLE 3)

	Variable	**Description**
Function	*Habitat Creation*	Serve as corridor between open spaces
Type	*Semi Intensive* *Intensive*	25-40-lb/sq. ft. 35-100 lb./sq. ft.
System	*Continuous* *Granular Drainage System*	Diverse plant community Semi-accessible, new
Ecosystem Service	*Supporting*	Biodiversity, Habitat, Pollination
Substrate	*Expanded-shale aggregate*	10% compost, 10% mulch
Irrigation	*Low*	Drought tolerant and self sustaining
Plant Species	*Herbs, Grass, Shrubs, Woody perennials*	Sedum, Salvia, Heuchera, Stachy

4. Aesthetic Value & Green Space (new)

The mixing or blending of species, as opposed to the use of blocks or groups, creates an effect that is visually more complex and naturalistic. This technique is used by Dutch garden designer Piet Oudolf and is apparent in the New York Highline. The Aesthetic Green Roof will serve as a park or garden accessible to urban dwellers.

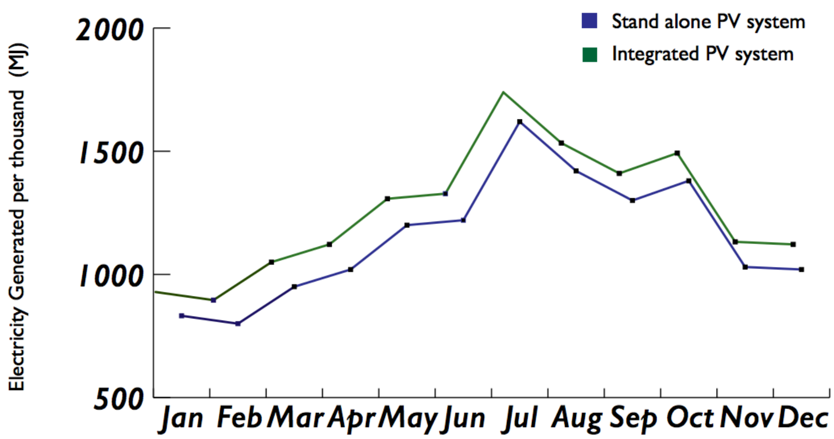
GREEN SPACE PARAMETERS (TABLE 4)

	Variable	Description
Function	*Green Space*	Serve as park or garden, educational
Type	*Intensive*	35-100 lb./sq. ft.
System	*Continuous* *Granular Drainage System*	Diverse plant community Accessible, new
Ecosystem Service	*Cultural*	Recreational benefits
Substrate	*Expanded-shale aggregate*	20% compost, 10% mulch
Irrigation	*Moderate*	Sustainable irrigation to keep aesthetic value year round
Plant Species	*Succulent, Herbs, Grass, Shrubs, Woody perennials*	Sedum, Salvia, Heuchera, Stachy

Overall, green roof design should be specific to the climatic region and the particular need of that site. The load bearing capacity of the structure is also a large determinant of design possibilities. Plant transpiration should be highly regarded if the overarching goal is for either storm water mitigation or energy efficiency. Deeper substrates can support a wider range of vegetation providing a more diversity. Lastly, granular drainage systems have a larger water retention capacity than do drainage boards.

Living Roof and Solar

Solar photovoltaic panels and green roofs do not need to compete for space. Studies show that they are mutually beneficial; each system is more productive when they are combined, forming a symbiotic relationship (Bousselot). Integrated systems enhance the function and effectiveness of solar PV and living roofs. Solar photovoltaic and living roofs as integrated systems enhance the function and effectiveness of both structures. Shading from PV reduces the temperatures of the living roof surface and soil. The cooling of plants (transpiration) achieves higher power output of the PV panel. These systems will create a more sustainable site by effectively managing and filtering storm water as well as working towards net-zero energy buildings.



Monthly power generation of stand-alone PV and green roof integrated PV systems. Source: Sam C. M. Hui

Limitations to Green Roof Technology

Stakeholders may choose to retrofit or install a green roof for one primary benefit; thermal performance, mitigation of the urban heat island or runoff, biodiversity enhancement, conservation, or provision of social space. Although green roofs do provide these ecosystem services, implementation poses several challenges including increased installation and maintenance costs as well as increased structural requirements. Limitations have also been identified in terms of environmental sustainability by use of excess materials and fertilizer. These factors have attributed to the slow adoption rate of green roof technology.

The most frequently addressed constraint of green roofs is the overall cost. Green roof technology is a long-term investment that has a large upfront cost. An extensive green roof generally costs between $10-$24 per square foot (GRHC). Predominantly, intensive roofs cost twice as much because they are dynamic systems that utilize more materials. The California Academy of Sciences' extensive green roof cost about $17 per square foot to install, an overall cost of $2 million (Jacobs 2009). The New York Highline is on average a semi-intensive system and a similar planted size to the California Academy of Sciences' green roof (2.5 acres). In comparison, the New York High line's initial cost was $238 million (Birge-Liberman). The vast difference in construction price is not only the difference of system (extensive vs. intensive) but can also be attributed to the design, structure, plant species, and other building materials. The maintenance and upkeep of green roofs is also a high cost factor. The New York Highline has an annual operating cost of $672,000, compared to Central Park with an annual operating cost of $32,000 (Birge-Liberman 133). Green roofs are limited systems, thus the vegetation requires additional maintenance to keep healthy. Supplemental irrigation, fertilization, weeding and replanting are often necessary.

Because the limited environment of a green roof requires fertilization of certain plants, the overall sustainability feature may be compromised. As observed in the Denver Mordecai Children's roof, the majority of pollutants tested for were reduced compared to the controls. The pollutants that increased in volume were Phosphorus, Nitrate, and Copper. This is in part due to the fertilization of annuals on this roof. Additionally, green roofs are designed with several layers such as the waterproof membrane, root barrier, and drainage layer. Usually these layers are composed of petroleum-based materials. The amounts of materials, plastics and lubricants that comprise an underlying system have deemed green roofs as input intensive. However, some designs utilize biodegradable and recycled material, as seen at the California Academy of Sciences. Instead of using plastic trays for the modular system, biodegradable coconut husks with strains of fungi were implemented, alleviating the use of excess material and fertilization.

A study conducted in Washingtong D.C determined that the installation cost of green roofs is 27% higher than the average conventional roof. However, when considering the assets over the lifetime of 40 years, the net present value (NPV) of the green roof is about 25% lower than the conventional roof (Nui 2010). It is difficult to estimate the value of the roof as it exemplifies additional functions to the intended primary benefit. Costs and benefits will vary with each roof given the design components and climatic conditions. Also, the initial investment can be significantly reduced by tax incentives, credits, and policies implemented by the city. For example, Portland Oregon offers a preferential property tax and a 35% reduction in storm water management charges for buildings with green roofs. Also, all city-owned green roofs in Portland are required to have a green roof covering no less than 70% of the area (Vijayaraghavan). The construction and renovations of underground piping, which make up the urban drainage structure, are very costly. These systems only serve one purpose, to capture and filter runoff. Although green roofs are also a high initial investment, the technology provides numerous secondary benefits, which supports the overall urban resilience. Though, it is difficult to get an exact measure of the benefits provided from green roofs because they influence ecological, economical, and social well being.

Conclusions and Future Study

Designing a green roof with the efficient delivery of ecosystem services is still not a mainstream consideration in the building construction industry. Plant health should be one of the primary objectives when designing a green roof. As displayed by the case studies, most green roofs are not self-sustaining and are very costly. Yet if designed for ecosystem service over aesthetic value, green roof technology can play a major role in adapting to climate change and mitigating its impact. Climate change presents designers with greater uncertainty and the potential for more extreme weather; resilient planting vegetation will mitigate future impacts. Historically, native plants have been the backbone of resilient vegetative systems because they are adapted to a given region and can serve as stable species in the vegetation mix. However, diversity is more important for resilience than regionally native plants because a diverse plant group fills more ecological niches (Oudolf). Many of the plants the green roof sector relies on are descended from one single introduction, and may be unrepresentative of the species as a whole (Oudolf). Therefore, introducing a wider gene pool of the species already in cultivation will increase plant diversity in addition to the cultivation of new domestic plants from the wild. Genetic diversity allows vegetative populations to adapt to changing environments. With more variation, it is more likely that some individuals in a population will possess variations of alleles (mutations) that are suited for the environment. Those individuals are more likely to survive to produce offspring with that allele via natural selection. The success of the population will continue for more generations forming ecological specializations or niches (National Biological Information Infrastructure). Genetic diversity among plant species allows ecological niches to be filled. This leads to resilient, self-regulating, healthy plant communities on green roofs and thus a greater urban resilience. Implementing green roofs that incorporate a diverse planting community will ensure more efficient transpiration (relating to energy conservation and water mitigation) and habitat creation. As cities continue to develop and increase in population, green roof technology will provide ecosystem services that regulate temperatures, energy use, pluvial flooding and pollution.

Expanding and retrofitting piped drainage is a large financial investment. Therefore, increasing infiltration and evapotranspiration offers an alternate, economical option. The indispensable appeal of roof top garden systems is the ability for one structure to provide several functions, increasing the urban resilience. To maintain 'biophilic' city status, Boulder should implement green infrastructure and rooftop gardens into their new developments and renovation projects to reach municipal water quality and energy goals. Green roof technology can play a part in the future developments such as Alpine-Balsam, which will exemplify sustainable city planning. Green roof technology will reflect the sustainable and innovative environment that is rooted in Boulder's distinct identity. Site-specific characteristics, like building in a floodplain, determine the primary function of the roof and directly relates to cost-effectiveness. It is cost effective to reduce flooding, and green roofs work to mitigate runoff while simultaneously providing several regulating ecosystem services to the site and region. The ecosystem services provided improve air and water quality, reduce energy use and runoff, extend roof lifetime and provide habitat space. Rooftop gardens are viable and preferable alternative to cities' conventional storm-water management systems because they simultaneously deliver multiple ecosystem services, take up no additional space, and provide ecological, economic, and social assets to a city.

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