The Benefits and Challenges of Green Roofs on Public and Commercial Buildings

A Report of the United States General Services Administration

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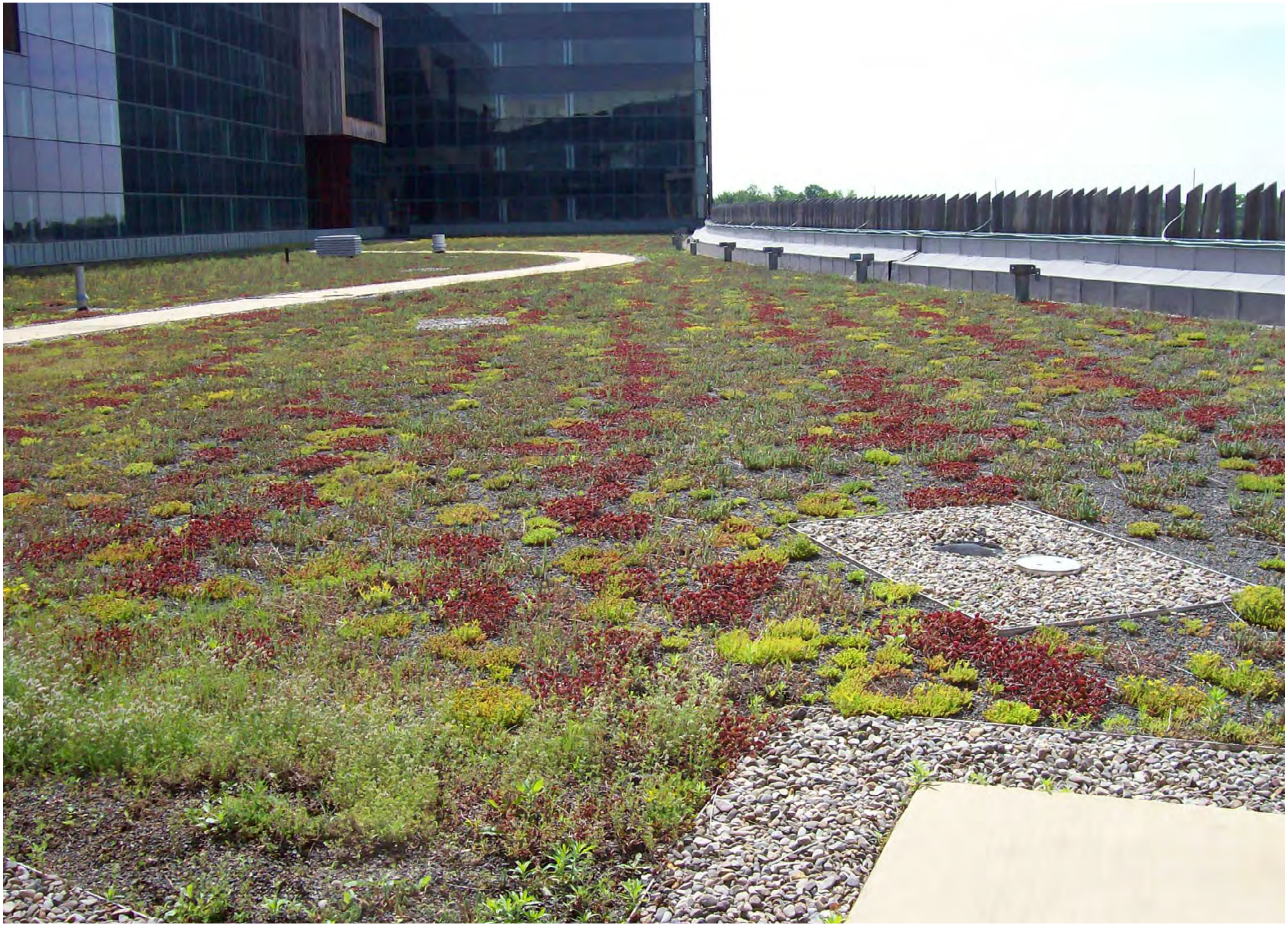
GSA

Front cover: Image of the green roof on the United States Department of Transportation Headquarters



GSA National Capital Region - United States Census Bureau Headquarters, Suitland, Maryland

The facility includes two extensive and intensive green roofs that total 85,000 square feet made accessible through walking paths.

GSA

BACKGROUND

Cities create remarkable social environments out of what had been untouched natural landscapes. It is important to understand what is lost in that process as well. Besides being attractive, natural landscapes absorb and infiltrate stormwater, provide cooling from excess heat, offer habitats to a diversity of species, and improve air and water quality.

The **urban hardscape**—a term for heavily urbanized areas with little bare soil—cuts cities off from these natural processes and creates problems like water pollution and increased temperatures through the urban heat island.

Green roofs—sometimes referred to as 'vegetated roofs' or 'eco-roofs'—consist of a waterproofing membrane, growing medium (soil) and vegetation (plants) overlying a traditional roof. Green roofs can help mitigate the problems that cities create by bringing the natural cooling, water-treatment and air filtration properties that vegetated landscapes provide to the urban environment. Architects and planners can use green roofs to help solve environmental problems by bringing nature back to the city in key ways. Green roofs properly designed, constructed and maintained, are beneficial socially, environmentally and fiscally. They are an important tool to increase sustainability and biodiversity and decrease energy consumption, urban heat island impacts and greenhouse gas generation.

PURPOSE OF STUDY

Congress authorized this study of green roofs. This report reached its findings through an extensive review and analysis of about 200 research studies on the costs, benefits, challenges and opportunities of green roofs, along with an original cost-benefit analysis, discussion of best practices and assessment of further research needs. A in-depth analysis of the benefits, challenges and opportunities of alternative roofs such as conventional roofs or white roofs was beyond the scope of this report.

GREEN ROOFS IN THE UNITED STATES

Green roofs have been around a long time. Prairie homesteaders built sod houses when settling the frontier. There have been green roofs on US Government buildings and parking structures for nearly a century—green roofs installed on several federal buildings in the Washington DC region have not been replaced since their installation in the 1930s. Although they have been used infrequently for decades, green roofs are now being revived and studied for their environmental benefits. The growth of green roofs in the US mirrors their use in other countries, like Germany, where they are more commonly seen.

The General Services Administration (GSA) has designed and maintained green roofs for decades and finds them to be economical amenities that make fiscal and environmental sense. The GSA currently maintains at least 24 green roofs in 13 cities around the country. GSA routinely installs green roofs on new and existing buildings.

ALTERNATIVE ROOFS

Conventional roofs are often known as **black roofs**, their traditional color. They are descended from the "tar beach" roofs once common in urban areas, and are still petroleum-based, whether made of polymer-modified bituminous sheets or synthetic rubber. Black roofs absorb significant energy from the sun and can reach temperatures as high as 150°F in summer. During storms, runoff from black roofs flows immediately into storm sewer systems, contributing to flooding and water pollution—creating environmental and human health hazards, particularly where stormwater and sewage systems are combined. Excessive stormwater runoff erodes soils and river banks and adds sediments and street pollutants to water bodies.

There is a third type of roof that is increasing in popularity—the cool or **white roof**. These roofs are made of light-colored material and do not heat up as much as black roofs in the sun. They, however, share the runoff problems of black roofs.

GREEN ROOF TYPES

A typical green roof includes a waterproof barrier to protect the building, a drainage layer to store and direct runoff, a soil or growth medium layer, and a plant layer.

There are two main types of green roofs: **extensive** roofs, which are relatively inexpensive to install and are used mainly for environmental benefit, and **intensive** roofs which allow a greater variety and size of plants such as shrubs and small trees but which are usually more expensive to install and maintain, partly due to the need for irrigation. Commercial and public buildings tend to use extensive roofs unless the roofs are intended primarily as occupied garden amenity space.

Extensive roofs have a thin soil layer and feature succulent plants like sedums that can survive in harsh conditions. Extensive roofs require little maintenance once they are established, and are generally cost-effective, particularly in buildings with long life spans. Intensive roofs have a thicker soil layer and should be considered a landscape with plants found in parks and gardens. These plants may require irrigation during dry periods. Because of their thicker soil, intensive roofs require greater structural support than extensive ones. However, intensive roofs also have greater potential for ecological benefit and amenity use than extensive roofs.

GREEN ROOF COSTS AND BENEFITS

The environmental benefits of installing green roofs on commercial and public buildings include:

- Improved water quality due to reduced stormwater runoff and fewer overflows of combined sanitary and stormwater sewage systems
- Increased habitat promoting biodiversity
- Lower temperatures for building roofs and the air above them in most climates
- Reduced energy consumption in some climates
- Improved sound absorption in the top floors of buildings
- Improved air quality

The economic costs of installing green roofs on commercial and public buildings include the cost of installing and maintaining the roof.

The economic benefits of installing green roofs include:

- Lower energy costs due to the cooling effect of plant respiration and the insulation, shading and thermal mass of the plant and soil layers
- A less frequent roof replacement schedule due to greater durability than conventional roofs
- Reduced stormwater management costs
- The creation of job opportunities in roof installation and maintenance and in the emerging field of urban agriculture

Green roofs provide a **payback** (based on a 50-year average annual savings) of approximately **6.2 years nationally** (internal rate of return of 5.2%) and **6.6 years in Washington DC** (internal rate of return of 4.2%), and conservative analysis puts the average life expectancy of a green roof at 40 years, versus 17 for a conventional roof.

In the National Capital Region, if green roofs were to replace conventional roofs on all 54 million square feet of real estate (an estimated 5.9 million square feet

United States Department of Transportation Headquarters, Washington DC of roof area), the cost-benefit analysis projects a 50-year NPV of $22.7 million, or $0.42 per square foot of building area. The community, or public benefits in the National Capital Region could total almost $180 million, or $3.30 per square foot of building area.

These financial benefits will likely increase as installation and maintenance premiums fall, energy costs rise, and stormwater regulations increase.

CHALLENGES TO GREEN ROOF CONSTRUCTION

The main design, installation and management challenges of green roofs include:

- Ensuring the building can support a green roof
- Quality installation and leak prevention
- Maintenance requirements
- Potential plant loss due to environmental conditions or mismanagement, among other items

Designers can maximize the benefits of green roofs by properly selecting plants, growth medium, drainage layers and other features tailored to the local climate and the building's surroundings.

FUTURE RESEARCH AND DATA NEEDS

Additional research in several issue areas is critical to better understanding the costs, benefits, challenges and opportunities of green roofs. These issues include:

- A thorough comparison of green and white roofs
- Stormwater and storm dynamics, field monitoring and computer simulation
- Validating stormwater runoff and delayed peak runoffs for stormwater regulation
- The interaction between green roofs and solar panels
- Long-term stormwater and energy performance
- The process of establishing native plants and created habitat for endangered fauna on green roofs
- Green roofs' influence on building energy use
- A thorough review of irrigated and non-irrigated roofs
- The economics of rooftop agriculture
- Air quality improvements associated with green roofs
- Employment analyses

Research has identified the following benefits for green roofs:

STORMWATER MANAGEMENT

In a typical urban area, rain that falls onto paved or built-on surfaces quickly flows into storm sewers and out into a nearby body of water. This excess stormwater runoff can cause numerous environmental problems, including damaging water quality by sweeping urban pollutants into water bodies, eroding river banks and flooding. In cities that built sewer systems before the 1930s, these storm drains are typically combined with the sanitary sewers that carry wastewater away from buildings to water treatment plants. This can be a problem during storms, when the large volume of stormwater can cause a **combined sewer overflow** (CSO), and lead to the discharge of untreated sewage into rivers and lakes. Particularly in urban areas with high-density development, green roofs may be the most practical way to address **wet weather flows**, especially when existing buildings must be retrofitted.

Green roof stormwater retention is affected by roof construction, size and slope, as well as the plants, drainage layer and growth medium used.

Green roofs can form a key part of a site-level stormwater management plan, reducing peak flow rates by up to 65% and increasing the amount of time it takes for water to flow from a site into the sewer by up to three hours, depending on the size of the roof and the distance the water has to travel. Green roofs reduce runoff rates after both large and small storms. Installing a green roof at least 3 inches thick on a large enough area can reduce the frequency of sewer overflows during the summer season.

United States Census Bureau, Suitland, Maryland

BIODIVERSITY AND HABITAT

Biodiversity is a measure of the variety of plants and animals in an area. Green roofs provide new habitat for beneficial plants and animals in urban areas, helping to increase biodiversity. Increased biodiversity can help ecosystems continue to function even when they are disturbed by development or in other ways.

Green roofs, particularly intensive ones, can be designed to integrate multiple habitats and microclimates, thus providing appropriate conditions for a variety of plants and animals to thrive. They can also be designed to mimic local native habitats, extending the area available for native species to colonize, or they can simulate early succession patterns of ground-level habitats, which can allow gains in biodiversity over time.

URBAN HEAT ISLANDS

Urban heat islands are highly built-up areas that are generally warmer than surrounding rural or suburban areas, due to the absorption of solar radiation by buildings and other man-made surfaces, and the lack of natural cooling from vegetation. Heat islands cause increased energy consumption, greater rates of heat-related illness and death, and increased air pollution. Reintroducing vegetation to urban areas through green roofs is one of the most promising solutions to mitigate the problem of heat islands.

Green roofs absorb less sunlight than dark roofs, through the process of **evapotranspiration** and by providing a shading effect to buildings. In the summer, green roofs cool buildings and the air around them through evapotranspiration, or the movement of water from the soil both by evaporation and by **transpiration**, the process by which water exits through pores in the leaves of plants. It takes energy to turn the liquid water into vapor, and the process of evapotranspiration therefore cools the plant. This creates a cooling effect on and around buildings. The peak temperatures of both green roofs and the air above them are typically lower than for black roofs.

Studies have shown green roof surface temperatures approximately 30–40°F cooler than black surface temperatures in the summer. A green roof program covering at least half the roof space in a city could result in citywide cooling throughout the day and during peak summer energy demand periods, particularly when combined with street tree planting and other large-scale greening efforts.

ENERGY

Green roofs reduce a building's energy use in hot, and to a lesser degree, cold seasons. As discussed above, the process of evapotranspiration cools green roofs in the summer, leading to reduced air conditioning needs.

In summer, green roofs can also act as an insulating layer, reducing **heat flux**, or the transfer of heat from a building's exterior to its interior through the roof by up to 72%. They also make roofs more energy efficient by reducing summer air temperatures directly above a building as cooler ambient air can reduce energy consumption related to building cooling. Depending on the climate, green roofs can reduce peak and daily summer cooling demands. In the winter, the insulating effect reduces heat loss through green roofs as compared with black roofs. Green roofs can therefore also reduce building heating demand in the winter although the marginal benefit is lessened with higher code-required insulation levels.

It is important to note that the insulating effect is not the primary energy benefit of green roofs—the evapotranspiration effect, thermal mass and shading effects are their primary contribution to energy savings.

URBAN AGRICULTURE

Compared with plants in a ground-level field, plants grown on rooftops are less subject to damage from insects, rodents, and deer. Growing plants on rooftops also contributes to job generation. Urban agriculture can potentially increase property values and building marketability. It can also provide easier

ATF, Washington DC

United States Environmental Protection Agency Region 8 Headquarters, Denver, Colorado

access to fresh produce and a way to educate the local community about food production and seasonal variety. Urban agriculture may also reduce carbon emissions associated with food distribution.

ACOUSTICS

Green roofs are better at absorbing sound than conventional and concrete roofs. When used on buildings without ceiling insulation, they can reduce the amount of noise transmitted inside the top floors of a building, particularly in areas with heavy air or automotive traffic.

AIR QUALITY

Plants have long been used in the urban environment to remove air pollutants like carbon dioxide and carbon monoxide, smog-forming compounds and particulate matter. A green roof's effectiveness at improving air quality depends on the type of plant grown and the depth of soil used. For example, the greater the leaf surface area, the more particulate matter can be captured.

Because green roofs also reduce a building's energy use, they can potentially reduce the amount of CO_2 and smog-causing pollutants emitted by power plants. The reduction in the urban heat island also contributes to smog reduction.

AESTHETICS AND QUALITY OF LIFE

Both intensive and extensive green roofs can create an attractive space for building occupants, and views for those in neighboring buildings. Intensive roofs in particular can offer a place of refuge and relaxation for people who work in a building, thus reducing stress and boosting worker productivity.

JOB GENERATION AND ECONOMIC DEVELOPMENT

Green roofs offer potential long-term job opportunities for both skilled and unskilled workers. They can also offer building developers and owners a more marketable building as compared to those that lack green roofs. Some evidence suggests that higher rental occupancy, purchase prices and faster sales may result from the presence of a green roof.

ROOF LONGEVITY

Properly installed green roofs more than double the number of years typically needed before a roof must be replaced, as compared with conventional and white roofs.

GSA Region 1 - John W. McCormack US Post Office and Courthouse, Boston, Massachusetts

A 9,654 square foot extensive green roof replacing an existing, weathered roof on an this historic building (1933).

The green roof is accessible by occupants and used as a filter for stormwater runoff from the surrounding, impervious rooftops.

1.1 PURPOSE OF STUDY

Green roofs—sometimes referred to as 'vegetated roofs' or 'eco-roofs'—consist of a waterproofing membrane, growing medium (soil) and vegetation (plants) overlying a traditional roof. Green roofs are used to achieve environmental benefits including reducing stormwater runoff, energy use, and the heat island effect. This study addresses the benefits and challenges of green roofs, as mandated by the U.S. Congress as a requirement of the US General Service Administration's (GSA's) Fiscal Year 2009 appropriation. The act states:

> *GSA shall conduct a study of the measurable benefits and challenges associated with the use of green roofs in GSA's diverse owned and leased inventory, using the National Capital Region as an example. The study shall address, among other things, the practical, environmental, and aesthetic benefits of green roofs, including the reduction of stormwater runoff. It shall include examples of existing or planned GSA green roofs. It should analyze building life-cycle cost, return on investment, energy savings, historic preservation considerations, and factors such as the size of the roof, structural capability, building age, and what, if any, sustainable design features might be important to justify the costs associated with green roofs. (HR: 110-920: 69 & J.E.S.: 985).*
>
> - Joint Explanatory Statement for the Fiscal Year 2009 Omnibus Appropriations Act (P.L. 111-8)

In accordance with Congress's mandate, this report answers the following questions:

1. What are the documented environmental benefits and impacts at the building, community, and societal levels of installing green roofs on commercial and public buildings?
2. What are the documented economic costs and benefits at the building, community, and societal levels, of installing green roofs on commercial and public buildings?
3. What are the design, installation, and management challenges of green roofs, and what practices may be used to maximize the identified benefits?
4. What research and data are critical to better understand the costs, benefits, challenges, and opportunities of green roofs?

The benefits and challenges uncovered in this analysis rely heavily on research and field data, but research and performance data on green roofs are still in their infancy. This is due to the relatively small numbers of green roofs that have been built, the relatively short-time frame most green roofs have been operating, and other limitations. The report provides some suggestions about current research gaps and data needs.

1.2 METHODOLOGY

The study included a review of approximately 200 reports, case studies, and research papers, which was supplemented by interviews with industry and government agencies to provide insight into practical experiences and research gaps associated with green roofs on public and commercial buildings. The literature review explored the cost-benefit methodologies and analyses performed for green roofs, green infrastructure, and green buildings to date. In-depth analysis of alternative roofs such as conventional roofs or white roofs was beyond the scope of this report. The studies cited in the report are listed in the References section.

The literature review highlighted potential benefits of green roofs, which can be categorized under the following focus areas:

- Stormwater management
- Biodiversity and habitat
- Urban heat island
- Energy
- Urban agriculture
- Acoustics
- Air quality
- Aesthetics and quality of life
- Job generation and economic development
- Roof longevity

Summaries of each focus area are provided in the Benefits section of the report (*Section* 2). Benefit data are also included in the cost-benefit analysis conducted for the study.

The report also examined common issues and challenges met in installing and maintaining green roofs. The report outlines recommendations for avoiding potential problems in the following areas:

- Building structural requirements
- Historic buildings
- Codes and standards
- Contractor skills
- Handling and knowledge of plants
- Safety training and personnel
- Plant establishment
- Leaks and leak detection
- Plant loss
- Wind scour
- Root penetration and biodegradation

There are still many areas that need further study. Future work may validate some of the benefits of green roofs, or help in understanding the details of their design and function. These "research and data needs" are addressed in the final section of the report (*Section* 5).

1.3 BACKGROUND TO GREEN ROOFS

Cities are full of hard, waterproof surfaces that have replaced natural terrain. These urban **hardscapes**, or heavily urbanized areas with ever-decreasing areas of available soil on which to plant vegetation, have lost the benefits that plants provide in natural, undeveloped areas. Development can lead to sewer overflows and higher temperatures in cities and suburbs.

Green roofs are a technology that can help to mitigate some of the negative effects of the urban hardscape by reintroducing a natural landscape into urban environments without making major changes to a **city's infrastructure**. Green landscapes can provide numerous social, environmental and economic benefits to a region.

Green roofs include drainage and soil layers, installed on top of conventional roofing and waterproofing system. There are two main types of green roofs: **extensive** roofs, which are relatively inexpensive to install and may not need irrigation, and **intensive** roofs allow a greater variety of plants and are typically nicer to look at, but which are more expensive to install and maintain.

Green roofs, which cover buildings with a layer of living plants, can help mitigate numerous problems of the urban hardscape by bringing the natural cooling and water-treatment capabilities of undeveloped areas into the urban environment. Architects and planners can use green roofs to help solve environmental problems by bringing nature back to the city in key ways.

While they are increasingly prominent as an environmental solution, green roofs are not a new idea. They can be traced back as far as the hanging gardens of Babylon in 600 BC. Scandinavians have used sod rooftops for centuries, taking advantage of their insulative properties, and sod roofs were also found in the sod homes built by Great Plains settlers in the United States.

Rainwater flows over the hardscape into the storm sewer, where it is combined with the sanitary sewage from the buildings (combined sewer). If the combined wastewater is beyond the pipeline's capacity, the excess wastewater is discharged directly into the receiving water body. Otherwise it is sent to the sewage treatment plant and treated.

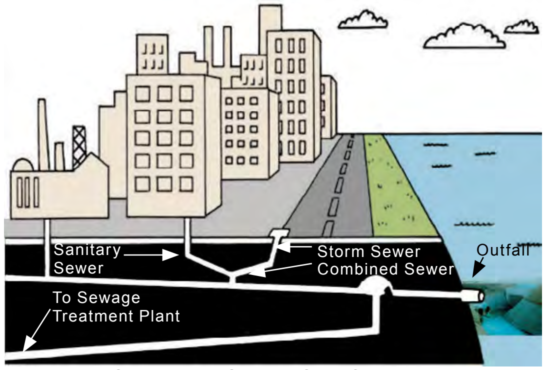


Figure 1: Combined Sewer Overflow network

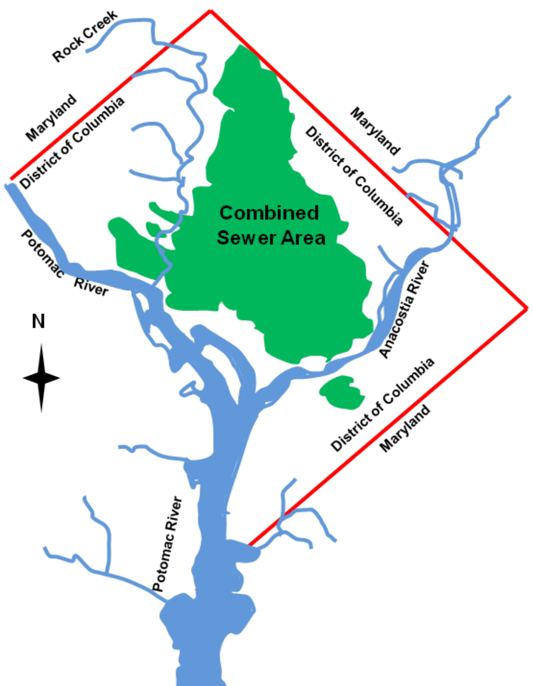


Image courtesy of DCWASA

Figure 2: The CSO region in the District of Columbia

More recently, architects such as Le Corbusier and Frank Lloyd Wright embraced green roofs for aesthetic purposes, and for their ability to integrate buildings more effectively into the surrounding landscape.

Modern green roofs became popular in Europe in the 1950s and 1960s after German studies demonstrated the viability of Sedum species growing on gravel covered roofs. Approximately 14% of flat rooftops in German are now green roofs. In addition, there have been green roofs on US Government buildings and structures for nearly a century. Green roofs installed on several federal buildings and structures in the Washington DC region such as the EPA West Building, the IRS Building, the Ariel Rios N. Courtyard, and the Federal Trade Commission Building have not been replaced since their installation in the 1930s.

Conventional, non-green roofs are often known as **black roofs**, because that is typically their color. Their dark colors cause these roofs to absorb energy from the sun to the point that they can reach temperatures as high as 150°F in summer. When it rains, runoff from black roofs flows immediately into sewer systems, contributing to flooding during storms.

There is a third type of roof that is becoming more popular–the cool or **white roof**. These roofs are made of light-colored material and do not heat up as much as black roofs in the sun. They share the runoff problems of black roofs, however.

1.3.1 POLICY DRIVERS

Although green roofs can provide benefits in a wide variety of areas, there is usually one primary driver behind a region's focus on increasing the number of green roofs in its area. The City of Chicago became interested in green roofs as a way to reduce the city's urban heat island effect. In Stuttgart, Germany, reducing air pollution was a focus of green roof policy. The policies of a number of Swiss cantons, or states, are motivated by saving energy and protecting biodiversity. Planning agencies in Seattle WA, Berlin, Germany and Singapore have adopted green area ratios (or factors) for new developments (or enhancements to large existing properties) to address ecological functions and aesthetics.* Stormwater management is a primary motivator for green roof policies in many regions.

Several cities have turned to green roofs as a way to significantly reduce the discharge of raw sewage into the local watershed during periods of heavy rainfall or snowmelt. At these times, inundation of a combined sanitary sewer and storm drain system can cause a combined sewer overflow (CSO), leading to the release of untreated sewage into rivers and lakes. These releases of sewage pollute the bodies of water into which storm sewers flow and present risks to human health and the environment. Green roofs are one way to reduce the impact and frequency of these events.† Cities as diverse as Portland OR, Berlin, Germany and Washington DC, have cited the reduction of sewer overflows as a motivating factor in their decisions to encourage the installation of green roofs. Figure 1 illustrates a combined sewer network.

About a third of the rain that falls in the District of Columbia flows into the same pipeline as the city's sanitary sewer discharge system. A study of the District funded by the U.S. Environmental Protection Agency (EPA) found that "installing 55 million square feet of green roofs in the CSO region would reduce CSO discharges by 435 million gallons or 19% each year." Figure 2 illustrates the CSO region in the District of Columbia.

The GSA owns and rents space that includes approximately 790,551 square feet of green roof nationwide.‡ Table 1 describes the extent and locations

*Green roofs help meet these standards.

†Many older cities in the United States have combined sewers and are required by the EPA to have Long Term Control Plans so that these discharges are in compliance with the Clean Water Act and with the National Pollutant Discharge Elimination System.

‡An additional 336,000 square feet of green roof is planned, in construction, or unconfirmed.

Table 1: Verified GSA planted roofs (by site)

BUILDING	CITY	STATE	SQUARE FOOTAGE
NOAA Satellite Operations Center	Suitland	MD	146,000
US Census Bureau Headquarters	Suitland	MD	85,000
SSA	Birmingham	AL	83,145
DOT	Washington	DC	68,000
IRS	Kansas City	MO	65,340
ATF	Washington	DC	55,000
FEMA	Winchester	VA	50,000
Edith Green - Wendell Wyatt	Portland	OR	40,000
IRS	Washington	DC	32,400
FDA	White Oak	MD	29,700
Sault St. Marie Border Station	Sault St. Marie	MI	23,200
US Tax Court Plaza	Washington	DC	19,592
EPA Region 8 Headquarters	Denver	CO	19,200
US Tax Court Plaza	Washington	DC	13,200
10 West Jackson	Chicago	IL	12,000
Ariel Rios N. Courtyard	Washington	DC	10,854
McCormack FOB	Boston	MA	9,654
EPA West Building	Washington	DC	7,560
Department of Interior	Washington	DC	6,495
Hastings Keith FOB	New Bedford	MA	4,000
Federal Trade Commission	Washington	DC	3,600
US Tax Court Fountain	Washington	DC	2,800
USDA - Whitten Building	Washington	DC	2,100
Potomac Yard	Arlington	VA	1,711
TOTAL			**790,551**

of green roofing already installed on the GSA estate. Other federal government agencies such as the Department of Defense have also installed green roofs nationally (e.g., Naval Legal Service Office, Norfolk VA, Peterson Air Force Base CO, William A. Jones III Building, Andrews Air Force Base MD, & Tobyhanna Army Depot, Tobyhanna PA).

1.3.2 TECHNOLOGY

Conventional roofs versus green roofs

Black roofs made of felt impregnated with asphalt or coal tar[§] once represented a major share of building

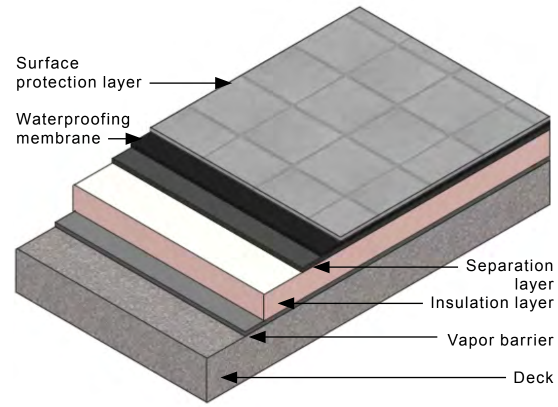


Figure 3: Diagram of a conventional roofing system

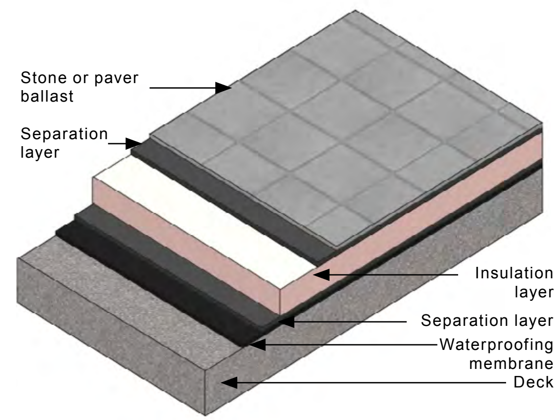


Figure 4: Diagram of a PMR roofing system

[§]Coal tar was banned in the District of Columbia, effective July 1, 2009

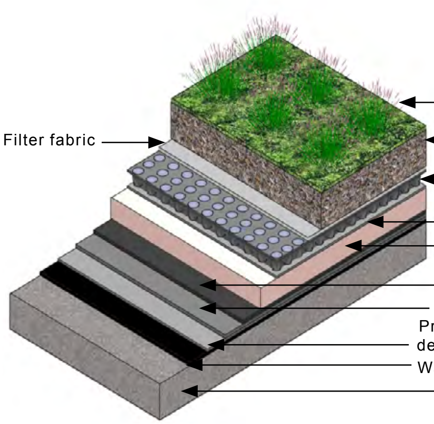


Figure 5: Diagram of a Multi-course Extensive green roof with a PMR configuration

rooftops. These **bituminous**, or asphalt-based, roofs are not very durable—the material is damaged by UV rays from the sun and expands and contracts as the temperature changes. This leads to degradation and cracking of the roof and leaks into the building beneath, and eventually the roof must be replaced. In addition, these bituminous roofing systems are subject to damage from bacteria, moss and plant roots, and contribute to urban heat island effects. Because of all these factors, these roofs are now installed less frequently around the country.

High-tech roofing materials that are much more durable than these impregnated-felt roofs have been developed over the last 30 years. In the Washington DC, area, the most common conventional roof types are now **polymer-modified bituminous sheet membranes** and related **hot liquid-applied membranes**. These are considered the **conventional "black" roof** type for this study. A conventional roof assembly and Protected Membrane Roof (PMR) assembly* is illustrated in Figure 3 and Figure 4. Other modern materials used in conventional roofs include EPDM (ethylene propylene diene monomer (M-Class) rubber), PVC (polyvinyl chloride), TPO (thermoplastic olefin polymer alloys), and liquid-applied polyurethane membranes.†

Green roof types

Green roofs can be added to existing buildings, with plants and soil going on top of a waterproofing system that can be installed on any flat or sloped roof. Green roofs can be adapted for the specific conditions with any roofing system and can increase their durability by protecting them from wear and tear.

In addition to the already mentioned distinction between extensive and intensive green roofs, these roofs are also categorized as "single-course" or "multi-course", indicating whether the green roof contains a discrete drainage layer or not. There are four types of green roofs commonly found around the world. These are: **single-course** and **multi-course extensive**, **semi-intensive** and **intensive**. They vary in terms of the type of plant grown, their need for irrigation, the type of **drainage layer** used to carry away excess water, and the composition of the **growth medium**, or the soil in which the plants are grown. Figure 6 illustrates these green roof types, which are further described in Table 2. Figure 5 illustrates a green roof with a PMR configuration.

This report focuses on **multi-course extensive** and **semi-intensive** green roofs between 3 and 6 inches thick, a range that includes green roofs that offer the greatest environmental benefit-to-cost ratio. In addition, these are the most common types of green roof in the US market and internationally. They have been well researched and offer the widest possible geographical application.

Drainage layers carry the excess stormwater runoff to the roof drains, and eventually off the roof. There are three main types of drainage layers used on green roofs: simple geocomposite drain layers, reservoir sheets, and granular mineral medium. Granular medium is the best at slowing and delaying runoff. Reservoir sheets are designed to capture rainwater in indentations in their surface. **Geocomposites**, or multi-layered materials made from a combination of synthetic polymers, are adapted for green roofs and designed to allow water to flow easily through the material, draining excess water away from a roof. These common drainage layers are described in more detail in Table 3.

Modular green roofs versus built-in-place

The typical **built-in-place** green roof is built in one continuous unit on the rooftop where it is installed. In contrast, **modular** green roofs are built using trays containing growing medium and vegetation, which are delivered to a building and installed as received. These systems are available in a range of depths and are a straightforward way to develop a green roof layer.‡ Modular systems are popular because they give the buyer confidence that they can easily be removed if the green roof leaks or fails, or if the layout needs to be changed. However, they are also typically more

*PMR configurations are popular in the NCR, especially when the waterproofing membrane is adhered to the roof deck. The insulation layer is then positioned above the waterproofing membrane to add protection compared to the conventional assembly (see Figure 3) which uses a surface protection layer to protect the membrane. There are a number of constraints to the PMR configuration. For example, it may be more difficult to identify flaws or damage to the roofing membrane; roof assembly can be more complex, giving rise to higher labor and materials costs; and increased moisture in the roof implies a need for additional insulation to compensate for losses in thermal efficiency.

†These roofing materials vary in their root resistance, suitability for specific roof deck growing medium, and compatibility with electric leak location methods.

‡A potential advantage is a tray can be removed and replaced with another tray in the event of a leak.

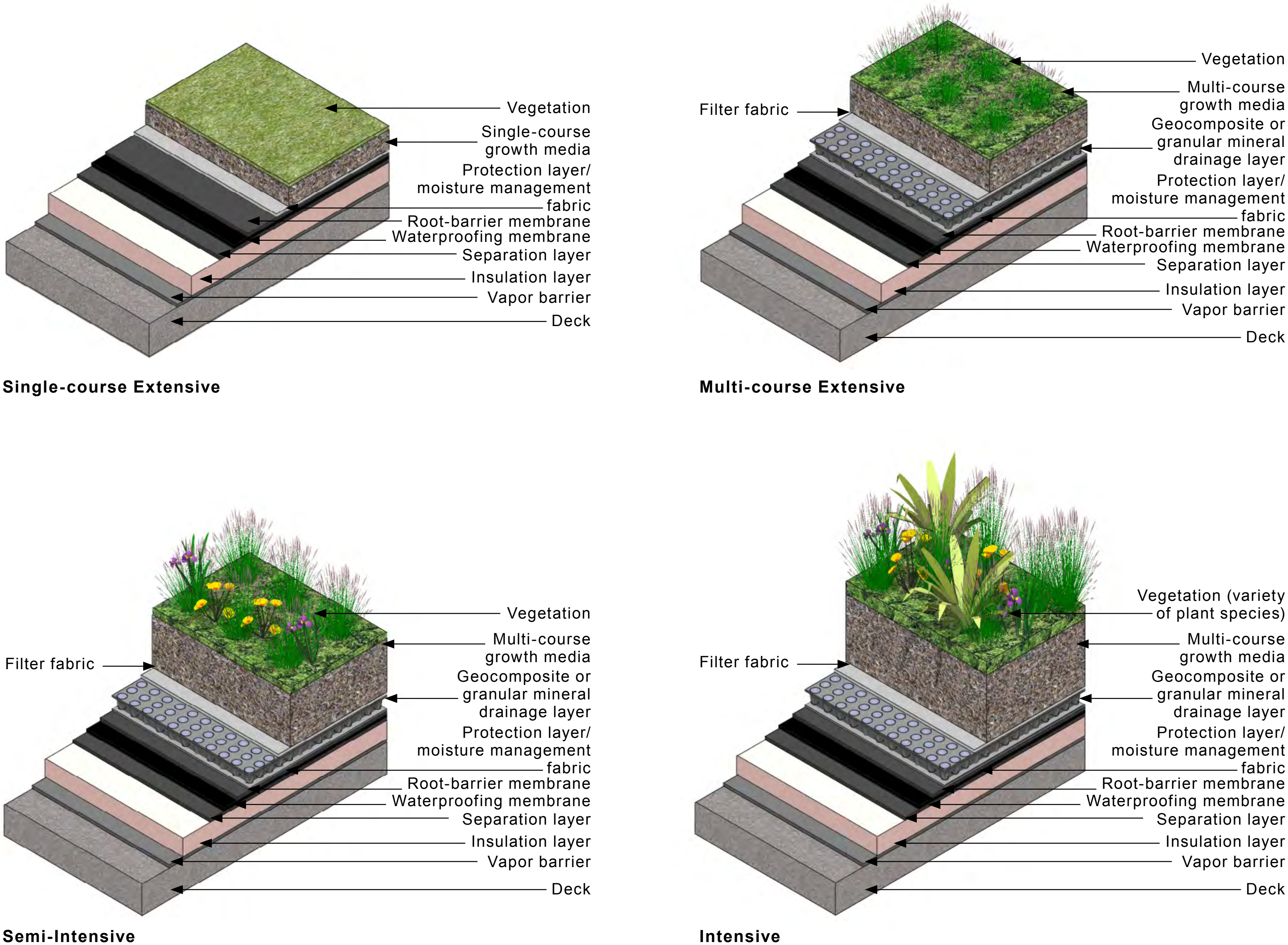


Figure 6: Green Roof Types

Figure 7: Extensive green roof

Figure 8: Intensive green roof

Table 2: Types of green roof systems

	SINGLE-COURSE EXTENSIVE	MULTI-COURSE EXTENSIVE	SEMI-INTENSIVE	INTENSIVE
THICKNESS	3-4 inches	4-6 inches[a]	6-12 inches[b]	over 12 inches
DRAINAGE LAYER	No discrete drainage layer.	Based on the growth media thickness, plants selected, local climactic conditions, and rooftop hydrologic conditions. Synthetic geocomposite are typical nationally.[d]	Discrete drainage layer.	Discrete drainage layer.
VEGETATION LAYER	Sedum or other succulents.	Sedum or other succulents. Potential for other plants as thickness increases or with permanent irrigation.	In the Mid-Atlantic and with irrigation, supports a variety of plants–meadow species, ornamental varieties, woody perennials, & turf grass.	Supports plant communities similar to ground-level landscapes (depending on thickness and exposure).
MEDIA TYPE	Coarse media over moisture-management layer.	Finer-grained growth media over discrete drainage layer.	Multi-course over discrete drainage layer.	Intensive growth media layer over discrete drainage layer. Topping media may be used (includes higher organic content, greater density, greater water holding capacity, and lower permeability).
IRRIGATION	Typically none.	Typically necessary in the first year to establish growth in Mid-Atlantic.	Required if turf grass is used.	Required.
PREVALENCE	Common internationally. Areas with sufficient precipitation is necessary.	Nationally the most common green roof type.	Common. Provides more variety in vegetation.	Less common than the other types. Structural capacity and maintenance are limiting factors (see *Section* 4.4.1 and 4.3)

Notes:

[a] Typical total media thickness (growth media, plus granular mineral drainage layer) is 4–6 inches (assemblies vary widely in thickness and complexity).

[b] Pedestrian traffic (typically turf grass) requires a 10–12 inch thickness.

[c] Common drainage layers are shown in Table 3.

[d] Internationally, granular mineral media drain layers are more common and offer advantages in terms of costs and performance.

expensive to buy and install than "built-in-place" green roofs, and their modular nature can negatively affect the roof's performance. The space left between each tray reduces the benefit of the green roof as a protective layer, as well as limiting the roof's horizontal drainage capacity and root growth to the size of each tray. Additional research is needed to gain a better understanding of the comparative performance of modular and built-in-place green roofs.

White (cool) roofs versus green roofs

Like green roofs, white, or "cool" roofs, can also contribute to reductions in the urban heat island effect and in the energy used to cool buildings in summer. However, these roof types work in very different ways. White roofs simply reflect most of the sunlight that falls on them, while green roofs absorb light, using this solar energy to turn water in their leaves into water vapor through evapotranspiration. This process, also called latent heat loss, lowers the temperature of the roof. High albedo roofs or white roofs also can reflect sunlight onto adjacent surfaces thereby warming them. These factors are often not accounted for in the analysis of the benefits of these systems.

White roofs can outperform green roofs in reducing energy use and heat islands in some climates, though the effectiveness of white roofs decreases over time as the roof weathers and gets less reflective due to deposition of dirt and other particles shown in Figure 9. This process, which is especially prominent in sooty urban areas, reduces a white roof's reflectivity, causing it to absorb more solar energy. As a result these roofs need to be cleaned to maintain performance. This study did not identify typical practices or maintenance costs to ensure that these roofs continue to perform as designed.

1.4 COSTS

The costs related to a green roof are primarily related to two factors:

- Expenses related to installation
- Expenses related to ongoing maintenance

In much the same way that a roof's design and installation affects its benefits, these factors also influence its costs. Extensive green roofs, those using a thin soil layer and succulent plants, are cheaper both to install and to maintain than intensive green roofs that use thicker soil layers and more ornamental plants.

These are discussed in greater detail in *Section* 3, Cost Benefit Analysis.

Figure 9: A clean white roof (top) and debris and particulates deposited on a white roof in New York City (bottom)

Table 3: Common green roof drainage layers

DRAINAGE LAYER TYPE	KEY CHARACTERISTICS
Simple geocomposite drain layers 	• Commonly used • Adapted for green roofs • Range in thickness and transmissivity
Reservoir sheets 	• Sub-class of geocomposite drain layers • Incorporate capacity to permanently capture and hold water in receptacles molded into upper surface • Drainage occurs principally on the upper side of the sheets • Moderate runoff • Support plants better when upper surface is in-filled with granular media • Commonly used where thermal insulation is placed above a primary membrane (PMRs, or protected membrane roofing)
Granular mineral media 	• Provides drainage above foundation fabric and separated from growth media with filter fabric • Typically a lower transmissivity than geocomposite drain layers (more effective in achieving peak rate attenuation and delay of runoff) • Typically 1–2 inch thickness

1.5 SCOPE OF REPORT

This report is divided into five sections. The introduction explains the construction and types of green roofs. *Section* 2, Benefits, reviews the benefits of green roofs in a range of focus areas. The cost-benefit analysis in *Section* 3 compares two types of green roofs compared with a conventional, black roof. *Section* 4 outlines the challenges of installing and maintaining a green roof and recommends ways to reduce the risks associated with them. Finally, *Section* 5 recommends areas for further research. There is a glossary of terms at the end of the report to assist readers who are less familiar with green roof terminology.

GSA National Capital Region - United States Department of Agriculture Jamie L. Whitten Building, Washington DC

A 3,700 square foot modular, extensive and accessible (via pedestrian path) green roof installed on this historic building that projects into the National Mall.

GSA

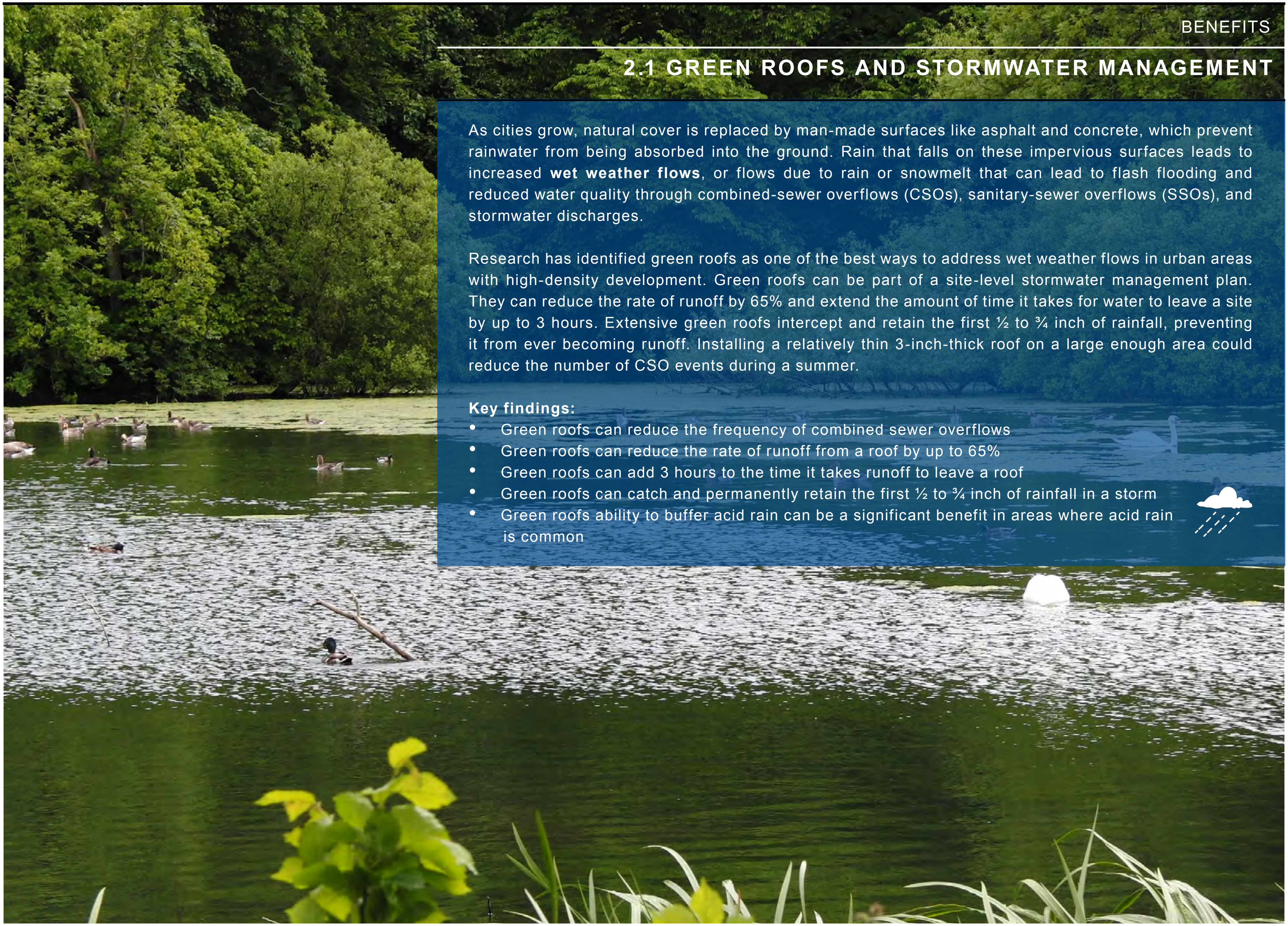
2.0 BENEFITS

Green roofs offer economic, environmental, and societal benefits for the individual building and the wider urban environment. These benefits range from stormwater management impacts on local infrastructure to amenity benefits for building occupants and the community.

This chapter categorizes the main benefits of green roof installation under the following focus areas:

- Stormwater management
- Biodiversity and habitat
- Urban heat island
- Energy
- Urban agriculture
- Acoustics
- Air quality
- Aesthetics and quality of life
- Job generation and economic development
- Roof longevity

Each focus area presents a brief background on the importance of the topic area, and discusses and analyzes the benefits of green roofs in regards to that issue.



2.1 GREEN ROOFS AND STORMWATER MANAGEMENT

As cities grow, natural cover is replaced by man-made surfaces like asphalt and concrete, which prevent rainwater from being absorbed into the ground. Rain that falls on these impervious surfaces leads to increased **wet weather flows**, or flows due to rain or snowmelt that can lead to flash flooding and reduced water quality through combined-sewer overflows (CSOs), sanitary-sewer overflows (SSOs), and stormwater discharges.

Research has identified green roofs as one of the best ways to address wet weather flows in urban areas with high-density development. Green roofs can be part of a site-level stormwater management plan. They can reduce the rate of runoff by 65% and extend the amount of time it takes for water to leave a site by up to 3 hours. Extensive green roofs intercept and retain the first ½ to ¾ inch of rainfall, preventing it from ever becoming runoff. Installing a relatively thin 3-inch-thick roof on a large enough area could reduce the number of CSO events during a summer.

Key findings:

- Green roofs can reduce the frequency of combined sewer overflows
- Green roofs can reduce the rate of runoff from a roof by up to 65%
- Green roofs can add 3 hours to the time it takes runoff to leave a roof
- Green roofs can catch and permanently retain the first ½ to ¾ inch of rainfall in a storm
- Green roofs ability to buffer acid rain can be a significant benefit in areas where acid rain is common

2.1.1 Introduction

Increased wet weather flows are of particular concern in areas with combined sewer systems, such as Washington DC. The Chesapeake Bay Foundation Scientific and Technical Advisory Committee projects that the area of developed land in the capitol region will grow by more than 60% over the next 20 years, suggesting that the region's drainage challenges will also continue to increase.

Stormwater can be managed in a number of ways to reduce the problems of stormwater runoff, especially sewer overflows and their impact on water quality. These can be divided into two primary groups:

- **Low-impact development (LID)**, a sustainable landscaping approach used to replicate or restore natural watershed functions and address targeted watershed goals and objectives, and
- **End-of-pipe best management practices (BMPs)**, or methods found to be the most effective, practical means of preventing or reducing pollution from non-point sources.

Unlike most other LID and structural BMPs, green roofs reduce runoff rates for both large and small storms.

Low-impact development aims to reduce total runoff, delay or reduce the maximum rate of runoff, and to filter out and detain pollutants. Green roofs are one example of a low-impact development technology that can help planners achieve each of these objectives. Research has also identified them as one of the best ways to address wet weather flows in urban areas with high-density development. Other low-impact development methods of addressing water overflows include cisterns, biofiltration systems, filter strips, expanded tree box planters and permeable pavements.*

This section addresses the identified benefits of green roofs in terms of:

- Slowing and retaining stormwater, and
- Reducing the level of pollutants in stormwater

Permeable pavements (left) and biofiltration (right)

Water on the green roof is evaporated by solar radiation, condenses and returns to the land as precipitation. Some of the water is stored by the vegetation, on the surface (puddles), or in soil pores, and is eventually evaporated. The remaining water either runs off the surface or infiltrates the green roof, where the water is collected and discharged off the roof.

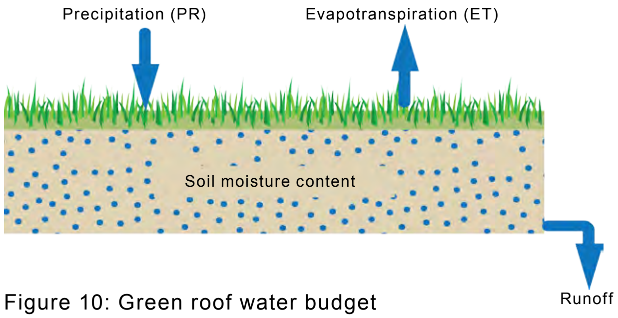


Figure 10: Green roof water budget

*Cisterns and infiltration basins may be installed under the street level, but the stormwater would still have to be discharged in a location other than the storm sewer; this requirement can render them impractical. Narrow bioswales might also be used as ground-level LID BMPs if space permits.

2.1.2 Slowing and Retaining Stormwater

A green roof affects runoff in two primary ways:

1. Increasing the amount of water that remains on a roof after a storm, and
2. Reducing the rate at which water flows from the roof into the sewer system

In contrast, black and white roofs have no effect on slowing or reducing rainwater runoff.

The plants, growth medium and other materials used in a green roof are what allow it to absorb stormwater. A green roof's ability to absorb and retain stormwater depends on a number of factors, including:

- The drainage layer
- The growing medium
- The plants (or vegetation)
- The roof slope
- The season and climate
- The roof size

The configuration of roof layers and the materials used are also important factors. The choice of plants used in a green roof also help maximize the amount of water it retains through the process of evapotranspiration.

Green roofs can reduce the **peak flow rate**, or the maximum rate of runoff, as well as the **time of concentration**, or the time it takes for water to flow from the most distant point on a runoff area to the measurement point. Studies have found that the reduction in the peak flow rate depends on the roof's drainage material and configuration, the growth medium, the roof's size and slope, the intensity and duration of the storm, and how damp the roof was before the storm began.

DRAINAGE LAYER

The type of drainage layer and the type of separation or moisture retention fabrics used in a roof will influence the roof's performance (see Table 3 in *Section* 1 for a more detailed comparison of drainage layers).

Multi-course systems are the most commonly installed green roofs in North America. In these systems, the growth medium covers a separate drainage layer that is typically either:

- a coarse aggregate material like sand, gravel or pebbles, covered with a fabric filter, or
- a synthetic geocomposite layer made of dimpled plastic, stiff filaments, or similar material.

Granular drainage layers like sand and gravel tend to increase retention time and delay the peak runoff. These drainage layers have low transmissivity, meaning they resist horizontal flow of stormwater. In addition, aggregate layers can help plants grow better roots, but are heavier and store less water than geocomposites.

Geocomposites are multi-layered materials made from a combination of synthetic polymer to fulfill a specific function like reducing the pressure of water against a green roof's waterproofing layer, or promoting drainage. Many geocomposite layers can also serve as reservoir sheets, and are designed to store water in addition to providing drainage.

The type of separation fabric used also influences the flow rate in roofs with synthetic geocomposite drainage, since dense materials with low hydraulic permittivity restrict and delay flows into the drainage layer.

Green roofs in Philadelphia have been shown to retain between 38% and 54% of precipitation with a 3-inch growing medium, or 40% to 50% with a depth of four inches using simulations in other cities. A 2005 study reported retention of over 80%, while retention of nearly all precipitation during summer storms has been reported for roofs as diverse as a 4-inch thick garden shed roof and a 75,000 square foot commercial roof in Chicago.

Preliminary studies in New York City suggest that modular green roofs have lower retention rates than built-in-place systems, due to the effect of tray boundaries on water flow, and of the reduction of growth medium due to spaces between the trays.

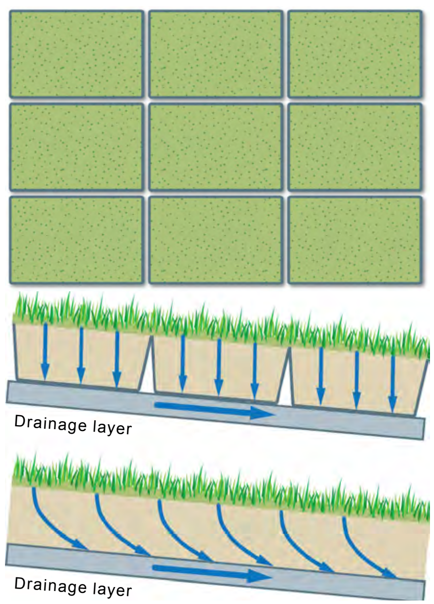


Figure 11: Boundary gaps in modular units (top) and drainage in modular units (middle) create more direct runoff routes than built in-place green roof systems (bottom)

GROWING MEDIUM

Germany's FLL Guidelines on green roofs suggest the medium used on a green roof generally retains from 30% to 60% of water by volume when totally saturated with water.

The size of growth medium particles, the types of materials used and the depth of the medium all affect the amount of moisture the medium can retain. Smaller particles have a higher surface area-to-mass ratio and smaller pores, both of which enhances the medium's water retention capacity and capillarity, or its ability to absorb water through the capillary action that draws water into a particle.

As the proportion of organic matter in growth medium increases, so does its water retention capacity. However, too much organic material in a medium can cause it to shrink as the material decomposes. If the organic material contains high levels of nutrient salts, or various phosphorus and nitrogen compounds that have a fertilizing effect, it can even decrease the quality of runoff from the roof.

The thicker the growth medium the more water the roof can absorb, at least up to a point. In general, a thicker roof can be expected to retain more water from an individual storm. A 4-inch roof can typically retain 1 to 1.5 inches of rain. This means that in the summer, when most storms produce less than 1 inch of precipitation, 90% of storms are largely retained.

The depth of growth medium is also a factor in reducing stormwater flow, with deeper layers delaying the peak and reducing the flow more than thinner layers, which was observed on green roofs in Auckland, New Zealand. However, benefits do not depend exclusively on depth, and thinner extensive green roofs yield the greatest benefit-to-cost ratio.

PLANTS

The choice of plants used in a green roof can help maximize the amount of water it retains. The plants on a green roof contribute to its water retention capabilities through the process of **evapotranspiration**). Plants take water up from the growth medium through their roots and release it into the air as vapor. Evapotranspiration rates vary depending on the species and environmental conditions. Choosing plants with higher evapotranspiration rates increases the stormwater absorption rates of a green roof.

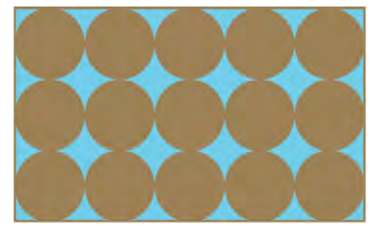
Succulent plants can retain significant amounts of water in their tissues, contributing to the overall storage of water on the roof and to the reduction in annual runoff. Succulents like sedums and *Delosperma* contribute to about 40% of the reduction in runoff attributed to the green roofs they grow in, with the remaining 60% due to evaporation from the growth medium.

To improve the water retention capabilities of a green roof, plants with higher evapotranspiration rates can be used. These typically require deeper growth medium and may also require a supplemental irrigation system to allow them to survive a drought. Irrigation may be needed even in the case of drought-resistant plants like succulents if their potential evapotranspiration rate is greater than the average annual rainfall. Any irrigation system must be carefully managed, as over-watering can reduce the roof's ability to retain stormwater and may reduce the viability of the plants growing on the roof (see *Section* 4.3.2 for over-watering issues).

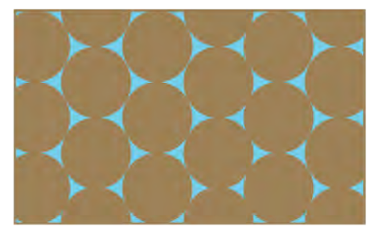
Plants slow runoff in the long-term by taking water up through their roofs, but they can also reduce peak runoff, particularly in the case of broadleaf plants. Plant roots may also allow water to flow horizontally within the growth medium, further reducing runoff.

The stormwater retention properties of a green roof can vary with the season. Typically, green roofs retain far less water in the winter than in the summer, because the growth medium takes longer to dry out or may be frozen, and the plants are less active. In dry climates with mild winters, green roofs are likely to retain more water in the summer than in the winter.

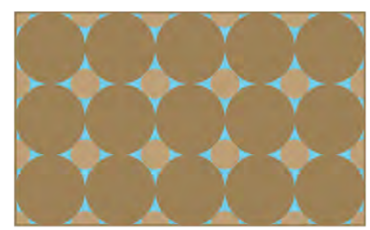
The tightly packed particle distribution (center) retains more water than the loosely packed particle distribution (left). A mixed particle distribution (right) and the addition of organic matter improves retention capacity. Too little pore space may prevent water infiltration.



Loosely packed,
uniform particle size



Tightly packed,
uniform particle size



Tightly packed,
mixed particle size

Figure 12: Particle size distribution in growing medium

As the media depth increases, the amount of the total pore space that is occupied by air at field capacity increases, hence the total moisture retained increases at a slower rate than media depth.

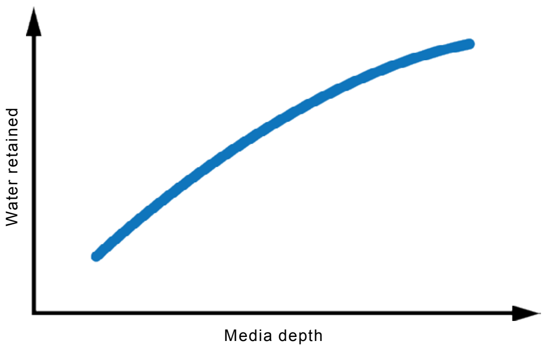


Figure 13: Media depth versus water retained

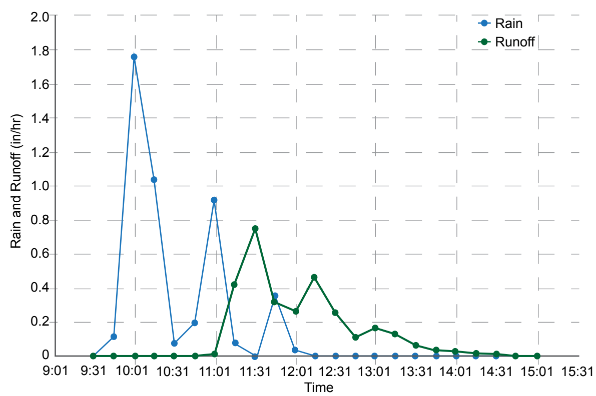


Figure 14: Rainfall and green roof runoff hydrograph from the 75,000 square foot Walmart roof in Chicago for a series of short peaks in June 2009

ROOF SLOPE

The flatter a roof, the greater its water-holding capacity. Sloped roofs also create a number of challenges.

Growth medium on roofs with a pitch of more than 16% will need to be stabilized to keep it in place.

Steep pitches can also create a **moisture gradient**, with the medium on the bottom of the roof typically wetter than that at the top, which may mean plant selection will also need to vary across the roof.

Roof slope has a smaller effect on peak flow rates than vegetation or medium depth. The slope's effect on flow rates depends on the type of drainage layer used. A steeper roof will increase peak flows more in a single-course system or one with restricted drainage than in other types of green roof.† The water retention of a sloped roof can be improved by increasing the depth of the growth medium on the green roof.

SEASON AND STORM ACTIVITY

Green roofs retain the most water in summer months, when plants are active and warm weather boosts evaporation. A 3-inch thick extensive roof on the Gratz factory roof in New York City, monitored by Earth Pledge, recorded seasonal volume reductions of 46% in summer, 35% in fall, 21% in winter, and 39% in spring. Similarly, a 4-inch modular sedum roof on a Con Edison facility in Queens, New York, recorded its highest retention rates during the summer months.

The reduction in the volume of rainwater runoff for any given storm will depend on the amount of rain that falls and how long it has been since the previous storm. The Wal-Mart store in Chicago retained 87% of storms with less than 1 inch of precipitation, and 58% of storms with 1–2 inches during warm months. However, some studies have not seen such clear correlations between total storm depth (the depth of rainfall at a point or over an area) and water retention.

Even a very wet green roof will reduce the peak flow rate of runoff to some extent, but a dry roof will reduce flows to a greater extent. This means that a roof's ability to reduce peak flows will be greater in short storms than in longer ones - as the roof gets more saturated, it will be less able to absorb the rain that falls. Similarly, roofs have a greater effect on peak flow rates in less intense storms. The intensity of a storm has little effect on the total amount of precipitation a green roof retains.

ROOF SIZE

Generally, larger green roofs are better at reducing peak flow rates and the time of runoff concentration than smaller roofs are. For example, the 75,000 square foot green roof on a Walmart in Chicago delays peak runoff for nearly two hours, longer than has been observed with smaller roofs. The non-green section of the roof delayed the peak runoff for 15 minutes or less.

†Flow path in a single-course assembly will be more uniformly within the plane of the green roof; whereas the flow in multi-course assemblies will be dominated by vertical percolation to the drainage layer, after which horizontal flow toward the outlet will be rapid.

2.1.3 Stormwater Pollutant Reduction

Do green roofs reduce the amount of pollutants in stormwater, thereby improving water quality once stormwater drains into lakes and streams? Research provides mixed results. On the positive side, green roofs reduce the volume of stormwater flowing from a roof and therefore the ability of stormwater to convey pollutants to water bodies. They can also neutralize acid rain. However, they can contribute potential **nutrient pollutants** like nitrogen and phosphorous to the runoff from their growth medium and any fertilizer that might be used. When considering the quality of runoff from a green roof, it is important to consider both the concentration and total amount of the pollutants. It is also important to compare the runoff from green roofs to that from black and white roofs, where there is no plant material to affect the chemical content of the rain.

Some studies suggest that green roofs improve the quality of rainwater runoff from roofs, as plants take up potential contaminants from the soil and store them in their tissues. Other studies have found that green roofs actually contribute nutrients to rainwater runoff, which can negatively affect surface water.

The amount of nutrients in runoff from a green roof depends on the content of the rain, whether fertilizer is used on the roof, and the materials used to produce the growth medium, particularly the compost.

The use of organic materials in the growth medium of green roofs and the application of fertilizer to a roof can also affect the quality of runoff water from the roof.

The definition of which chemicals in stormwater runoff are considered pollutants depends on the characteristics of the **receiving waters** into which the runoff will flow. If they are low on a particular nutrient, its presence in runoff may be seen as beneficial.

NUTRIENTS

Plants need nitrates and phosphorous to survive, but these chemicals can also have negative effects on water quality. Phosphorous and nitrates are added to green roofs as fertilizer. Nitrogen is also found in rainwater, and is added to roofs when rain falls. If roofs are managed to reduce total nutrient impacts, a green roof can have a positive influence on the total amount of nitrogen in rainwater runoff. On the other hand, there is not much phosphorous in rainwater, so green roofs can increase both the concentration and total amount of phosphorous in runoff, as compared with an asphalt roof, as observed on a number of green roofs in Pennsylvania. It should be noted that nutrient loading typically peaks during roof establishment and diminishes after the roof is established.

In a study of green roofs that were managed with minimal application of fertilizer, runoff showed no significant difference in nitrate concentration from rainwater runoff from asphalt roofs. Because the green roofs retained water and reduced the total volume of runoff, they reduced the total mass of nitrogen in the runoff. The study also showed higher concentrations of copper, iron, manganese, and zinc in the green roof runoff than in that of asphalt roofs.

When considering runoff quality, it is critical to compare green roof runoff with runoff from black and white roofs. It is also important to consider whether the stormwater discharges to a combined sewer system or to a separately sewered stormwater system and whether the

Figure 15: Sloped green roof with sedums and other plants

In Washington DC

The Casey Trees Endowment Fund Study used a model developed by Limno-Tech Inc. to analyze the effects green roofs can have on stormwater flows in Washington DC. The city is subject to combined sewer overflows during heavy rainfalls, which can lead to the flow of untreated sewage into the Anacostia and Potomac rivers and Rock Creek.

The study found that an extensive green roof can reduce runoff volumes by about 65%, and intensive green roofs by about 85%. The study considered the effect of installing green roofs on all "green roof-ready" buildings in Washington DC, which included about 75 million square feet of rooftop area. Using a ratio of 80% extensive roofs to 20% intensive roofs, it found that such an installation program would decrease roof runoff volume by up to 69% as compared with conventional roofing on the same buildings.

body of water that ultimately receives the runoff is low in nitrates or phosphorous, in which case the addition of these chemicals may not be seen as polluting.

ACIDITY

Acid rain (defined as precipitation with a pH below 5.6), which is caused by air pollution, can damage buildings and harm ponds and lakes. The growth medium on green roofs can neutralize the acid in acid rain, because the growth medium itself is typically basic, with a pH from 7 to 8. The roofs seem capable of neutralizing acid rain in this way for 10 years or more, because the medium is well buffered, i.e., capable of absorbing and neutralizing acids. This feature of green roofs could be a significant benefit in areas such as the Northeast US, where acid rain is common. Runoff from a green roof generally has a pH above 6.5.

2.1.4 Economic Analysis

GREEN ROOFS IN CONTEXT

Are green roofs a cost-effective solution to stormwater management? Depending on local stormwater regulations and incentives, they can contribute to cost-avoidance for both building owners and municipalities. Green roofs should be evaluated in comparison with other measures designed to reduce stormwater runoff and combined sewer overflows, as part of a holistic review of the infrastructure. Other possible stormwater management measures include bioretention basins, permeable pavement, and infiltration chambers.

The costs and benefits of green roofs as compared with other stormwater management tools may depend on the objectives of a particular project.

Green roofs are recognized for their ability to mimic natural hydrological processes as part of a watershed management approach to drainage, in which a coordinated framework for environmental management focuses public and private efforts on the highest priority problems within hydrologically-defined geographic areas, or watersheds, taking into consideration both ground and surface water flow.

Table 4 describes other low-impact development water retention measures used at the ground-level like filter strips, bioretention basins and permeable pavements that can be used in place of or in conjunction with green roofs as part of an overall green infrastructure strategy or CSO/stormwater runoff mitigation scheme. These tools are only useful when the prepared sub-grade soil sustains a percolation rate of at least 1 inch per hour, when the underlying geology and topography are suitable, and where the soil is not contaminated. In addition, these alternatives typically require a large area to retain the water.

Technologies such as infiltration chambers and cisterns can also be used to satisfy stormwater retention requirements (Table 4). Infiltration chambers use rigid arches or rectangular galleries installed in trenches and backfilled with coarse stones. They can be used where space is limited or where stormwater management measures must be installed under paved areas. Compared to structural stormwater measures, implementing LID's can reduce costs by approximately 15 to 80 percent, according to research by the USEPA.

Cisterns can be used in areas where stormwater does not percolate into the soil, and where the water collected will be put to use in irrigation, for toilet flushing or in other ways. The typical capital costs of structural BMPs (including installing pumps and control systems to support these other systems) and LID BMPs are less than green roof per volume of stormwater.

For purposes of the cost-benefit analysis (see *Section* 3), the costs avoided to the owner by installing a green roof versus a conventional roof were $4.15 per square foot of roof nationally and $4.77 in Washington DC. These were only applied in Year 1 under the idea that regulation would require stormwater management during a major renovation such as installing a new roof. The maintenance for such systems was found to be $0.14 per square foot of roof per year.

PUBLIC INFRASTRUCTURE

Installing a green roof can help reduce wastewater treatment costs in areas with combined sewers, by reducing the volume of runoff and slowing its flow, thereby reducing the frequency of CSO events.

Table 4: Best Management Practices (BMP) to retain stormwater and/or reduce runoff

LOW-IMPACT DEVELOPMENT	STRUCTURAL
Bioretention	Infiltration chambers
Infiltration basins	Cisterns (external to building)
Permeable pavement	Cisterns (inside)

In communities where combined sewer overflows are a problem, the cost of treating stormwater as wastewater typically accrues to the taxpayer or rate payer. In the Washington DC area, it costs about $615 per million gallons to treat stormwater as wastewater. These costs are mainly due to additional pumping and treatment expenses at the Blue Plains Wastewater Treatment Plant. A study by the Casey Tree Foundation in the Washington DC combined sewer area concluded that if trees, tree boxes, and green roofs are installed throughout the combined sewer area, the District of Columbia Water and Sewer Authority (DCWASA) could potentially have an annual operational savings of $1.4–$5.1 million per year due to reduced pumping and treatment costs.

GREEN ROOF REGULATION FEES

For the purposes of the cost-benefit analysis, annual savings were based on regulatory fees charged at a rate based on the amount of impervious surface, with green roofs not counting as impervious. Green roofs were found to provide annual savings of $0.084 per square foot nationally and $0.078 per square foot in Washington DC, as compared with a conventional roof. A detailed discussion on stormwater regulation follows this section. However, Washington DC regulations would not generate any additional discounts for green roofs versus conventional roofs given the hypothetical projects that fully comply by using green roofs and/or BMPs. Therefore only the avoided stormwater costs discussed earlier were applied to the Washington DC cost-benefit analysis.

Stormwater Regulation and Policy in Washington DC

In urban areas with high-density development, green roofs may be the only practical way to address wet weather flows, especially where retrofit measures are required. Various requirements (federal, state, and local) drive stormwater management regulations. Green roofs are one way to comply (or help comply) with these regulations. Cities are offering green roof incentives and/or imposing fees regarding site stormwater management. The District of Columbia is an example of a jurisdiction that actively incentivizes the installation of green roofs. This Case Study provides an analysis of the stormwater management regulations of Washington DC and the federal government as they relate to green roofs.

INCENTIVES AND FEES

In Washington DC, the District Department of the Environment (DDOE) offers a green roof grant worth up to $5 per square foot, with a cap of $25,000 for qualifying projects, though the cap does not apply for retrofits of existing buildings. This grant, administered through local, non-profit partners, may also be available to non-federal buildings leased by the federal government, though buildings owned by the GSA and other federal agencies are not eligible.

A new amendment to the Federal Water Pollution Control Act (P.L. 111-378) expanded the types of state and local assessments (whether denominated as fees or taxes) associated with stormwater control for which federal agencies are responsible. As a result of this change in law, according to an opinion issued by the US Department of Justice's Office of Legal Counsel (25 February 2011), both types of stormwater assessments imposed by the District of Columbia are now payable by federal agencies:

- The assessment to offset the costs of constructing an enhanced combined sewage/ stormwater system for the District of Columbia and
- The assessment to offset the costs of managing stormwater runoff regardless of its pathway to the receiving streams of the District of Columbia

In addition to regular sewer usage fees, these two assessments are calculated based on the amount of impervious area a property owner owns, with non-residential customers charged $3.45 per month per equivalent residential unit (ERU). One ERU equals 1,000 square feet, and the fee is rounded down to the nearest 100 square feet.[†]

ANALYSIS OF FEDERAL AND LOCAL REGULATIONS

Section 438 of the 2007 Energy Independence and Security Act (EISA) requires all new federal developments and re-development projects with more than 5,000 square feet of affected land to maintain or restore pre-development hydrology to the **greatest extent technically feasible**, through **infiltration, evapotranspiration** or **reuse on-site**, among other methods.

GSA's implementation of Section 438, and its application of U.S. EPA's 2009 Technical Guidance, will be achieved with due consideration of the District's standards. In that regard, it is anticipated that the District will be publishing regulations in 2011 that will clarify how it intends to work with federal agencies in the District, as these agencies implement EISA Section 438. The district is expected to take a flexible approach to satisfying the law that makes compliance more practical and affordable. Experts anticipate that the District will consider sites to be compliant with the law provided that LID BMPs have a combined interception volume equal to the design rainfall event, and that sites demonstrating higher interception volumes may receive Retention Credits that can be sold or traded.[‡]

The Technical Guidance on Implementing the Stormwater Runoff Requirements for Federal Projects defines the pre-development condition as the green-field undeveloped condition, and offers two options for complying with EISA Section 438.

Option 1: Retain rainfall associated with the 95th percentile rainfall event
Rainfall depth is calculated from historical data. In Washington, DC, the 95th percentile rainfall event is 1.7 inches. Runoff volume for a particular plot can be calculated using an approved analysis method.

The **EISA Section 438 Technical Guidance Document** recommends the use of green roofs, though it omits any discussion on how green roofs or any other best management practices contribute to satisfying the stormwater requirement. The guidance document implicitly treats green roofs differently from other best management practices.

Option 2: Conduct a site-specific hydrologic analysis using a continuous model simulation and implement a design that will preserve or restore pre-development runoff characteristics.

The advantage of this approach is that it recognizes the contribution a green roof can make toward modifying the overall hydrology of a site by reducing runoff rates and volumes through evapotranspiration,

† At the time of the study, legislation was being drafted that would let customers reduce this fee by managing stormwater and reducing impervious area. However specific details about the reduction were not available.

‡ Individual practices in the retention credit market will be capped at a volume of 1.7”. Projects required to comply with EISA may not qualify as retention credit sites but Federal sites can buy retention credits to comply when sites have retention deficits.

and by slowing the release of runoff.

In this option, continuous simulation modeling determines the runoff quantity, rate and duration of a site.

See the 2009 Technical Guidance for exclusions to EISA Section 438 that are recognized by US EPA.

In the case of the District of Columbia, all sites must meet the minimum standards in EISA Section 438. At challenging sites, the balance of the requirement can be met through offsite mitigation, which must be accomplished as retrofits to existing structures, or a fee in lieu (documentation of why the site did not meet the retention requirements is also required).

DDOE District of Columbia Storm Water Management Regulations (1988)

In addition to the stormwater management requirements set forth by the Energy Independence and Security Act of 2007, federal projects must comply with the various long-existent federal, state and local stormwater standards that emanate from the Federal Water Pollution Control Act. In this case the DDOE regulates stormwater compliance and offers guidance for compliance in their Stormwater Guidebook. Currently, DDOE has two requirements that are typical of many municipal stormwater regulations across the country, and which will be retained in the new regulation: rate reduction and volume reduction. Volume reduction requirements state that the Water Quality Volume (WQV) must be treated with an appropriate BMP. At present the WQV is equal to the first 0.5 inch of water collected from parking lots and 0.3 inch collected from all rooftops and sidewalks. Green roofs are not specifically mentioned as appropriate BMPs, however they are currently used as water quality BMPs in practice; the ability of a green roof to satisfy water quality requirements depends on the ability of the growth medium to detain the WQV in voids. Conversations with DDOE staff indicate that their regulation will be updated in mid-2011, and will more closely reflect the US EPA requirements for Federal Buildings discussed above, with a WQV associated with the 90th percentile event (1.2 inches) for private developments and the 95th percentile event (1.7 inches) for public projects.

The rate reduction requirement states that runoff rates for specified storm events shall not exceed runoff rates associated with a meadow in good condition. Specified events are the 2- and 15-year 24-hour storms with a type II (NRCS) rainfall distribution pattern. Antecedent moisture conditions are not specified. Green roofs contribute toward satisfying rate reduction requirements by lowering the overall site runoff curve number or rate coefficient, and lengthening the time of concentration for green roof areas.

‡In the revised regulations the WQV will not be included. The regulation will be limited to the retention standard of 1.2 inches and the flood protection requirements for the 2-year and 15-year rain events.

2.2 GREEN ROOFS AND BIODIVERSITY AND HABITAT

The term “biodiversity” refers to the variety of plants and animals in an area. A region is considered to have high biodiversity if it contains many different species, and enough individuals of each species to maintain a viable population size over the years. Increased biodiversity helps ecosystems to continue to function even when they are disturbed by development or in other ways.

Green roofs can provide new habitat for plants and animals in urban areas, increasing local biodiversity. Vegetation type, growing medium depth and variation in plant height and spacing are the three most important factors in encouraging biodiversity on a green roof. Studies suggest that the depth, topography, plant composition and age of a green roof, as well as the local landscape, can affect a roof’s ability to enhance biodiversity.

In addition, design components that promote biodiversity may also help a roof improve performance on other criteria like reducing stormwater runoff and lowering summer surface temperatures. Reductions in summer surface temperatures have also been identified in comparisons between ranges of different vegetation types.

Key findings:

- Green roofs are found to attract species including birds and invertebrates
- The type of vegetation used is the most important factor in a green roof’s ability to encourage biodiversity
- Growing medium depth and variation in plant height and spacing also affect biodiversity
- Intensive roofs typically support a greater diversity of rare bird species than extensive roofs

Image Courtesy of Renee Davies, Head of Department of Landscape Architecture, Unitec, Auckland

2.2.1 Introduction

Diversity of plant and animal species can make an ecosystem more resilient. Green roofs can encourage biodiversity by providing new habitat for plants and animals in an urban area. They can attract native plants and animals, as well as migrating birds.

The type of vegetation used is the primary factor in a green roof's ability to encourage biodiversity.

Some of the measures that enhance biodiversity on green roofs also create new design requirements that must be addressed for a roof to succeed. To mimic a wetland environment, for example, a roof must be designed to hold a limited additional amount of water, which requires careful modifications to the structural, waterproofing and drainage design. If deeper medium areas with larger vegetation are to be accommodated, the structural design must be tailored to suit the needs of the green roof.

The green roof of the California Academy of Sciences in San Francisco includes food sources for adult and juvenile Bay Checkerspot butterflies, an endangered species.

Figure 16: California Academy of Sciences green roof

2.2.2 Design and Management for Biodiversity

Figure 17: Bird on an extensive green roof

The three most important factors in encouraging biodiversity on a green roof are:

- vegetation type,
- growing medium depth, and
- variation in plant height and spacing.

The **plant layer** of a green roof is the main way designers can promote biodiversity. In general, an intensive roof with a mix of plant types and a varied composition may outperform an intensive monoculture roof of uniform height in terms of increasing biodiversity. Experts disagree on whether it is better to use native or imported species when planting a roof, though both types can serve particular purposes. **Native plants** may be harder to establish on a green roof but may be more successful in the long run.

In addition, variations in the growing medium can allow a green roof to contribute to biodiversity. Designers can create a series of diverse habitats on a roof by varying the depth of the rooftop soil. Deeper medium provides a potential habitat for a greater number of plants and animals than thinner medium. Shallow and deep roofs can be designed to simulate a range of environments from forest understory to ravine.

Green roofs provide permanent habitats for some insects and plants, and possibly birds and other animals. Designers can tweak a roof to provide habitat and food for breeding birds and their chicks, sometimes going so far as to target a specific species using careful analysis, design and monitoring. For example, an urban extensive green roof was designed to attract Lapwing (*Vanellinae*) and Plover (*Charadriinae*) using plants like moss, grasses and herbs that both species of bird prefer in their habitats.

Any green roof can become a nesting site, so designers need to consider providing options for water and shelter to boost the survival chances of chicks hatched on the roof.

Green roofs may support a substantial and diverse population of invertebrates like spiders, beetles, wasps and bees as observed in the United Kingdom and Switzerland. A variety of sedums with two or three other species can attract honeybees to a roof. Spiders can be a sign of good ecological function, as structural diversity to provide moisture and shade, and a steady supply of prey insects are needed to establish a sustainable community. Butterflies, a useful indicator of biodiversity, are also found on green roofs. Planting a roof with species that can be food for butterflies and insects can boost their populations. For example, the green roof of the California Academy of Sciences in San Francisco includes food sources for adult and juvenile Bay Checkerspot butterflies, an endangered species.

VEGETATION TYPE

The type of vegetation used is the most important factor in a green roof's ability to encourage biodiversity. Intensive roofs typically support a greater diversity of rare spider and bird species than extensive roofs, which are generally visited by more common bird species. Both types of roof attract a similar number of insect species.

An important consideration in planting a green roof is deciding whether to use native or imported species, otherwise known as exotic plants. Some designers argue that green roofs composed of native plants may be more successful than non-native ones because they require less fertilizer, maintenance and water. However, it can be difficult to establish native species on a roof because of specific habitat and water requirements.

The Habitat Template Approach to picking plants for a green roof identifies species that grow in environments similar to that of the roof. The method takes into account soil depth, available moisture, and wind. Experiments throughout North America have shown that this approach can help native plants achieve a **cover value**, or a percentage of the terrain covered by plants, that is comparable to the best non-native species, with a high rate of survival and growth.

A roof that mimics a specific grade-level habitat could be colonized by rare native species based on observations in England and Switzerland. However, a roof may also be colonized by exotic species that originate in a habitat similar to the environment found on the roof. Prairie grassland is one of the few specific landscapes that have been recreated on green roofs in North America. Extensive green roofs can mimic dry meadow grassland through their minimal supply of nutrients, quick drainage and sun exposure.

Studies show that using plants that are common locally encourages speedy **colonization** of a roof by native insect species. Growing medium, spatial and vertical vegetation structure and the overall diversity of content on a roof are more important than the specific species used when it comes to colonization by certain insect species.

GROWING MEDIUM

Variations in growing medium can affect the ability of a green roof to promote biodiversity. Deeper growing medium provides a potential habitat for a greater number of plants and animals because of its increased ability to hold water and nutrients and its ability to accommodate plants with deeper roots. The shallow growth medium commonly used in extensive green roofs is less effective, as it intensifies the already extreme rooftop environment. Tolerant pioneer species may grow there, in addition to native plants that find in green roofs a refuge from common invasive species such as thistle and buckhorn, which have a hard time growing there (as observed on green roofs in London). Alvars and mineral ferns also grow on these roofs, which are similar to their native landscapes.

Designers can create a series of microclimates and **diverse habitats** on a roof by varying the depth of the growth medium. Shallow and deep roofs can be designed to simulate a range of environments from forest understory or ravine to riverbank or wetland, and many others.

Using natural, local growing medium that mimics local environments can create habitat by promoting the survival of native plants, which are already adapted to that particular soil environment. For example, in urban environments featuring existing landscapes like abandoned industrial sites at ground level, existing growing mediums may be used for green roof design to extend the available habitat for flora and invertebrates adapted to these environments.

STRUCTURAL DIVERSITY

Creating structural diversity through the use of a varied composition, abundance and spacing of plants is a third way to encourage biodiversity on a green roof.

> While limited by a roof's size and load-bearing capacity, designers can create green roofs that provide a range of structural complexity that mimics natural habitats. Creating a variety of microhabitats is one way to boost biodiversity on a green roof.

Rooftop features like parapets, equipment for heating, ventilation and air conditioning, and solar panels

Figure 18: Bee on an extensive green roof

contribute to the complexity of a green roof. Building systems create shaded, damp areas that can increase the diversity of a roof's population of invertebrates**.**

Designers may purposely create microclimates by adding branches, stones, sand piles and rubble to a green roof. Branches can be used to encourage birds to rest, and structures like bird and bat boxes can be used to encourage animals to nest and breed on a roof.

An intensive roof with a mix of plant types and variations in depth and surface structure may outperform an intensive monoculture roof of uniform height in terms of increasing biodiversity. Such roofs also produce a greater reduction of stormwater runoff and summer surface temperatures, as observed on green roofs in Halifax, Canada and Toronto, Canada. Plants like sedums with lower evapotranspiration rates have a smaller effect on reducing summer surface temperatures than other vegetation types.

MATURITY AND STAGING

Green roofs show greater biodiversity as they get older. Growth medium degrades over time, as does natural terrain. Over time, growth medium will lose bulk, gain organic matter, and show a greater abundance of a wider variety of species.

2.2.3 Economic Analysis

A green roof's contribution to biodiversity is difficult to measure economically. One way to measure the value of biodiversity on a roof is to compare the value it adds to the overall diversity of an area with that of a wildlife corridor or open space. In practice, regulators, investors and building occupants determine the value of green roof biodiversity, and the way in which biodiversity contributes to their sustainability goals. The green roof requirements of certain Swiss cantons, or states, were motivated predominantly by the desire to protect (and reintroduce) biodiversity.[*]

Governments and organizations are working to develop ways to measure the financial value of a natural ecosystem. For example, Australia's BushBroker scheme provides credits for "pre-vegetating" previously cleared areas like impervious urban sites with native species.[†] The price of a credit under this scheme ranges from US$0.42–$1.46 per square foot ($42,000 to $157,000/hectare), and is applied once over a 10-year period. In the United States, a biodiversity banking system exists to protect threatened or endangered species.[‡] The sale price for these credits averages approximately $0.41 per square foot.[§] Pollination by bees attracted to green roofs of flowers and crops is another potential benefit of economic importance.

[*] To attract animal species, specific medium and plant species types are required.
[†] The agreement requires a management plan for a 10-year period with annual reporting in perpetuity.
[‡] Conservation Banking Agreement requires third party oversight.
[§] The BushBroker scheme and the Biodiversity banking system are typically meant for large banks of land and may not be applicable to green roofs.

2.3 GREEN ROOFS AND URBAN HEAT ISLANDS

Urban Heat Islands (UHI) refers to the effect whereby near-surface air temperatures are higher in cities than in nearby suburban or rural areas. This effect is common in cities where natural landscapes, which absorb a significant portion of solar radiation to create water vapor, have been replaced with non-reflective surfaces that absorb most of the solar radiation and re-radiate back into the environment as heat. Heat islands cause increased energy consumption, heat-related illness and death, and increased air pollution.

Heat islands can cause heat-related illness and mortality, particularly during heat waves, which amplify the heat island effect. Prolonged exposure to high temperatures can cause heat cramps, heat exhaustion, heat stroke, heat syncope, and death. Heat exposure may also exacerbate cardiovascular illness, diabetes, and respiratory disease. Health impacts of the heat island effect are expected to worsen with climate change.

Green roofs can reduce the urban heat island effect by reducing temperatures and cooling buildings through the natural functions of plants.

Key findings:

- Heat islands increase energy consumption and can cause heat-related illness and mortality
- Plants can help mitigate the heat island effect common to the urban environment
- Green roof surface temperatures are cooler than black surface temperatures in all summer studies
- Evaporation and transpiration by plants play a key role in cooling green roofs

2.3.1 Introduction

Reintroducing vegetation on roofs is one of the most promising solutions to the problem of urban heat islands, as plants can help mitigate the heat island effect common to the urban environment. Green roofs also reduce summer air temperatures directly above the roof, making them more habitable and energy efficient.

Green roofs can influence heat islands in the following ways:

- By increasing the amount of solar energy that is reflected rather than absorbed
- By warming up more slowly in sunlight than conventional roofs
- By cooling buildings through the natural processes of plants

A green roof program covering 50% or more of roof space in a city, when implemented in coordination with other large-scale greening efforts like street tree planting, could result in city-wide cooling throughout the day and during peak summertime energy demand periods.

Heat islands may be observed adjacent to the building and infrastructure surfaces (e.g., roofs and roads), in the canopy layer—extending from ground level to the top of buildings, and in the boundary layer—extending from the top of buildings upwards to a height of 0.6 miles (1 kilometer) or more. In some cities the heat island effect, as measured by air temperatures relative to surrounding non-urban areas, is greater at night than during the day.

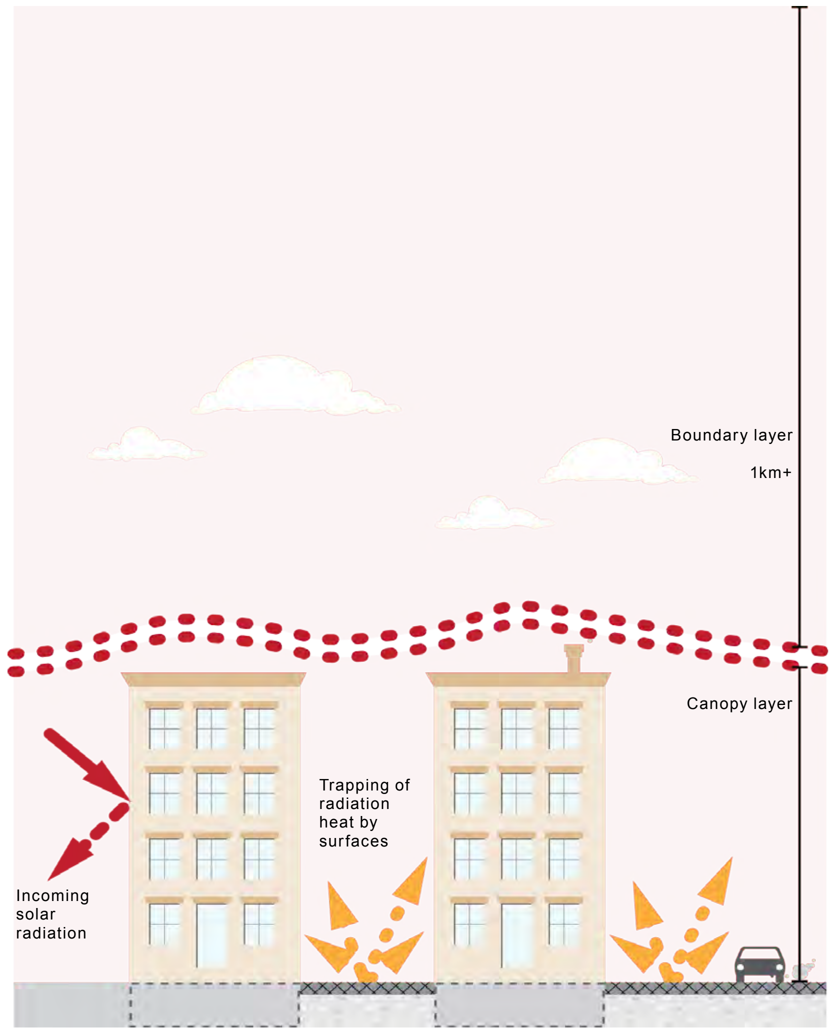


Figure 19: Urban Heat Island effects

2.3.2 Analysis

Heat islands increase air pollution by forming an inversion layer that inhibits the dispersion of air pollutants. Elevated air temperatures facilitate the production of ozone, a major component of photochemical smog. Increased concentrations of atmospheric ozone have been linked with increased rates of daily mortality and higher incidence of cardiovascular and respiratory mortality.

Dark materials like asphalt and tar have low albedo values, meaning they absorb a lot of sunlight. For example, 80-95% of solar radiation is absorbed by asphalt and transformed into heat energy. White roofs have higher albedo values, meaning they reflect more sunlight than asphalt and tar surfaces. Materials that have high albedo values are cooler in summer because they reflect more energy from the sun than materials with low albedo value. The green roofs ability to reduce urban heat island is not albedo dependent but based on transforming the absorbed sunlight into water vapor through evapotranspiration.

Table 5: Albedo for typical surfaces in cities

MATERIAL	ALBEDO VALUE
Brick	0.20-0.40
Roofing tiles	0.10-0.35
Concrete	0.10-0.35
Tar/gravel	0.08-0.18
Asphalt	0.05-0.20
White roofs	0.75-0.80+
Vegetation/green roof	0.25-0.30

Green roofs have very different properties from conventional and white roofs in the context of urban heat islands.

PROPERTIES OF VEGETATION VERSUS IMPERVIOUS SURFACES

Evapotranspiration by plants plays a key role in transferring heat away from the surface on which the plants are growing. As water evaporates, it absorbs **latent heat**, which is energy used to convert matter from one phase to another, such as from a liquid to a gas. Through evapotranspiration, plants can use up to half the solar energy that hits a surface to convert liquid water in their leaves into water vapor they release to the atmosphere.

This process keeps some of the sunlight from contributing to raising the temperature of the roof, thus reducing surface temperatures and ambient temperatures above the roof's surface. Later, the heat is released in the troposphere as the water re-condenses, creating a "latent heat flux" from the ground upwards. The absence of this natural cooling in urban areas without plants is one of the greatest contributions to the heat island effect.

This cooling effect can create benefits in other areas. For example, the voltage produced by a solar panel falls as its temperature increases, so solar panels on a cooler roof will produce more power than those on a hotter one. This means that solar panels can operate more efficiently on a green roof than they do on a conventional roof, which heats up more in the sun. The electricial output of solar panels on green roofs in Berlin, Germany, and Portland OR, has been observed to increase by up to 6%; evidence that these technologies can co-exist.

PROPERTIES OF VEGETATION VERSUS BUILDING MATERIALS

Studies show green roofs have lower temperatures than conventional roofs (approximately 30 to 40ºF). Concrete and asphalt absorb, store and emit more solar energy than plants do, altering the surface energy balance in urban areas in two primary ways:

- **Albedo** is a measure of how much light a surface reflects. Albedo values range from 0 for a perfectly absorbing surface to 1 for a perfectly reflecting surface. Darker surfaces have lower albedos and absorb more light than lighter-colored surfaces. They may conduct heat into a building, raising indoor air temperatures, or they may absorb and then release heat, raising ambient air temperatures. The extent of these effects depends on the material.

- **Heat capacity** measures the amount of thermal energy needed to raise the temperature of a material. Concrete, asphalt and brick have high heat capacities, meaning they store greater amounts of heat energy as their temperatures increase during the day. When they release it at night, this energy contributes to the urban heat island effect.

Green roofs and urban forestry can reduce the area of low reflectivity and high heat capacity surfaces in an area, thus reducing the heat island effect. In addition, the vegetative cover on green roofs increases shading, which helps cool buildings.

It is difficult to measure the impact of green roofs on UHI as no city has collected sufficient data on the heat island effect before beginning a campaign of green roof building. It is not clear that any city has yet built enough green roofs to reduce its heat island effect, though we can estimate how much coverage would be required to do so. Simulations suggest that the simultaneous use of green roofs and green walls is significantly more effective than the use of green roofs alone in reducing surface and ambient air temperatures in urban canyons and over rooftops. Green roofs can also enhance the cooling effect provided by other vegetation in the area.

Heat islands increase energy consumption because electricity use grows as building cooling requirements increase. Every 1.08°F (0.6°C) increase in air temperature can add 1.5–2.0% to peak demand for cooling.

In Washington DC
A recent NASA study found the summer land surface temperature in Northeastern cities was an average of 13°F to 16°F (7°C to 9°C) warmer than that of surrounding rural areas. A 2007 study found average night time temperatures increased the closer they were to the Federal Triangle area of Washington DC, and that this effect extended up to 37 miles (60 kilometers) away.

2.3.3 Economic Analysis

It is difficult to measure the cost-benefit of reducing heat islands at the building level. At the community level, the reduction in average and peak temperatures, heat-related illness and mortality and air pollution are all potential benefits of reducing the heat island effect, though they are also challenging to measure.

In Ontario, Canada for every 1.8ºF above 64ºF, electricity consumption increases by 4%. In Washington DC, local power savings from a 0.18ºF reduction in temperature is worth $600 for every kilowatt shaved from the peak load.

In the cost-benefit analysis contained in the report, the UHI impact was conservatively estimated to be 0.70% reduction in energy. This plus the peak load savings amounted to an annual savings of $0.23 per square foot of roof per year. This was accounted for as a community benefit, not an owner benefit.

2.4 ENERGY

Energy prices and greenhouse gas emissions are increasing as fossil fuel energy sources such as coal, oil and natural gas decline. Executive Order 13423 issued in January 2007, requires federal buildings to reduce their energy use by 3% per year, resulting in a 30% reduction in energy use by 2015. An energy conservation measure like green roofs may help federal government facilities meet this target, and help other commercial buildings reduce their energy use.

Green roofs can reduce the amount of energy a building uses for cooling in the summer and heating in the winter. Green roofs can reduce the amount of heating from solar radiation a building experiences in the summer, and can insulate buildings, providing heat retention in the winter. The exact amount of energy saved depends on the climate, the type of roof and building, the height of the building and its neighbors, the amount of moisture on a roof, the variability of temperature changes throughout the day, and seasonal variations in temperature.

Key findings:

- Green roofs can reduce the amount of energy a building uses in summer and, to a lesser degree, winter
- Green roofs can reduce peak loads during the summer
- Evaporation from soil and transpiration by plants reduces the amount of heating from solar radiation a building experiences in the summer
- Green roofs insulate, shade and add thermal mass to buildings, providing heat retention in the winter and cooling in the summer
- Green roofs can moderate air temperatures immediately above the roof, which can be expected to lead to efficiencies at rooftop HVAC units
- The upper level floors show the greatest reductions in energy use

2.4.1 Introduction

The energy savings due to green roofs are strongly dependant on factors such as climate, type of roof, type of building, hourly temperature changes and the season.

During the summer, green roofs have a higher rate of evapotranspiration than conventional roofs made of impervious materials, creating a cooling effect on and around buildings, thus reducing the heat island effect, and reducing energy demand.

In both summer and winter, green roofs have an insulating effect on buildings, reducing peak heating and cooling demands in hot and cold seasons. This makes a smaller contribution to energy savings than the evapotranspiration effect.

The figure illustrates the main fluxes of energy at the roof surface. The soil layer of the green roof acts to reduce the heat conduction flux (in red). The plant canopy of the green roof exchanges with the shortwave and long-wave radiation (in yellow). Evapotranspiration (or latent heat loss) at the plant and soil layers reduce temperatures (in blue).

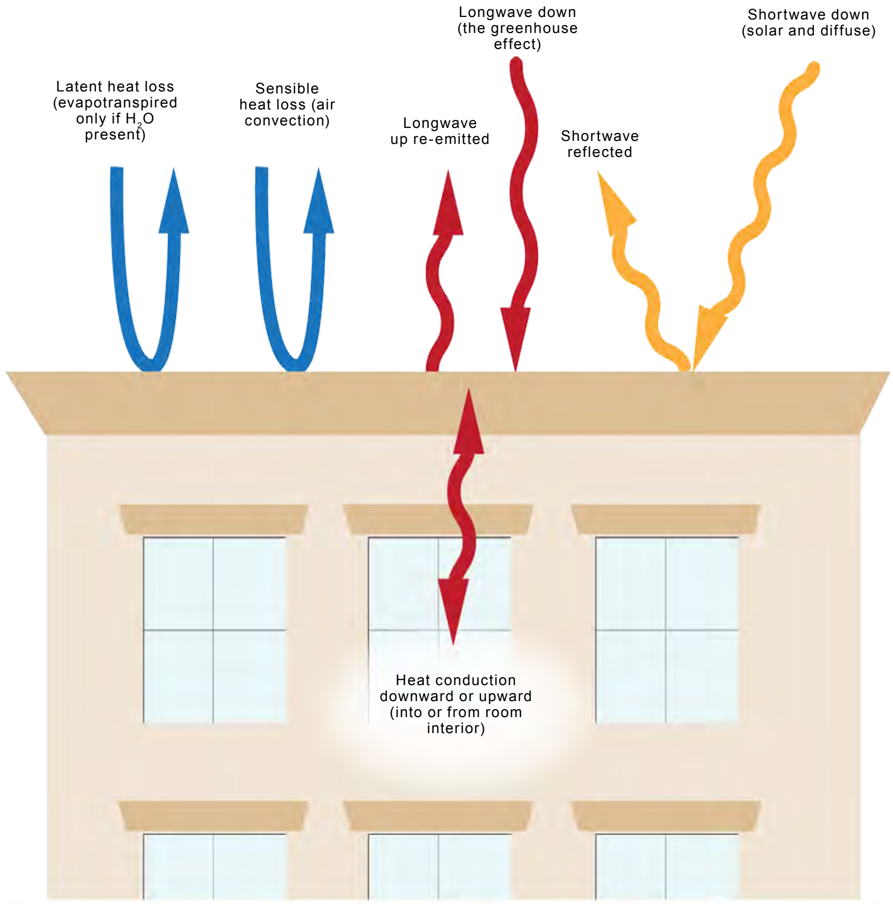


Figure 20: Surface energy balance for a roof

2.4.2 Analysis

SUMMER

Evapotranspiration creates a cooling effect on rooftops in summer. In the summer, the peak temperature of a roof's surface and membrane, and nearby air temperatures are lower on green roofs than on conventional roofs. Quantified results have been obtained for reduced surface temperatures in various climates such as Moscow, Russia, Riyadh, Saudi Arabia, Tokyo, Japan,Orlando, Florida, and Singapore.

Heat gain, the increase in building temperature due to solar radiation and high outdoor temperatures, is significantly lower on green roofs than black roofs**.** The thermal heat gain by a green roof can be up to 84% lower than that of a black roof. **Heat flux**, or the transfer of heat into or out of a building through the roof, can be reduced by as much as 72% compared to a black roof**.** Lower surface temperatures reduce **thermal loading** during the summer and reduce the amount of energy needed to cool a building. Deeper growing medium can enhance this effect, due to the greater insulating effect of the thicker growing medium and the additional thermal mass of the medium. Shading from plants can also enhance this benefit by reducing the amount of solar radiation that reaches the growing medium. A green roof on a three-story building in Japan was found to reduce the amount of energy needed to cool the top floor of a three-story building by 21 times.

Green roofs take longer to heat up and cool than conventional roofs, because of their **higher heat capacity (thermal mass)**. This reduces deterioration of roof membranes over time, and is one reason why green roofs last four times longer than conventional ones. The membrane of a green roof reaches its peak temperature several hours after that of a conventional roof. This "thermal lag" leads to a reduced mid-day peak heat gain as well as to warmer nighttime temperatures for green roofs, which can benefit buildings occupied 24-hours a day.

The specific components of a roof may also affect its performance. Light-colored rocks, porous aggregates, and certain plant species like *Sedum spurium* and *Sedum kamtschaticum* can be used to maximize temperature reductions throughout the year. In addition, climate plays a role. The evaporative cooling effect of irrigated green roofs is more pronounced in dry climates than in humid ones.

WINTER

Studies show that green roofs also outperform conventional roofs in the winter (though to a lesser degree than in summer), leading to energy savings from 13% to 33% through higher thermal resistance, or a greater capacity to resist heat flow. Winter heat loss for green roofs is estimated to be 34% lower than for black roofs, with a similar savings effect for white roofs. In addition, the thermal lag can reduce the amount of energy needed to heat a building in the morning. These benefits depend on climate, wind and snow cover.*

Recent observations of a 75,000-square-foot commercial green roof in Chicago and simulations of similar green roofs in Chicago and in Houston show a reduced heat loss and reduced energy consumption in the winter compared to similar white roofs.

*Snow cover will add further insulation to the roof reducing the heat loss and the flux of temperature at the membrane.

YEAR-ROUND

Green roofs have lower surface temperatures and reduce building energy consumption year-round, though the effect varies by season. An 8-story building in Madrid, Spain reported a 1% annual reduction in energy use, with 0.5% savings in winter and 6% in summer. Higher floors showed greater reductions in energy use.

Heat flux has been shown to be lower on a green roof than a black one. This can reduce peak and daily cooling demands during the summer, and heating demand in the winter. The magnitude of the savings depends on climate zone, site characteristics and building design.

The reduction in energy demand potentially reduces **greenhouse gas emissions** by indirectly reducing the amount of fossil fuels required at the utility's power plant or at the building's heating/cooling energy source, assuming that the energy comes from fossil fuels

Many buildings have ventilation air intakes and/or cooling and heating equipment located on the roof. Limited studies have shown that the tempered environment above a green roof produces a notable shift in air temperature at the point of air intake for this equipment. This means that the equipment requires less energy to cool the building in summer and to heat it in winter. The savings potential from this effect may exceed that of direct heat flux reductions, but it requires more study.

Photovoltaics installed on the United States Environmental Protection Agency Region 8 Headquarters, Denver, Colorado

2.4.3 Economic Analysis

The local climate, energy costs, location, and building design are vital in potential building energy savings. The annual energy savings attributable to green roofs were found to be approximately $0.166 per square foot of green roof nationally and $0.169 in Washington DC (despite different energy prices).

As savings are mostly realized in the uppermost floors, the cost-benefit analysis assumed a particular height: 8-stories. As the size of the roof varied (5,000, 10,000, and 50,000 square feet), the degree of savings changed as the amount of space realizing savings changed. In the cost-benefit analysis, this was accounted for using a model generated by Centre for Environment at the University of Toronto. For a building with a 5,000 square foot roof, the average energy savings was $0.155 per square foot of roof while the 50,000 square foot roof building experienced a savings of $0.190 per square foot of roof. Savings will likely diminish with each additional floor.

Several green roof studies also included the savings from the reduction in rooftop heating and cooling equipment, though this report did not because heating and cooling equipment are not always located on the rooftop. The justification is that with a more stable thermal environment above the roof—one that is cooler when it is hot and warmer when it is cold—the building's equipment potentially runs more efficiently and lasts longer. These savings would apply equally to multi-story and single-story buildings. Additionally, if a green roof retrofit were to coincide with an HVAC upgrade, the internal heating and cooling savings could reduce demand and thus reduce the sizing of the upgraded equipment.

Green roofs may potentially reduce the amount of carbon dioxide and smog-causing pollutants emitted by power plants by reducing the peak and annual cooling and heating energy use in buildings through improved roof performance. Regulators, building occupants and investors all demand these reductions in energy related emissions.

2.5 URBAN AGRICULTURE

The current food production system relies on several resources such as water, soil, nutrients and energy. On average, Americans consume 300 gallons of oil annually for the sole purpose of food production. Using green roofs to grow food might reduce carbon emissions associated with food distribution.

Urban agriculture on rooftops potentially increases property values through an additional building service and added marketability. In addition, the roofs of office buildings are hard for vermin to reach, potentially protecting crops from damage by pests.

Depending on structural loads and accessibility, agriculture on green roofs could offer an outlet to educate urban residents about food production and seasonal variety, and may boost local gardening efforts. Rooftop farming could also help generate jobs.

Key findings:

- Green roof gardens with growth medium more than six inches deep (intensive) can support a variety of crops, however, herbs have grown on growth medium less than six inches deep
- Agricultural services like food, biofuel and nursery growth on a roof create potential economic and social benefits not available on conventional roofs
- Security is a potential issue with providing access to federal building roofs for agriculture

Image Courtesy of Sarah Khalid

2.5.1 Introduction

Over the last few years, rooftop gardens and farms have been recognized as a promising form of urban agriculture, and a way to take advantage of a significant amount of flat space that receives steady sunlight throughout the day.

Using rooftop space for food production might help reduce the distance food travels to reach consumers, potentially reducing carbon emissions associated with food distribution. It could also provide fresh and local food options to building occupants and the local population. It could even provide an outlet to educate the local community about food production and seasonal variety. It could also boost property values through the addition of a new building service, and help create jobs.

Urban agriculture can appear in a variety of forms, such as container gardens, hydroponics, aquaponics, vertical farming, multi-tiered farming, technologies, apiculture, and rooftop gardens. This last form of urban agriculture, rooftop gardens, is one that can utilize available space over a somewhat limited environment.

2.5.2 Analysis

The success of a rooftop garden depends on rooftop access, maintenance needs, exposure to sun and wind, and the local climate. Local zoning may prohibit the use of rooftop space for urban agriculture, although such policies can be changed. For example, in 2010, the Seattle City Council adopted Council Bill 116907 to allow urban farms and gardens in all zones.

The load-bearing capacity of existing roofs is an important issue when considering urban agriculture. Rooftop farms and gardens typically have growth medium more than six inches deep, which can support a wide variety of crops. Some crops are difficult to grow without at least 18 inches of soil. Roofs with less than six inches of growth medium can support the growth of some herbs. Kale, spinach and lettuce crops have been grown on a modular green roof in Toronto, Canada with less than 3 inches of growing medium.

Farming is labor intensive, requiring continual attention to manage crop production and distribution. This may raise safety and liability issues as compared with a low-maintenance green roof.

For federal buildings, security is the major challenge to incorporating an urban farm in a green roof, if it were to be tended by non-federal workers. Background checks would likely be required, and roof accessibility and the accountability of metal gardening equipment would also create challenges.

The Pocket Habitat on a roof in Gloucestershire, England

2.5.3 Economic Analysis

A Toronto study estimated that using all the rooftop space in the city to grow crops could create a value return of CAN$1.7 billion. **Agricultural services** like food, biofuel and nursery growth create potential benefits from green roofs, though they are typically not seen on roofs with 3- or 6-inch growth medium. This was not accounted for in the cost-benefit model, due to the newness of urban agriculture and lack of usable data.

Rooftop gardens in London, England

2.6 ACOUSTICS

On a pound-for-pound basis, green roofs are better at noise reduction than traditional and concrete roofs. When used on buildings without sufficient ceiling insulation, green roofs can improve noise reduction on the upper levels, especially in areas with heavy motor or air traffic.

Key findings:

- Green roofs provide acoustic insulation
- The benefit of noise reduction by a green roof depends on the building's location, with those near highways or under areas of high air traffic receiving the greatest benefit
- The acoustic benefits of green roofs are greatest within the top floors of a building

2.6.1 Introduction

Green roofs can reduce noise pollution from airplanes, elevated transit and traffic, particularly for low- and medium-frequency waves. They have better noise reduction per unit of weight than traditional or concrete roofs. This reduction will primarily affect a building's top floor. Green roofs can enhance the attenuation of diffracted sound and reduce the transmission of sound through a buildings' roof, particularly in buildings without additional ceiling insulation.

2.6.2 Analysis

According to extensive studies, roofs 2 to 6 inches thick have reduced the noise level of a roof by 8 decibels or more, depending on the water content in the growing medium. The greater the proportion of a roof covered in green roofing, the greater the reduction in sound pressure from noises traveling across the roof. The weight of a roof determines the amount of insulation available to attenuate surrounding noise. The texture of growth medium can affect this attenuation. Green roofs have the potential to reduce both low frequency sounds (blocked by the growing medium) and high frequency sounds (blocked by the vegetation).

The growing medium, drainage layers, and vegetation determine the weight of a roof, and therefore the amount of insulation thereby available to attenuate surrounding noise.

2.6.3 Economic Analysis

The benefit of noise reduction by a green roof depends on the building's location, with those near highways or under areas of high air traffic receiving the greatest benefit. A 2004 study found that the potential savings to airport authorities in terms of the potential reduction of noise mitigation costs paid was $0.43 per square foot of green roof per year, though this savings depends on the local real estate market, and would likely be seen through a higher rental rate. This was not accounted for in the cost-benefit model.

2.7 AIR QUALITY

Plants have long been used in the urban environment to remove air pollutants and greenhouse gases like carbon dioxide, particulate matter, nitrogen dioxide, sulfur dioxide and carbon monoxide. Green roofs can reduce air pollution, depending on the types of plants and the soil depth.

A green roof could be used as a carbon sink in a cap-and-trade system, which provides a mandatory cap on carbon emissions.

Key findings:

- The vegetation on green roofs can absorb air pollutants
- The amount of carbon required to create and install a green roof is typically higher than the amount of carbon it can absorb but when energy savings are factored in, a green roof can be a net carbon sink

2.7.1 Introduction

Greenhouse gases are gases that trap heat in the atmosphere. A major greenhouse gas, **carbon dioxide (CO_2)** is emitted to the atmosphere through natural and anthropogenic processes. Carbon is sequestered in plants through photosynthesis, and it is stored in the soil and roots. At the end of the plants' lifetimes, carbon is released into the atmosphere as the plants decompose and the soil is disturbed.

Nitrogen-oxides (NOx) and **particulate matter (PM)** are the types of pollutants that can most easily be reduced through green roofs. Nitrogen- oxides are produced in combustion and create smog and acid rain. Plants remove gaseous pollution from the air through their pores, or stomates.

With the rise of industrialization and urbanization, pollution and waste treatments have introduced a significant amount of heavy metals into the environment. The annual release of heavy metals worldwide in 2003 reached 22,000 metric tons for cadmium, 939,000 metric tons for copper, 783,000 for lead, and 1,350,000 for zinc. Plant tissues absorb poly-aromatic hydrocarbons and heavy metals.

2.7.2 Analysis

Green roofs remove pollution from the air in several ways. Plant stomates absorb gaseous pollutants, the leaves intercept particulate matter, and plant tissues absorb poly-aromatic hydrocarbons and heavy metals. Furthermore, harmful ground-level ozone is reduced through the effect that vegetation has on air temperature cooling, and therefore photochemical reaction rates are reduced.

A green roof's ability to act as a carbon sink depends on the type of vegetation and the surrounding environment. The amount of carbon required to create and install a green roof typically exceeds the amount of carbon it can absorb.

Using the US Department of Energy's (USDOE) carbon offset projects, the embodied carbon needed to create a green roof was calculated to be 0.0006 metric tons of emissions per square foot, roughly equal to the heating and cooling emissions savings a typical green roof creates. The benefit of increased carbon sequestration and reflectivity is measured at 0.0002 metric tons per square foot with sequestration realizing the slightest of benefits of $30x10^{-8}$ metric tons per square foot.

Thicker growth medium or growth medium that includes expanded clays and shales* can allow a roof to sequester large amounts of carbon dioxide. Plants like large perennials can also increase a roof's ability to sequester carbon, while the application of fertilizer, composition of growth medium and irrigation can also have an effect.

A two-year study in Michigan on a 2.5 inch-thick extensive sedum roof showed a net carbon sequestration of 378 grams of carbon per square meter in the plant material, root biomass and growth medium.

*Expanded clays and shales have a high embodied energy due to the manufacturing process

2.7.3 Economic Analysis

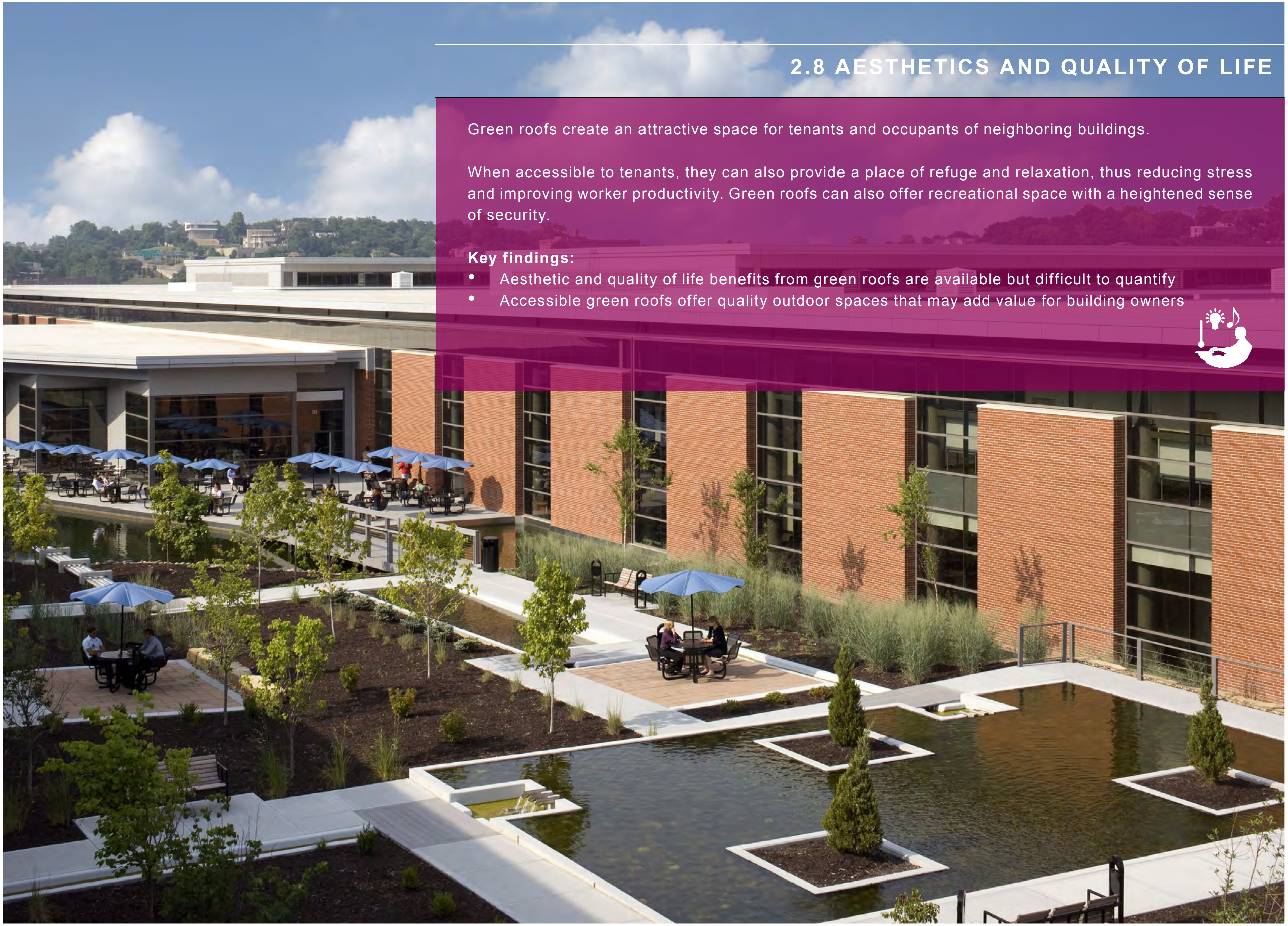
In Washington DC
Air in Washington DC has high concentrations of ground-level ozone and particulate matter. Using a United States Department of Agriculture (USDA) Forest Service Urban Forest Effects model, the Casey Trees Endowment Fund Study evaluated the air quality benefits of a mixture of trees and vegetation in intensive and extensive green roofs in the city. The study considered the effect of installing green roofs on all “green roof-ready” buildings in the District, or about 75 million square feet of rooftop area. The model found that this 100% coverage scenario would remove about 58 metric tons of pollutants from the air, the equivalent of planting 85,000 to 115,000 trees. Under this scenario, particulate matter was the primary pollutant removed from the air, though sulfur dioxide, nitrogen dioxide and carbon monoxide were also removed.

In addition, some plants used in green roofs, like *Sedum album* and *Sedum spurium*, are metal hyperaccumulators, with unusually high intake and storage levels of elemental metals.

The reduction in nitrogen-oxide compounds by a green roof is calculated to be worth $0.0008 to $0.589 per square foot of green roof. The amount of nitrogen-oxides compounds taken up by a roof depends primarily on the type of vegetation used.

The nitrogen-oxide costs assume either costs for replacement or addition of equipment, such as a flue gas scrubbing system, or human benefit costs that were evaluated as part of an EPA study. This same logic could be used for Particulate Matter less than 10 micrometers (PM_{10}), sulfur-oxygen compounds and carbon monoxide, which would result in benefit of $0.00115 per square foot of green roof, $0.000002 per square foot of green roof, and $0.000096 per square foot of green roof, respectively.

In addition to pollutant capture, the report “Cool Communities: Strategies for Heat Island Mitigation and Smog Reduction” showed that there is a correlation between air quality and reduction in temperature (see *Section* 2.3 for more details). Specifically, the report states that for every 5.4°F (3°C) reduction in environmental temperature, nitrogen-oxides are reduced by 50 times with pollutant capture reductions. The cost-benefit analysis used a conservative (0.81°F or 0.45°C) reduction due to green roofs, which yielded a multiplication of NOx benefits by 7.5 times.



2.8 AESTHETICS AND QUALITY OF LIFE

Green roofs create an attractive space for tenants and occupants of neighboring buildings.

When accessible to tenants, they can also provide a place of refuge and relaxation, thus reducing stress and improving worker productivity. Green roofs can also offer recreational space with a heightened sense of security.

Key findings:

- Aesthetic and quality of life benefits from green roofs are available but difficult to quantify
- Accessible green roofs offer quality outdoor spaces that may add value for building owners

2.8.1 Introduction

Converting flat building roofs into recreational green space can benefit building occupants by providing a safe place to eat lunch and relax outside. Plants and natural surroundings have been found to reduce stress, lower blood pressure and increase satisfaction in users. Green roofs can also create an attractive space for occupants of neighboring buildings. In addition, green roofs have higher aesthetic value than structural infrastructure like catch basins and drainage pipes.

A case study of Alta Bates Medical Center in Berkeley CA, looked at the benefits of a rooftop garden for both patients and staff. Several people in the garden were interviewed as to what types of activities they engaged in on the roof and there were overall themes in the responses: relaxing, talking, eating, strolling, and "outdoor therapy." A brief escape from the demands of work would be beneficial to any GSA employee or GSA building occupant. Other research by Frances Kuo has shown that green space can reduce stress, decrease recovery time and diminish crime. Green roofs can provide some of these benefits.

2.8.2 Analysis

A green building with a green roof allows not only building occupants but users of nearby buildings views of and contact with the natural environment.

The height of parapets and the nature of other structural components will determine a green roof's effectiveness as an open or recreational space. Benches or seats are typically provided to create an amenity space for building occupants as part of a green roof. Adding windscreens to shield amenity areas can make a green roof more attractive to potential users.

Accessible roof at the John W. McCormack Post Office and Courthouse, Boston, Massachusetts

2.8.3 Economic Analysis

Aesthetics and quality of life are difficult to quantify, especially in regards to green roofs. Still, some research has found that green roofs can provide significant value to a building's owner and tenants through greater productivity and reduced absenteeism. They can also benefit the larger community through improved aesthetics and views of the green roof.

Although researchers have not addressed green roofs specifically, one study has shown the overall effect of green buildings to have a net present value of $12 per gross square foot in terms of greater productivity and lower absenteeism. Additional research has found that office workers are 2.9% more productive when the view out of their office windows includes vegetation.

Because these studies are not specifically related to green roofs and the methodology is open to debate, productivity, absenteeism, aesthetics, and views were not accounted for in the cost benefit analysis. The overall evidence, however, is that green roofs have the capacity to provide significant value in terms of productivity and absenteeism to the tenants (and thus the owner) as well as to the community at large who benefit from the improved aesthetics and views of the green roof.

Accessible green roof at the 10 West Jackson Street Building, Chicago, Illinois

2.9 JOB GENERATION AND ECONOMIC DEVELOPMENT

Green infrastructure is an "effective response to a variety of environmental challenges that is cost-effective, sustainable, and provides multiple desirable outcomes." The green infrastructure movement provides opportunities for future employees, specifically unskilled labor, to develop marketable skills in the areas of landscaping and green roof maintenance.

A **green job** is one that plays a direct role improving the environment. These jobs should also be sustainable, providing workers long-term career opportunities.

Green roofs offer job opportunities for both skilled and unskilled workers. They also offer building owners more marketable buildings in comparison to those without green roofs.

Key findings:

- Green roofs can provide green job generation through the production, installation and maintenance of green roofs
- Green roofs can provide investment benefits for building developers and owners and provide marketing opportunities to the building

2.9.1 Introduction

Green roofs, which are considered green infrastructure, can create employment opportunities in production, installation, and maintenance of the roof.

Green roofs also can provide marketing opportunities and investment benefits for developers and buildings owners.

2.9.2 Analysis

In the US, employment from green roofs rose over 80% from 2004 to 2005. Green roofs can create a range of jobs including: suppliers and manufacturers of roof membranes, root repellent layers, drainage layers, landscaping fabrics and other materials; suppliers and manufacturers of growing medium, soil and soil amendments like compost, peat moss, or fertilizer; nurseries, especially organizations specializing in plants for green roofs; designers, engineers and roof contractors; and building contractors, maintenance contractors and engineers.

A market for jobs related to green roofs has existed in Germany since the introduction of FLL standards and some incentives in the 1980s. Researchers found that the German green roof industry has grown 15% to 20% a year since 1982, and has helped created jobs in the industries listed above.

A study found that green roof investment by the government over a one-year period could create from 600 to 1,800 jobs per year* in the Washington DC area (Table 6). Economists disagree about the actual employment potential resulting from incentives and government investment, and some believe that job gains related to green roofs would be offset by the loss of jobs related to conventional roofs. Even green roofs have some need of workers who specialize in conventional roofs, to install a membrane beneath the green roof.

Green Roofs for Healthy Cities (GRHC), a not-for-profit industry association, established the **Green Roof Professional** program in January 2007. The accreditation potentially enhances job opportunities in the green roof industry for professionals who

A 2009 study contracted through the Washington DC Office of Planning performed a job demand analysis regarding Green Collar Jobs. Part of the analysis included the jobs created by the green roof industry based on the amount of investment required. The analysis used the Casey Trees Endowment Fund Study, "Re-greening Washington DC: A Green Roof Vision Based on Quantifying Stormwater and Air Quality Benefits" as its basis.

Table 6: Green roof job generation in Washington DC

SCENARIO TYPE	JOBS CREATED PER YEAR (AVERAGE)	INVESTMENT (IN MILLIONS)
Pessimistic	590	$299.9
Conservative	1,179	$599.8
Aggressive	1,769	$899.6

*Estimates were made in 2006 and based on a direct investment over a 10 year period understand the elements of green roof assembly, such as waterproofing, structural engineering, project and water management, growing medium, plants and maintenance. This occupational standard helps building developers, owners and designers identify landscape designers and contractors who understand the elements needed to install and maintain a green roof, potentially mitigating liabilities when compared with hiring inexperienced designers and contractors.

Reintroducing green space to an urban environment adds aesthetic value to nearby properties. Proximity to green space, in particular views of parks and tree cove, can boost the value of a building by up to 15%. A study of green roofs in Nuremberg, Germany, found that green roofs led to higher occupancy and higher rental rates, even during a real estate downturn. However, quantifying the benefits of green buildings—let alone green roofs—is challenging.

As with any building attribute, the realized value of a green roof depends on its effect on performance and the general recognition by the relative market. In the capitol region, both performance and market recognition are better understood; however, this study must still contend with the difficulties of attributing performance and recognition to a single component: a green roof.

2.9.3 Economic Analysis

Neither changes in employment and value (which would lead to increased tax revenue) were accounted for in the cost-benefit analysis. This is because the data is limited and the applicability extremely varied. However, the data does suggest that installing green roofs versus conventional roofs would lead to more jobs and higher property values.

A supplemental analysis was conducted to predict the market's valuation of a green roof. Average commercial rents, expenses, vacancy, discount rates, absorption, and lease lengths were identified and modified based on an expectation that, like green buildings, the market values green roofs.

An analysis to predict the market's valuation of a green roof estimated that they would have a **real estate effect** of **$13 per square foot of green roof nationally** and **$10 in the Washington DC** area. Net present value of 50 years of these savings amounted to $110 and $90 per square foot of roof, respectively. Data from real estate information provider Costar and the USGBC found that green buildings realize 5.7% more rent than conventional buildings nationwide, and 7.4% more rent in Washington DC.

Using average construction costs, green building premiums, and the premium costs of green roofs, it was assumed that green roofs account for 44% of the total green construction premium. Collectively, these two premiums suggest a rental premium of 2.5% nationally and 3.3% in Washington DC.†

In Washington DC

Non-profit organizations in the Washington DC area such as Casey Trees and DC Greenworks offer educational training in urban forestry and green roof maintenance. In addition, DC Greenworks also trains low-income residents in plant nursery work and landscaping.

1425 K Street NW is the first high-rise building in the District with a green roof. It was installed through a partnership between Casey Trees, DC Greenworks, Covenant House and Blake Real Estate, the building's owner and property manager. The roof was funded by grants from the DC Department of Health and the National Fish and Wildlife Foundation. In addition to serving as an amenity for workers in the office building, the roof is a demonstration project designed to increase public familiarity with, understanding of and support for green roofs.

†When considering the proportion of a green building premium attributable to green roofs, it is important to keep in mind that most green buildings (e.g., LEED certified) do not include a green roof. Most upgrades needed to earn green building credits add from 2-10% to the cost of a building, and involve substituting less-efficient equipment with higher-cost and higher-efficiency models. A green roof, in contrast, is an entirely new piece of equipment installed in addition to a conventional roofing layer.

2.10 ROOF LONGEVITY

Properly installed green roofs more than double the number of years before a roof needs to be replaced, as compared with conventional and white counterparts.

Key findings:

- Studies suggest that the average life expectancy of a green roof is 40 years, versus 17 for a conventional roof, however, numerous green roofs have outlived that time period
- A properly installed green roof will likely only need to be replaced if the membrane below has aged to the point where it needs repair

2.10.1 Introduction

The lifespan of a roof's membrane largely determines a roof's longevity. Properly installed green roofs more than double the number of years required before a roof needs to be replaced, as compared with conventional and white counterparts. This is because a green roof's vegetation layer and growing medium protect the roofing membrane from damaging UV radiation and from fluctuations in temperature extremes. Temperature fluctuations cause daily expansion and contraction in the membrane, wearing it out over time.

2.10.2 Analysis

Our study puts the average life expectancy of a green roof at 40 years versus 17 years for a black roof. The lifetimes of green roofs are difficult to predict because some do not need to be replaced even more than 50 years after installation. Green roofs installed on several federal buildings in the National Capital Region have not been replaced since their installation in the 1930s.

A green roof's soil and vegetative layers provide significant protection to its base layer, which is almost identical to that of a black or white roof. Soil and vegetation minimize the negative effects of exposure to UV rays, wind, water and mechanical damage (see *Section* 4.3.1 and *Section* 4.3.3 for leak and wind scour issues). Thermal mass and simple physical separation are mostly responsible for these benefits. Table 7 below illustrates the varying research relating to expected roof lifetimes:

Table 7: Green roof membrane lifetime versus conventional roof membrane lifetime

LIFETIME, YEARS	GREEN	BLACK
GRHC Life Cycle Cost Calculator	25	17
LBNL Research	29	14
Fraunhofer Institute	40	15
European Federation of Green Roof Associations	60	30
Mann, G. (2002) *Approaches to object-related cost-benefit analysis*.	50	25
Single Ply Systems & Glass, GAF Materials Corp, SBS/TPO average*	n/a	14
AOC Dirksen Green Roof Study	50	17

*The data represents an average. Actual costs can vary significantly depending on the building condition, the exact location (due to building codes etc), and the local labor rates.

2.10.3 Economic Analysis

The cost-benefit model used the previously mentioned 40-year lifespan for green roofs and 17-year estimated lifespan for conventional roofs.[†] *Section* 3 references the cost premium of green roofs compared to black roofs.

There is very little data regarding replacement of green roofs. Since green roofs prolong a membrane's lifetime, a properly installed green roof will likely only need to be replaced if the membrane has aged to the point where it needs repair. If this is the case, the green roof medium can be salvaged and stockpiled for reuse, and the vegetation can be replanted. However, the membrane layer will need to be disposed of in a landfill, as would a conventional roof after replacement. This study used a green roof replacement cost of 33.5% of the installation cost to account for the labor needed to remove the roof medium.

[†]Cost benefit analysis weighted the longevity of green roofs and black roofs using various studies (see Table 7)

GSA Region 8 - United States Environmental Protection Agency Region 8 Headquarters, Denver, Colorado

A 19,200 square foot accessible, extensive green roof installed on the new EPA headquarters (2006). Tests have shown an approximate 40% decrease in heat transmitted through the roof compared to the control roof (next door) and an approximate 85% stormwater retention rate for all ½-inch or less storm events. The green roof also reduced the size of the cistern in the basement, which allowed more space for parking.

Key findings:

- Compared to a black roof, a 3-inch to 6-inch green roof covering 10,000 feet has a Net Present Value of $2.70 per square foot per year, Payback of 6.2 years and an Internal Rate of Return of 5.2% nationally.
- The longevity of green roofs has the greatest effect on savings, whereas installation and maintenance have the greatest effect on cost (maintenance costs are even greater than the installation premium).
- Over a 50-year period, stormwater, energy, equivalent carbon dioxide (CO_2e, which measures the potential global warming effect of a greenhouse gas) and community earnings of green roofs more than made up for the increased premium of installing, maintaining and replacing them. Results can vary depending on one's relationship to the subject real estate.
- The fewer floors a building has, the greater the energy savings are for a green roof compared to a black roof.
- The greater the surface area, the greater the stormwater management savings are for a green roof compared to a black roof.
- Cost savings will increase as stormwater regulations become more stringent and green roofs become more acceptable as mitigation measures.

A major goal of this report is to compare the costs of green roofs with the benefits they provide. This requires an understanding of the costs of green roofs, a quantification of the benefits, savings and value produced by green roofs, a comparison of these costs and benefits, and an analysis of the results. This section includes each of these required steps.

3.1 PURPOSE

This report has thus far described many of the costs and benefits of installing a green roof instead of a conventional black roof. However, to put the cost and benefit of each type of roof in context, an analysis was conducted in which the expected cash flows of both green and conventional roofs were modeled over time. For instance, the additional cost of installing a green roof was accounted for in year one but was followed by years of energy savings as a result of this installation. This analysis thus gives a financial overview of a green roof as an investment, and allows this investment to be compared to similar, building-level investments. Building owners, as do most investors, typically choose to make investments with the greatest expected return, though they often weigh competing, non-financial influences such as building image, as well.

3.2 METHODOLOGY

The cost-benefit analysis presented in this section is based on a direct comparison between installing either a black roof or a state-of-the-art extensive green roof as a replacement for an existing conventional roof. The costs and benefits of the extensive green roof are averaged between a 3-inch multi-course extensive profile and a 6-inch semi-intensive profile. Because the size of green roofs on commercial and institutional projects can vary greatly, this study included three roof sizes: 5,000, 10,000, and 50,000 square feet.

The relative costs, cost-saving benefits and added value of a green roof versus a black roof over a 50-year timeframe was then accounted for and discounted back to present value. Six separate cash flows were created to allow data segregation and identification of the relative benefits:

- Installation, replacement and maintenance
- Stormwater
- Energy
- Carbon
- Community benefits
- Real estate effects

The cash flows from the following benefits were not included in the analysis:

- Urban agriculture
- Acoustics
- Job generation
- Productivity

The costs and benefits are experienced by the following:

- Directly by the developer through installation, rent or operations,
- By the municipality through reduced infrastructure maintenance or replacement costs,
- By the community through improved aesthetics, biodiversity or job generation, or
- To building occupants through productivity gains or improved health (productivity and improved health was not integrated into this analysis due to the difficulty in assigning a particular performance attributable to either roofing type).

For transparency purposes, rather than aggregating all of the data and stating an overall **net present value (NPV) or internal rate of return (IRR)**, this analysis openly shares its data and keeps the results separated to demonstrate the relative costs and benefits of green roofs versus their conventional counterparts.

3.3 ASSUMPTIONS

Users should be aware that the intent of this analysis is to present "average" costs and benefits on a very broad, national level and on a more specific, metropolitan level, for Washington DC. Results may differ for specific states or municipalities.

3.3.1 COST

The decision of whether to install a green roof should be considered on a case-by-case basis. Variability in structure, municipality, ownership, tenant, investment, technology, climate and other aspects requires specific attention to ensure accuracy. This analysis aims to limit some of these variables by focusing only on roof replacements and on the financial performance "premium" between state-of-the-art extensive green roofs and state-of-the-art black roofing. The cost-benefit model includes inflation, growth rates for labor and materials, energy, stormwater, community benefits, diminishing returns (based on expected increase in supply), a discount rate evaluation, a 50-year timeline and community (public) benefits of green roofs. A detailed description of the assumptions is in Appendix B.

For the purposes of this study, we conducted a cost-benefit analysis comparing the two simplest, beneficial and least expensive examples of the extensive and intensive varieties of green roof with a conventional, black roof. These were a 3-inch multi-course extensive roof with a geosynthetic drain layer, and a 6-inch semi-intensive roof.

The 3-inch profile is the minimum recommended for maintenance requirements and stable plant coverage without permanent irrigation, and is used in places where stormwater management is the main reason to install a green roof. The 6-inch profile includes four inches of growth medium over two inches of drainage medium, and includes permanent base-level capillary irrigation to sustain plants. These roofs are typically used where garden aesthetics and biodiversity are priorities, in addition to stormwater management. Performance characteristics, layers, recommended plant lists and wet weight loads (see *Section* 4.1.1 for structural issues) of both roofs examined are detailed in Appendix A.

Key findings:

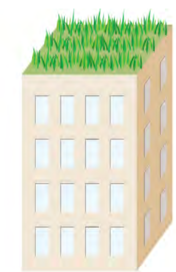
- Green roof installation costs per square foot decrease as size increases.
- The installed cost premium for multi-course extensive green roofs ranges from \$10.30 to \$12.50 per square foot more compared to a conventional, black roof.
- The installed cost premium for semi-intensive green roofs ranges from \$16.20 to \$19.70 per square foot more compared to a conventional, black roof.
- Annual maintenance for a green roof is typically higher than for a black roof, by \$0.21 to \$0.31 per square foot.

Green roof installation costs

This analysis developed a standardized cost for both intensive and extensive roofs using the federal prevailing wage rates for Washington DC, and current material costs.* As demonstrated in Figure 21, extensive green roofs are approximately \$6 to \$8 per square foot cheaper to install than semi-intensive green roofs, and in both cases larger green roofs cost less per square foot to install than smaller green roofs.

This analysis found that the typical installation cost for a green roof depends on its size, with the price per square foot decreasing as the size increases. The cost premium of installing an extensive green roof ranges from \$10.30 to \$12.50 per square foot more compared

5,000 sqft



10,000 sqft

50,000 sqft

*Roofmeadow verified these costs by comparison with projects that it has completed in each green roof profile/size configuration. The specific projects are not discussed for reasons of client confidentiality.

to a black roof, while installing a semi-intensive green roof costs from \$16.20 to \$19.70 per square foot more compared to a black roof (see *Section* 4.2 for installation issues).

Green roof maintenance

The first years of a green roof's existence are considered an **establishment period**, in which maintenance is critical to the roof's long-term success and maintenance requirements are greatest. Maintenance of a green roof includes weeding, harvesting cuttings and distributing them in bare spots to improve coverage, checking for loss of growth medium, and inspecting for other potential problems. Maintenance costs will be higher any time a green roof includes a landscaped design, as workers will also need to spend time maintaining the design aesthetic. A typical maintenance crew includes two workers, though more may be needed for a larger roof. For this study, labor hours were rounded up to the next half-day for cost estimating purposes.

A minimum of three maintenance visits per year is recommended for an extensive green roof during the establishment period. The typical labor requirement is 4 person-hours per 1,000 square feet per year, or 1.33 person-hours per 1,000 square feet per visit. Maintenance requirements will decrease after the establishment period; this analysis assumes a reduction to two visits a year for this type of green roof.

For an intensive green roof established with plants listed in Appendix A, a minimum of four maintenance visits per year is recommended during the establishment period. The spring and fall visits will be more labor intensive, requiring cutting and removal of dead grasses, removal of organic litter, and other tasks. The typical labor requirement is six person-hours per 1,000 square feet per year, or 1.5 person hours per square feet per visit. After the establishment period, maintenance demands will decrease but the number of visits will hold steady at four per year (see *Section* 4.3 for maintenance issues).

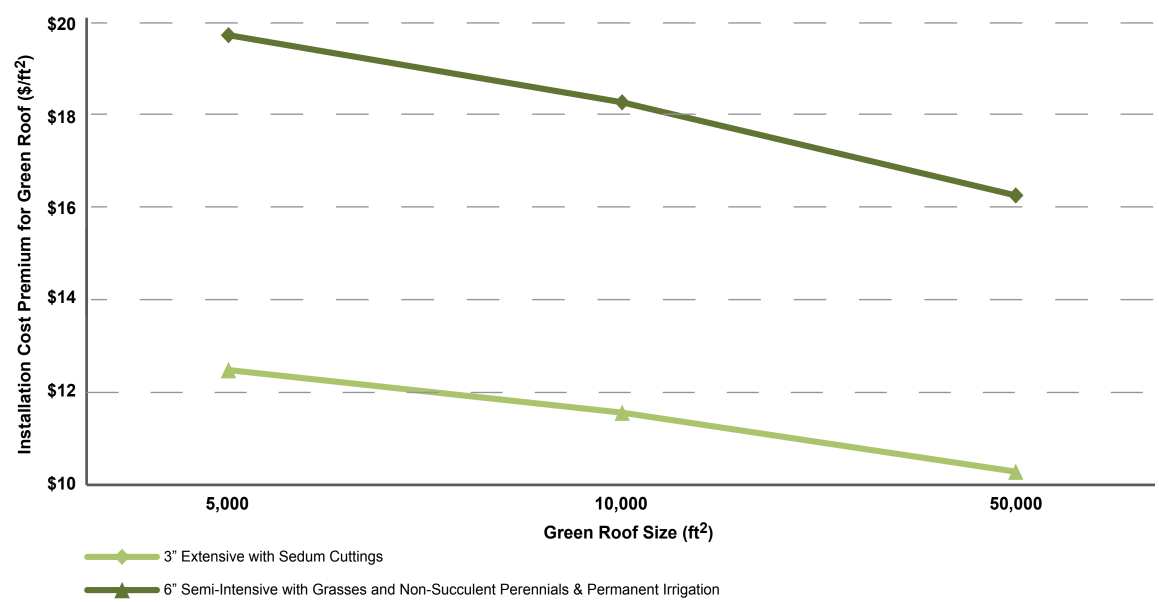


Figure 21: Green roof installation premiums

In general, maintenance costs for both types of green roofs are greatest during the establishment period, or the two years after installation. Intensive roofs require more frequent and longer maintenance visits than extensive roofs, both during the establishment period and afterward.

Annual maintenance of green roofs costs from 21 cents to 31 cents more per square foot per year than maintenance of a black roof. White roofs typically need more maintenance than black roofs, as they must be kept free from debris to continue to reflect solar radiation as expected.

3.3.2 BENEFITS

The benefits of an extensive green roof versus a conventional black roof are described at the end of each subsection in the Benefits Section. The benefits specifically accounted for in this analysis fall in two groups:

- Those that **directly affect owners/occupants/investors**, including installation, replacement and repair, stormwater and energy
- **Other financial impacts**, including greenhouse gas savings, market-based savings, and community benefits.

Additional details can be found in Appendix B of this report.

3.4 RESULTS

The results presented below are itemized to show the relative differences in costs and benefits, in an effort to help the reader to understand the relative impacts on the costs and benefits of installing a green roof.

3.4.1 NET PRESENT VALUE PER SQUARE FOOT OF ROOF

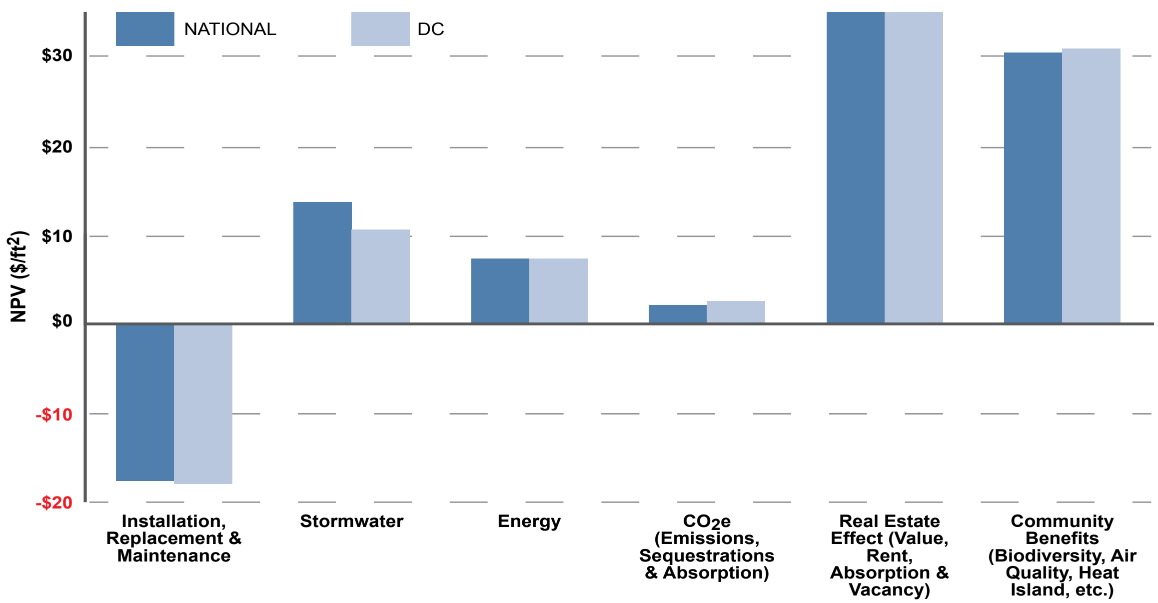


Figure 22: NPV cost-benefit analysis results of green roof versus black roofs

Key terms:

- **Net Present Value (NPV)** is a measure of the potential profitability of an investment. It takes the expected value of the future costs and benefits associated with this investment, and accounts for the effect of inflation. A positive net present value means an investment will produce greater returns over the time frame being considered than an alternate investment.
- **Internal Rate of Return (IRR)** is a measure of the expected annual financial benefit yielded by an investment over a given time frame (e.g., an IRR of 6% suggests a stream of cash growing, on average, at 6% per year). This benefit can be compared with the expected yields of other investments over the same period.
- **Payback** is the number of years it takes to recoup an initial investment through the income from that investment.
- **Return on Investment (ROI)** is percent of money gained or lost on an investment, relative to the initial cost.

Over a 50-year period:

- The installation, replacement and maintenance of a green roof has the greatest negative impact on net present value at a cost of approximately $18 per square foot of roof.
- Stormwater and energy savings make up for this cost by providing a benefit of approximately $19 per square foot of roof.
- Benefits to the community have the greatest positive impact on net present value at a savings of almost $38 per square foot of roof.

Table 8: Cost-benefit analysis results of green roof vs black roofs

NATIONAL LEVEL RESULTS	ROOF SIZE (ft^2)		
	5,000	**10,000**	**50,000**
Impact on Owners/Occupants/Investors			
Initial Premium, \$/ft^2 of roof (extra cost of installing a green roof instead of a black roof)	-\$12.6	-\$11.4	-\$9.7
NPV of Installation, Replacement, & Maintenance, \$/ft^2 of roof	-\$18.2	-\$17.7	-\$17.0
NPV of Stormwater, \$/ft^2 of roof (savings from reduced infrastructure improvements and/or stormwater fees)	\$14.1	\$13.6	\$13.2
NPV of Energy, \$/ft^2 of roof (energy savings from cooling and heating)	\$6.6	\$6.8	\$8.2
Net Present Value (installation, replacement & maintenance + stormwater + energy NPV)	\$2.5	\$2.7	\$4.5
Internal Rate of Return (IRR)	*5.0%*	*5.2%*	*5.9%*
***Payback**, years*	*6.4*	*6.2*	*5.6*
Return on Investment (ROI)	*220%*	*224%*	*247%*
Other Financial Impacts (less realizable)			
NPV of CO_2e, \$/ft^2 of roof (emissions, sequestration & absorption)	\$2.1	\$2.1	\$2.1
NPV of Real Estate Effect, \$/ft^2 of roof (value, rent, absorption & vacancy)	\$120.1	\$111.3	\$99.1
NPV of Community Benefits, \$/ft^2 of roof (biodiversity, air quality, heat island, etc.)	\$30.4	\$30.4	\$30.4

WASHINGTON DC RESULTS	ROOF SIZE (ft^2)		
	5,000	**10,000**	**50,000**
Impact on Owners/Occupants/Investors			
Initial Premium, \$/ft^2 of roof (extra cost of installing a green roof instead of a black roof)	-\$10.7	-\$9.5	-\$8.0
NPV of Installation, Replacement, & Maintenance, \$/ft^2 of roof	-\$18.1	-\$17.9	-\$17.7
NPV of Stormwater, \$/ft^2 of roof (savings from reduced infrastructure improvements and/or stormwater fees)	\$11.0	\$10.5	\$10.2
NPV of Energy, \$/ft^2 of roof (energy savings from cooling and heating)	\$6.8	\$6.8	\$8.3
Net Present Value (installation, replacement & maintenance + stormwater + energy NPV)	-\$0.2	-\$0.6	\$0.7
Internal Rate of Return (IRR)	*4.3%*	*4.2%*	*4.7%*
***Payback**, years*	*6.6*	*6.5*	*6.0*
Return on Investment (ROI)	*198%*	*194%*	*209%*
Other Financial Impacts (less realizable)			
NPV of CO_2e, \$/ft^2 of roof (emissions, sequestration & absorption)	\$2.6	\$2.6	\$2.6
NPV of Real Estate Effect, \$/ft^2 of roof (value, rent, absorption & vacancy)	\$98.4	\$88.2	\$74.1
NPV of Community Benefits, \$/ft^2 of roof (biodiversity, air quality, heat island, etc.)	\$30.9	\$30.9	\$30.9

In regards to the ROI, on a national level, a dollar invested in a green roof today suggests a return of $1.29 in today's dollars after 50 years. For Washington DC, the same dollar invested would yield one dollar in return (in today's dollars); in other words, the green roof investment is the same as an average, alternative investment of 4.4%. If CO_2e and community benefits were added in, that same dollar invested would result in $3.19 and $3.57, respectively.

3.4.2 SENSITIVITY ANALYSIS

A sensitivity analysis was also conducted to identify the more important variables based on their ability to impact the total NPV. The factors that most influence the value/costs of a green roof are:

HARD COST VARIABLES	CHANGE IN TOTAL NPV PER 1% CHANGE IN VARIABLE
Roof Longevity (1-year change)	13.24%
Installation Costs	11.32%
Discount Rate	4.89%
Maintenance Costs	3.38%
Energy Savings	2.51%
Stormwater Equipment Cost	1.44%
Stormwater Surcharge	1.35%
Green Roof Risk Contingency	1.21%

3.4.3 NPV BY REAL ESTATE RELATIONSHIP

The NPV analysis in *Section* 3.4 provides seven different areas of either costs or benefits, however, these costs and savings vary because of significant differences in ownership. Additional analysis appropriately separates costs and benefits according to the relationship of each to the subject real estate:

- Owner
- Owner/occupant (i.e., an owner who occupies its building)
- Tenant
- Community

The results in Table 9 and Figure 23 indicate NPV per square foot of roof based on ones relationship to real estate. The assumptions of the analysis are in Appendix B.

Table 9: NPV of a green roof based on ones relationship to its real estate

	OWNER	OWNER/ OCCUPANT	TENANT	COMMUNITY	MARKET EXPECTATION (YEAR 1)
NATIONAL	$0.06	$6.0	$5.4	$29.8	$12.9
WASHINGTON DC	-$1.0	$3.1	$4.1	$30.3	$10.0
TOP 2 DRIVERS	Maintenance Costs & Avoided Stormwater Infrastructure	Maintenance Costs & Avoided Stormwater Infrastructure	Maintenance Costs & Energy Savings	Biodiversity & Urban Heat Island	Longer leases & Rent

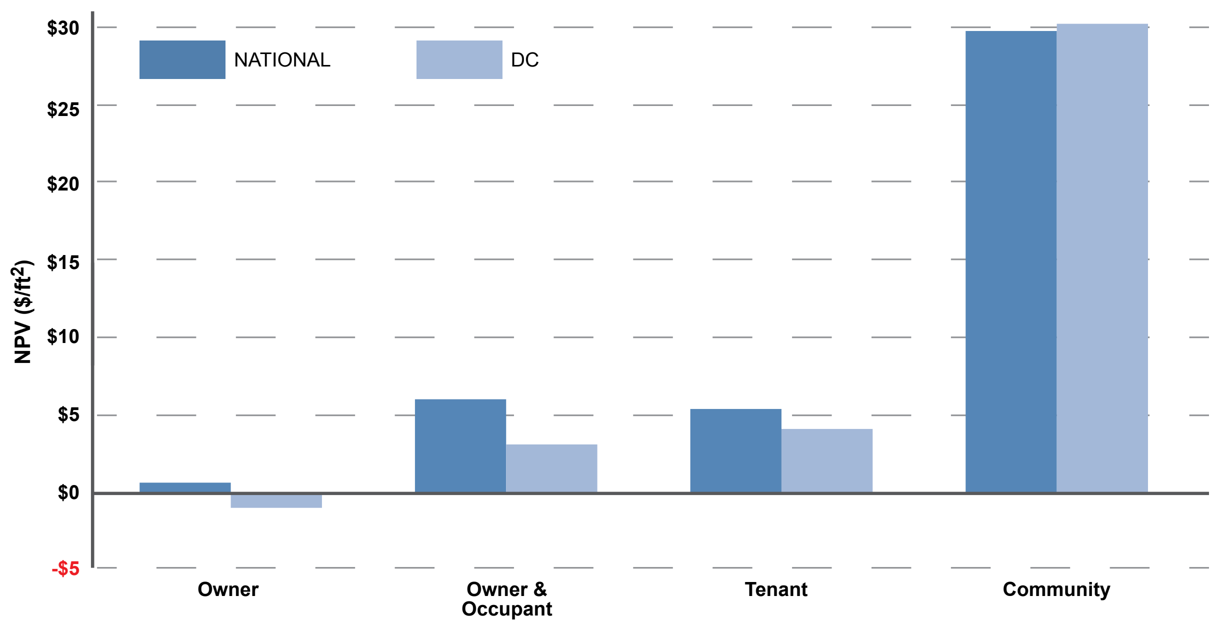


Figure 23: NPV of a green roof based on ones relationship to its real estate

3.5 DISCUSSION

The added cost of installing a green roof is mostly made up for by its increased longevity; however, the added maintenance costs are significant. Over a 50-year period, the stormwater, energy, carbon dioxide equivalent (CO_2e, which measures the potential global warming effect of a greenhouse gas) and community earnings of green roofs more than made up for the increased premium of installing and maintaining them. A detailed look at the net present value per square foot of roof on a cash flow basis shows an installation and replacement cost of -$1.10, as compared with a maintenance burden of -$16.89, for Washington DC.

Although building and site characteristics, stormwater regulations and energy costs vary greatly, long-term savings of green roofs help make up for their maintenance costs. The fewer floors a building has, the greater the energy savings will be. The greater the surface area of a green roof as a proportion of the overall site surface area, the greater the stormwater management savings will be. These savings are expected to increase as stormwater regulations become more stringent and green roofs are increasingly viewed as an acceptable stormwater mitigation measure.

As energy prices increase, the energy-related savings also will increase. The additional analysis suggests that the costs and benefits vary significantly depending on perspective. An owner/operator such as the GSA might yield strong financial benefits from replacing non-green roofs of their assets with green roofs. In the National Capital Region, if green roofs were to replace conventional roofs on all 54 million square feet of real estate (an estimated 5.9 million square feet of roof area*), this cost-benefit analysis projects a 50-year NPV of $22.7 million,[†] or $0.42 per square foot of building area. The community benefits in the National Capital Region could total almost $180 million, or $3.30 per square foot of building area.

Significant consideration should be given to competing and symbiotic initiatives. This cost-benefit analysis does not consider the question of whether an existing building even needs a new roof. The decision of whether to install a green roof should consider the impact of this work on building tenants.

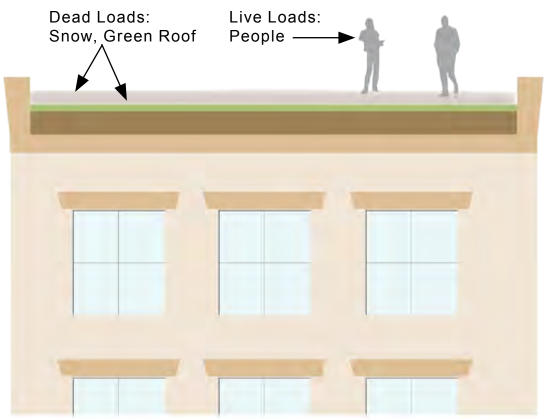
This analysis supports the general cost-benefit analysis finding that green roofs offer great potential savings and benefits. The specific real estate effect of green roofs, or their impact on real estate economics from a market and financial perspective, yields varying benefits that can affect a building's net operating income and market valuation. A onetime valuation of this real estate effect is similar to the NPV of the actual benefits, whereas the NPV of these ongoing savings and a greater building value are hard to realize.

The various aspects considered in the community portion of the cost-benefit analysis are only part of the actual impact of a green roof. If real estate value and the productivity of neighboring properties were included, the benefits would potentially far outweigh the costs. Similarly, the value and productivity of the building itself could add to the already positive NPV. Market acceptance of green roofs and the value of the work occurring in the space are two areas that need to be better understood before they can be accounted for.

*This assumes a 9-story average for all GSA buildings in the National Capital Region

† This assumes a 24% owner/occupancy and 76% tenancy for GSA in the National Capital Region

GSA Region 3 - FEMA Disaster Operations Center, Winchester, Virginia
A 50,000 square foot extensive green roof planted on the new LEED Certified building (2008).



Variations from the design weight can lead to structural failure.

Other considerations in addition to potential costs and benefits can influence building owners' acceptance of green roofs. Challenges associated with installing green roofs on new or existing buildings, if not properly reviewed or addressed, can increase costs and deter owners from installing such roofs.

Potential challenges can include structural considerations, issues associated with installing a green roof on a historic building, knowledge of applicable codes, and issues associated with roof construction and maintenance.

Green roofs occasionally fail to perform at the level for which they were designed. Potential failures include leaks, plant loss, inadequate drainage, soil erosion and slope instability.

This section sets out best practices and lessons learned for each potential risk to help owners, design teams and maintenance staff anticipate and overcome these challenges, and to help smooth the planning, implementation and maintenance of green roofs. It is designed to influence green roof design and encourage acceptance of green roofs, and aims to keep building owners from missing opportunities to benefit their own and their community's financial, environmental and social bottom lines through the installation of green roofs.

4.1 SITING AND DESIGN

Key findings:

- Variations from a roof's design weight can result in structural failure
- The dead load of a green roof assembly should be determined on a project-specific basis
- Engineers should assess the likelihood that a green roof will have a material impact on other load areas, including seismic loads, snow drifts, and intentional rainwater retention
- Designers should review architectural plans to determine design load capacities, or back-calculate them from an assessment of the existing structure
- Supplemental reinforcement measures may be taken to allow a building to support a green roof, but these can be cost prohibitive

4.1.1 BUILDING STRUCTURAL CONSIDERATIONS

Issue: *Variation in Dead Load of a Green Roof*

The **dead load** of a green roof system is influenced by a number of factors, including **contractor skill, medium components,** and **potential water retention**. Variation from the design weight can result in structural failure.

Recommendations

The dead load of a green roof assembly should be determined on a project-specific basis, because growth medium composition varies from job to job. ASTM E2397 is the established standard procedure for determining the dead and live loads associated with green roof systems.

The preface in the standard says that the results can only be regarded as a prediction, not as the true weight of the green roof system. Variations in actual green roof dead loads result from normal variations in material thickness and density, from variation in the finished growth medium product, from human error in the distribution and grading of the growth medium, and from variations in plant biomass.

The green roof dead load is independent of other dead loads, such as snow load, included in the guiding building code.

Issue: *Other load implications*
The structural design of green roofs concerns more than the dead load of the growth medium and landscaping.

Recommendations
Roof landscaping may change snow drift patterns, seismic loads, and ponding from rain accumulation; these changes may be in excess of typical or previous design allowances. Depending on the type of construction, the climate, and the proposed system, engineers should assess the likelihood that the introduction of a green roof will have a material impact on other loading.

Issue: *Retrofit of existing structure to accommodate a green roof*
A feasibility study should be conducted on an existing structure to determine the capacity of a building to accept the weight of a green roof. A roof may have enough structural capacity built in to support a green roof of a given depth, or reinforcement may be needed.

Recommendations
Determine the type of existing construction: steel frame, concrete flat slab, masonry, or light wood, for example. Review the existing structural and architectural plans to determine the design loads. Alternatively, design loads can be back-calculated from an assessment of the existing structure. If the roof does not have sufficient reserve capacity to carry the additional weight, imposed loads may be redistributed at the architect and engineer's discretion. For example, an existing roof may be designed for public occupancy (100 pounds per square foot). One option would be to restrict access and to reallocate a portion of the design live load to the green roof. Some roofs are finished with substantial architectural build-ups such as concrete pavers or stone. Removing unnecessary finishes may provide sufficient capacity for a green roof of equal weight. The allowable depth of the green roof is determined by the load capacity that can be allocated to it.

Depending on the type of construction, supplemental reinforcement measures might be taken, but these are often cost prohibitive. Examples include adding depth to existing beams or reducing the tributary area by providing additional full-length members parallel to the existing beams. If a member is reinforced to take extra load, the connections and supporting members must also be evaluated for capacity.

Plumbing must also be coordinated with the structure. Core drilling and saw cutting through slabs must be reviewed by an engineer and caution must be taken to avoid cutting beams and reinforcement.

Issue: *Roof access*
Roof occupancy will contribute to determining the live load and the safety requirements.

Recommendations
Review the type of desired occupancy with the architect. If a formerly unoccupied roof becomes publicly accessible, consider both load and safety measures. A handrail or parapet may be required at the roof perimeter. Structural provisions must be made to accommodate the load and the attachments associated with a handrail or parapet.

4.1.2 INSTALLATIONS ON HISTORIC BUILDINGS
Historic buildings create an opportunity for green roofs because of the original, well-engineered quality that many of these structures have. Many pre-World War II buildings were designed and engineered for durability.

Low-growing, ground cover plantings behind existing parapets of historic buildings so that vegetation is not visible from the public right-of-way.

Figure 24: Compatible green roof on a rehabilitated office/retail building

Figure 25: Incompatible green roof on a rehabilitated office/retail building

The GSA and EPA worked together to renovate this historic building using 99% of the original structure and adding an assessable green roof covering the 4th and 5th floors. The green roof insulates the McCormack POCH reducing energy use and costs, provides a pleasant environment for building occupants and provides visible plantings from other floors of the building.

Figure 26: John W. McCormack Post Office and Courthouse (PCOH).

*Method E2399 includes tests to measure moisture-retention potential and saturated water permeability of media.

Issue: *Building character*

The character of the building must be retained for historic buildings. Federal buildings must meet the Secretary of the Interior's Standards for Rehabilitation, which requires any vegetation planted on a green roof to not be visible above the roofline from public thoroughfare, as it would negatively impact the character of the building (Figure 24 and Figure 25).

Recommendations

Low-growing, ground cover plantings (e.g., sedum) should be planted behind existing parapets so that vegetation is not visible from the public right-of-way.

There are no additional construction permitting requirements for installing a green roof on historic buildings. However, construction permits for historic buildings will be reviewed by the state Historic Preservation Office (in the NCR, this is the Washington DC Historic Preservation Office). The preservation office will review permits to ensure that alterations are "compatible" with historic building character. A flat roof should not conflict a new green roof, as compared with the installation of solar panels, which stick up and alter the building's outline or façade.

Washington DC does not separate "certificates of appropriateness" for historic properties.

4.1.3 CODES AND STANDARDS

Issue: *What codes and standards are pertinent to green roof installations?*

Recommendations

The District of Columbia has adopted the 2006 International Codes (I-Codes) published by the International Code Council (ICC), and the 2005 National Electric Code (NEC) published by the National Fire Protection Association (NFPA), subject to any changes, deletions or additions as set forth in Title 12 of the District of Columbia Municipal Regulations (DCMR).

The following recommended standards reference green roofs, though they are not required by the District:

- ASTM E2396 – Standard Testing Method for Saturated Water Permeability of Granular Drainage Media [Falling-Head Method] for Green Roof Systems
- ASTM E2397 – Standard Practice for Determination of Dead Loads and Live Loads Associated with Green Roof Systems
- ASTM E2398 – Standard Test Method for Water Capture and Media Retention of Geocomposite Drain Layers for Green Roof Systems
- ASTM E2399 – Standard Test Method for Maximum Media Density for Dead Load Analysis*
- ASTM E2400 – Standard Guide for Selection, Installation, and Maintenance of Plants for Green Roof Systems
- ANSI/SPRI VF-1 External Fire Design Standard for Vegetative Roofs

For stormwater regulations, see *Section 2.1.*

4.2 INSTALLATION AND CONSTRUCTION

4.2.1 CONTRACTOR SELECTION

Key findings:
- Inexperienced green roofing contractors can cause budget overruns and improperly installed green roofs.
- An installer's lack of skill can lead to chronic performance problems.
- An experienced contractor should be able to efficiently and accurately coordinate construction schedules with the General Contractor, and install a high quality product within budget and on schedule, with minimal disturbance to other trades and without compromising the Owner's warranty.

Issue: *Contractor inexperience*
Lack of experience by green roofing contractors likely delay the administrative and construction process, likely result in budget overruns, and can result in incorrectly installed green roofs.

One frequently observed problem is that the installation of fabric, drainage, and growth medium layers takes longer than anticipated, and therefore the optimum window for planting is missed (the optimum planting window depends on the specific plants and local climate). When this happens, the green roof contractor must re-mobilize later and install the plants when weather conditions are more favorable. Damage to the green roof or waterproofing during the period between installation and planting can cause disputes among the green roof installer, other trades, and the General Contractor and can result in exclusions in the Owner's warranty.

An installer's lack of skill may not be apparent before or during construction, but can result in chronic performance problems. Improper material installation can result in failure of the green roof. In the worst cases, the green roof must be removed. If the symptoms of the failure arise after the warranty period, the Owner must absorb the cost of replacement or removal.

Recommendations
An experienced contractor should be able to efficiently and accurately coordinate construction schedules with the General Contractor. The following green roof construction best practices are recommended when a contractor is selected to install a green roof.

Contractor — an experienced green roof contractor should install a high quality product, within budget and on schedule, with minimal disturbance to other trades, and without compromising the Owner's warranty.
- A knowledgeable and qualified proposal should be provided.
- The performance characteristics of individual green roof components should be known (an inexperienced contractor may submit inappropriate materials, thus delaying the administrative and construction process).
- Communication and coordination with the General Contractor and the Roofing Contractor is essential for minimizing unforeseen challenges, e.g., all trades that require roof access need to finish their work before green roof construction begins.
- A visit to the site before construction should help the Green Roof Contractor understand site-specific construction logistics.
- Construction in urban environments typically requires street closures and police presence.

Material storage — the green roof contractor should anticipate probable material storage logistics during the bidding phase and should arrange final material storage logistics with the General Contractor prior to green roof installation.

- On-site material storage can save time and

Green roof contractors using a pneumatic blower to install the growing medium

A "super-sack" of growing medium hoisted above the roof.

A crane delivering "super-sacks" of growing medium to the rooftop

therefore cost, as opposed to retrieving materials from an off-site storage location.
- On-site storage is not always feasible on retrofit projects.
- Material must not be stockpiled on the roof in a single area such that structural capacities are surpassed.

Medium installation — the contractor should use the medium installation method that is most appropriate for the specific characteristics of the project. Medium installation is the longest stage of green roof construction.

A crane can install the medium at a rate of about 8 cubic yards per hour. The medium is delivered to the site in **super-sacks** of about 2 cubic yards each, which are hoisted individually to the roof. The bagging cost for delivery is up to $30 per cubic yard.

A pneumatic blower truck can install the medium at a rate of about 12 cubic yards per hour. The medium is delivered in bulk. The cost of renting a truck is typically high and varies from project to project; however, blower trucks are typically more affordable than cranes on larger projects. An experienced blower truck company with a history of green roof installation will typically include installation and grading in the contract price.

Irrigating a sloped green roof during the establishment period

4.2.2 HANDLING/KNOWLEDGE OF PLANTS

Key findings:
- Landscaping and roofing are the key trades involved in successful green roof installation.

Issue: *Improper plant handling*
Improper plant handling techniques can lead to plant mortality and unsuccessful establishment of the green roof.

Recommendations
The green roof contractor should have a working knowledge of plant handling and establishment techniques. A green roof is a living building component, and the plants must be stored and handled with care to ensure their viability. Landscaping is a key trade for the successful installation of a green roof, and landscape contractors have the knowledge and experience with plant material to ensure that the green roof is properly installed and to ensure that precautionary measures are in place to respond to variable climactic conditions. Recognizing the need for this expertise, many roofing contractors who are serious about integrating green roofs into their business models have developed green roof divisions that focus on plant handling, installation, and maintenance.

Issue: *Liability and warranty*
In addition to landscaping, the other trade involved that is key for the successful installation of green roofs is roofing. However, liability and warranty issues can arise when the scope of the green roof installation is divided and performed by two separate contractors or trades people (that is, by separate roofers and landscapers). This division of scope can mean that the warranty provisions are not adequately coordinated. A common scenario is for a roofer to install the waterproofing and green roof foundation components, such as foundation fabrics, drainage layers, and separation fabrics. A separate landscape contractor (who may or may not be a sub-contractor to the roofer) then installs the green roof medium and the plants. If a single contractor is not responsible for installing and providing a workmanship warranty for all of the green roof components, liability disputes can arise when the green roof does not perform as specified. Plant viability and replacement might be covered under the installer's workmanship warranty, but it might be excluded by the landscape contractor because they cannot be sure whether plant mortality is caused by a component installed by the roofer.

Recommendations
A single contractor must be responsible for supplying all the materials and labor associated with the green roof assembly—that is, all components above the waterproofing. The green roof installer should provide

a long-term warranty to the Owner that covers durability of the cover materials, workmanship, and performance of the plant ground cover. The roofing installer should provide a long-term material and labor warranty that covers the underlying waterproofing system. To reduce potential disputes, job specifications should clearly delineate responsibilities for leak location, uncovering of the membrane, and repairs to the waterproofing and to the green roof assembly. One way of insuring comprehensive coverage is for the Owner to request a single-source warranty. However, single-source warranties may not always be advisable, because they can add to cost and limit choice. In addition, care should be exercised that warranties identified as "single-source" are truly inclusive of plant viability and performance.

4.2.3 SAFETY TRAINING AND PERSONNEL

Issue: *Safety issues*
Safety training and precautions are required by law for all roof types.

Recommendations
The green roof contractor must comply with all Occupational Safety and Health Administration (OSHA) safety requirements that pertain to green roof installation:

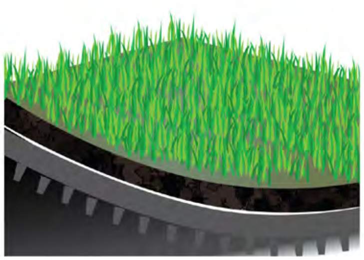
- *Fall protection* — During installation, any worker exposed to a fall distance greater than 6 feet must be protected by a guardrail system, safety net system, or personal fall arrest system. During maintenance, any worker exposed to a fall distance greater than 4 feet must be similarly protected.
- *Protective Equipment* — The construction team must assess the project site to determine any additional protective equipment. A hard hat and steel-toed boots are always required. Other common safety equipment used by green roof installers includes safety glasses, reflective vests, and fall arrest harness or lanyard systems (when parapet heights necessitate them).
- *Exposure to Silica Dust* — If the installation requires cutting, grinding, or drilling of concrete or masonry, workers may be exposed to silica dust. If this is the case, workers require hazard communication training and a respirator.
- *Other safety considerations* — Operating equipment such as cranes, derricks, hoists, and industrial trucks must meet the same requirements as with any other roof installation. As with any roof installation, electrical hazards and excessive exposure to heat and cold need to be considered.

Full-time safety coordinators are required on some sites to ensure compliance with safety protocols.

Use of protective equipment such as hard hats and steel-toed boots during green roof installation

Plugs: Pre-grown; flexible; greatest diversity in vegetation

Cuttings: Least expensive option; uniform coverage; can be hydroseeded



Pre-grown mats or trays: Most expensive option; provides immediate cover; must be fitted quickly and secured until rooted

Figure 27: The common methods of plant establishment on a green roof.

4.2.4 PLANT ESTABLISHMENT

Issue: *The green roof environment is especially harsh compared with on-grade conditions, and not all plants are able to successfully establish on green roofs.*

Recommendations

Sedum varieties are the preferred plants for extensive green roofs. The three common methods of plant establishment are **cuttings**, **plugs**, and **pre-grown mats**. Coverage rates will vary seasonally, but the foliage of a typical healthy green roof will have 80% coverage during the growing season. With regular maintenance, each of the three planting methods should result in 80% coverage after two years, and this is a common requirement of green roof installer workmanship warranties. The initial aesthetic, the variety of plants, and the cost vary with planting method.

Cuttings are small, healthy pieces of the plant that are placed on the media surface and become established by developing new roots that grow into the media. The use of cuttings is the least expensive method and provides high coverage rates, though it limits the type of plants that can be grown. Installing **plugs** is labor intensive, but allows a wider variety of plants. Whether cuttings or plugs are used for the initial installation, maintenance includes picking new cuttings from established plants to spread in bare spots. **Pre-grown mats** are comparable to turf sod; cuttings are established on amended green roof media in a nursery setting, grown to maturity and harvested (with the media) immediately prior to delivery.

Temporary irrigation during the first growing season is recommended for all projects, but is particularly important for the establishment of plants grown from cuttings and pre-grown mats.

When plants are established from plug/pot form, appropriate sizes should be used. The appropriate plug/pot form size depends on system thickness, planting density and other factors.

4.3 MAINTENANCE AND OPERATION

Key findings:
- Wholesale roof failure is the inability of a green roof to perform at the level for which it was designed.
- Wholesale failures include leaks, plant loss, inadequate drainage, soil erosion, and slope instability.

Maintenance of a green roof may prevent failure of the green roof system. The phrase **modes of failure** addresses **wholesale green roof failure**, or the inability of the green roof to perform at the level it was designed for, not general client aesthetic dissatisfaction. Wholesale failures include leaks, plant loss, inadequate drainage conditions, soil erosion due to wind and water, and slope instability. A client should be adequately educated on the type of green roof system and its purpose, and on the type of plants that are used in the green roof. This can also help the client understand the maintenance requirements for the green roof.

4.3.1 LEAKS AND LEAK DETECTION

Key findings:
- Leak-detection methods include flood tests and low-voltage electric leak detection.
- Flood tests are the industry standard on conventional roofs, but become more difficult after a green roof is installed.
- Low-voltage leak detection allows precise identification of leak locations, but certain roof constructions do not permit the use of this technique.

Issue: *Leaks*

Leaks are generally caused by poor workmanship. Unless the problems are ubiquitous, a project failure will not result. However, the process of identifying and repairing leaks is relevant to consider.

Recommendations

As in typical, non-green roofs, presence of a leak is typically confirmed from water damage inside the building. There are two main methods to locate leaks: **flood test** and **low-voltage electric leak detection**.†

The green roof and waterproofing vendor should be consulted to determine the most appropriate method for locating a leak. During the process of leak detection and repair, the green roof is excavated, the waterproofing is repaired, and the green roof is replaced. Only an agent of the green roof system provider should excavate the green roof; an owner's warranty may be compromised if an unapproved party excavates the green roof. Proper medium handling techniques include:

- Segregating different types of medium (failure to do so may cause impeded drainage conditions)
- Proper plant-handling techniques (to allow successful replanting)
- Proper medium placement and grading techniques (to provide even system thickness and weight)

Flood tests are the industry standard in typical roof construction. This test is used on many green roof projects prior to green roof installation, but becomes more difficult after the green roof is installed. An agent of the green roof system provider determines the region of the roof where the leak is likely to originate. The region is isolated and water is directed onto the area. In most instances drains must be plugged during this type of test. If the roof structure will not support the added weight, then the suspect area must be uncovered before flooding. By observing how flooding influences the rate of the leak, the damaged area can often be identified. Leaks are identified and patched; if no leaks are identified, a new region of the roof is investigated and the process repeats. Once all leaks are found and patched, the whole roof should be soaked to verify that leaks no longer exist. The process can be long and can result in significant damage to the green roof. Efforts should be made to properly store and re-plant plants, but in some cases new vegetation will have to be purchased.

Low-voltage leak detection allows precise identification of leak locations. However, certain roof build-ups do not allow the use of low-voltage leak detection. The method requires a grounding plane underneath the waterproofing membrane; examples of appropriate grounding planes are reinforced concrete (except hollow core planks) and metal roof decks. When decks are constructed from electrically non-conductive materials, metal screens or foils can be placed under the waterproofing membrane and connected to a building ground such as steel plumbing. The leak detection technician introduces a low voltage electric charge onto the surface of the membrane. In practice this is done by creating an electrical charge in the wet medium that covers the membrane. The charge travels through moisture in the vegetated cover, through any penetrations in the waterproofing, connects with the grounding layer, and is registered by the technician. Low-voltage leak detection can be performed before and after the green roof is installed, on appropriately designed green roofs. Leaks can be detected with precision, which minimizes damage to the green roof.

4.3.2 PLANT LOSS

Plant loss can be caused by a number of factors. Depending on the cause, the appropriate response will vary from maintenance activities to green roof demolition.

Issue: *Foot traffic*

Recommendations

Foot traffic should be strictly limited to green roof maintenance activities. If significant building maintenance traffic not related to the green roof is expected, pavers or gravel walkways should be placed in primary paths. Paver plazas should be used if the green roof is intended to be an amenity space, and access to the vegetated area should be restricted. Sedum and other succulents can take low levels of foot traffic, but sustained traffic will kill the plants. Non-

†High-voltage leak surveys are only applicable as a construction quality assurance measure and therefore are not relevant when considering methods to locate active leaks after completion of the vegetated cover.

succulent plants are generally less tolerant of foot traffic than succulents are. On a sedum/succulent roof, damaged areas can usually be re-established using cuttings collected from un-damaged areas. On non-sedum/succulent roofs plant damage usually requires purchasing and installing new plants.

Issue: *Impaired drainage conditions*
Impaired drainage can result from unsuitable medium or from improper installation of drainage components. Aside from plant loss, impaired drainage conditions may result in overloading the roof, and in water intruding into the building via door thresholds, skylights, or hatches. Inappropriate medium is the most common cause of green roof failures. Medium with high silt or clay content will frequently lead to plant failures.

Recommendations
Green roof media should have moderate to high **permeability** and **porosity.** Guidelines for media selection are available from several sources, including the FLL Guide.

Typical plants used in green roofs are selected to be tolerant of drought conditions and are generally not tolerant of extended periods of saturation. In extreme cases, the medium may have to be removed and replaced with a more suitable green roof medium. An improperly installed drainage component has the potential to impede proper drainage, resulting in extended medium saturation. In this case, the drainage element must be replaced, often requiring disruptions to large areas of the green roof.

Issue: *Over-watering and over-fertilizing*
Over-watering and over-fertilizing typically occur when the cause of plant loss is not apparent. The symptoms of over-watering are very similar to the symptoms of under-watering, and the same is true for over-fertilization, therefore, they are easy to misdiagnose.

Recommendations
Over-watering can be corrected by cutting off supplemental water. Over-fertilizing can be ameliorated in some cases by adding other amendments to balance nutrient ratios available to plants. It does take time for nutrient levels to stabilize, and additional maintenance may be required during this time. Laboratory testing of growth medium samples should be conducted before beginning a nutrient amendment course.

Issue: *Improper plant selection*
Appropriate plant selection is the most critical factor in successful plant establishment. Sedum and other succulents are the most pervasive plants used in green roofs, and are the only appropriate plants for thin extensive profiles in most cases. Increased medium thickness and supplemental irrigation do allow a greater variety of plants to be used, but cannot fully counteract the unique and extreme conditions experienced on a green roof. Where inappropriate plant selections prevail the plants must be replaced wholesale.

Recommendations
Designers should consult the green roof system provider to determine appropriate plants or confirm that plant selections will be eligible for the system provider's warranty.

4.3.3 WIND SCOUR AND UPLIFT
Wind scour can be a serious problem in coastal environments, in open areas with few obstructions, and in urban areas where adjacent structures cause turbulence. Typical wind stabilization measures are located at the roof perimeter; examples include high parapets and ballast (e.g., stone, architectural pavers, and turf pavers). The goal of these measures is to break up the wind at the perimeter, and to provide a heavy perimeter margin that will be less vulnerable to scour.

Issue: *Wind scour*
Wind scour can result in loss of growth medium, and, in

extreme cases, in green roof delamination. The primary area of concern with wind scour is at the roof perimeter.

Recommendations
Wind scour in the field of the green roof is of less concern because of the scour-resisting characteristics of the plants themselves. The foliage of the plants creates a rough surface, which in turn creates low-level turbulence that disrupts the wind streamlines. Plant roots form a widespread network of anchors that stabilize the growth medium and integrate the layers of the green roof together.

There is no established green roof wind design standard; current methods in use include ASCE 7, FM, and SPRI methodologies, but these do not account for the anchoring capability of plant roots or other conditions specific to green roofs.

ISSUE: *Wind uplift*

Recommendations
Wind uplift is not an important threat to most green roofs, because the materials are air permeable and cannot support significant pressure differentials. In addition, surfaces roughened by plant foliage or coarse stone will result in low uplift potential. Concern for green roof damage related to uplift may be warranted where 1) an internal layer is not air permeable, or 2) smooth hard surfaces are incorporated, such as architectural pavers. Layers that are not permeable to air may include thermal insulation installed in a PMR (protected membrane roof) configuration, or membrane root-barriers.

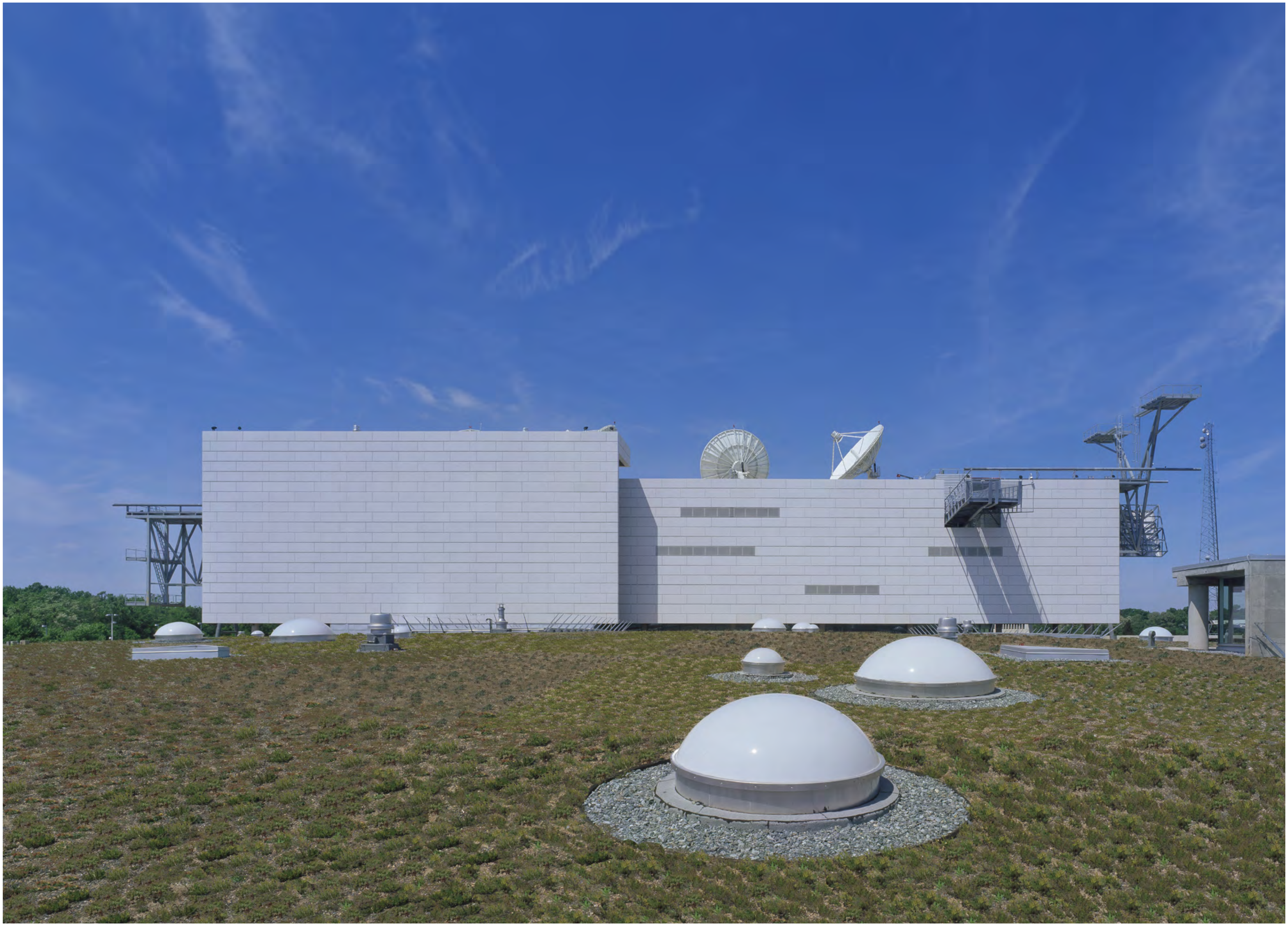
4.3.4 ROOT PENETRATON AND BIODEGRADATION
Two types of failure attributable to biological factors are root penetration and biodegradation of medium

Issue: *Root penetration*
Plants with aggressive roots will, over time, damage the water-proofing layer of green roofs. Waterproofing manufactured from asphalt is at the highest risk. Chemical root-inhibiting products are not recommended on green roofs because they leach over long periods of time and could cause water pollution issues. Failure to use root-resistant waterproofing without providing a root-barrier can cause catastrophic damage, and therefore can subsequently lead to demolition of the green roof and the underlying waterproofing.

Recommendations
Thermoplastic membranes offer the most reliable type of root barrier. All waterproofing membranes used in conjunction with green roofs should be tested for root-resistance. Tests are available to gauge the vulnerability of waterproofing membranes to root damage.

Issue: *Biodegradation of media*
Biodegradation of plant fibers and other organic constituents in medium that contains high levels of organic matter can lead to a collapse of the soil structure, to reduced drainage capacity, and to anoxic conditions that inhibit plant growth. Failed medium can rarely be improved by amendment, and failure usually results in removal and replacement of the material.

Recommendations
Medium properties should follow conventional recommendations for green roofs. In temperate climatic zones like the NCR region, growing medium should have low organic matter content.



GSA National Capital Region - NOAA Satellite Operations Facility (NSOF), Suitland, Maryland

A 146,000 square foot extensive green roof installed on the new LEED Gold certified operations center (2006).

Lysimeter used to measure the amount of evapotransipiration released by plants.

The findings of this report are founded upon robust scientific evidence. Extensive research has provided a reliable understanding of the benefits and costs related to green roof installation and use. The ongoing evolution of the knowledge base is well-recognized, and uncertainties have been handled carefully through the cost-benefit analysis process.

A number of areas in which additional investigation may provide more clarity on some of the conclusions reached were identified during the study. The following sections summarize potential next steps for consideration.

The GSA encourages other federal agencies to more vigorously evaluate green roofs. Other agencies could be involved in data collection and performance modeling. Information gathered in this process could be used as an objective basis for decisions on whether to install a green roof on a particular building.

5.1 STORMWATER MANAGEMENT

1. LONG-TERM STORMWATER PERFORMANCE

Ample evidence supports conclusions of volume reductions in annual runoff from green roofs. However, there is little data to describe the long-term performance of these systems. Additional information on the influences of slope, drainage, and other moisture-retaining materials would support a better understanding of their performances in the field.

2. GREEN ROOFS AS A BEST MANAGEMENT PRACTICE (BMP)

Green roofs are often thought of and regulated with expectations that they may perform the role of traditional infiltration BMPs. However, because of the limited thickness of a typical extensive green roof and their lack of true infiltration capacity, green roofs have limited capacity to remove water from the urban water cycle for large and more frequent storms.

This study has highlighted that green roofs are better understood as runoff modulation measures that contribute to the restoration of naturalistic runoff patterns. Such patterns are characterized by lower rates, delayed peak development, and extended runoff times. These effects have positive consequences for flood control, CSO avoidance, and river base-flow nourishment. Future research should focus on validating runoff rates, delayed peak runoff and time of concentration so that these quantifications can be recognized as beneficial aspects of green roofs.

3. STORM DYNAMICS DATA

To incorporate large, commercial-scale green roof systems into stormwater management models at the watershed scale, additional data on storm dynamics should be gathered.

Most of the data for green roof stormwater performance comes from smaller roofs or from laboratory or field test beds. Although this data is useful, evidence from the few studies of larger roof areas suggests that the benefits of large roofs are greater than those suggested from the small-scale studies.

In addition, all of the available data for storm flow dynamics has been obtained in relatively short term studies (1–3 years). Gathering longer-term data from larger roofs may be beneficial to corroborate the conclusions reached in this study.

Such data would be useful to develop and calibrate algorithms that can more reliably predict runoff patterns from green roofs. Robust simulation algorithms tailored to the hydrology of green roofs are not available to support design innovation or the formulation of regulations. The use of algorithms developed for watersheds may not be accurate, especially because they process flow accumulation and infiltration in ways that are not specific to green roofs. Much of the runoff treated as infiltration in conventional runoff generation algorithms returns in a green roof as delayed and gradual runoff. Green roofs might be better understood and modeled as shallow groundwater systems. Experimental 2D unsaturated porous flow models have been used successfully to simulate runoff from green roofs.

4. FIELD MONITORING AND COMPUTER SIMULATION

New research, such as field-scale monitoring and computer simulation programming, is required to ensure that the design and regulation of green roofs will realize their potential. A centrally coordinated effort should be pursued, similar to that undertaken 50 years ago by the US Department of Agriculture, which resulted in the development of algorithms for modeling watershed hydrology. The cost of this work would be modest. The Department of Energy, USEPA, HUD and the Department of Commerce including NIST should be involved at a minimum in this effort.

5.2 BIODIVERSITY AND HABITAT

1. ESTABLISHING NATIVE PLANTS ON GREEN ROOFS

Establishing native plants is a major challenge when using green roofs to create habitat. This practice should be researched in more detail to reach a better understanding of techniques.

2. CREATING HABITAT FOR ENDANGERED FAUNA

Green roofs have been used in London and Basel to create habitat for endangered or rare fauna, but the "green roof as refugia" is a largely unexplored concept in most locales.

3. STRATEGIC SITING OF GREEN ROOFS

Further research may reach stronger conclusions about the appropriate siting of green roofs to enhance biodiversity: whether they should be located near other ecosystems to create a biodiversity "corridor" or isolated in an attempt to mimic the advantages of islands in protecting biodiversity. Existing studies show that surrounding habitat would influence plant diversity on a green roof. This could be examined in other locales to generate more robust conclusions.

4. SYNERGIES BETWEEN BIODIVERSITY AND OTHER GREEN ROOF BENEFITS

Plant diversity has been demonstrated to enhance other green roof benefits in some circumstances, but this research has not yet been replicated in other locales. Research should be expanded to generate more robust conclusions across geographies.

5.3 URBAN HEAT ISLAND

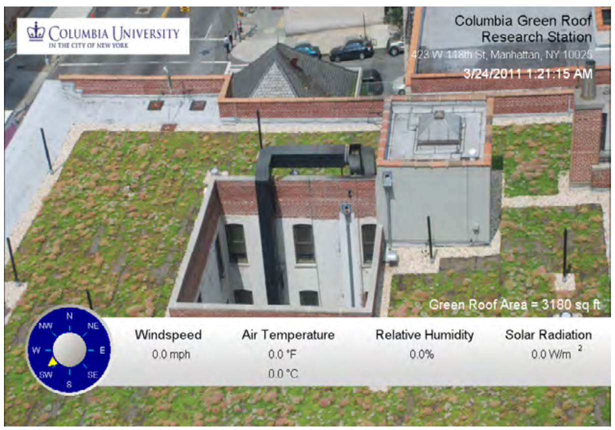
Most conclusions about the impacts of green roofs on the UHI are based on extrapolation of observations from a few roofs or are the results of simulation models. Two of the biggest challenges are confirming the impact of green roofs on the UHI and validating model output when green roofs are added to buildings. The following steps should be taken.

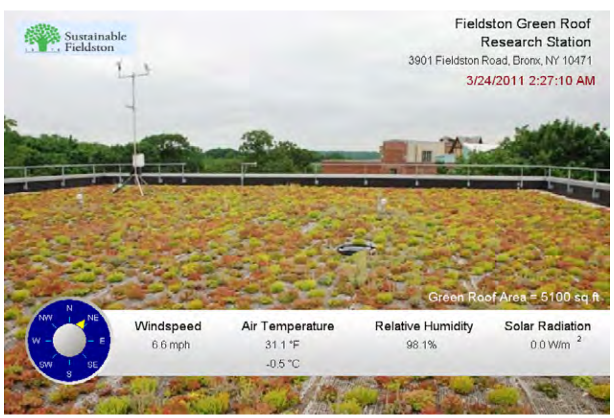
1. ADDRESS THE LACK OF LONG-TERM OBSERVATIONS

A set of temperature transects should be collected over a few days—before and after green roof coverage—supplemented by infrared imagery of the area and by simulation modeling. This data collection should be done in representative urban areas of at most 250 acres (1 square kilometer), to minimize cost and to make use of tools like ENVI-Met (a micro-climatological, high-resolution simulation model for urban areas that has been used for UHI research). The challenge in this research is coordination, so that the UHI is measured before the green roof is large enough to have an effect.

Image courtesy Stuart Gaffin

Data logger during the installation of an experimental green roof





Green roof dashboards

2. REPRESENT SEDUMS IN ATMOSPHERIC SIMULATION MODELS

Data from sedum roofs should be gathered to match the plant and soil parameterizations required in an atmospheric simulation model, thereby enabling green roof impacts on UHI to be modeled through existing tools. For example, ENVI-Met would require details of plant features and characteristics, soil profiles, and soil types. Much of this information is not yet available for sedums and other succulents.

3. POTENTIAL SYNERGY BETWEEN UHI AND SOCIAL BENEFITS OF GREEN ROOFS

A green roof must be of considerable size if it is to influence the UHI. A green area of sufficient size would offer other community-wide or city-wide benefits such as urban biodiversity, stormwater runoff attenuation, air quality improvements, urban agriculture, and green amenity space.

5.4 ENERGY

1. INFLUENCE ON BUILDING ENERGY USE

Additional research should be undertaken to determine the potential for cooler green roof surface temperatures to reduce the air intake temperature and related energy usage for rooftop heating and cooling units.

Future studies should focus on determining the insulative and other thermal properties of different types of vegetation and of different types and depths of growing media. The impact of design modifications to encourage energy savings (such as maintaining higher minimum moisture content to promote evaporative cooling) would also be valuable to study. Additional research on these topics would enable more efficient green roof design in cases where energy savings are a key objective.

The relationship between the size of green roofs and the magnitude of energy savings should also be explored further.

Research should be conducted on the energy consumption, urban heat island impacts, and other factors relating to building and landscaper performance as they relate to green roofs, reflective roofs, heating and cooling systems (HVAC), water retention, evaporative cooling, materials lifespan, etc.

2. CLIMATIC CONTEXT

Further research should consider the energy performance of green roofs in a wider variety of climates. Most of the studies analyzed for this report were conducted in temperate climates with warm-to-hot, moist summers and with cold winters (North America, Sweden, Germany, etc.). A few were conducted in tropical locations (Singapore, Brazil, and India), a few were in subtropical locations (China and Japan), and three were in Mediterranean climates (Spain, Greece, and Italy). Understanding the performance impact of individual weather variables, such as windspeed, humidity and cloud cover, would allow owners to better identify regions and sites where green roofs would provide greater benefit.

Existing research does not sufficiently assess the performance of green roofs in winter conditions, or the heating benefits of green roofs in a cold climate. These areas should be investigated further to provide a stronger basis for conclusions.

3. WHITE ROOFS VERSUS GREEN ROOFS

The energy performance of white roofs ("cool roofs") as compared with that of green roofs should be assessed in more depth (although studies exist), especially with respect to their influence on energy demand reduction.

4. IRRIGATED GREEN ROOFS

Further research is needed on irrigated green roofs in the summer, particularly in dry climates.

5. INTERACTION WITH SOLAR PANELS

Few studies have been published that look at solar panel installations in conjunction with green roofs. The positive synergies between energy production, temperature reductions and plant protection below the solar panel from the green roof should be researched.

5.5 ACOUSTICS

ACOUSTIC PROPERTIES

Increased attention should be applied to the acoustic properties of each individual layer of a green roof to provide a stronger understanding of acoustic performance and of methods to optimize performance through design.

5.6 URBAN AGRICULTURE

1. ECONOMICS OF ROOFTOP AGRICULTURE

Additional economic evaluation of rooftop agriculture projects can provide stronger data to underpin cost-benefit analyses.

2. LIFE CYCLE ASSESSMENT OF ROOFTOP AGRICULTURE

An assessment of the expenditure of resources required to provide food using local rooftop agriculture versus remote conventional farming would be valuable. Criteria of interest include water and energy use and greenhouse gas emissions.

3. CASE STUDY DEVELOPMENT

A library of rooftop agriculture case studies could help local governments streamline policy and code requirements.

5.7 AIR QUALITY

AIR QUALITY IMPROVEMENTS

Increased research could help to determine the ability of green roof planting to reduce particulate matter, volatile organic compounds and other air pollutants.

5.8 JOB GENERATION AND ECONOMIC DEVELOPMENT

1. EMPLOYMENT ANALYSES

Economic studies of the abilities of green roof technologies to stimulate a new green jobs market should compare the labor requirements of conventional roofs with those of green roofs.

2. REGULATORY INCENTIVES

An evaluation of policy and incentives in cities such as Portland OR, Toronto, Canada, Chicago IL, Washington DC, and Seattle WA should be compared to job generation statistics and changes in the economic values of retrofitted buildings.

3. RENT ANALYSIS

An analysis of the rents of commercial buildings with green roofs that GSA leases compared to those without green roofs.

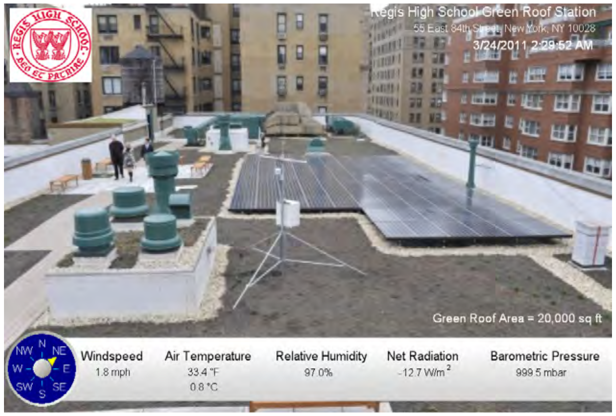
5.9 AESTHETICS AND QUALITY OF LIFE

1. SOCIAL WELLBEING AND PRODUCTIVITY SURVEYS

Limited studies have been undertaken about the health, wellbeing, and work productivity of people with a green view from their window. Additional studies would be valuable particularly in office environments, as most existing studies focus on healthcare. These studies should be augmented by the impact of new green roof installments in urban environments.

2. EVALUATION OF AMENITY VALUE

The evaluation of amenity and productivity benefits is notoriously difficult to do reliably, yet could be an area for future development to enhance green roof analyses.



Green roof dashboards

GSA

GSA Region 5 - 10 West Jackson Street Building, Chicago, Illinois

A 12,000 square foot extensive green roof replacement of an existing, modified bitumen (black) roof.

Green roofs can help mitigate the ecological problems that cities create by bringing the natural cooling and water-treatment capabilities of undeveloped areas into the urban environment. Architects and planners can use green roofs to help solve environmental problems by bringing nature back to the city in key ways.

Green roofs offer great potential savings and benefits. Although the added maintenance costs of a green roof as compared with a conventional roof are significant, these added costs are more than made up for over the roof's lifetime by its increased longevity. This analysis puts the average life expectancy at 40 years, versus 17 for a conventional roof. Numerous green roofs have outlived that time period, including green roofs on government buildings in Washington DC, in place since the 1930s.

In addition to greater lifespan, green roofs reduce costs by producing savings related to stormwater regulations and reduced stormwater runoff impacts, notably combined sewer overflows, due to their water absorption properties, as well as year-round energy savings due to their cooling, shading, and insulative abilities. These savings are expected to increase as stormwater regulations become more stringent. As energy prices increase, the ability of green roofs to generate energy-related savings will increase.

Unlike most low-impact developments and structural best management practices, green roofs reduce runoff rates for both large and small storms. Green roofs also benefit biodiversity, providing potential habitat for rare plant and animal species. Their ability to reduce the heat island effect could reduce heat-related illness and mortality in cities. A green roof can provide a space for urban agriculture, as well as an area that building occupants can use for relaxation and recreation. Green roofs provide views of natural greenery and absorb sound and air pollutants, benefiting the occupants of neighboring buildings. They are also a potential source of jobs.

In general, buildings with fewer floors will show relatively greater energy savings for installing a green roof than a building with more floors. And a larger green roof will show larger stormwater management savings than a smaller one.

Many challenges to installing green roofs exist, including structural considerations, issues associated with installing green roofs on historic buildings, and knowledge of applicable codes, as well as possible problems during installation and maintenance. Best practices exist to manage each of these potential challenges.

Additional research in several areas is critical to better understanding the costs, benefits, challenges and opportunities of green roofs.

1. On **stormwater management**, research is needed on the long-term performance of green roofs. Green roofs also need to be evaluated as a best management practice. In addition, additional storm dynamics data, field monitoring and computer simulation are needed.

2. On the area of **biodiversity**, research is needed on establishing native plants on green roofs,

creating habitats for endangered fauna, strategic siting of green roofs, and the relationship between biodiversity and other green roof benefits.

3. On the area of **heat islands**, further research is needed to address the lack of long-term observations. Atmospheric models must be developed that include sedums in simulations. In addition, the potential synergies between urban heat island reduction and the social benefits of green roofs should be evaluated.

4. On the area of **energy**, additional research is needed to determine the potential for green roofs to reduce the air intake temperature and other energy usage issues for rooftop heating and cooling units. Future studies should focus on determining the insulative and other thermal properties of different types of vegetation and of different types and depths of growing media, and should consider the energy performance of green roofs in a wider variety of climates. The relationship between the size of green roofs and the magnitude of energy savings should also be explored further. In addition, existing research does not sufficiently assess the performance of green roofs in winter conditions, or the heating benefits of green roofs in a cold climate. The energy performance of white roofs ("cool roofs") as compared with that of green roofs should be assessed in more depth, as should the performance of solar panels installed in conjunction with green roofs.

5. On the area of **acoustics**, research is needed on the acoustic properties of each individual layer of a green roof, to provide a stronger understanding of acoustic performance and of methods to optimize performance through design.

6. On the area of **urban agriculture**, additional economic evaluation of rooftop agriculture projects could provide stronger data to underpin cost-benefit analyses.

7. On the area of **air pollution**, increased research could help to determine the ability of green roof planting to reduce particulate matter, volatile organic compounds and other air pollutants.

8. On the area of **job creation**, economic studies of the abilities of green roof technologies to stimulate a new green jobs market are needed, as is an evaluation of policy and incentives in cities such as Portland, Toronto, Chicago, Washington DC, and Seattle.

9. On the area of **aesthetics**, additional studies would be valuable to evaluate the health, wellbeing, and work productivity effects of green roof views in office environments. While the evaluation of amenity and productivity benefits is notoriously difficult to do reliably, this could also be an area for future development to enhance understanding of green roof costs and benefits.

GSA National Capital Region - United States Tax Court, Washington DC
A 19,600 square foot green roof installed in the plaza.

TERM	DEFINITION
Abiotic	Non-living
Alavars	A rare habitat type characterized by areas of relatively flat terrain composed of limestone bedrock where the soils were scraped away long ago by the retreating glaciers
Best Management Practices	Methods that have been determined to be the most effective, practical means of preventing or reducing pollution from non-point sources.
Biodegradation	The decomposition of organic material by microorganisms
Biotic	Natural, or living
Capillarity	The rise or depression of a liquid in a small passage such as a tube of small cross-sectional area, like the spaces between the fibers of a towel or the openings in a porous material
Broadleaf	Having relatively broad rather than needle-like or scale-like leaves
Certificates of Appropriateness	Certificate issued by a preservation commission to indicate its approval of an application to alter, demolish, move, or add on to a protected resource
Cistern	A receptacle for holding water or other liquid, especially a tank for catching and storing water.
CoStar Group, Inc. (Costar)	A provider of information services to commercial real estate professionals.
Cuttings	Small sections of plant material that are taken from a mature plant
Dead load	The weight of the physical structure and the non-moving materials and objects attached to the structure such as the roof
Deck	The structural component of the roof assembly to which the roof system is secured
Delamination	Separation of the layers in a roof system or separation of laminated layers of insulation.
Desiccation	Drying out, or cracking
Direct Determination Method	Methodology for determining runoff volume

Discharge	The addition of water (or pollutants) to receiving waters from conveyance
Duration	The period of time during which rain fell
ENVI-Met	A micro-climatological, high-resolution simulation model for urban areas that has been used for Urban Heat Island research
Evapotranspiration	The loss of water from the soil both by evaporation and by transpiration from the plants growing in the soil
Fens	Peat-forming wetlands that receive water from precipitation, runoff, and groundwater movement. They are recharged by groundwater and runoff from surrounding mineral soils and typically form a narrow wetland in protected embayments in coastal areas
Flow Accumulation	The amount of water accumulated in overland flow over a surface
Flow Path	The route taken by stormwater runoff
Factory Mutual Research Corporation (FM)	Factory Mutual Research Corporation; an insurance-industry, standards-setting laboratory
Geocomposite	A multi-layered material made from any combination of geosynthetic products to fulfill a specific function or functions such as relieve hydrostatic pressure against waterproofing and promote drainage
Granular Drainage Layers	A layer of materials such as sand or gravel that promotes drainage
Green Building	The practice of creating structures and using processes that are environmentally responsible and resource-efficient throughout a building's life-cycle from siting to design, construction, operation, maintenance, renovation and deconstruction
Green Roofs for Healthy Cities (GRHC)	A not-for-profit industry association working to promote green roofs throughout North America
Green Wall	A wall that is partially or completely covered with vegetation, and soil or a growing medium
Hydrological Simulation Program--Fortran (HSPF)	A simulation of watershed hydrology and water quality for both conventional and toxic organic pollutants
Hydraulic Permittivity	A measure of the cross plane or perpendicular flow of water through a geotextile
Hydrograph	Runoff flow rate plotted as a function of time
Hydrology	A science dealing with the properties, distribution and circulation of the earth's water

Insulation	A variety of materials designed to reduce the flow of heat, either from or into a building
Intensity	Depth of rainfall per unit time (depth/duration)
Intensive Green Roof	A green roof, over 12 inches in thickness, with a intensive growth medium over a discrete drainage layer that can supported variety of vegetation type
Latent Heat	The heat released or absorbed by a chemical substance or a thermodynamic system
Live Load	A moving/variable weight added to the intrinsic weight of a structure
Low Impact Development	A sustainable landscaping approach that can be used to replicate or restore natural watershed functions and/or address targeted watershed goals and objectives
Kilowatt Hour (kWh)	A unit of energy of one kilowatt of power expended after one hour of time
Multi-course Extensive Green Roof	A green roof, typically 4 to 6 inches in thickness, with a finer grained medium over a discrete drainage layer (or geocomposite drainage layer), that typically supports sedum or other succulents (potential for other plant types depending on thickness and permanent irrigation)
Nutrient Salts	Various phosphorus and nitrogen compounds that have a fertilizing effect
Organic Matter	Carbonaceous material that contains living organisms or non-living material derived from organisms
Peak Flow Rate	The maximum rate of runoff expressed in units of volume of effluent and surface water movement
Permeability	The rate at which liquids pass through soil or other materials in a specified direction
Permeable Pavements	Pavements for roadways, sidewalks, or plazas that are designed to infiltrate runoff, including pervious concrete, pervious asphalt, and crushed gravel
Pioneer Species	The first species to colonize an area that is previously uninhabited
Plugs	Young plants that have developed from root structures
Protected Membrane Roof (PMR)	An insulated and ballasted roofing assembly, in which the insulation and ballast are applied on top of the membrane (may be referred to as an inverted roof assembly)
Ponding	The accumulation of water at low-lying areas on a roof
Porosity	Degree to which soil, gravel, sediment, or rock is permeated with pores or cavities through which water or air can move
Porous Aggregate	An aggregate containing pores or voids
Rainfall Event	(or design storms) are statistical abstractions drawn from rainfall records
Rational Method	A method of calculating runoff flows based on rainfall intensity, tributary area, and a factor representing the proportion of rainfall that runs off

Retention	The practice of holding stormwater and allowing it to slowly infiltrate to groundwater
River Base Flow	Precipitation that infiltrates into the soil and eventually moves through the soil to the stream channel (rather than over the land surface)
Root Barrier	A membrane designed to provide protection to the underling waterproofing membrane from root penetration and provide protection from microorganisms in the growth medium
Saturation	The condition of a liquid when it has taken into solution the maximum possible quantity of a given substance at a given temperature and pressure
Semi-Intensive Green Roof	A green roof, typically 6 to 12 inches in thickness, with a multi-course growth medium over a discrete drainage layer that can support more diverse vegetation than multi-coarse extensive
Single Course Extensive Green Roof	(eco roofs) A green roof typically 3 to 4 inches in thickness, with a coarse medium over a moisture management layer that can support sedum or other succulents
Soil Amendments	Materials added to soil, such as compost, peat moss, or fertilizer, to improve its capacity to support plant life
Soil Moisture Gradient	The rate of change in the water contained in the pore space of the unsaturated zone. (EPA and added words)
Storm Depth	(or rainfall depth) Depth of rainfall at a point or over an area (typically in inches)
Structural Diversity	The diversity of the composition, abundance, spacing and other attributes of living and dead vegetation, both standing, and on the ground in a community which provides a variety of habitat for plants and animals
Succulents	Water-retaining plants adapted to arid climate or soil conditions
Storm Water Management Model (SWMM)	A dynamic rainfall-runoff simulation model used for single event or long-term (continuous) simulation of runoff quantity and quality from primarily urban areas
Thermal Equilibrium	A state in which all parts of a system are at the same temperature
Thermal Resistance	(R-Value) The capacity of the surface or a layer of a body to resist the propagation of thermal molecular motion, or heat flow
Thermoplastic Membranes	Membrane which is hot-air welded or permanently fused without dependence on primers, adhesives, or caulking
Time of Concentration	The time required for water to flow from the most distant point on a runoff area to the measurement or collection point.
Tonnes	A metric ton; a unit of mass equivalent to 1,000 kilograms

Technical Release 55 (TR-55)	Procedures to calculate storm runoff volume, peak rate of discharge, hydrographs, and storage volumes for stormwater
Transmissivity	A measure of horizontal flow capacity
Waterproof Membrane	A membrane designed to protect the building components from the weather, over which the vegetative roof system is installed
Watershed	The land area that drains into a stream; the watershed for a major river may encompass a number of smaller watersheds that ultimately combine at a common point
Watershed Approach	A coordinated framework for environmental management that focuses public and private efforts on the highest priority problems within hydrologically-defined geographic areas taking into consideration both ground and surface water flow
Wet Weather Flows (WWF)	Storm generated flows (rain, snowmelt), which include combined-sewer overflows (CSOs), sanitary-sewer overflows (SSOs), and stormwater discharges
White Roofs	A reflective, white or white coated roof membranes
Wind Blanket	Organic or inorganic material placed over growth medium and vegetation to minimize erosion and aid in stabilization of the root systems in newly planted vegetation
Wind Scour	Erosion caused by wind
Wind Uplift	The force generated by wind on a roof system or components in a roof system resulting from wind-induced pressures

ABBREVIATIONS AND ACRONYMS

ASCE	American Society of Civil Engineers
ASTM	American Society of Testing and Materials
ATF	Alcohol, Tobacco, Firearms and Explosives
CSO	Combined-sewer Overflows
SSO	Sanitary-sewer Overflows
DDOE	District Department of Environment
EPA	Environmental Protection Agency
FLL	Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau (The Research Society for Landscape Development and Landscape Design)
FM	Factory Mutual Research Corporation
HSPF	Hydrological Simulation Program -- Fortran
HVAC	Heating, Ventilation, and Air Conditioning
IRR	Internal Rate of Return
kWh	Kilowatt Hour
NRCS	Natural Resources Conservation Service
PMR	Protected Membrane Roof
QUALYHYMO	Quality Hydrology Model
SPRI	Single Ply Roofing Industry
SWMM	Storm Water Management Model
TR-55	Technical Release 55
UHI	Urban Heat Island
USDOE	United States Department of Energy
USDOT	United States Department of Transportation
USEPA	United States Environmental Protection Agency
USGBC	United States Green Building Council
WWF	Wet Weather Flows

APPENDIX A

SELECTED GREEN ROOF CHARACTERISTICS—MULTI-COURSE EXTENSIVE AND SEMI-INTENSIVE

PERFORMANCE CHARACTERISTICS OF THE SELECTED GREEN ROOFS—MULTI-COURSE EXTENSIVE AND SEMI-INTENSIVE

Performance criteria were selected with the objective of optimizing the stormwater control benefits of the green roofs.

- Medium properties for the two assemblies comply with FLL recommendations for medium used in multi-course extensive and intensive green roofs.
- Climatic conditions in the NCR align well with the assumptions that underlie the FLL guide. The permeability of the granular drain layer was as assumed to be 25 in/min (ASTM E3396).
- The geosynthetic drain layer used in the extensive green roof was assumed to be a thin simple sheet, without significant water retention capability.
- The transmissivity (a measure of horizontal flow capacity) assumed for this sheet was 5 gallons/minute/linear foot, measured at a hydraulic gradient of 1.0 (ASTM D1647).*
- Total maximum medium moisture retention (ASTM E2399) for the growth medium will equal, or exceed 33%. Air-filled porosity (ASTM E2399), the pore volume remaining after the medium is soaked to capacity, will exceed 10%.
- A dense foundation fabric was selected for the semi-intensive green roof profile which will have a significant capillary potential.†
- The annual irrigation requirement for the semi-intensive green roof assembly was assumed to be 5 gallons per square foot per month during the growing season, from late March to November.

Table A1: Layers for extensive and semi-intensive roof-types

EXTENSIVE	SEMI-INTENSIVE
Waterproofing membrane, with supplemental thermoplastic root-barrier membrane if the waterproofing is not inherently root-resistant	Waterproofing membrane, with supplemental thermoplastic root-barrier membrane if the waterproofing is not inherently root-resistant
Non-woven foundation fabric	Capillary fabric (in conjunction with drip irrigation)
Geosynthetic drain layer	1.5 inches of granular mineral media
3 inches of media	Filter fabric
Sedum foliage layer	4.5 inches of growth media
	Mixtures of Sedum and non-Sedum perennial foliage layer

Recommended plant lists for the two green roof profiles are provided in Table 11 for the 3” Single-Course System and for the 6” Multi-Course System.

*This is much lower than most geosynthetic drain layers currently in use in the United States.

†This type of fabric promotes uniform moisture distribution and is designed to support a basal drip irrigation system.

Table A2: Recommend plant list for selected roof-types

3" EXTENSIVE	6" SEMI-INTENSIVE
Succulents	**Perennials supplemented with Sedum**
Delosperma cooperi	*Achillea millefolium* Cultivars
Potentilla verna	*Allium cernum*
Sedum album	*Aster novae-angliae*
Sedum floriferum 'Weihenstephaner Gold'	*Echinacea purpurea* Cultivars
Sedum reflexum Cultivars	*Phlox pilosa*
Sedum rupestre Cultivars	*Tradescantia ohiensis*
Sedum sexangulare	**Grasses supplemented with Sedum**
Sedum spruium Cultivars	*Festuca glauca* 'Elijah Blue'
	Muhlenbergia capillaris
	Pennisetum alopecuroides Cultivars
	Schizachurium scoparium 'The Blues'

As part of this study, the materials in the recommended green roof profiles were evaluated in accordance to ASTM E2397. The measured wet weight (i.e. approximated maximum dead load) is listed below. Please note that these numbers should only be used as a guide.

Table A3: Wet weight load of green roof layers

3" TYPE II		6" TYPE III	
16 oz. Protection Fabric	1.17 lb/ft2	Capillary Fabric	1.38 lb/ft2
Moisture Management Layer	0.21 lb/ft2	2" Drainage Media	10.97 lb/ft2
		4 oz. Separation Fabric	0.24 lb/ft2
3" Growth Medium	16.45 lb/ft2	4" Growth Media	26.41 lb/ft2
Wind Blanket	0.23 lb/ft2	Wind Blanket	0.23 lb/ft2
Plants	2.0 lb/ft2	Plants	3.0 lb/ft2
Total System Dead Load	20.06 lb/ft2	Total System Dead Load	42.23 lb/ft2

APPENDIX B

COST-BENEFIT ANALYSIS ASSUMPTIONS

B1 COST-BENEFIT ANALYSIS ASSUMPTIONS

B1.1 INFLATION AND GROWTH

Inflation and growth in this study were derived from the Bureau of Labor Statistics and are accounted for in the labor and materials, stormwater, energy and inflations cash flows. The labor and materials growth rate was assumed to be 4.91% and was used in the costs, maintenance and replacement cash flows. A 2.40% growth rate was used for energy, a 4.09% growth rate was used for stormwater cash flows and a 2.49% growth rate was used for community benefits. A negative growth rate of 5% was used in the supplemental market analysis to account for diminishing returns based on expected increase in supply.

B1.2 DISCOUNT RATE

One of the most important variables in any future cash flow analysis, the discount rate, was carefully chosen to account for the cost of capital. The following table outlines some typical rates:

Table B1: Discount Rates

RATE	DESCRIPTION
4.4%	GSA-supplied discount (hurdle) rate for 20-year maturity, based on Office of Management and Budget (OMB).
8.0%	Treasury’s default rate for projects that are difficult to categorize, including regulatory proposals
6.5%	Treasury’s rate for general purpose office and accommodation buildings
8.0%	Treasury’s rate for infrastructure and special purpose (single-use buildings)
9.5%	Treasury’s rate for telecommunications, medium & technology, IT & equipment, and knowledge economy (R&D)
7.0%	Rate used to reflect expected returns in the private sector
2.4%	OMB’s cost-effectiveness, lease-purchase, internal government investment, and asset sales analyses rate, which is based on the Treasury's borrowing rate Circular No. A-94
7.0%	OMB’s rate for public investment and regulatory analyses, Circular No. A-94

Because the GSA is the specific owner/occupier in this analysis, its given rate of 4.4% was used and understood to be its cost of capital.

The above rates were averaged according to their applicability to the various cash flows and their risks to address the perceived additional risk that the market places on green roofs, resulting in a rate of 6.74%. The GSA’s accepted risk was then subtracted from this rate to derive a risk premium of 2.34% that is taken as a contingency and included in all cash flows.

This risk premium is the amount by which the expected return of a green roof would have to exceed the return of a conventional roof in our analysis to be considered equivalent in the mind of an investor. This 2.34% premium is meant to account for the risk perceived by investors of using a seemingly new technology like a green roof versus a familiar, black roof.

B1.3 TIMELINE

With the GSA as a long-term holder, a 50-year timeline was chosen. This timeline is designed to capture the entire lifetime of both types of roof, although it significantly benefits long-term owners and is less useful to short-term investors. To mitigate some of these effects at year 50, remaining values were calculated to prevent any unlucky bias resulting from taking a replacement hit immediately before the end of the analysis.

B1.4 COMMUNITY

The community benefits of green roofs include energy saved by wastewater treatment plants, biodiversity benefits, increased air quality—as measured using nitrogen-oxygen compounds—and positive impacts for neighboring buildings like energy savings from reduction in summer temperatures and reductions in the heat island effect. The existence of these benefits should not be doubted, although they should be considered cautiously.

B1.5 SPECIFIC ASSUMPTIONS

Table B2 and B3 identifies the important assumptions and variables in the cost-benefit analysis. In many cases, the number identified is the result of a weighted average of many previous studies.

B1.6 BREAKDOWN OF ASSUMPTIONS FOR REAL ESTATE RELATIONSHIP ANALYSIS

COST/BENEFITS	OWNER	OWNER/ OCCUPIER	TENANT	COMMUNITY
Installation & Replacement	90%	100%	10%	0%
Maintenance	75%	100%	25%	0%
Stormwater Fees	75%	100%	25%	0%
Avoided Stormwater Costs	90%	100%	10%	0%
Energy Costs	25%	100%	75%	0%
Carbon Emissions to Owner	90%	100%	10%	0%
Carbon Emissions to Tenant	25%	100%	75%	0%
Productivity & Absenteeism	0%	0%	0%	0%
Community Benefits (Biodiversity, Habitat, Heat Island, Views, etc.)	5%	10%	5%	90%

Table B2: Assumptions

GENERAL ASSUMPTIONS	
Discount Rate, %	4.4%
Investment Outlook, years	50
Green Roof Medium, inches	3-6”
Green Roof Size, sf	10,000

NOMINAL GROWTH RATES	
Labor and Materials	4.91%
Stormwater Costs	4.09%
Energy Prices	2.40%
Carbon (included in price of carbon)	0.00%
Community Benefits (Inflation)	2.49%
Rent, Absorb and Retention	(5.00%)
Green Roof Risk Contingency	2.34%

Table B3: Variables

PERFORMANCE VARIABLES	NATIONAL		WASHINGTON DC		
	GREEN	BLACK	GREEN	BLACK	
Installation, Maintenance & Replacement					
Average Installation cost, $/sf of roof	$24.50	$8.99	$23.95	$9.66	*initial/replacement*
Replacement premium, %	33.5%	0%	33.5%	0%	*replacement*
Maintenance costs, $/sf of roof	$0.27	$0.06	$0.36	$0.06	*annual*
Roof longevity, years	40	17	40	16	
Disposal costs, $/sf of roof	$0.12	$0.37	$0.12	$0.37	*initial/replacement*
Stormwater Management					
Stormwater equipment Cost, $/sf of roof	$0.00	$4.15	$0.00	$4.77	*onetime/ replacement*
BMP maintenance Cost, $/sf of roof	$0.00	$0.13	$0.00	$0.13	*annual*
Stormwater surcharges, $/sf of roof	($0.084)	$0.00	n/a	$0.00	*annual*
Energy					
Electricity Price, $/kWh	$0.1118		$0.1100		
Natural gas price, $/MCF	$12.08		$12.54		
Heating/cooling costs, $/sf of roof	($0.166)	$0.00	($0.169)	$0.00	*annual*
Air Quality, CO_2e					
Embodied carbon, tonnes of CO_2e/sf of roof	0.0006	0.0000	0.0006	0.0000	*onetime/ replacement*
Carbon offset, metric tonnes of CO_2e	0.0002	0.0000	0.0002	0.0000	*annual*
Carbon savings from heating/cooling	0.0006	0.0000	0.0007	0.0000	*annual*
Community Benefits					
Stormwater energy savings, $/sf of roof	$0.0004	n/a	$0.0004	n/a	*annual*
Biodiversity & habitat, $/sf of roof	$0.42	n/a	$0.42	n/a	*annual*
Air quality, $/sf of roof	$0.035	n/a	$0.035	n/a	*annual*
Heat island energy savings	$0.030	n/a	$0.045	n/a	*annual*
Heat island peak shaving savings	$0.200	n/a	$0.200	n/a	*annual*
Heat island air quality effect (7.5x)	$0.30	n/a	$0.30	n/a	*annual*
Real Estate					
Avg. rent, $/sf/yr	$21.78	$21.25	$15.02	$14.54	*annual*
Avg. value, $/sf	$254	$248	$182	$176	
Average vacancy, %	16.97%	17.40%	6.32%	6.54%	
Cap rate, %	7.38%	7.55%	6.40%	6.61%	
Absorption, months	7.8	8.0	5.8	6.0	
Tenant retention, months	53.1	52.6	53.3	52.6	
Other (Used in Real Estate Analysis)					
Green building performance improvement	5.7%	n/a	7.4%	n/a	
Green roof proportion of green bldg benefits	44.2%	n/a	44.4%	n/a	

SOURCES

The sources for the information used in the cost-benefit analysis are mostly domestic. Multiple inputs were sought for each variable and then weighted to generate averages that fairly represent costs or benefits. Each of the resources listed at the end of this report were used when appropriate. Additionally, significant professional experience was used to generate installation costs, which vary across the country. This information should be thought of as a generalized analysis of whether green roofs provide economic benefit, rather than taken as fact. A list of the sources used in the cost-benefit model is below:

Installation costs, lifetime, maintenance:

1. Roofmeadow
2. NYCDEC
3. American Psychological Association Headquarters (Ward 6)
4. Atlantic Buillding (Existing historical building)
5. Buchanan R-Mer Lite
6. Buchanan White PVC
7. Chicago Walmart
8. Con Edison
9. Denver EPA Region 8 Headquarters
10. District Department of Parks and Recreation
11. GSA facility (Interior's National Business Center), 1849 C Street, NW
12. Morris Library
13. Niu Study
14. NYC DDC Study
15. Peterson AFB
16. Powell Middle School
17. Rapson Hall
18. Singapore Extensive
19. Singapore Shrubs
20. Singapore Trees
21. Tanyard
22. Tremskope
23. USPS Bldg. EPDM
24. USPS Bldg. White PVC
25. WFM-Cary
26. Single Ply Systems & Glass, GAF Materials Corp (The data represent an average. Actual costs can vary significantly depending on the building condition, the exact location (due to building codes etc), and the local labor rates etc)
27. Mann, G. (2002). Approaches to object-related cost-benefit analysis. http://www.gruendaecher.de
28. CMU Center for Building Performance/ABSIC. (2008) AOC DIRKSEN Green Roof Study. *CBPD CHAPTERS BIDS™ year-end report. Appendix D.*
29. Fraunhofer Institute. http://www.zinco-usa.com/faq/faq4.html
30. European Federation of Green Roof Associations. http://www.efb-greenroof.eu/verband/fachbei/fa02_englisch.htm

Discount rates:

1. GSA memorandum
2. Office of Management and Budget . Guidelines and Discount Rates for Benefit-Cost Analysis of Federal Programs. Circular No. A-94 Revised. October 29, 1992.
3. http://www.whitehouse.gov/omb/circulars_a094
4. New Zealand Treasury. Public Sector Discount Rates for Cost Benefit Analysis. October 19, 2010
5. http://www.treasury.govt.nz/publications/guidance/planning/costbenefitanalysis/discountrates (This discount rate analysis serves as a methodology in calculating various types of public sector projects)
6. Producer Price Index Industry Data

Stormwater:

1. Roofmeadow
2. Lawrence Berkeley National Laboratory (LBNL) studies
3. District Department of Environment (DDOE)
4. District of Columbia Water and Sewer Authority
5. Berghage, R.D., C. Miller, B. Bass, D. Moseley, and K. Weeks. (2010). *Stormwater runoff from a large commercial roof in Chicago*. In Proceeding of the Cities Alive Conference, Vancouver, BC. 2010.
6. NC State University, An Evaluation of Cost and Benefits of Structural Stormwater Best Management Practices in North Carolina
7. Davis., G. Use of Green Roofs to Meet New Development Runoff Requirements. Nov. 2007
8. DC WASA Long Term Control Plan. District of Columbia Water and Sewer Authority, Combined Sewer System Long Term Control Plan, July 2002
9. Philadelphia Combined Sewer Overflow Long Term Control Plan Update, Volume 3, Basis of Cost Opinions, September 2009
10. ECONorthwest. 2007. The Economics of Low-Impact Development: A Literature Review. Eugene, Oregon.
11. NYCDEP. Rapid assessment of the cost-effectiveness of low impact development for CSO control

Energy:

1. Lawrence Berkeley National Laboratory (LBNL) studies
2. Miller, C. Bass, B. Weeks, K. Berghage, R., and Berg, S. (2010). Stormwater policy as a green roof (dis) incentive for retail developers. In Proceedings: The Cities Alive Conference, Vancouver, BC
3. Gaffin, S. R., Rosenzweig, C., Eichenbaum-Pikser, J., Khanbilvardi, R. and Susca, T. (2010). A Temperature and Seasonal Energy Analysis of Green, White, and Black Roofs. Columbia University, Center for Climate Systems Research. New York. 19 pages.
4. Energy Price Indices and Discount Factors for Life-Cycle Cost Analysis-2010. NISTIR 85-3273-25. Annual Supplement to NIST Handbook 135 and NBS Special Publication 709, pp. 43
5. ASHRAE 90.1-2004 energy model of 275,000 gfa (25,000 sf roof) office building in Washington DC
6. University of Toronto Green roof Energy analysis
7. Clark, C., Adriaens, P., and Talbot, F.B. (2008). Green Roof Valuation: A Probabilistic Economic Analysis of Environmental Benefits. *Environmental Science & Technology 42 (6)*: 2155-2161

Carbon Dioxide (CO_2):

1. Getter, K.L., Rowe, D.B., Robertson, G.P., Cregg, B.M., Andresen, J.A., 2009b. Carbon sequestration potential of extensive green roofs. *Environmental Science and Technology 43 (19),* 7564-7570.
2. Energy Price Indices and Discount Factors for Life-Cycle Cost Analysis-2010. NISTIR 85-3273-25. Annual Supplement to NIST Handbook 135 and NBS Special Publication 709, pp. 46-47

Biodiversity and habitat:

1. Australia's BushBroker scheme

Heat island:

1. Acks, K. (2006). *A Framework for Cost-Benefit Analysis of Green Roofs*: Initial Estimates. in Green Roofs in the Metropolitan Region: Research Report. C. Rosenzweig, S. Gaffin, and L.
2. Parshall (Eds.) Columbia Center for Climate Systems Research and NASA Goddard Institute for Space Studies

Air quality:

1. Clark, C. Adriaens, P., & Talbot, F.B. *Green Roof Valuation: A Probabilistic Economic Analysis of Environmental Benefits.* University of Michigan
2. Niu, H., Clark, C., Zhou, J., & Adriaens, P. (2010) Scaling of Economic Benefits from Green Roof Implementation in Washington, DC. *Environmental Science Technology*
3. Casey Trees Study (DC) Based on the cost on installing selective catalytic reduction on a 10MW natural gas turbine
4. A.H. Rosenfeld, H. Akbari, J.J. Romm and M. Pomerantz. (1998). Cool communities: strategies for heat island mitigation and smog reduction. *Energy and Buildings 28*:51-62

Real estate:

1. Real Capital Analytics Midyear Review, July 22, 2010
2. TIAA-CREF Q32010
3. Reed Construction Data®. (2010, February 17). "Construction Forecasts: RSMeans' dollars-per-square-foot construction costs: four office building types of structure nnovations". Retrieved November 2010, from Reed Construction Data®.: http://www.reedconstructiondata.com/construction-forecast/news/2010/02/rsmeans-dollars-per-square-foot-construction-costs-four-office-building-typ
4. Davis Langdon Adamson. (2004) Costing Green: A Comprehensive Cost Database and Budgeting Methodology.
5. Climate Progress (2010, September 24). "Costs and benefits of green buildings". Retrieved December 2010, from Climate Progress. http://climateprogress.org/2010/09/24/costs-and-benefits-of-green-buildings/ (took green roof cost and divided it by average green cost premium of construction (4%) per sf of roof)
6. Delta Associates. "Cap Rate Study: District of Columbia." Prepared for Office of Tax and Revenue Real Property Tax Administration. January 2010. http://aoba-metro.org/uploads/FINAL%2029275%20Cap%20Rate%20Study%20DC.PDF
7. Cassidy Turley: Commercial Real Estate Services. (2010, October 13). " DC Overtakes NYC for Highest Office Rents". Retrieved November 2010, from Cassidy Turley: Commercial Real Estate Services. http://www.cassidyturley.com/News/PressReleases/Entry.aspx?topic=Cassidy_Turley_eports_U_S_Office_Sector_Continuing_to_Rebound_

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