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The Role of Extensive Green Roofs in Sustainable Development

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***Abstract.* As forests, agricultural fields, and suburban and urban lands are replaced with impervious surfaces resulting from development, the necessity to recover green space is becoming increasingly critical to maintain environmental quality. Vegetated or green roofs are one potential remedy for this problem. Establishing plant material on rooftops provides numerous ecological and economic benefits, including stormwater management, energy conservation, mitigation of the urban heat island effect, and increased longevity of roofing membranes, as well as providing a more aesthetically pleasing environment in which to work and live. Furthermore, the construction and maintenance of green roofs provide business opportunities for nurseries, landscape contractors, irrigation specialists, and other green industry members while addressing the issues of environmental stewardship. This paper is a review of current knowledge regarding the benefits of green roofs, plant selection and culture, and barriers to their acceptance in the United States. Because of building weight restrictions and costs, shallow-substrate extensive roofs are much more common than deeper intensive roofs. Therefore, the focus of this review is primarily on extensive green roofs.**

Before human development began disturbing natural habitats, soil and vegetation constituted part of a balanced ecosystem that managed precipitation and solar energy effectively. In natural areas, much of the rainwater infiltrates into the ground or is returned to the atmosphere via evapotranspiration, thus absorbing rainwater and performing a cooling function for excess solar loads. As the human population began expanding, more construction ensued, which disturbed these natural habitats. Cities, towns, and suburbs all add more impervious surfaces as we construct buildings, roads, and parking lots. In the United States, it is estimated that 10% of residential developments and 71% to 95% of industrial areas and shopping centers are covered with impervious surfaces (Ferguson, 1998). Today, two-thirds of all impervious area is in the form of parking lots, driveways, roads, and highways (Water Resources Group, 1998), and this loss of natural areas causes many problems.

Volume of stormwater runoff

Because an impervious surface cannot absorb precipitation, this water flows off surfaces and reduces infiltration into groundwater. In forests, ~95% of rainfall is absorbed, whereas only about 25% is absorbed in cities (Scholz–Barth, 2001). Excessive runoff increases the chances for flooding downstream as stormwater exceeds channel capacities, resulting in the probability of property damage and human harm. A high volume of stormwater runoff can also overwhelm municipal sewer systems. Combined sewer systems consist of a single pipe that takes wastewater and stormwater to treatment plants. When stormwater exceeds capacity, the combined sewage can overflow into relief points, resulting into raw waste being dumped into our rivers, an event called a combined sewage overflow (CSO). In New York City, about half of all rainfall events result in a CSO event. These CSO events dump 40 billion gallons of untreated wastewater into New York's surface waters annually (Cheney, 2005).

Quality of stormwater runoff

Impervious surfaces collect pollutants such as oil, heavy metals, salts, pesticides, and animal wastes. During runoff events, these contaminants may wash into waterways. Novotny and Chesters (1981) described the quality of urban runoff water as approaching that of treated sewage or even worse. Research supports the link between runoff from impervious surfaces and the reduction of water quality in streams. Even 10% of a land area covered with impervious surfaces can have an effect on stream quality (Ferguson, 1998). Runoff that contains a large amount of organic matter can also cause eutrophication of the surface waters, reducing oxygen availability and resulting in loss of aquatic species (Barnes et al., 2001). Not only does polluted runoff impact the ecosystem, but it can affect human health as well. For example, untreated urban runoff onto public beaches has caused surfers twice as many health problems than beaches not exposed to urban runoff (Dwight et al., 2004).

Energy conservation and the urban heat island

Because water is not retained in the soil as a result of runoff from these surfaces, the quantity of water available for evapotranspiration is reduced. Therefore, a great deal of incoming solar energy that would have been used to evaporate water is instead transformed into sensible heat (Barnes et al., 2001). In addition, many impervious surfaces tend to be heat-absorbing structures. The albedo of a surface is a measure of the incoming solar radiation that is reflected off the surface and thus is not absorbed and transformed into heat energy. The albedo of urban surfaces is generally 10% lower than the albedo of rural surfaces (Oliver, 1973).

Loss of vegetation and water resulting from the creation of impervious surfaces combined with the heat-absorbing properties of such structures results in higher internal building temperatures and ambient air temperatures outside the building compared with the surrounding suburbs or countryside. According to the USEPA (2003), urban air temperatures can be up to 5.6 °C warmer than the surrounding countryside. In an urban heat island effect situation, even night air temperatures are warmer because built surfaces absorb heat and radiate it back during the evening hours. In Berlin, temperatures on a clear windless night were 9 °C higher than in the countryside (Von Stulpnagel et al., 1990).

Because of the health effects associated with excess heat, the Environmental Protection Agency (EPA) has developed a Heat Island Reduction Initiative (HIRI). Through this program, the EPA works with researchers, community groups, and public officials to identify and implement methods that reduce heat islands. They cite that excessively hot air temperatures can result in physiological disruptions, organ damage, and death (USEPA, 2003). The Department of Health and Human Services' Centers for Disease Control and Prevention (CDC) says that high-temperature events have caused more deaths in the United States each year than hurricanes, lightning, tornadoes, floods, and earthquakes combined. The CDC estimated that for the 23-y period between 1979 and 2002, 8966 deaths resulted from excessive heat exposure in the United States (Department of Health and Human Services, 2005).

A potential solution: vegetated green roofs

Green roof technology offers an alternative to spending millions of dollars to renovate

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outdated stormwater infrastructures and to power air conditioners. Green roofs involve growing plants on rooftops, thus replacing the vegetated footprint that was destroyed when the building was constructed. They are similar to other cool-roof technologies in that they have a high albedo (ranging, from 0.7–0.85), depending on water availability (Gaffin et al., 2005). Other cool-roof technologies, such as white roofs, may start with an albedo of 0.8, but reflectivity can decline up to 11% from dust and debris accumulation. Conventional roof surfaces have much lower albedos, ranging from 0.05 to 0.25 (USEPA, 2005).

Even though green roofs are not very common in the United States, they are not a new idea. One of the first above-ground gardens were the hanging gardens of Babylon built around 500 BC. During the Middle Ages and the Renaissance, roof gardens were mainly for the rich, although Benedictine monks were fond of them as well. In the 1600s to 1800s, Norwegians covered roofs with soil for insulation and then planted grasses and other species for stability. Early American settlers of the Great Plains also used this technique in the late 1800s because of a lack of timber (Osmundson, 1999).

Germany is recognized as the place of origin for modern-day green roofs. In the 1880s, Germany experienced rapid industrialization and urbanization. Inexpensive housing was often built with highly flammable tar as the roofing material. A roofer named H. Koch developed a method to reduce the fire hazard by covering the tar with sand and then gravel. Seeds naturally colonized these roofs eventually to form meadows. As of 1980, 50 of these roofs were still intact and still completely waterproof (Kohler and Keeley, 2005).

The Great Depression and World War II led to a general lull in roof greening. However, Britain benefited from the camouflaging capabilities of green roofs by using them to cover military airfield hangars in the form of turf during the 1930s (Frith and Gedge, 2005). Despite the failing economy during the Depression, the first prominent US modern green roof was built at the Rockefeller Center in New York City during that time (Osmundson, 1999). Today in the United States, green roofs are becoming less of a novelty, although other countries are far more advanced in the adoption of this technology. In Germany, it is estimated that 14% of all flat roofs are green (Kohler and Keeley, 2005).

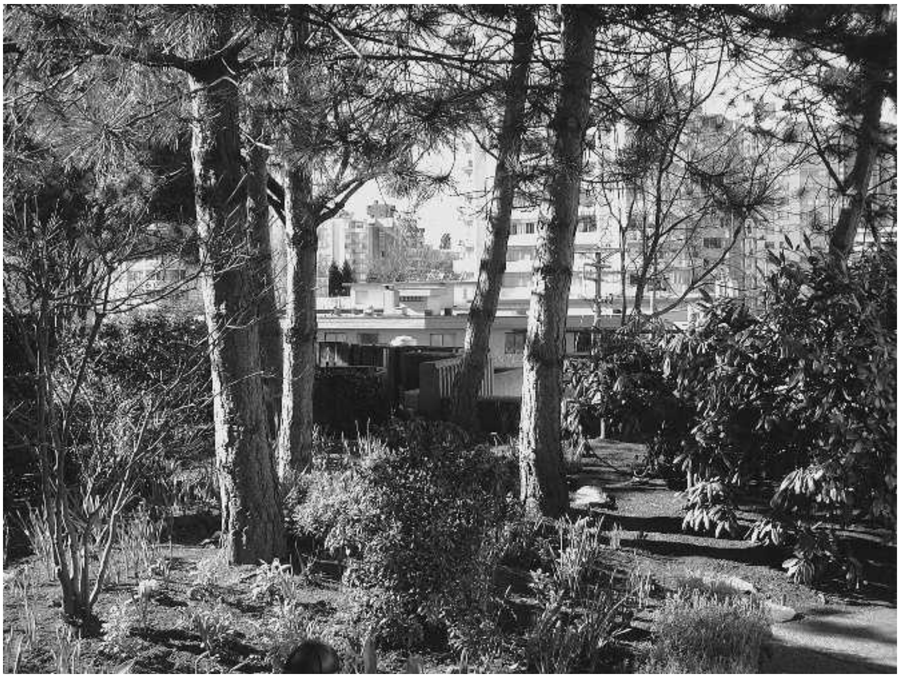

Fig. 1. An intensive green roof on the Coast Plaza Hotel in Vancouver, British Columbia.

Fig. 2. Portion of a 10.4-acre extensive green roof on an assembly plant at Ford Motor Company in Dearborn, Mich. Plant material consists of 13 species and cultivars of *Sedum.*

Modern green roofs can be categorized as "intensive" or "extensive" systems depending on the plant material and the planned usage for the roof area (Figs. 1 and 2). Intensive green roofs are so named because of their "intense" maintenance needs. They are designed to be similar to landscaping found at natural ground level. They typically use a wide variety of plant species that may include trees and shrubs and thus require deeper substrate layers (usually >15.2 cm) than extensive roofs. Because they are often parklike areas accessible to the public, they are generally limited to flat roofs.

In contrast, extensive roofs generally require minimal maintenance. They are typically not accessible to the public and may not even be visible. Because of their shallower media depth (<15.2 cm), plant species are limited to herbs, grasses, mosses, and drought-tolerant succulents such as *Sedum.* In addition, extensive green roofs can be built upon a sloped surface.

Most green roofs have similar construction components (Fig. 3). A root barrier installed on top of the normal roofing membrane protects the roof from root penetration damage. A drainage layer above the root barrier allows excess water to flow away from the roof. On top of the drainage layer is a filter fabric, which keeps silt and particulate matter in the media from clogging the drainage layer. An optional water retention fabric may be laid on top of this, which

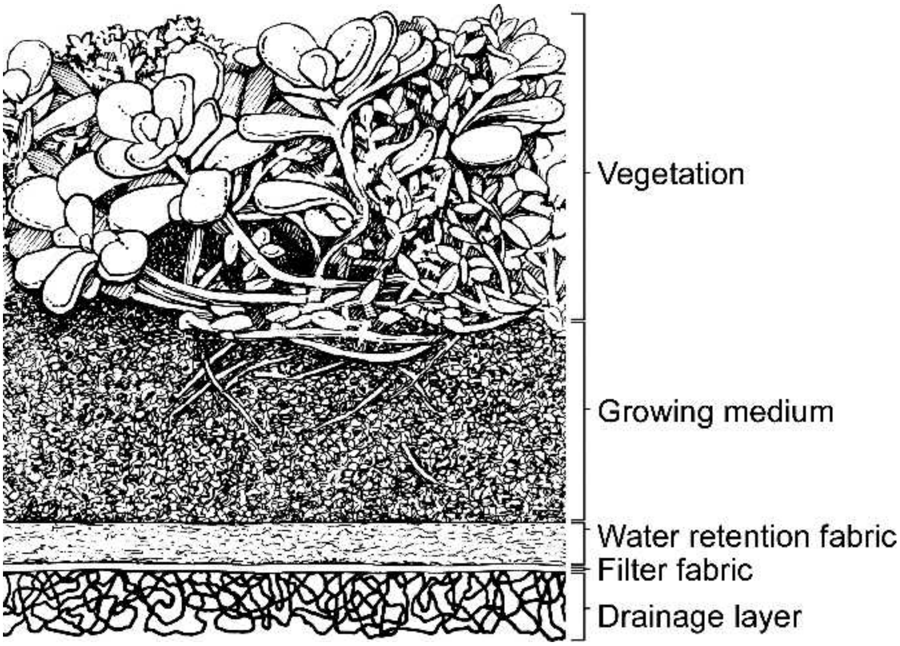

Fig. 3. Cross-section of a representative extensive green roof system including typically used layers. The drainage layer is place over a root barrier that covers the roofing membrane. The water retention fabric is optional and the media depth and plant material vary depending on design specifications.

Fig. 4. An extensive green roof native plant community on the convention center of the Church of Jesus Christ of Latter-day Saints in Salt Lake City, Utah.

allows extra water to be retained for the benefit of the plants. Finally, a growing substrate is placed that supports plant growth. Design of these components depends on the purpose of the greening project and building load capabilities.

Benefits of Green Roofs

Reduced volume of stormwater runoff

Probably the single greatest environmental service that green roofs provide is the reduction of total amounts of stormwater runoff. In a green roof system, much of the precipitation is captured in the media or vegetation and will eventually evaporate from the soil surface or will be released back into the atmosphere by transpiration. Kolb (2004) reported that 45% of all rainfall can be recycled in this manner. Green roofs may reduce runoff by 60% to 100%, depending on the type of green roof system (DeNardo et al., 2005; Liescke, 1998; Moran et al., 2004; Rowe et al., 2003; VanWoert et al., 2005a). Water retention depends on design factors such as substrate depth, composition, and plant species, as well as weather factors such as intensity and duration of rainfall.

The effect of slope on rainfall detention is unclear. In Germany, Schade (2000) and Liesecke (1998) found no significant difference in retention amounts across differently sloped roofs. Other studies suggest increasing slope increases runoff (VanWoert et al., 2005a; Villarreal and Bengtsson, 2005). The contradicting results may be the result of rainfall patterns in different environments. Many researchers have observed that dry substrate conditions before rainfall results in more stormwater retention compared with initially wet conditions (Connelly and Liu, 2005; Villarreal and Bengtsson, 2005).

Because green roofs retain stormwater, they can mitigate the effects of impervious surface runoff. For example, if 6% of the roof surface area in Toronto were green, Peck (2005) estimated that the impact on stormwater retention would be equal to building a $60 million (CDN) storage tunnel. Deutsch and colleagues (2005) calculated that if 20% of all buildings in Washington, D.C., that could support a green roof had one, that they would add more than 71 million L to the city's stormwater storage capacity and store ~958 million L of rainwater in an average year.

Delayed stormwater runoff

Even though green roof systems retain stormwater, runoff will still occur after the media becomes saturated. However, runoff is delayed because it takes time for the media to become saturated and for the water to drain through the media. This delay can prevent stormwater sewer systems from overflowing, by allowing it to process runoff for a longer time at a lower flow rate. Green roofs can delay runoff between 95 min (Liu, 2003) and 4 h (Moran et al., 2004), compared with the reference roofs for which runoff was nearly instantaneous. After runoff begins on a green roof system, the rate at which the rain leaves the roof is slower than a nongreened roof because of the nature of the green roofing components. Liu (2003) found that when initial rainfall was 2.8 mm/h, runoff from the green roof was reduced to 0.5 mm/h. North Carolina researchers found a 57% to 87% reduction in flow rates on a green roof (Moran et al., 2005). By slowing down the rate of runoff and turning it out over a longer period of time, green roofs can help mitigate the erosional power of runoff that does enter streams, either through direct runoff or storm sewers.

Increased life span of roofing membranes

Growing media and plant material protect roofing membranes from solar exposure and ultraviolet radiation that can damage the traditional bituminous roof membrane. These materials also reduce day/night temperature fluctuations at the membrane, which reduces the stress of daily expansions and contractions. One study demonstrated diurnal fluctuations for a nongreen roof to be 50 °C, whereas a green roof's diurnal fluctuation was only 3 °C (Connelly and Liu, 2005). Research supports the stress differential on roof membranes between a conventional roof and a green roof. In Toronto, Canada, the roof membrane temperature on a nongreened roof reached 70 °C in the afternoon, whereas the roof membrane on the green roof was only 25 °C (Liu and Baskaran, 2003). Peck and associates (1999) estimated that temperature moderation can extend the membrane life two to three times.

Energy conservation and the urban heat island

In addition to increasing roof membrane life, green roofs provide shade and insulation, resulting in energy savings and mitigation of the urban heat island effect. Media depth, shade from plant material, and transpiration can reduce solar energy gain by up to 90% compared with nonshaded buildings. Green roofs have reduced indoor temperatures 3 to 4 °C when outdoor temperatures were between 25 °C and 30 °C (Peck et al., 1999). Every decrease in internal building air temperature of 0.5 °C may reduce electricity use for air-conditioning up to 8% (Dunnett and Kingsbury, 2004).

Air temperatures above the building have been shown to be 30 °C lower when vegetated compared with a conventional roof (Wong et al., 2003), resulting in up to 15% annual energy consumption savings. But the amount of shading is highly dependent on the types of plants chosen, because leaf area index has a significant impact on the shading effect (Wong et al., 2003). Over a 30-d warm fall period in British Columbia, total heat flow through a reference roof and green roof was 2.634 kW/m^2 and 0.7 kW/m^2 respectively—a 70% reduction (Connelly and Liu, 2005).

Because buildings consume 36% of total energy use and 65% total electricity consumption, green roof implementation on a wide scale could significantly impact energy savings (Kula, 2005). Laberge (2003) estimated that for the Chicago city hall, energy savings alone could result in $4000 annually for heating and cooling combined. If all of Chicago had green roofs, the savings could be $100,000,000 annually Laberge, (2003). Most of the insulation benefits result from cooling, as heating reductions range from 0.12% to 0.2% and cooling reductions range from 6.2% to 6.4% (Saiz–Alcazar and Bass, 2005). This is partly the result of how large air-conditioning systems work: There is lower power demand when intake air is cooler. When intake air exceeds 35 °C (95 °F), power requirements for the air conditioner increase and cooling capacity drops (Leonard and Leonard, 2005).

Most energy savings from green roofs will occur during the summer months. This is because the insulation properties of the substrate are greater when air space exists in the pores as opposed to when they are saturated, which is normally the case during winter. Even so, they do help to insulate buildings during the winter. On the Plant and Soil Sciences Building at Michigan State University, we are currently collecting data on heat flux through portions of a green and conventional roof. Although these data are still being collected and analyzed, it is obvious that there is some effect when snow has melted from the conventional side, but still exists on the vegetated portion. Regardless, if energy savings were the only reason for installing a green roof, it would be much less expensive to install additional insulation when constructing the building rather than installing a green roof.

Increase biodiversity and provide habitat

Because most extensive green roofs are inaccessible to the public, they can provide undisturbed habitat for microorganisms, insects, and birds. In a biodiversity study of 17 green roofs in Basel, Switzerland, 78 spider and 254 beetle species were identified during the first 3 years. Eighteen percent of those spiders and 11% of the beetles were listed as endangered or rare (Brenneisen, 2003). In a West Berlin study of 50-y-old green roofs, Darius and Drepper (1984) found grasshoppers, white grubs, beetles, and a high number of mites. In northeastern Switzerland, nine orchid species and other rare and endangered plant species existed on a 90-y-old green roof (Brenneisen, 2004). In addition, many birds have been recorded using green roofs in Germany, Switzerland, and England (Brenneisen, 2003; Gedge, 2003).

Even relatively new green roofs can provide habitat. One of the worlds' largest green roofs is in Dearborn, Mich., on top of a Ford Motor Company assembly plant. The 42,900 m^2 greened roof consists of a mix of 13 *Sedum* species planted in less than 7.6 cm media. Within 2 years of initial plant establishment, 29 insect species, seven spider species, and two bird species were identified (Coffman and Davis, 2005).

Some researchers are evaluating roofs as a potential way to restore native plant species to an area. (Dewey and colleagues 2004) evaluated 35 native grasses and wildflowers on an irrigated intensive green roof and found that 21 species were suitable for a meadow mixture with a 1.0-m media depth. Others are evaluating natives on nonirrigated extensive green roofs (Monterusso et al., 2005). One would expect that a green roof consisting of a native plant community would provide greater biodiversity than a typical *Sedum*-based roof. However, depending on the area, there may not be native vegetation that can withstand the normal environmental stresses encountered on a rooftop.

Improved aesthetic value

When humans view green plants and nature, it has beneficial health effects, such as reducing stress, lowering blood pressure, releasing muscle tension, and increasing positive feelings (Ulrich and Simmons, 1986). These benefits can be translated into improved health and worker productivity. Kaplan and colleagues (1988) reported that employees who had a view of nature, such as trees and flowers, were less stressed, experienced greater job satisfaction, and reported fewer headaches and other illnesses than those who had no natural view. Ulrich (1984) noted that patients experience faster recoveries from surgery when they have a natural view. Not only are the green surroundings aesthetically pleasing, but landlords can often increase tenancy rates and hotels are able to charge more for a "room with a view" compared with traditional barren roof scenery.

Mitigation of air pollution

Plants can filter out particulate matter and gaseous pollutants in the air. Particles will eventually be washed away into the soil via rainwater movement, and some of the pollutants will be absorbed into plant tissues. A variety of airborne contaminants can be alleviated by green roofs. A German study demonstrated that green roof vegetation can significantly reduce diesel engine air pollution (Liesecke and Borgwardt, 1997). Yok Tan and Sia (2005) found a 37% and 21% reduction of sulfur dioxide and nitrous acid respectively directly above a newly installed green roof. Others have estimated that green roofs can remove dust particles on the order of 0.2 kg of particulates per year per square meter of grass roof (Peck and Kuhn, 2001).

The adverse health effects of particulate air pollution include increased respiratory problems, decreased lung function, and increased hospitalizations and other health care visits for respiratory and cardiovascular disease. Increased respiratory morbidity, as measured by absenteeism from work or school or other restrictions in activity, and increased cardiopulmonary disease mortality are also induced by air pollution (Pope et al., 1995).

But air pollution as it relates to health is not the only issue. Some municipalities such as Washington, D.C., are in danger of losing federal funds because they do not meet federal air quality standards for particulate matter. If 20% of all existing "green roof-ready" buildings in Washington, D.C., implemented the technology, the resulting plantings would remove the same amount of air pollution as 17,000 street trees (Deutsch et al., 2005). An air quality model for greening all rooftops in Chicago predicts a reduction of 417,309.26 kg of nitrogen oxide and 517,100.61 kg of sulfur oxide emissions per year (Laberge, 2003). At the University of Michigan, Clark et al. (2005) estimate that if 20% of all industrial and commercial roof surfaces in Detroit, Mich., were traditional extensive *Sedum* green roofs, more than 800,000 kg per year of NO_2 (or 0.5% of that area's emissions) would be removed.

Noise reduction

Hard surfaces in urban areas are more likely to reflect sound, whereas green roofs absorb sound waves because of the nature of the substrate and vegetation. At the airport in Frankfurt, Germany, a 10-cm-deep green roof reduced noise levels by 5 dB (Dunnett and Kingsbury, 2004). Other research shows that 12 cm of green roof substrate alone can diminish noise by 40 dB (Peck and Kuhn, 2001). There have been ample scientific studies on the effects of noise exposure to humans, with hearing impairment, hypertension and ischemic heart disease, annoyance, sleep disturbance, and decreased school performance being just some of the problems found (Passchier–Vermeer and Passchier, 2000).

Leadership in energy and environmental design (LEED) standards

Implementing green roofs can lead to additional credits in the LEED program administered by the US Green Building Council—an agency that promotes "the design and construction of buildings that are environmentally responsible, profitable, and healthy places to live and work" (US Green Building Council, 2005, p.2). The LEED program was created to establish standards and guidelines for designing and constructing buildings that reduce the negative impact that buildings have on the environment and occupants. Participation in the program can increase the building's valuation, decrease vacancy and improve retention, reduce liability, and improve occupant performance. If at least 50% of the building is covered with a green roof, one LEED point each will be awarded for reducing heat islands and for stormwater management (Oberlander et al., 2002). In fact, with quality green roof design, one can earn as many as 15 LEED credits in the categories of sustainable sites, water efficiency, and energy and atmosphere (Kula, 2005).

Plant Performance on Green Roofs

If the benefits of green roofs are to be realized, then green roof plant performance is extremely important. Factors that must be considered include aesthetic appeal, environmental conditions including macro- and microclimate, substrate composition and depth, plant selection, installation methods, and maintenance.

Aesthetics. Design intent and available installation and maintenance budgets are key factors in determining substrate depth and plant selection, which in turn influence aesthetics. Expectations of aesthetics must be addressed before selection of plant species, because many species have dormant periods during which the green roof may not appear so "green." For example, many native prairie grasses and perennials will normally dry and brown in the summer. Although, a natural occurrence, some may find this to be unacceptable. Visual appeal is generally more important on intensive roofs designed for public visitation compared with some shallow extensive roofs with the main purpose of stormwater management. Some extensive roofs may not even be seen except from the air.

Combinations of evergreens and flowering plants with a long blooming season provide a visual impact when grown together. However, summer droughts can turn flowering perennial plants into a mass of browned-out, dead-looking plants that could be a fire hazard. Similarly, grasses are difficult to keep green throughout the summer, especially on extensive roofs. To grow most annuals, perennial flowering herbaceous plants, and grasses, either irrigation must be present or substrate depths must be deeper than normally found on extensive roofs. If irrigation is not available, then succulent species such as *Sedum*, *Sempervivum*, and *Delosperma* are considered good choices because of their ability to withstand extended drought conditions and other adverse environmental conditions often present on a rooftop (Snodgrass, 2005). However, these taxa may not have the same aesthetic appeal. Visual appearance may not be a concern if the roof is not normally visible and was installed primarily for its functional attributes such as stormwater retention. Thin-layer *Sedum* roofs can serve this function, possibly without the added costs of structural reinforcement to the building. The aesthetic value of the roof will continually change throughout the growing season and over time. Plant competition and succession will occur as in any landscape. Similarly, identical plant palettes will look and behave differently depending on the local environmental conditions.

Environmental conditions

Regardless of the desired aesthetic effect, climate and microclimate have a major impact on plant selection. In particular, average high and low temperatures, extreme hot and cold temperatures, irradiance levels, wind, and the amount and distribution of rainfall throughout the year will determine what species can survive in a specific area. Drought tolerance is important because high levels of solar radiation and low media moisture are usually the norm, especially in shallow extensive systems. Likewise, microclimates on the roof must be considered: roof slope and orientation may influence the intensity of the sun and substrate moisture content, surrounding structures may shade a portion of the roof, air vents from heating and air-conditioning units may dry the substrate, and chemical exhaust from industrial buildings may influence plant growth. Environmental conditions, especially the amount and distribution of rainfall and temperature extremes, will eliminate the use of certain species or will dictate the need for irrigation. Although, aesthetic appeal is an important criteria on many roofs, the chosen plants must first be capable of surviving.

Substrate composition and depth

Substrate composition has a major impact on plant selection for green roof systems. The ideal substrate is comprised of a balance of lightweight, well-drained material, has adequate water and nutrient holding capacity, and will not break down over time. The major component of green roof substrates should be mineral-based materials such as expanded slate, shale, or clay. Other inorganic components may include sand, pumice, perlite, vermiculite, and crushed recycled clay bricks or tiles (Beattie and Berghage, 2004; Dunnett and Kingsbury, 2004). High levels of compost are not recommended because it will decompose and result in substrate shrinkage (Beattie and Berghage, 2004), and it can result in increased N and P in the runoff (Moran et al., 2005). Also, it is not feasible or practical to replace the substrate on a rooftop continually. Substrate composition will depend on what materials are available locally and can be formulated for the intended plant selection, climatic zone, and anticipated level of maintenance.

Rowe et al. (2006) compared five planting substrate compositions containing 60%, 70%, 80%, 90%, and 100% of heat-expanded slate to evaluate the establishment, growth, and survival of two stonecrops (*Sedum* spp.) and six nonsucculent natives to the midwestern US prairie. Grown in 10 cm of substrate without any supplemental irrigation, the higher levels of heat-expanded slate in the substrate generally resulted in slightly less growth and lower visual ratings across all species. By the end of 3 years, the majority of the nonsucculents were dead, but both stonecrops (*Sedum* spp.) achieved 100% coverage after one season and maintained this coverage throughout the study. Results suggest that moderately high levels of heat-expanded slate (up to 80%) can be incorporated into a green roof growing substrate when growing succulents such as stonecrop, without sacrificing plant health, and at the same time reducing the load placed on a building. However, the nonsucculents used in this study require deeper substrates, additional organic matter, or supplemental irrigation.

High levels of organic matter or the addition of fertilizer to the substrate can also result in a substrate that is too fertile. High fertility will encourage lush growth that is more subject to the inevitable drought stress on roofs that are not irrigated. In a fertility study, Rowe et al. (2006) found that plants of smooth aster (*Aster laevis* L.), junegrass (*Koeleria macrantha* Regel), and showy goldenrod (*Solidago speciosa* L.) survived in greater numbers when they were not fertilized. Presumably, these plants could survive drought conditions for a longer period of time because they had less biomass to maintain. Similarly, a German study reported that stonecrop sprouts did not survive when strongly fertilized (Jauch, 1993), although the author did not indicate what is considered "strong." Furthermore, substrates with a low to medium fertility level may encourage a more diverse plant community, reducing the likelihood of dominant aggressive species (Dunnett and Kingsbury, 2004). As with compost, applying the minimal amount of fertilizer to maintain plant health, potential contaminated discharge of N, P, and other nutrients from green roofs is likely to be reduced.

Substrate depth also influences the plants that can be grown (Gómez–Campo, 1994; Gómez–Campo and Gómez–Tortosa, 1996). Deeper substrates are necessary for woody species, grasses, and many annual or perennial flowering plants. Shallower substrate depths will dry out faster (Dunnett and Nolan, 2004; VanWoert et al., 2005b), but some taxa are naturally found growing under these conditions. In Madrid, Spain, Gómez–Campo (1994) found *S. album* growing spontaneously on roofs, suggesting minimal needs for substrate depth. Research at Michigan State University has shown that substrate depth influences rate of substrate coverage and plant growth regardless of species Durhman et al., (2004). Deeper substrates are beneficial for both increased water-holding capacity and as a buffer for overwintering survival because shallow substrates are more subject to fluctuations in temperature. A shallow depth will likely make root systems more susceptible to cold damage (Boivin et al., 2001) because roots are generally not as cold tolerant as the tops of plants (Wu et al., 2000). Despite the cultural limitations of shallow substrate depths, they are often desirable because the building must be structurally strong enough to support the added weight of the green roof.

Plant selection

Criteria for selecting plant material include design intent; aesthetic appeal; local environmental conditions; plant characteristics such as rate of establishment, longevity, and disease and pest resistance; and the substrate composition and depth available for planting. A wide array of taxa are potential choices for intensive roofs because of deeper substrate depths and the likelihood of available supplemental irrigation. In contrast, drought tolerance is one of the most limiting factors on extensive green roof systems given their shallow substrate depths (<10 cm) and usual reliance on natural precipitation events to sustain plant life.

Successful candidates for extensive green roofs must exhibit characteristics such as easy propagation, rapid establishment, and high ground cover density (White and Snodgrass, 2003). Low-growing plants that spread and cover the substrate in a short period of time reduce potential erosion problems and inhibit weeds. Although rapid coverage is important, the ability of the plant species to be self-sustaining reduces the need for future replanting and maintenance. Species that are long lived, that reseed themselves, or that spread vegetatively should continue to provide 100% coverage as long as environmental conditions are favorable.

Succulent plants have been identified as being well adapted to the conditions often found on extensive green roofs because of their ability to limit transpiration and store excess water. The genus *Sedum* is a popular choice among extensive green roofing projects as a result of its tolerance for drought and shallow substrate adaptability (Dunnett and Kingsbury, 2004). Many S*edum* spp. have been identified as exhibiting some form of Crassulacean acid metabolism (CAM; Gravatt, 2003; Gravatt and Martin, 1992; Kluge, 1977; Lee and Kim, 1994; Sayed et al., 1994; Teeri et al., 1986). CAM is a unique form of photosynthetic carbon fixation. It operates such that stomata open during the night to uptake CO_2 and store it in the form of an organic acid (usually malate) in the cells vacuoles. During the following daylight period, stomata remain closed while stored organic acid is decarboxylated back into CO_2 as the source for the normal photosynthetic carbon reduction cycle (Cushman, 2001).

Drought tolerance of *Sedum* species has been well tested. Lassalle (1998) found that *S. album* L. (white stonecrop) could survive more than 100 d without water. Others have confirmed that *S. album* is a drought-hardy species (Kirschstein, 1997), along with *S. acre* L. (biting stonecrop), *S. kamtschaticum ellacombianum* Fischer & Meyer (orange stonecrop), *S. pulchellum* Michaux (bird's claw sedum), *S. reflexum* L. (crooked stonecrop), *S. spurium Bieb.* '*Coccineum*' (creeping sedum), and *S. spurium Bieb.* '*Summer Glory*', all of which survived 88 days without water (VanWoert et al., 2005b). One species of *Sedum*, *S. rubrotinctum* R. T. Clausen (stonecrop), was found to survive at least 2 years without water in a greenhouse (Teeri et al., 1986).

Not only do many *Sedum* species tolerate drought conditions, they also have strong persistent qualities. In Germany, Liesecke (1999) tested different types of green roof constructions and found that *S. album* was a dominant persistence species for all types of construction tested, followed closely by *S. sexangulare* L. (tasteless stonecrop). Monterusso et al. (2005) reported 100% survival of several *Sedum* spp. during the course of 3 years when grown on roof platforms.

Besides *Sedum* spp., other succulents such as *Delosperma*, *Euphorbia*, and *Sempervivum* can be appropriate choices for extensive roofs because they have many of the same characteristics as *Sedum*. Here again, local climatic conditions will dictate possibilities. *D. nubigenum* (Schltr.) L. Bol. (iceplant) is an excellent choice in Maryland, but has yet to survive a winter in Michigan. Other taxa have been tested and can be used on green roofs as well. Liesecke (2001) found seven tuberous plants to be good choices for German extensive green roofs and there is a good argument to limit the monoculture of *Sedum*-based roofs and include more native species.

In the midwestern United States there is a great deal of interest in using native species and recreating natural prairies on rooftops. In Michigan, 18 native taxa and nine *Sedum* spp. were evaluated on nonirrigated extensive green roof platforms during a 3-y period (2001–2004) for growth, survival during both establishment and overwintering, and visual appearance (Monterusso et al., 2005; Rowe et al., 2005). All nine *Sedum* spp. tested were found to be suitable for use on Midwestern green roofs. However, of the 18 native taxa studied, *Allium cernuum* L. (nodding wild onion), *Coreopsis lanceolata* L. (lanceleaf coreopsis), *Opuntia humifusa* Raf. (prickly pear), and *Tradescantia ohiensis* L. (spiderwort) were the only species that still existed after 3 y. If irrigation had been available, then other native species would have likely survived. Even so, the species that did survive could be incorporated into a standard *Sedum* roof that is not irrigated to add diversity and aesthetic appeal. The upright form of both nodding wild onion and spiderwort would provide contrast to the horizontal spreading stonecrops.

Although the majority of the plants tested were considered to be drought tolerant, most native prairie species rely on deep tap roots to obtain moisture—a situation that cannot exist on a shallow extensive roof. All 18 of the above mentioned nonsucculent native species thrived when irrigated during the first season, but suffered when irrigation was not provided during the second and third season (Monterusso et al., 2005). An alternate strategy is to consider plants native to the shortgrass prairies found further west in locations such as Colorado. These plant communities receive less annual rainfall and many have shallower root systems. An excellent example of an extensive green roof native plant community is the convention center of the Church of Jesus Christ of Latter-day Saints in Salt Lake City, Utah (Fig. 4). However, to maintain the roof's high visual appeal, the roof requires irrigation and intense maintenance. Regardless, many native species may be suitable and a need for further testing is needed.

Because of the variability of green roof design and climate in the United States, it would be impractical to list every possible plant candidate for extensive green roofs. However, as a general rule, potentially suitable species can be found by looking at the microclimate (media depth, solar levels, water availability, and so on) of the green roof in question and comparing it with a plant's native habitat. Dunnett and Kingsbury (2004) suggest that species that evolved in extreme conditions, such as mountainous terrain, high-altitude environments, coasts, limestone substrates, or semideserts, are probably suitable for green roof habitation. These authors give further in-depth analysis of potential plant species as well.

Plant installation and maintenance

Plants can be established directly upon the green roof media via seed, plugs, or cuttings. Alternatively, vegetation can be pregrown at ground level in the form of a blanket, mat, or tray and then placed on the roof. This latter method has the logistical disadvantage of hauling the pregrown vegetation up to the roof, but offers immediate gratification in the form of 100% coverage. If planting plugs, the plant species, substrate depth, and availability of water are all factors in determining the appropriate planting density of each species to achieve optimal green roof coverage in the desired time frame. Another option is spontaneous colonization, during which growing substrate is installed and one waits for plants to colonize the roof. Although, this method is less expensive, sustainable, and may ensure that local species will result, it does not guarantee that these species are actually native to the area. Also, the visual appeal may be questionable to some.

Regardless of installation method, the ideal time to plant is in the spring after the last frost, or during the autumn before the first frost. Depending on location, installation during the summer may require supplemental irrigation (especially for cuttings that may dry out before they root) and possibly shade cloth (to protect seeds and cuttings from scorching). Initial irrigation will be required immediately after planting, and the frequency of watering during the first few weeks of establishment will depend on the amount of rainfall. Thereafter, vegetation can be slowly weaned off supplemental watering. The need to provide long-term irrigation depends on climate, plant selection, substrate composition and depth, and desired aesthetic quality.

When vegetation has been established, a roof inspection is recommended once or twice per year for optimal roof and plant performance (ASTME, 2006; Dunnett and Kingsbury, 2004; FLL, 1995). This involves determining the need for fertilization, weeding of undesirable species, infilling bare spots (with cuttings, plugs, or seeds), replacing eroded substrate, pruning vegetation back from building structures, and clearing plant debris away from roof drains. Keeping drains clear is of particular importance, because a clogged drain could result in standing water over the vegetation, possibly leading to plant fungal diseases and dieback (Dunnett and Kingsbury, 2004).

Fertilizers and pesticides should be used with caution, especially if stormwater runoff quality is of particular concern. If needed, a slow-release NPK fertilizer for extensive green roofs is recommended at the rate of $5\ g\cdot m^{-2}$ of N (FLL, 1995). As mentioned earlier, Rowe et al. (2006) reported that three herbaceous perennials that received no fertilizer produced the least amount of growth, but exhibited higher survival rates than those that received fertilizer. In contrast to containerized nursery stock in a production schedule, maximum growth is not always desirable on a green roof. Ideally, a green roof fertilization schedule would use enough fertilizer to maintain acceptable plant health and aesthetics while minimizing the amount of runoff contamination. Emilsson (2004) studied three fertilization levels (low and medium rates of controlled-release fertilizer [CRF] and CRF in combination with water-soluble applications) on two types of green roof vegetation in Sweden (old prevegetated mats and fertilization of newly established green roofs). All had the potential for nutrients leaching into stormwater runoff. In addition, fungicides, herbicides, and insecticides should be used sparingly or not at all because of the potential for premature degradation of roof membranes and runoff concerns (ASTM, 2006).

Also, maintaining vigorous, healthy green growth throughout a drought period will maintain a roof's aesthetic appeal and does not necessarily influence the functional qualities of the roof. VanWoert et al. (2005a) compared stormwater retention on vegetated, substrate only, and conventional roofs with a gravel ballast. There were no significant differences in stormwater retention between the roofs that were vegetated with stonecrop and those that were covered with substrate only. This suggests that the main factor for water retention is the physical properties of the media.

However, plant species can influence stormwater retention of green roofs as a result of differences in shading and rates of transpiration (Dunnett et al., 2005). VanWoert et al. (2005b) showed that even though several *Sedum* spp. survived for 88 d without water, their evapotranspiration rates dropped to nearly zero by day 4. Such low rates of evapotranspiration would likely diminish the potential of a green roof system to provide cooling to the building underneath. If sufficient substrate moisture was available, either naturally or through supplemental irrigation, then taxa exhibiting higher transpiration rates may result in decreased water runoff, as well as greater evaporative cooling potential.

The Future of Green Roofs in North America

Will green roofs ever catch on in the United States as they have in Europe? Several barriers to widespread acceptance exist; however, the same barriers have been overcome in Germany. First, there is a lack of awareness regarding green roofs, but education can help alleviate this problem. Green Roofs for Healthy Cities (GRHC), a nonprofit organization based in Toronto, has increased public awareness by offering classes in green roof implementation; encouraging interaction among industry professionals, public policymakers, and academic researchers; and organizing an annual green roof conference. The first GRHC conference in North America took place in Chicago during 2003. Public awareness of green roofs has increased dramatically during the past few years. Whenever a green roof is constructed, it usually draws attention. During Ford Motor Company's centennial celebration in 2003, their 42,900 m^2 green roof was the subject of much media coverage.

Second, green roofs may cost up to twice as much to install. However, the lifetime of a conventional roof is about 20 years, whereas a green roof should last 40 years or longer. Plus, there are all the added benefits such as energy savings to the building owner, stormwater management benefits for developers, as well as the other ecological, economic, aesthetic, and psychological benefits to society as a whole. Although the benefits to the building owner and the community at large (less waste to go to a landfill when the roof is replaced) are obvious, a roofing contractor that replaces roofs may not look at this as a positive.

Third, there is still a lack of quantifiable data pertaining to the benefits that green roofs can provide to the building owner, its occupants, and the community. Data of this nature exist for some areas (primarily Germany), but most is not transferable to specific climatic conditions found in North America and is not written in English. Also, much of the current information is anecdotal in nature, proprietary, or the experiments were not performed in a replicated study. In the United States, academic green roof research programs have been established at Penn State, North Carolina State, and Michigan State universities to address these problems. Researchers are addressing questions of plant species, substrates, water retention and water quality issues, energy conservation, and cost/benefit analysis.

Fourth, there is a lack of technical information on how to build them. The Germans have had written green roof standards for construction for more than a decade. On the other hand, standards and building codes pertaining to green roof design and construction do not exist in the United States. How do roofing contractors know if they are doing the job correctly when there are no directions or experience to rely on? How do they prepare an accurate bid? An American Society for Testing of Materials (www.astm.org) international committee of professionals from industry and academia are currently writing green roof standards for the United States. Five standard documents pertaining to green roofs have been published within the last 6 months, including a standard guide for selection, installation, and maintenance of plants for green roofs; a standard practice for determination of dead loads and live loads associated with green roof systems; and standard test methods for maximum media density for dead load analysis, for water capture and media retention of geocomposite drain layers, and for saturated water permeability of granular drainage media. In the near future, additional standards will be available and the lack of technical information and experienced contractors will be a thing of the past. In addition, Penn State University is now offering a service for testing and certifying green roof substrates and roofing membranes.

Finally, Germany has experienced a 10% to 15% growth per year in the green roof industry during the past 10 y. Many cities in Germany have incentives of one kind or another to encourage the building of green roofs, because the widespread adoption of this technology saves the cities from building additional expensive detention mechanisms. For example, the city of Esslingen in Germany will pay up to 50% of the cost of installing a new green roof, and the city of Darmstadt will pay up to 5000 Euros toward a new green roof. The city of Bonn reduces the landowners' monthly stormwater fees by 0.75 Euro/m^2, and the cities of Cologne and Mannheim will slice the stormwater fee in half (Herman, 2003).

Other municipalities throughout the globe are following suit with these incentives. In Tokyo there is an ordinance that new buildings with more than 100 m^2 of rooftop must have a vegetated roof (Liu and Baskaran, 2003). In Canada, Quebec's Energy Board approved a \$10.76/m^2 incentive for green roof implementation in 2003, as long as the roof meets certain design criteria (Mishra, 2004). In Basel, Switzerland, homeowners can claim 20% of green roof investment costs for converting unused rooftops to vegetative rooftops. This policy was so successful that in 18 months an area the size of seven football fields was greened. Now, there is a new law in that city that all new flat roofs must be greened (Brenneisen, 2004).

In the United States, there are promising strides toward encouraging green roofs as well. In 2003, the city of Atlanta implemented a credit system for the detention or retention of stormwater in which green roofs qualify for a discount on your monthly stormwater bills (Taube, 2003). The cities of Portland, Ore., and Chicago both provide incentives for the creation of green roofs and in some cases the city of Chicago requires green roofs (Liu and Baskaran, 2003). For Chicago, these incentives appear to be working. As of summer 2004, the city has seen more than 92,903 m^2 in green roof commitments or implementation (City of Chicago, Department of Environment, 2004).

Beyond tax incentives, some building owners are providing green roofs for other reasons as well. In New York City, the Earth Pledge office constructed a rooftop garden that provides food for all its workers (Loder and Peck, 2004). In fact, some businesses are reclaiming the unused roof space to save money on food costs. The Fairmont hotel in Vancouver uses its roof to grow food for their restaurant, resulting in a savings of \$30,000 (CDN) per year (Peck, 2005). Other developers are using green roofs as a means to overcome community resistance to infill development, by giving back green space to the community when an unpopular building project is proposed (Loder and Peck, 2004).

Conclusions

Green roofs are one potential method to counteract the destruction of natural habitats as we further our built environment. Today, we have identified environmental benefits that green roofs can provide such as stormwater retention, stormwater runoff delay and rate reduction, increase roofing membrane life, shading and insulation benefits, biodiversity and habitat, aesthetics, and control of noise and air pollution. Because roofs represent 21% to 26% of urban areas, both residential and nonresidential (Wong, 2005), they provide a unique opportunity. These typically unused spaces can become a way to reclaim habitat that was lost as a result of construction while also aiding in the protection of our environment through more sustainable practices.

Green roofs can provide economic benefits to the green industry. Nurseries that are growing ground covers, perennials, or grasses will have the most to gain. Although woody plants can be used as green roof plants, they require a much deeper substrate, additional maintenance, and the need for a more structurally sound building. For landscape contractors, the potential exists for installations and maintenance contracts. In Germany, many landscape contractors may have construction, maintenance, and green roof divisions, and others may specialize in green roofs alone. In North America, the concept of green roofs is just now being introduced and will likely become more common in the future. They represent an entirely new market for nursery stock and landscape contractors, and the potential market consists of all existing and future roofs in the country.

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