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STORMWATER RETENTION AND WATER USE BY
EXTENSIVE GREEN ROOFS

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STORMWATER RETENTION AND WATER USE BY EXTENSIVE GREEN ROOFS

By

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ABSTRACT

STORMWATER RETENTION AND WATER USE BY EXTENSIVE GREEN ROOFS

By

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Impervious surfaces dominate urban areas and generate considerably more stormwater runoff than natural areas of the same size. Green roofs are one practice that can aid in mitigating stormwater runoff. To determine the degree that green roofs aid stormwater mitigation, simulated roof platforms were utilized to compare stormwater retention capabilities of various roof surfaces, roof slopes, and media depths. On average, the vegetated green roofs composed of *Sedum* spp. retained 34% more stormwater per rain event than the standard roofs. In the roof slope and media depth study, the greatest retention (87%) occurred on platforms set at a 2% slope with a 4 cm media depth. Results from both studies indicate that green roofs also delay the start of runoff for several minutes and spread it out over a longer period of time. A third study determined water use trends and minimum irrigation requirements for green roof vegetation consisting of seven *Sedum* spp. After watering, substrate moisture was often reduced to zero in as little as 24 hours. *Sedum* in deeper substrates resulted in greater growth if provided with sufficient water, but these plants also experienced an increased evapotranspiration rate. Over the 88 day study, water was required at least once every seven days to promote growth in the shallowest green roof substrates and every 28 days with 6 cm of media.

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LITERATURE REVIEW

Stormwater Retention and Water Use by Extensive Green Roofs

Brief History

The concept of vegetated rooftops, commonly referred to as "green roofs", can be traced back for centuries (Osmundson, 1999). The earliest record of plant installations on above-ground structures were the ziggurats built in ancient Mesopotamia during the fourth millennium B.C. Later, around 600 B.C. in this same region, one of the most famous ancient green roofs was built, the Hanging Gardens of Babylon. In the 14th and 15th centuries, during the Italian Renaissance, extravagant roof plantings were sometimes built by the wealthy. Around this same time on the other side of the world, the Aztecs installed roof gardens in the city of Tenochtitlán, now the site of modern-day Mexico City (Osmundson, 1999). In 18th century Germany, it was considered fashionable for flat-roofed castles and manor houses to be covered with vegetation (Herman, 2003). Most of these historical roofs no longer exist, but remnants of the sod covered houses of Norway and of the Great Plains of North America can still be found (Osmundson, 1999).

Modern Green Roofs

Today, modern vegetated roofs are categorized into either intensive or extensive green roofs, depending on their construction and purpose (Beattie and Berghage, 2001). Intensive roofs are generally much more extravagant and expensive. They are usually limited to flat roofs and may include sod, shrubs, and even trees as plant material (Panayiotis et al., 2003) with areas for human traffic that creates a park-like setting. Because of the plants used in intensive green roof installations, substrate depths of 25 cm or more are often required. Intensive roofs require considerable maintenance such as irrigation and fertilization as well as mowing if sod has been installed (Giesel, 2001). Intensive green roofs may also be utilized as community gardens for vegetable and herb production. Some famous sites incorporating intensive green roofs in their architecture include Rockefeller Center in New York City, the Museums of African and Asian Art at the Smithsonian Institution in Washington, D.C., and Union Square in San Francisco (Osmundson, 1999).

While intensive green roofs are installed mainly for human enjoyment, extensive green roofs rarely include public access. These roofs are installed primarily for their environmental and economic benefits, but still add aesthetic value. Drought tolerant plants are common because substrate depths are in the range of 2.5 to 15 cm and irrigation systems are rarely permanently installed. Extensive green roofs are generally considered to be low-maintenance, needing only an annual fertilization, periodic inspection, and cleaning of roof drains to keep them free of vegetation. Chicago City Hall, Schiphol International Airport in Amsterdam, Ford Motor Company's Rouge Assembly Plant (Dearborn, Michigan), and the GAP Inc. headquarters (San Bruno, California) all utilize extensive green roofs on portions of their buildings.

Extensive Green Roofs

Extensive green roofs are often referred to as "layered systems" because they consist of several layered components. A representative profile from the roof deck upward may include: a waterproofing membrane, root barrier, drainage layer, water retention layer, a filter fabric for sediment retention, substrate, and vegetation. Green roof suppliers modify this profile depending on the materials they offer and the local climate where the project is located, but most extensive green roofs are similarly constructed. An exception would be modular units which are essentially planted containers placed side by side on the roof.

Membranes, Drainage Layer, and Filter Fabric. The waterproofing membrane is arguably the most important layer of the roof profile. Generally, this membrane is composed of flexible materials such as styrene butadiene styrene (SBS)-modified bitumen, elastomeric asphalt, or polyvinyl chloride (PVC) based products. Two components are used that aid in extending the life of the waterproofing membrane: a membrane resistant to root growth and a drainage layer. One commonly used root-proofing membrane is high density polyethylene (HDPE). Certain manufacturers offer membranes that serve as both water- and root-proofing due to either the strength of the membrane or a chemical treatment (Boivin et al., 2001).

The drainage layer, located above the water proofing membrane and root barrier, prevents standing water by allowing excess water to exit the roof. This layer is the most variable among green roof suppliers. One choice on the market is a drainage system composed of an egg-crate-like plastic sheet that also retains water for plant use. Another supplier uses a product with nylon coils attached to the underside of geotextile filter fabric. In combination with a water-retaining fleece layer, this design also increases the amount of water available to the vegetation in times of drought. Above the water retention layer, a geotextile filter fabric is highly recommended to prevent the growing substrate from eroding and exiting the roof.

Substrate. Two important attributes of growing substrates for extensive green roofs are water holding capacity (WHC) and weight. Given substrate depths in the range of 2.5 to 15 cm, the substrate should have a WHC high enough to sustain plant life, yet maintain a relatively light saturated weight. Many substrates are used by green roof suppliers and the composition of these substrates is often considered proprietary information. Using a combination of heat-expanded slate (PermaTill®, a lightweight mineral substrate component commonly used for green roofs), sand, and organic matter, Monterusso (2003) studied the effect of substrate composition on plant establishment and vigor for extensive green roofs. Substrate volumes of PermaTill® ranging from 60 to 100% were studied with varying results. *Sedum middendorfianum* 'Diffusum' L. and *S. spurium* L. survived and resulted in 100% coverage even when grown in a substrate consisting of 100% PermaTill®. However, when planting Michigan native herbaceous species, substrates containing greater than 80% PermaTill® reduced plant vigor (Monterusso, 2003). Lassalle (1998) studied the effects of substrate depth (5, 10, and 15 cm) and substrate WHC (58.4% and 27.4% maximum WHC) on drought stress for three plant species that could be used on extensive green roofs. In all treatments, *S. album* L. outperformed *Festuca glauca* Vill. and *Chrysanthemum leucanthemum* L. concerning visual appearance under drought conditions. *F. glauca* and *C. leucanthemum* both performed better in the substrate with a higher WHC, although an increase in substrate depth lessened the effect from differences in WHC between the two tested substrates.

As previously mentioned, green roofs can be extremely heavy due primarily to the weight of the planting substrate (Panayiotis et al., 2003). Weights can be as low as 43 kg•m^{-2} for the shallowest extensive green roof, and can range up to 488 kg•m^{-2} or more for intensive roof gardens. Extensive roofs are usually fairly uniform in their weight distribution because the substrate is evenly installed, eliminating the need for special structural support in localized areas of the roof.

Vegetation. The top vegetative layer of extensive green roofs can also be relatively variable between green roof companies. In general, the vegetation should be tolerant of drought, high winds, intense sunlight, and low fertility (Fischer and Jauch, 1992; Koehler, 2003). In fact, Jauch (1993) found that many *Sedum* spp. commonly used on green roofs do not survive when excessively fertilized. The plants should also be relatively low growing and fast spreading while requiring minimal maintenance (Panayiotis et al., 2003). *Sedum* spp. are likely the most commonly used plants for extensive green roofs, but *Allium* spp., mosses, and other succulent plants are also used (Koehler, 2003; Kolb, 1995).

In certain climates, the vegetation must tolerate both large annual temperature swings as well as snowfall. Past studies have documented the effects of substrate depth on plant propagation, growth, and survival (Boivin et al., 2001; Durhman et al., 2004; Lassalle, 1998). In Quebec, Boivin et al. (2001) found that substrate depth can influence freezing injury in certain herbaceous perennials. Of the six species tested, creeping baby's breath (*Gypsophila repens* L.), and stonecrop (*S.* x *hybridum*) experienced significantly more damage when planted in 5 cm of substrate compared to 10 cm and 15 cm. Sandwort (*Arenaria verna* 'Aurea' L.), sea pink (*Armeria maritima* Willd.), and whitlow grass (*Draba aizoides* L.) all exhibited cold damage, although substrate depth had no effect. Growth of bugleweed (*Ajuga reptans* L.) tended to be affected by substrate depth, but only in one of the two years of study. The researchers concluded that in their climatic region, a minimum substrate depth of 10 cm should be used for the green roof system constructed for their study (Boivin et al., 2001). However, climate is only one of the important considerations that must be addressed for each site of an extensive green roof.

Another consideration for extensive green roofs is plant establishment. Five methods are currently used for establishing vegetation: 1) seeding, 2) planting plugs, 3) distributing plant cuttings, 4) modular trays, and 5) vegetation mats. The first three are self-explanatory. With modular trays, the vegetation is grown off-site in plastic trays and, when installed, creates an "instant" green roof. Vegetated mats are relatively similar to modular trays in its ability to create a pre-vegetated green roof. However, mats are propagated and grown in a field, either cut into sections or rolled up like sod, transported to the site, and then placed on the roof. Most of these methods and products have been developed in Germany where studies on extensive green roofs have been conducted for more than 20 years (Herman, 2003).

Sedum

Numerous experiments have been conducted in Germany studying *Sedum* as the primary genus for extensive green roofs. The success of *Sedum* in Germany has led to research in other parts of the world to determine the potential of this genus for use in other climates. In Spain, researchers have developed a large plant palette of *Sedum* species for use on green roofs near Madrid (Gómez-Campo, 1994; Gómez-Campo and Gómez-Tortosa 1996). Preliminary results from research in Sweden indicate that several *Sedum* species will survive on extensive green roofs in that climate (Emilsson, 2003). In Michigan, Monterusso (2003) found that *S. middendorfianum* 'Diffusum' and *S. spurium* 'Royal Pink' outperformed many Michigan native herbaceous perennial taxa with respect to their aesthetic qualities and their tolerance to drought. Their study showed that these cultivars and many other *Sedum* species, were suitable for extensive green roofs in the climate of the Midwestern United States.

Generally, *Sedum* is favored for extensive green roofs because with proper species selection, the plants meet most of the previously mentioned general requirements of the vegetation layer. *Sedum* spp. are able to meet the drought requirement because of their method of photosynthetic carbon metabolism and their ability to store water. All *Sedum* spp. are succulents, and are categorized as crassulacean acid metabolism (CAM) plants, one of three mechanisms for the uptake of CO_2. CAM plants have the ability to fix CO_2 in the dark for later use in photosynthesis. By opening their stomata at night for the uptake of CO_2, they limit water loss due to transpiration (Ting, 1985). The other pathways of CO_2 uptake, C_3 and C_4, result in the stomata being open throughout the daylight hours for the uptake of CO_2 to use in photosynthesis, leading to greater rates of transpiration. Facultative CAM plants are a variation of CAM and are able to shift between C_3 metabolism and CAM depending on soil moisture conditions (Lee and Kim, 1994; Ting, 1985). This ability to shift from one method of metabolism to the other is very beneficial when water becomes available to the plant (Borland and Griffiths, 1990). Several *Sedum* species have shown the facultative CAM trait, including *S. kamtschaticum* Fisch. (Lee and Kim, 1994).

One key to survival under drought stress is water use efficiency (WUE), which is increased in CAM plants. *Sedum* species have been shown to have greater WUE values than most C_3 and C_4 plants (Gravatt and Martin, 1992). Staats and Klett (1995) found that *S. acre* L. required less irrigation to maintain a pleasing leaf color when compared with C_3 and C_4 plants in a study that explored alternatives for lawn utilization. They also found that the quality of this species with no supplemental irrigation was almost as good as that of irrigated plants.

The degree of CAM expression can be quite variable within the same species. For example, researchers discovered great variability between populations of *S. wrightii* A. Gray from different altitudes with regard to WUE and plant survival under drought stress (Gurevitch et al., 1986). In a controlled environment, they compared plants propagated from wild populations collected from three different elevations. Plants originating from elevations of ca. 360 meters exhibited WUE values more than twice those of plants originating from elevations of ca. 1,500 and ca. 2,400 meters.

Some *Sedum* species are able to store extra water in their leaves and shoots (Kirschstein, 1997b; Teeri et al., 1986). Teeri et al. (1986) showed that apical portions of *S. rubrotinctum* R.T. Clausen could survive at least two years without supplemental water in a greenhouse due to its ability to reallocate water to viable plant parts. Kirschstein (1997b) studied the root water potential of *Sedum* and concluded that this mechanism also helps the plant survive periods of drought. Kirschstein (1997a) explained that the frequency of rain was more important to succulent plants than the total amount of rain because they are able to recover with only small amounts of moisture. After a period of drought in a greenhouse, many *Sedum* spp. recovered within one week of soil rehydration.

Several *Sedum* species are available for use on green roofs, but, *S. album* may be the most widely used. Gómez-Campo (1994) observed that *S. album* resists drought and cold. It reaches 10 to 12 cm in height while its roots only penetrate 2 to 3 cm into the soil. Stephenson (1994) notes that *S. album* is generally a rapid spreader. This plant can also add aesthetic interest due to its white flowers and changing leaf color depending on environmental conditions.

Numerous other species of *Sedum* such as *S. acre*, *S. kamtschaticum ellacombianum*, *S. pulchellum* Mich., *S. reflexum* L., and *S. spurium*, among others, are commonly used on green roofs. *S. acre*, a vigorous, yellow-flowered species, is approximately 10 cm in height when mature. *S. kamtschaticum ellacombianum* is very adaptable to different climatic conditions. This yellow-flowered species reaches 10 to 15 cm in height, and spreads quickly, forming a dense mat of vegetation. *S. pulchellum* sometimes acts as an annual, but is still used for green roofs. The plant produces pink inflorescences on stems up to 15 cm tall, although the vegetative stems are usually shorter. *S. reflexum*, also referred to as *S. rupestre* L., is a 10 to 30 cm tall, grayish-green plant that is suited to drought conditions and full sun. *S. spurium* has numerous cultivars; most are fast growers. The plant height is usually less than 10 cm, although the creeping stems are often much longer (Kirschstein, 1997b; Stephenson, 1994).

Benefits of Green Roofs

Numerous economic and/or environmental benefits can be attributed to extensive green roofs. Green roofs can extend the life of waterproofing membranes, reduce summer cooling costs, and aid in reducing Urban Heat Islands (UHI), all due to the thermal regulation and UV radiation diffusion effects they offer. The vegetation of a green roof can reduce both air and water pollution. They are also able to retain stormwater, lessening the burden on storm sewers.

Stormwater Management – Stormwater Retention. One of the most important environmental benefits of green roofs is that they are a valuable management tool for controlling the quantity and quality of stormwater runoff. A modeling study conducted in the Vancouver, Canada region found that over the next 50 years the effects of climate change and the changes in land use could be nullified by retrofitting existing buildings with green roofs (Graham and Kim, 2003). The study also showed that over time, this practice could help restore the health of the area watershed.

Certain local governments realize the benefits that green roofs can have on stormwater management. Some Swiss and German municipalities have passed laws promoting the use of green roofs and many offer incentives (Beattie and Berhage, 2001; Osmundson, 1999; Peck et al., 1999). Osmundson (1999) reports that 25% of all new commercial construction in Swiss cities must utilize vegetation in an environmentally conscious manner; green roofs are one method of meeting this requirement. The government of Stuttgart, Germany subsidizes half the cost of the city's green roof installations (Osmundson, 1999). Since 1977, the city of Portland, Oregon has collected a stormwater fee from developed properties with impervious surfaces such as roofs and pavement. Termed "ecoroofs" in Portland, green roofs have been recognized by the city government as an effective method for managing stormwater. The city is working to reduce stormwater fees by 2006 for properties utilizing green roofs (Liptan, 2003).

Numerous studies quantifying the capabilities of green roofs to retain and delay stormwater from exiting roofed surfaces have been conducted around the world (Liesecke, 1999; Liu, 2003; Moran et al., 2003; Monterusso et al., 2004; Rowe et al., 2003; Schade, 2000). German studies have shown that a green roof with a depth of 2 to 4 cm and a vegetation mix of mosses and *Sedum* can retain 40% to 45% of the annual precipitation that falls on it (Liesecke, 1998). A mixture of *Sedum,* grass, and herbs on a 10 to 15 cm deep green roof can retain up to 60% of the stormwater (Liesecke, 1993). However, there were noticeable differences in warm weather (summer) versus cool weather (spring and fall) retention with the shallow substrate depth retaining 11% more stormwater in warm weather than it did during cold weather (Liesecke, 1993). The effect of the deeper substrate was even more pronounced with a warm weather retention rate over 20% higher than it was during cool weather. Liesecke (1998, 1993) attributed this seasonal difference to the fact that the rate of evapotranspiration on the green roof was essentially zero during cold weather. After a dry period, Liesecke (1999) noted that green roofs have a higher level of water retention. Studies conducted on a research roof in Ottawa, Canada also show the effect on water retention green roofs provide (Liu, 2003). Over a six month period in 2002, the green roof reduced the total runoff by 54%.

Several studies have shown a delay in peak flow and reduced rate of runoff from a green roof when compared to a standard roof and also extending the runoff out over a longer period of time (Liesecke, 1999; Liu, 2003; Moran et al., 2003; Schade, 2000). In a controlled environment, with all rain events with an intensity of 13.5 mm in 15 minutes averaged, 96% of the water from graveled test-roofs, and 100% of the water from membrane-only test-roofs had exited the roof 30 minutes after the rain event (Liesecke, 1994). However, on some of the various green roofs, only 35% to 51% of the water had been allowed to run off after the same time period. Liesecke (1999) generalized that considerable amounts of runoff do not occur until 15 minutes after the start of a rain event in which 27 mm of rainfall occurs in 15 minutes on green roofs. Liu (2003) also demonstrated the stormwater runoff delay that green roofs provide. During a light rain (19 mm in 6.5 hours), the green roof delayed the discharge of stormwater for 95 minutes. However, during a heavy rain (21 mm in 21 minutes) the delay was only four minutes.

Schade (2000) and Liesecke (1999) have shown that in certain cases, increasing roof slope does not necessarily increase runoff volume. In a study of the effect roof slope has on runoff from green roofs, it was found that there was no significant difference in total runoff between green roofs at 1.15°, 10°, 20°, and 30° slopes when a pre-cultivated vegetation mat construction style was utilized (Schade, 2000). Liesecke (1999) conducted studies on roofs with an 8.7% slope and found the annual retention rates comparable to roofs at a 2% slope. Annual retention rates for the roofs with an 8.7% slope were in the range of 55% to 65%. Differences in slope were least noticeable when the substrate was already wet or completely saturated.

Stormwater Management – Runoff Quality. The reduction in quantity of runoff from roofs may lead to an increase in stormwater runoff quality, and eventually surface water quality. This fact becomes important because according to the United States Environmental Protection Agency (USEPA) (2003), "The most recent National Water Quality Inventory reports that runoff from urbanized areas is the leading source of water quality impairments to surveyed estuaries and the third-largest source of impairments to surveyed lakes". Most stormwater runoff is allowed to enter directly into natural waterways. During heavy rain events large quantities of rapidly moving runoff flows into waterways causing erosion and carrying sediments with it downstream. Other problems are also associated with paved and tar-sealed surface runoff water, such as higher temperatures due to the water traveling across hot, impervious surfaces like roofs, roads, and parking lots (USEPA, 2003).

A large number of studies have been conducted in Switzerland concerning the quality of roof runoff (Bucheli et al., 1998a). Bucheli et al. (1998a) detected low levels of three common classes of pesticides in roof runoff from atmospheric particulate deposits. Other studies of roof runoff contained higher amounts of numerous heavy metals and nutrients when compared to rainfall, likely due to the runoff mobilizing particulate pollutants when flowing across the roof (Mason et al., 1999; Quek and Förster, 1993). Researchers have concluded that such roof derived pollutants will impact water resource quality if no cleansing measures are taken (Zobrist et al., 2000). Green roofs could provide benefits for roof runoff content by retaining particulate matter in the substrate and by reducing the total water flow off of the roof, therefore reducing the total mass of pollutants leaving the roof. However, one study the researchers conducted found elevated levels of a herbicide in the roof runoff relative to the corresponding rainwater (Bucheli et al., 1998b). The source of the pollutant was found to be the roof sealing agents that were used, which ironically, incorporated the herbicide to serve as a root barrier for use in green roofs. This data suggests that manufacturers of root protection membranes should use great caution when incorporating herbicides for root protection. It should be noted that most root protection membranes/layers do not use herbicides.

Energy Conservation. The thermal performance of extensive green roofs provides both economic and environmental benefits. The economic benefits come in two forms: less-frequent waterproofing membrane replacement and lower energy costs during warm weather. The large membrane temperature fluctuations found on typical dark roofs hasten deterioration of the membranes because of repeated daily expansion and contraction (Stein, 1990). Normally dark membrane surfaces absorb solar radiation during the day and are heated to very high temperatures, then cool at night (Liu, 2003). Temperature stabilization of the waterproofing membranes by green roof coverage may extend their useful life by more than 20 years (USEPA, 2000).

Lükenga and Wessels (2001) showed that green roofs stabilize the temperature fluctuation caused by solar radiation over both daily cycles and the course of the year. They found that black bituminous covered roofs can reach up to 90°C in Osnabrück, Germany, while the maximum temperature of green roofs only reached 20°C. Liu (2003) obtained similar results in Ottawa, Canada on experimental roof sections comparing a green roof and a standard reference roof. The bituminous membrane on the unvegetated reference roof reached temperatures over 70°C in summer, while the membrane underneath the green roof only reached 30°C. The membrane on the reference roof reached 30°C on 342 of the 660 days of the study, but the membrane underneath the green roof only reached that temperature on 18 days. For the 60°C level, the reference roof and green roof surfaces reached that level 89 days and zero days, respectively.

During warm weather, green roofs provide a cooling effect by reducing the thermal flux through the roof, thus lowering the energy demands of the building's cooling system (Del Barrio, 1998; Eumorfopoulou and Aravantinos, 1998;

Lükenga and Wessels, 2001; Niachou et al., 2001; Theodosiou, 2003). Wong et al. (2003b) studied heat flux through intensive green roofs in the tropical environment of Singapore. Heat transfer through the green roof was less than 10% of that of a reference hard surfaced roof over a typical day. The researchers also made comparisons of heat flux beneath individual plant species. Over the course of the study, heat gain was never recorded under Raphis palm (*Rhapis excelsa* (Thunb.) Henry). Overall, vegetative covered roofs experienced more heat loss than gain which is positive in tropical environments. Research in Japan has also shown favorable results (Onmura et al., 2001). The researchers estimated that their research green roof reduced incoming heat flux by 50% on a building in Japan. Similar results were obtained in Ottawa, Canada, where a 47% reduction in total heat flow (heat gain and heat loss) was demonstrated over the course of study (Liu, 2003). A 95% reduction in heat gain was also demonstrated. Averaged over the course of study, the daily energy demand for the building covered with a green roof was 75% less than the demand placed on the building with a reference roof.

Urban Heat Island Effect. A common occurrence in urban areas, rising temperatures due to the urban heat island effect (UHIE) are likely to continue if additional green space is not added. The UHIE forms when the constructed surfaces of urban areas collectively raise the ambient air temperature by up to 6.7°C higher than that of surrounding rural areas (Osmundson, 1999). The constructed surfaces cause the UHIE by emitting infrared heat from their surfaces that they collect throughout the day (Osmundson, 1999). Dimoudi and

Nikolopoulou (2003) have shown that vegetation can help reduce the often-higher ambient air temperatures in an urban environment. They predict that in their simulated urban areas, a 10% increase in the current levels of the ratio of green space to constructed surfaces will lead to a 0.8°C reduction in ambient air temperature. Wong et al. (2003b) concluded that green roof vegetation promotes temperature reduction for the UHIE. They found that temperatures at 300 mm above the roof surface were up to 4.2°C lower on a green roof compared to a reference roof.

Other Benefits. Green roofs also offer other environmental benefits. Herman (2003) indicates that green roofs are often installed to replace lost green space due to urbanization. Liesecke and Borgwardt (1997) reported that extensive green roofs reduce the amount of pollutants from diesel and gasoline engine exhaust. An ecology study conducted on green roofs in West Berlin, Germany, found numbers of oribatid mites, good indicators of a functioning ecosystem, three to more than eight times higher than numbers found in park lawns (Darius and Drepper, 1984). Brenneisen (2003) conducted a field survey and found endangered species of beetles and spiders, among other organisms, on a green roof in Switzerland indicating that a certain level of biodiversity can be reached on these unique ecosystems. A London conservation organization is promoting the utilization of green roofs because they promise to be a new nesting area for the endangered bird species, the black redstart (*Phoenicurus ochruros*) (Gedge, 2003). In addition to the ecological benefits, several economic benefits can be had as well including the formation of a whole new industry sector to promote, provide, and maintain green roof installations (Wong et al., 2003a). Rowe (2003) reported that plant material orders totaled more than $200,000 for the green roof on Ford Motor Company's Rouge Assembly Plant in Dearborn, Michigan. Various studies have documented the positive influence of plants on human well-being and reduced stress (Relf and Lohr, 2003) and there is no reason why green roofs would not result in similar environmental and economic benefits.

Conclusion

German green roof research has been driven by several forces: environmentally-minded citizens with concerns about stormwater management, lost green space, energy savings, and cost savings (Herman, 2003). Green roofs have been installed on an estimated 14% of all flat roofs in Germany (Herman, 2003). Researchers have conducted studies on numerous aspects of green roofs including growing substrate composition, plant selection, and construction methods, and have published more than 950 reports of their findings. The Forschungsgesellschaft Landschaftsentwicklung und Landschaftsbau (FLL), a German landscaping and land development research society, has produced the "Guidelines for the Planning, Implementation, and Maintenance of Green Roofs", commonly known as the FLL standards in the green roof industry (FLL, 1995). The FLL standards have generally been accepted internationally to maintain the quality of installed green roofs (Herman, 2003). However, updated standards for North America are currently being written by ASTM International.

Although various forms of green roofs have been around for centuries, researchers have only recently begun to quantify their benefits. Numerous sources of information can be found, both scientific and popular, to educate and inform the public about green roofs, although most are not in English. However, limited scientific research has been performed in North America, more specifically, the Midwestern United States. In order for green roofs to gain acceptance in the United States, there needs to be published regional research that resolves the many claims offered by researchers in other parts of the world.

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CHAPTER ONE

Roof Surface Comparison of Stormwater Retention: Benefits of Green Roofs

Roof surface comparison of stormwater retention: Benefits of green roofs

Additional index words. ecoroof, rain retention, *Sedum*, stormwater management, stormwater runoff, vegetative roof

Abstract

Urban areas generate considerably more stormwater runoff than natural areas of the same size due to a greater percentage of impervious surfaces that impede water infiltration. Roof surfaces account for a large portion of this impervious cover. Establishing vegetation on rooftops, known as green roofs, is one method of recovering lost green space, which can aid in mitigating stormwater runoff. We constructed simulated roof platforms using three different roof surface treatments to quantify the difference in stormwater retention for standard commercial roofs with gravel ballast, extensive green roof systems without vegetation, and typical extensive green roofs with vegetation. Runoff from each roof treatment was quantified and compared relative to incoming rainfall. Overall, mean percent rainfall retention ranged from 48.7% (gravel) to 82.8% (vegetated). When rain events were categorized as light (<2 mm), medium (2-6 mm), or heavy (>6 mm), mean percent retention was greatest during light events ranging from nearly 100% for the unvegetated and vegetated roofs to 85% for the gravel ballast. Mean percent retention ranged from 37.7% to 85.7% during medium rain events and 26.4% to 65.0% during heavy. The vegetated treatment not only reduced the amount of stormwater runoff, it also

delayed the start of runoff for several minutes depending on rainfall category and spread it out over a longer period of time.

Introduction

Urban stormwater runoff has come to the forefront as an environmental concern. The United States Environmental Protection Agency has indicated that a typical city block generates more than five times more runoff than a woodlot of the same size (USEPA, 2003). Urban stormwater runoff carries with it numerous environmental contaminants including pesticides, heavy metals, and nutrients, which may eventually flow into lakes and streams (Bucheli et al., 1998; Mason et al., 1999). According to the USEPA (2003), "The most recent National Water Quality Inventory reports that runoff from urbanized areas is the leading source of water quality impairments to surveyed estuaries and the third-largest source of impairments to surveyed lakes".

Establishing vegetation on rooftops, commonly referred to as green roofs, is an emerging strategy for mitigating stormwater runoff (Monterusso et al. 2004; Moran et al., 2003; Rowe et al., 2003; Schade, 2000). In addition, green roofs offer numerous other benefits beyond stormwater mitigation. They provide insulation for buildings, thus saving on energy consumption (Niachou et al., 2001; Wong et al., 2003); increase the life span of a typical roof by protecting the roof components from damaging ultra violet rays, extreme temperatures, and rapid temperature fluctuations (Giesel, 2001); filter harmful air pollutants (Liesecke and Borgwardt, 1997); provide a more aesthetically pleasing environment to live and work; provide habitat for a range of organisms from microbes to birds (Brenneisen, 2003; Gedge, 2003); and have the potential to reduce the Urban Heat Island Effect (Dimoudi and Nikolopoulou, 2003; Rosenfeld et al., 1998; Wong et al., 2003).

However, stormwater runoff mitigation may be the primary benefit of green roofs due to the combination of the prevalence of impervious surfaces in urban and commercial areas and a failing stormwater management infrastructure (Liptan, 2003). Rapid runoff from roofs and other impervious surfaces can exacerbate flooding, increase erosion, and result in combined sewer overflows that could potentially discharge raw sewage directly into our waterways. Green roofs help mitigate the impact of high density commercial and residential development by restoring displaced vegetation. Studies have shown that green roofs can absorb water and release it slowly over a period of time as opposed to a conventional roof where stormwater is immediately discharged (Liesecke, 1999; Moran et al., 2003; Schade, 2000). Research has indicated that an extensive green roof, depending on substrate depth, can retain 60-100% of incoming rainfall (Liesecke, 1998; Monterusso et al., 2004; Schade, 2000).

This reduction in quantity of runoff from a green roof leads to improved stormwater runoff and surface water quality. Results from a Vancouver, BC modeling study suggest that if all of Vancouver's existing buildings were retrofitted with green roofs over the next 50 years, the health of the area watershed could be restored to natural conditions (Graham and Kim, 2003). This would occur because green roofs have the ability to filter numerous contaminants from rainwater that has flowed across the roof surface (Dramstad et al., 1996). Although minimal, Bucheli et al. (1998) detected concentrations of three common classes of pesticides in non-green roof runoff due to atmospheric deposits. Other studies showed roof runoff contained higher amounts of numerous heavy metals and nutrients when compared to rainfall, likely due to the runoff picking up particulate pollutants when flowing across the roof (Mason et al., 1999). For green roofs, these pollutants can be taken up and degraded by the plants or bound in the growing substrate of green roofs (Johnston and Newton, 1996). Zobrist et al. (2000) concluded that without corrective measures, roof runoff pollutants will lower the water quality of surrounding water bodies.

An estimated 14% of all flat roofs are green in Germany, a nation widely considered the leader in green roof research, technology, and usage (Herman, 2003). In North America, the concept of green roofs is in its infancy. If green roof installations are to become commonplace in the upper Midwest of the United States, quantifiable data that document the ability of green roofs to retain stormwater under the climatic conditions of the region must be available. Data of this nature exist for particular drainage systems in other areas of the continent and Europe, but most is not transferable to these specific climatic conditions. Also, much of the current information is anecdotal in nature, the information is proprietary, or the experiments were not performed in a replicated study. Therefore, our objective was to quantify the differences in water retention among an extensive green roof, an extensive green roof without vegetation, and a standard gravel ballast roof in a replicated study. This information can then be utilized to make decisions concerning green roof usage to mitigate stormwater runoff.

Materials and Methods

Platforms. Three simulated roof platforms with overall dimensions of 2.44 m x 2.44 m were constructed by ChristenDetroit (Detroit, MI) at the Michigan State University Horticulture Teaching and Research Center (East Lansing, MI) (Figure 1). Each platform simulated a commercial roof, including an insulation layer, protective layers, and waterproofing membrane. The platforms were divided into three equal sections measuring 0.67 m x 2.44 m using wood dividers that were also covered with the waterproofing membrane. Lining the platform deck was 3.8 cm of ENRGY 2™ insulation board (Johns Manville, Denver, CO), composed of a closed cell polyisocyanurate foam core and fiberglass reinforced facers. Above the ENRGY 2™ layer was a 1.9 cm thick insulation layer of Fesco® Board consisting of expanded perlite, blended with selected binders and fibers (Johns Manville, Denver, CO). The top layer was a combination of Paradiene 20 (Siplast Inc., Irving, TX), a flexible membrane with an elastomeric asphalt base, and Teranap (Siplast Inc., Irving, TX), a polyester mat coated with styrene butadiene styrene (SBS)-modified bitumen, with a root-resistant polyester film covering the top side.

Aluminum sheet metal troughs were attached on the low end of the platforms to direct stormwater runoff through the measuring devices used to quantify runoff. Each trough was divided into three separate sections corresponding to the three divided sections. The wood-framed platforms included sides that extended 20.3 cm above the platform deck, also covered with the waterproofing membrane. Platforms were set at a 2% slope with the top edge of the high end 0.9 m above ground level and oriented with the low end of the slope facing south to maximize sun exposure.

Drainage System and Vegetation Carrier. Two of the three self-contained sections on each platform used the Xero Flor XF108 drainage layer (Wolfgang Behrens Systementwicklung, GmbH, Groß Ippener, Germany) installed over the Teranap Waterproofing System. A cross section of a representative extensive green roof system is shown in Figure 2. The drainage layer consisted of a geotextile fabric with nylon coils attached on the underside. The total thickness of this layer is approximately 1.5 cm. For additional water holding capacity, a 0.75 cm thick moisture retention fabric (Xero Flor XF158) capable of retaining up to 1,200 $g \cdot m^{-2}$ of water was placed over the drainage layer. The moisture retention fabric is composed of a recycled synthetic fiber mixture consisting of polyester, polyamide, polypropylene, and acrylic fibers. Above the retention fabric was the vegetation carrier (Xero Flor XF301) which included a recycled synthetic fiber fabric similar to XF158 used for water retention sewn to an inverted layer of XF108 that held media and vegetation. This water retention layer could hold up to 800 $g \cdot m^{-2}$ of water and was approximately 0.75 cm thick. The total thickness of the drainage layer and vegetation carrier was approximately 4.5 cm. The system as a whole permits water exceeding the holding capacity of the retention fabric and planting media to drain through the nylon coils and exit the roof.

Plant Establishment. One hundred percent coverage (no visible growing media) was achieved on the vegetated section prior to the initiation of data collection. Plant species used in this study included *Saxifraga granulata* L., *Sedum acre* L., *S. album* L., *S. kamtschaticum ellacombianum* Fisch., *S. pulchellum* Michx., *S. reflexum* L., *S. spurium* Bieb. 'Coccineum', and *S. spurium* Bieb. 'Summer Glory'. The plant mix was applied as seed on 14 May 2002 at a rate of 1.3 $g \cdot m^{-2}$ for each species. All seeds were evenly mixed in dry sand to ensure even distribution when the mixture was sown by hand on the platforms. Seeds were obtained from Jelitto Staudensamen, GmbH (Schwarmstedt, Germany).

Growing media consisted of 40% heat-expanded slate (gradation 3 mm to 5 mm) (PermaTill®, Carolina Stalite Company, Salisbury, NC), 40% USGA (United States Golf Association) grade sand (Osburn Industries, Taylor, MI), 10% Michigan Peat (Osburn Industries, Taylor, MI), 5% Dolomite (Osburn Industries, Taylor, MI), 3.33% composted yard waste (Kalamazoo Landscape Supplies, Kalamazoo, MI), and 1.67% composted poultry litter (Herbruck's, Saranac, MI) by volume. At time of planting, electrical conductivity (EC) and pH of the media were 3.29 $mmho \cdot cm^{-1}$ and 7.9, respectively. Each green roof system platform section was filled with planting media to a depth of 2.5 cm. All sections of the platforms, except gravel, had 100 $g \cdot m^{-2}$ of Nutricote® type 100, 20N-7P_2O_5-

$10K_2O$ controlled release fertilizer (Agrivert, Webster, TX) hand-applied at the time of planting and on 19 May 2003.

Platforms were covered with a plastic shade cloth (Wolfgang Behrens Systementwicklung, GmbH, Groß Ippener, Germany) for the first 52 d after the seed was sown to enhance germination and plant establishment. Seedlings were acclimated from days 52 through 57 by periodically removing the shade cloth depending on the intensity of the sun, after which it was removed permanently.

Upon seed distribution, an automated overhead irrigation system (Rainbird, Azusa, CA) was programmed to run six 10-minute cycles daily (9:00 AM, 11:00 AM, 1:00 PM, 3:00 PM, 5:00 PM, and 7:00 PM) through 15 July 2002. From 16 July until 31 July 2002, the irrigation was reduced to four 10-minute cycles daily (9:00 AM, 1:00 PM, 5:00 PM, and 7:00 PM). Irrigation was terminated on 31 July 2002 once the plants had become established and had achieved 100% coverage.

Roof Treatments. Three roof types were tested: an extensive green roof with vegetation, an extensive green roof without vegetation (media-only), and a conventional commercial roof with a 2 cm depth gravel ballast. A gravel ballast is commonly used on flat commercial roofs to hold the waterproofing membrane in place. The vegetated and media-only sections each contained a green roof drainage system and vegetation carrier as described previously. Roof treatments were arranged in a randomized complete block design (RCBD) with three replications; each platform represented one block and the vegetation, media-only, or gravel ballast treatment was randomly assigned within sections of each platform.

Data Collection and Analysis. Model TE525WS tipping bucket rain gauges (Campbell Scientific, Inc., Logan, UT) were mounted under the drain of each platform section to quantify stormwater runoff. An additional tipping bucket was mounted above each gravel section to record precipitation, catching and releasing quantified water onto the top end of the gravel surface. A model CM6 automated weather station (Campbell Scientific, Inc., Logan, UT) was installed on the research site to record meteorological parameters. The weather station included an ambient air temperature and relative humidity probe covered by a 6-plate gill radiation shield. The weather station also included instruments to measure wind speed and direction as well as photosynthetically active radiation.

Data from the tipping bucket rain gauges and tripod weather station were collected at five minute intervals 24 hours a day from 28 Aug. 2002 through 31 Oct. 2003 using a Campbell Scientific CR10X datalogger equipped with switch closure modules and a storage module.

Retention data were analyzed from all rain events that occurred during temperatures above 0°C as a percentage of total rainfall for each rain event. Frozen precipitation was not physically removed from the platforms. Melting precipitation was allowed into the data set if it fully occurred in temperatures above 0°C. Independent rain events were defined as precipitation events separated by six or more hours. In the event runoff was still occurring six hours after the first event, the two events were combined. Rain events were arbitrarily categorized as light (<2 mm), medium (2 – 6 mm), or heavy (>6 mm). The extent of each category was chosen to get rain event sample sizes that were similar across all three categories.

Data were analyzed as mean percent retention per rain event using an ANOVA model with platform as a random effect and roof treatment and rainfall category as fixed effects. Although original means are presented, all runoff values were transformed prior to analysis using a power transformation (0.4) to stabilize the variance and normalize the data. Significant differences between treatments were determined using multiple comparisons with Tukey-Kramer adjustments (PROC MIXED, SAS version 8.02, SAS Institute, Cary, NC). Total retention values for the study are presented, but were not subjected to statistical analysis due to the limited number of data points.

Results

Measurable precipitation (>0 mm) was recorded on 162 of the 430 days of the study (38%) (Figure 3). Daily precipitation amounts ranged from 0.08 to 53.59 mm. Of the 83 rain events measured during temperatures above 0°C, there were 26 light (<2 mm), 30 medium (2 – 6 mm), and 27 heavy (>6 mm) rain events. A histogram of measured rain events used in our analysis shows the distribution of the measured rain events (Figure 4). Generally, low volume rain events were more frequent than larger rain events.

Daily maximum and minimum ambient air temperatures are shown in Figure 5. Daily low temperatures ranged from -24.6°C to 20.8°C and daily high temperatures ranged from -9.9°C to 34.2°C.

Representative hydrographs (Figure 6) and cumulative hydrographs (Figure 7) from a selected rain event with each rainfall category show the effects that the roof treatments had on quantity, delay of the start, and time duration of runoff. During a representative light rain event, the start of runoff from the vegetated treatments did not begin until 55 minutes after the initial rainfall was measured. This delay was 15 minutes after the time when runoff was detected from the gravel ballast treatment. The start of runoff from the gravel treatments was delayed 10 minutes past the initial rainfall during the representative medium rain event, and 15 minutes for both the media-only and vegetated treatments. Following a delay of 15 minutes after the initial rainfall, runoff from all treatments was detected within 5 minutes of each other during the representative heavy rain event. Runoff was not only delayed during the heavy rain event with the media-only and vegetated treatments, it was spread out over time; the last measured runoff was recorded nearly 3 hours after the rain event ended which was 30 minutes past the last runoff from the gravel ballast treatment.

Over the 14 month period, the vegetated roof treatment retained 337 mm of the 556 mm of cumulative rainfall from the 83 measured rain events (60.6%). The media-only treatment retained 281 mm (50.4%) and, as expected, the gravel ballast roof retained the least rainfall, 151 mm (27.2%). When total rainfall from all light rain events was combined (25 mm), the media-only treatment retained the highest percentage, 99.3% while the vegetated roof retained 96.2% and the gravel ballast roof retained 79.9%. For combined medium rain events (113 mm), the gravel ballast treatment retained the least (33.9%) and the vegetated treatment retained the most (82.9%) rainfall. The same trend occurred for combined heavy rain events (418 mm) with gravel ballast retaining 22.2% and vegetated retaining 52.4% of the rainfall.

When rainfall was separated into distinct rain events and retention percentages from each rain event were averaged together, retention percentages were lowest for the gravel ballast, followed by the media-only, and vegetated roof treatments; all means were different ($P \leq 0.05$) (Figure 8). However, when the rain events were categorized into light, medium, and heavy, the media-only and the vegetated treatments were not different in any of the rainfall categories, although both were different from the gravel ballast treatment. The lowest retention percentage for all treatments occurred during heavy rain events where 26.3%, 52.6%, and 65.0% was retained for the gravel ballast, media-only, and vegetated treatments, respectively. During medium rain events, the media-only and vegetated treatments each retained an average of 85.7% of the rainfall per rain event. The gravel ballast treatment retained an average of 37.7% of the rainfall for these events. The gravel ballast treatment retained an average of 84.6% of the rainfall for the light rain events, followed by the vegetated treatment (97.9%) and media-only (99.6%).

All treatments retained 100% of the rainfall from a rain event on several occasions. This occurred seven, fifteen, and twenty times on the gravel ballast, media-only, and vegetated treatments, respectively. The heaviest rainfall for which 100% retention was achieved for the vegetated treatment was 5.56 mm. For the gravel ballast treatment, the heaviest event with complete retention was 0.76 mm. The least retention (12%) from the vegetated treatment occurred during a rain event of 73 mm that spanned three days. Individual rain event retention percentages under 15% occurred numerous times for the gravel ballast treatment during rain events ranging from 0.68 to 73 mm.

Discussion

It was originally assumed that the gravel ballast roof would yield considerably more runoff than the other two roof treatments, but it was unclear what effect vegetation would provide compared to the media only treatment because, to our knowledge, this has not been explored. As expected, the gravel ballast roof retained less water in all rainfall categories when compared to the other two roof treatments on both a per rain event basis and for total rainfall. This occurrence is likely due to the high surface area of the expanded slate based media which is very porous and allows for a higher water holding capacity relative to the open spaces within the gravel ballast typically found on conventional roofs (Liesecke, 1998). The largest difference between the vegetated and gravel ballast treatments occurred during medium rain events when the vegetated treatment retained an average of 48% more water per rain event. The unexpected finding from this study was the fact that the media-only and vegetated treatments were not significantly different when the rain events were categorized. It should be noted that past studies have indicated that media moisture content immediately prior to a rain event plays a large role in the amount of water retained through that rain event (Monterusso et al., 2004; Moran et al., 2003). Rainfall intensity and duration reportedly also play a part in water retention.

The vegetated treatments retained 60% of the rainfall they received during the measured rain events which is about 10% higher than the findings of Monterusso et al. (2004), but similar to the findings of Liesecke (1998) and Schade (2000) when similarly designed green roof systems were utilized. The discrepancy between this study and that of Monterusso et al. is likely due to the lower number of rain events measured in the Monterusso et al. study. Past studies have offered results of retention per year percentages. However, they are not possible with the data collected from this study because the tipping bucket rain gauges did not function properly in temperatures below 0°C. However, we could assume lower retention percentages during the winter months because evapotranspiration and soil infiltration are greatly reduced during this time (Liesecke, 1998).

Several studies have shown a delay in peak flow of runoff from a green roof when compared to a standard roof (Liesecke, 1999; Moran et al., 2003; Schade, 2000). From both plots during the representative heavy rainfall event (Figures 5 and 6), we can see that a delay in the onset of runoff on the green roof treatment is evident when compared with the gravel ballast. No delay can be seen for the light and medium rainfall events due to the green roof treatments retaining nearly all of the rainfall. The cumulative hydrographs offer another valuable method of looking at the reduction green roofs provide. In all three cumulative hydrographs, runoff from the gravel ballast treatment is evident unlike the representative plots for the media-only and vegetated treatments. The peak flow reduction and the tendency to extend the runoff over longer periods is very important for stormwater management because the total amount of water and rain event duration is often not the problem, it is the rate that the incoming water needs to be treated.

The results of this study support earlier findings that green roofs can reduce runoff from buildings. There did not appear to be a substantial difference between our findings and those that have been published from Germany. Past studies have indicated that media depth plays an important roll in water retention (Liesecke, 1998). From this information, we can imply that media is one of the most important factors for water retention. To our knowledge, the effect of vegetation relative to media-only has not been studied even though it has generally been felt that vegetation plays a large role in water retention. However, our findings indicate that vegetation is much less of an effect in aiding water retention when compared to media. Even so, vegetation plays other important roles such as preventing erosion of the media from wind and water and providing thermal benefits to the building and its surroundings (Lükenga and Wessels, 2001; Dimoudi and Nikolopoulou, 2003). The possibility exists that the similar results for the vegetated and unvegetated treatments could be due to roof slope. The platforms used for this study were set at a relatively flat, 2% slope. A vegetated roof on a steeper slope may be better at demonstrating the effects of water uptake and evapotranspiration relative to an unvegetated, media-only roof.

The reduction in runoff that green roofs provide should be taken seriously by those in charge of managing stormwater. With the continual increase of area covered by impervious surfaces, the already important problem of stormwater management will only become more of an issue. Green roofs offer a new tool that shows promise as a technology which can aid in providing a sustainable built environment.

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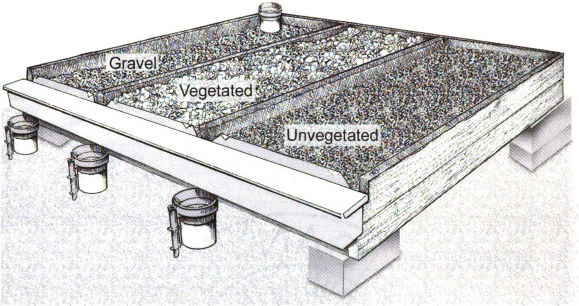
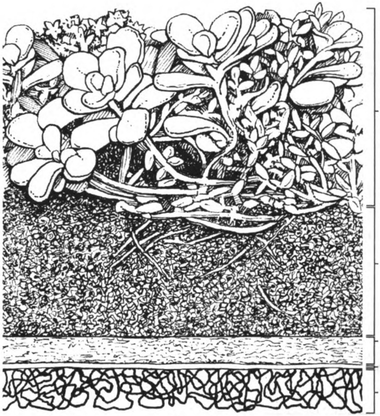
Figure 1.



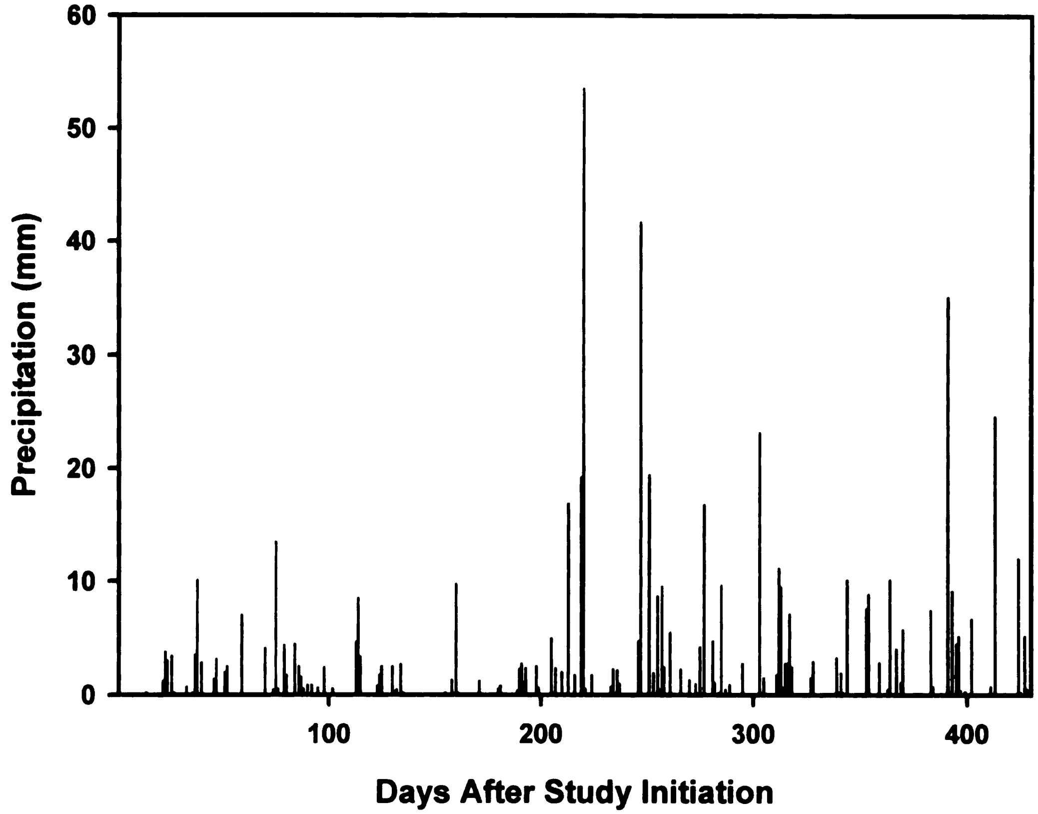
Graphic representation of the model scale roof platforms used to evaluate stormwater retention in the roof surface comparison study.

Figure 2.



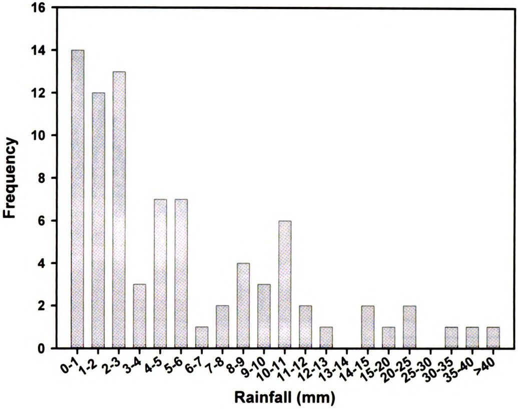
A cross section of a representative extensive green roof system including typically used layers.

Figure 3.



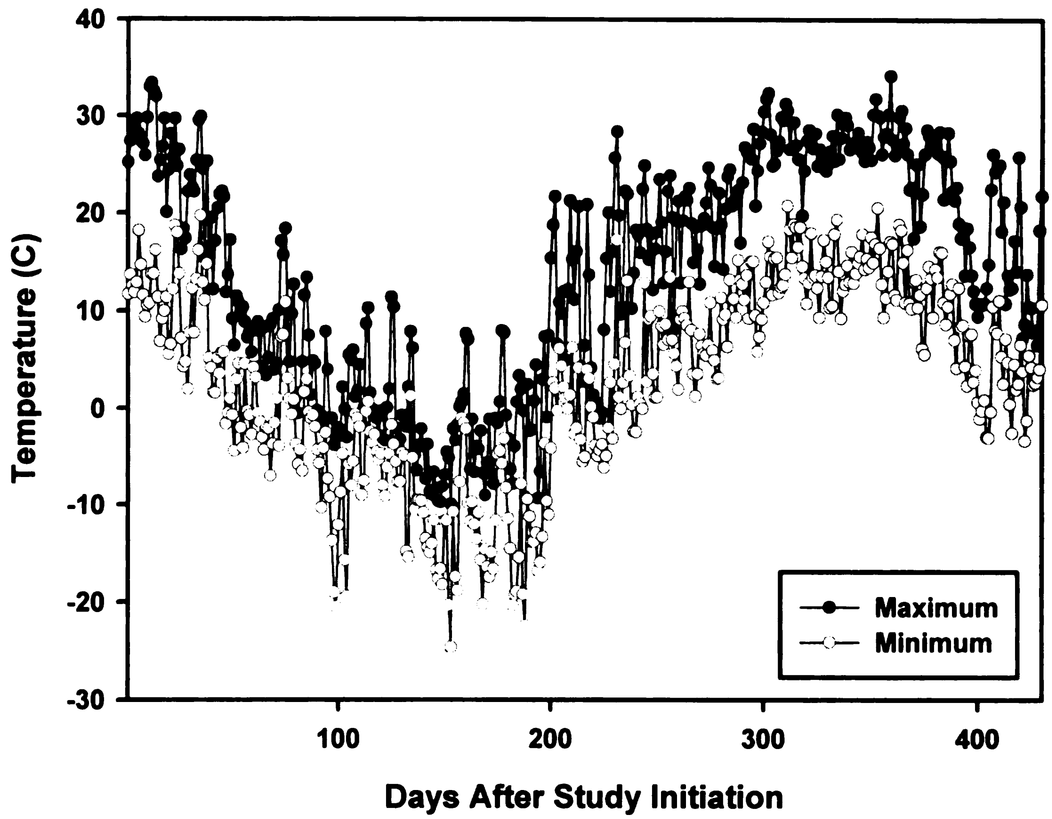
Daily precipitation (mm) during the experimental study (28 Aug. 2002 through 31 Oct. 2003). Values are averages of measurements taken using three tipping bucket rain gauges mounted at the research site.

Figure 4.



Frequency of rain events that occurred above 0 °C from 28 Aug. 2002 through 31 Oct. 2003. Rainfall measurements were averages from three tipping bucket rain gauges mounted at the research site.

Figure 5.

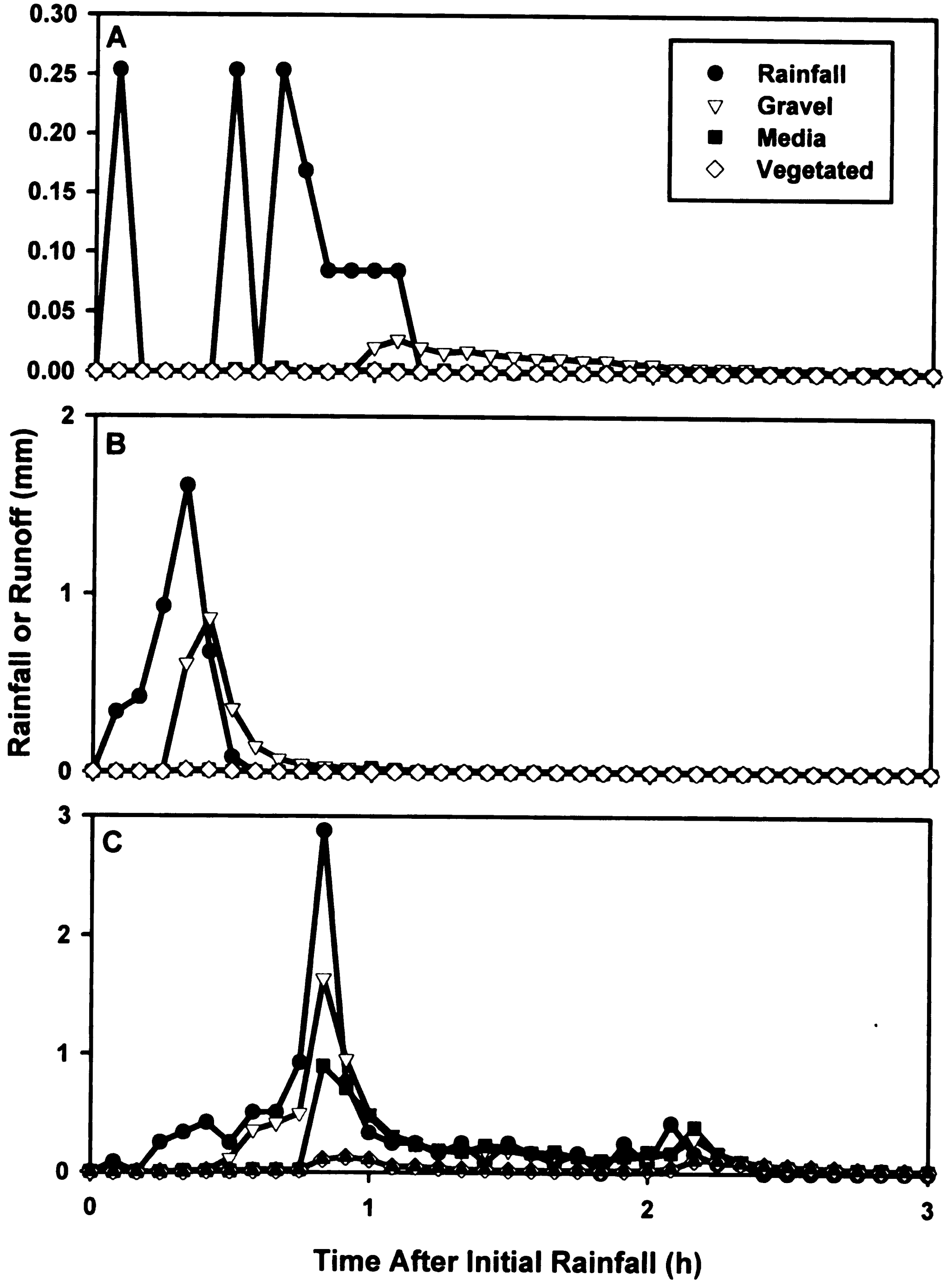


Daily maximum and minimum temperatures (°C) during the experimental study (28 Aug. 2002 through 31 Oct. 2003). Temperatures were taken using the Michigan Automated Weather Network's East Lansing weather station (located adjacent to the research site).

Figure 6.

Runoff hydrographs of selected representative (A) light (1.27 mm), (B) medium (4.06 mm), and (C) heavy (10.08 mm) rain events. Lines represent either rainfall (mm) or runoff (mm) from gravel ballast, media-only, or vegetated roof treatments. Values are averages of measurements taken using three tipping bucket rain gauges. Note the different y-axis scales.

Figure 6.

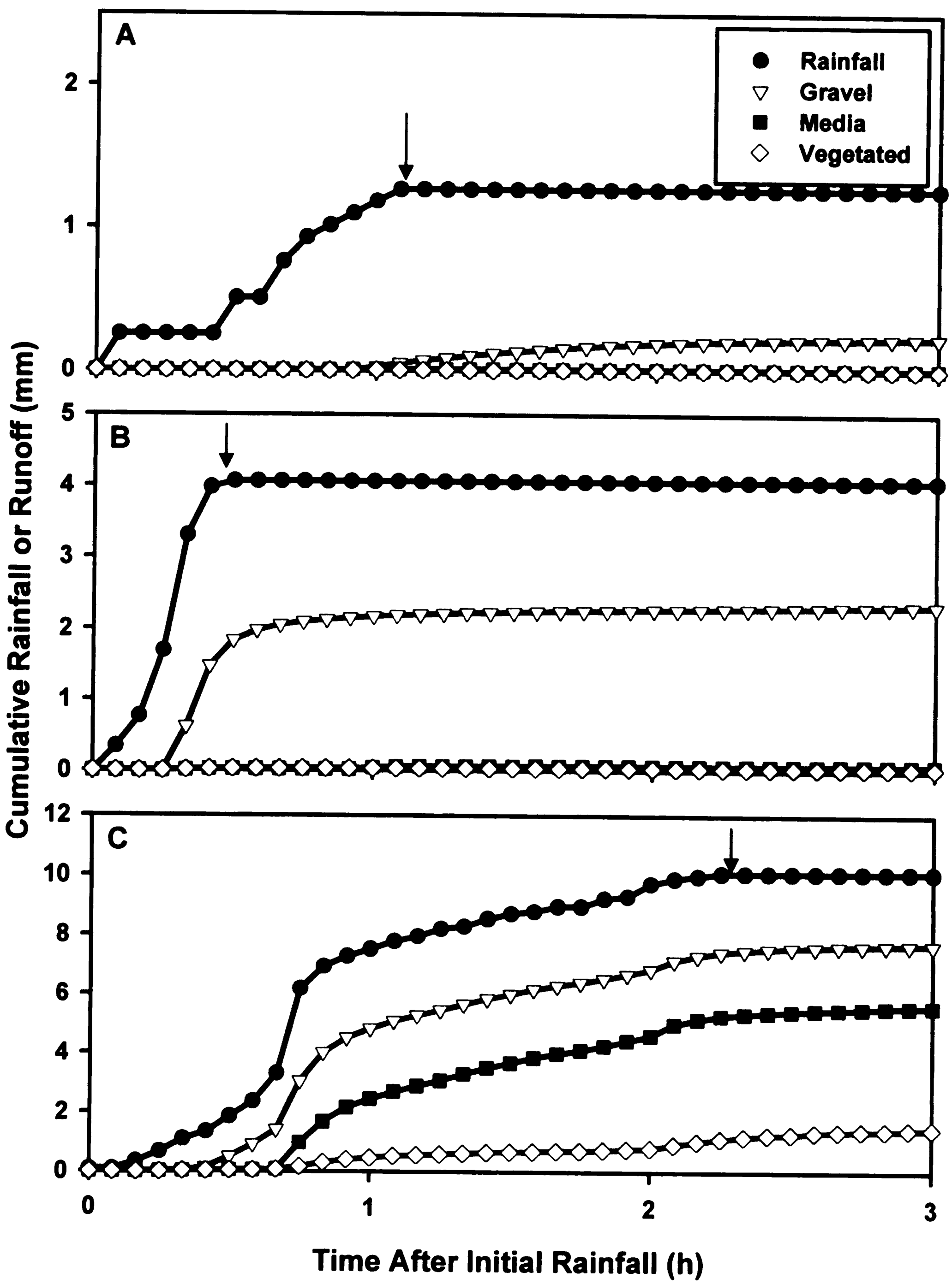


A
B
C
Rainfall
Gravel
Media
Vegetated
0.30
0.25
0.20
0.15
0.10
0.05
0.00
2
1
0
3
2
1
0
0
1
2
3
Rainfall or Runoff (mm)
Time After Initial Rainfall (h)

Figure 7.

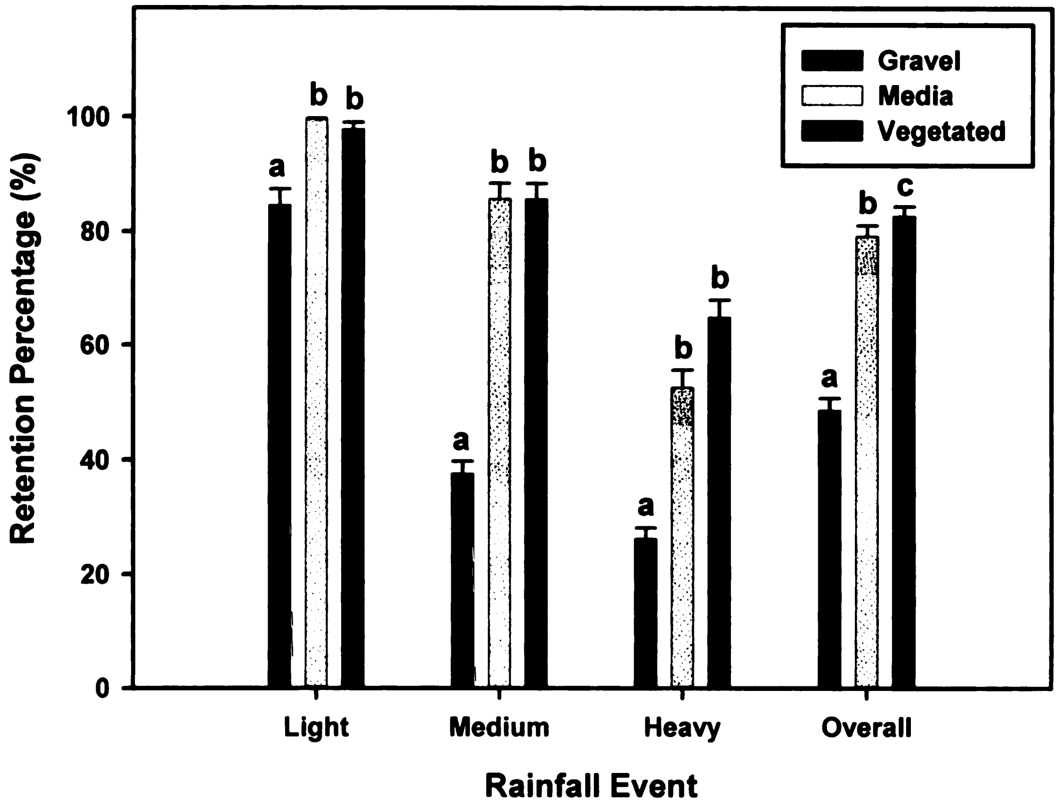
Cumulative runoff hydrographs of selected representative (A) light (1.27 mm), (B) medium (4.06 mm), and (C) heavy (10.08 mm) rain events. Lines represent either rainfall (mm) or runoff (mm) from gravel ballast, media-only, or vegetated roof treatments. Values are averages of measurements taken using three tipping bucket rain gauges. Arrows denote the end of rainfall. Note the different y-axis scales.

Figure 7.



A
B
C
Rainfall
Gravel
Media
Vegetated
Cumulative Rainfall or Runoff (mm)
Time After Initial Rainfall (h)
0
1
2
3
4
5
6
8
10
12

Figure 8.



Retention percentage (%) averaged for all measured rain events in respective categories (light, n=26; medium, n=30; heavy, n=27; overall, N=83) for each roof treatment. Mean separation among treatments within each rainfall category by Tukey's Studentized Range (HSD) test, $P \leq 0.05$, n=3. Error bars represent standard error.

CHAPTER TWO

Stormwater Retention from Extensive Green Roofs of Differing Roof Slopes and Media Depths

Stormwater Retention from Extensive Green Roofs of Differing Roof Slopes and Media Depths

Additional index words. ecoroof, rain retention, *Sedum*, stormwater management, stormwater runoff, vegetative roof

Abstract

Impervious surfaces such as pavement and rooftops dominate urban landscapes. Vegetated rooftops, known as green roofs, are an emerging technology that can aid stormwater runoff mitigation. To test the influence of roof slope and green roof media depth on stormwater retention, runoff was quantified from twelve simulated extensive green roof platforms constructed at two different slopes (2% and 6.5%) and three different growing media depths (2.5 cm, 4.0 cm, and 6.0 cm). Rain events were categorized as light (<2 mm), medium (2-6 mm), or heavy (>6 mm). For all combined rain events, platforms at 2% slope with a 4 cm media depth had the greatest mean retention, 87%, although it was minimal. During light rain events, mean rainfall retention was greater than 96% regardless of slope or media depth. The combination of reduced slope and deeper media clearly reduced the total quantity of runoff. All green roof system combinations extended runoff duration over a period of time beyond the actual rain event. Roof surface runoff reduction and longer runoff dispersal time are important benefits for stormwater management.

Introduction

As forests and agricultural lands are replaced with impervious surfaces due to urban and suburban development, recovery of lost green space is becoming increasingly critical for environmental and public health. Green roofs can help these concerns by aiding the reduction of stormwater runoff that enters municipal stormwater infrastructure systems (Liesecke, 1998; Monterusso et al. 2004; Rowe et al., 2003; Schade, 2000). They also provide numerous other environmental and economic benefits including energy savings through providing building insulation (Niachou et al., 2001; Wong et al., 2003), and increasing the life span of the various roof components by protecting them from damaging UV rays, extreme temperatures, and rapid temperature fluctuations (Giesel, 2001). In addition, green roofs provide a more aesthetically pleasing environment in which to live and work, provide habitat for a range of organisms from microbes to birds (Brenneisen, 2003; Gedge, 2003), and have the potential to reduce the Urban Heat Island Effect because green roof vegetation reduces the absorption of solar radiation so air temperatures above the building do not increase and add to the urban heat problem which takes place above typical roofs with black waterproofing membranes (Rosenfeld et al., 1998; Wong et al., 2003).

The mitigation of stormwater runoff is considered to be the primary benefit of green roofs in urban and commercial areas due to the many detrimental effects of runoff. According to the USEPA (2003), "because of impervious surfaces like pavement and rooftops, a typical city block generates more than five times more runoff than a woodland area of the same size". Rapid runoff from roof surfaces exacerbates flooding, increases erosion, and may result in direct surface water discharges of raw sewage. Green roofs help mitigate the impact of greater runoff caused by development by replacing the footprint of vegetation that was displaced when constructing the building. Typical green roofs have been shown to retain 60-100% of the stormwater they receive (Liesecke, 1998; Moran et al., 2003; Schade, 2000). A properly installed and maintained green roof will absorb water and release it slowly as opposed to a conventional roof that discharges runoff immediately (Liesecke, 1999).

In addition, green roofs have the ability to filter contaminants from rainwater (Dramstad et al., 1996). The physical and chemical properties of the growing substrate as well as the green vegetative cover helps control contaminants generated by industrial activities from exiting the roof surface. Heavy metals and nutrients found in stormwater are bound in the green roof growing substrate instead of being discharged into groundwater, streams, or rivers (Johnston and Newton, 1996).

Germany is widely considered the leader in green roof research, technology, and usage. An estimated 14% of all flat roofs in Germany are green and the German green roof industry continues to grow (Herman, 2003). In Michigan and the rest of North America, the concept of green roofs is just now being introduced. Numerous municipalities in Europe and other parts of the world encourage the use of green roofs by developing building codes, providing subsidies, and offering tax breaks (Liptan, 2003). Historically, this has not been a common practice in the United States. However, governments in Portland, Oregon, and New York State are now in the process of providing incentives for building practices that aid stormwater management (Liptan, 2003; State of New York Law 11006, 2001).

If green roof installations are to be successful in the U.S., then quantifiable data pertaining to the effects of roof slope and substrate depth on stormwater management must be available. Although data regarding stormwater runoff from green roofs exists, most of this information has been produced in Europe and is not transferable to the wide range of climatic conditions present in the United States. Also, much of the current information is anecdotal in nature, the information is proprietary, or the experiments were not performed in a replicated study. Therefore, our objective was to quantify the differences in water retention among various substrate depths and roof slopes in a replicated study. This information can then be used to develop models to predict stormwater runoff during the design of green roof systems.

Materials and Methods

Green Roof Testing Platforms. Twelve simulated roof platforms with dimensions of 2.44 m x 2.44 m were constructed by ChristenDetroit (Detroit, MI) at the Michigan State University Horticulture Teaching and Research Center (East Lansing, MI). Each platform simulated a commercial extensive green roof, including an insulation, protective, and waterproofing membrane layers. Lining the platform deck was 3.8 cm of ENRGY 2™ insulation board (Johns Manville, Denver, CO), composed of a closed cell polyisocyanurate foam core and fiber glass reinforced facers. Above the ENRGY 2™ layer was a 1.9 cm thick insulation layer of Fesco® Board consisting of expanded perlite, blended with selected binders and fibers (Johns Manville, Denver, CO). The top layer was a waterproofing membrane consisting of a combination of Paradiene 20 (Siplast Inc., Irving, TX), a flexible membrane with an elastomeric asphalt base, and Teranap (Siplast Inc., Irving, TX), a polyester mat coated with styrene butadiene styrene (SBS)-modified bitumen, with a root-resistant polyester film covering the top side.

Aluminum sheet metal troughs were attached on the low end of the platforms to direct stormwater runoff through the measuring devices used to quantify runoff. The wood-framed platforms included sides that extended 20.3 cm above the platform deck, also covered with waterproofing membrane. All platforms were oriented with the low end of the slope facing south to maximize sun exposure.

Drainage System and Vegetation Carrier. Each platform used the Xero Flor XF108 drainage layer (Wolfgang Behrens Systementwicklung, GmbH, Groß Ippener, Germany) installed over the Teranap Waterproofing System. The drainage layer consists of a geotextile fabric with nylon coils attached on the underside and has a total thickness of approximately 1.5 cm. For additional water holding capacity, a 0.75 cm thick moisture retention fabric (Xero Flor XF158) capable of retaining up to 1,200 $g \cdot m^{-2}$ of water was placed over the drainage layer. The moisture retention fabric is composed of a recycled synthetic fiber mixture consisting of polyester, polyamide, polypropylene, and acrylic fibers.

Above the retention fabric was the vegetation carrier (Xero Flor XF301) which included a recycled synthetic fabric similar to XF 158 used for water retention sewn to an inverted layer of XF108 that held media and vegetation. This water retention layer could hold up to 800 $g \cdot m^{-2}$ of water and was approximately 0.75 cm thick. The total thickness of the drainage layer and vegetation carrier was approximately 4.5 cm. The system as a whole permits water exceeding the water holding capacity of the mat layers and planting media to drain through the nylon coils and exit the roof.

Plant Establishment. One hundred percent vegetation coverage (no visible growing media) was achieved on the platforms prior to the initiation of data collection. Plant species used in this study included *Saxifraga granulata* L., *Sedum acre* L., *Sedum album* L., *Sedum kamtschaticum ellacombianum* Fisch., *Sedum pulchellum* Michx., *Sedum reflexum* L., *Sedum spurium* Bieb. 'Coccineum', and *Sedum spurium* Bieb. 'Summer Glory'. The plant mix was applied as seed on 11 May 2002 at a rate of 1.3 $g \cdot m^{-2}$ for each species. All seeds were evenly mixed in dry sand to ensure even distribution when the mixture was sown by hand on the platforms. Seeds were obtained from Jelitto Staudensamen, GmbH (Schwarmstedt, Germany).

Growing media consisted of 40% heat-expanded slate (gradation 3 mm to 5 mm) (PermaTill®, Carolina Stalite Company, Salisbury, NC), 40% USGA (United States Golf Association) grade sand (Osburn Industries, Taylor, MI), 10% Michigan Peat (Osburn Industries, Taylor, MI), 5% Dolomite (Osburn Industries, Taylor, MI), 3.33% composted yard waste (Kalamazoo Landscape Supplies, Kalamazoo, MI), and 1.67% composted poultry litter (Herbruck's, Saranac, MI) by volume. Electrical conductivity (EC) and pH of the media were 3.29 mmho•cm^{-1} and 7.9, respectively. All platforms had 100 g•m^{-2} of Nutricote® type 100, 20N-$7P_2O_5$-$10K_2O$ controlled release fertilizer (Agrivert, Webster, TX) hand-applied at the time of planting and on 19 May 2003.

Platforms were covered with a plastic shade cloth (Wolfgang Behrens Systementwicklung, GmbH, Groß Ippener, Germany) for the first 55 d after the seed was sown to enhance germination and plant establishment. Seedlings were acclimated from days 55 through 60 by periodically removing the shade cloth depending on the intensity of the sun, after which it was removed permanently.

Upon seed distribution, an automated overhead irrigation system (Rainbird, Azusa, CA) was programmed to run six 10-minute cycles daily (9:00 AM, 11:00 AM, 1:00 PM, 3:00 PM, 5:00 PM, and 7:00 PM) through 15 July 2002. From 16 July until 31 July 2002, the irrigation was reduced to four 10-minute cycles daily (9:00 AM, 1:00 PM, 5:00 PM, and 7:00 PM). Irrigation was terminated on 31 July 2002 once the plants had become established and had achieved 100% coverage.

Treatments. Two factors were examined in this study, roof slope and media depth. Treatments were arranged in a completely randomized design (CRD) with three replications. Six platforms were set at a 2% slope and six were set at a 6.5% slope. A total of three growing media depths were examined, with two depths tested at each slope. For the 2% slope, media depths of 2.5 cm (0.98

inch) and 4.0 cm (1.57 inch) were tested while depths of 4.0 cm (1.57 inch) and 6.0 cm (2.36 inch) were tested on the 6.5% slope platforms.

Data Collection and Analysis. Model TE525WS tipping bucket rain gauges (Campbell Scientific, Inc., Logan, UT) were mounted under the drain of each platform to quantify stormwater runoff. Three additional tipping buckets were mounted around the research site to record actual rainfall. A model CM6 automated weather station (Campbell Scientific, Inc., Logan, UT) was installed on the research site to record meteorological parameters. The weather station included an ambient air temperature and relative humidity probe covered by a 6-plate gill radiation shield. The weather station also included instruments to measure wind speed and direction as well as photosynthetically active radiation.

Data from the tipping bucket rain gauges and tripod weather station were collected at five minute intervals 24 hours a day from 28 Aug. 2002 through 31 Oct. 2003 using a Campbell Scientific CR10X datalogger equipped with switch closure modules and a storage module.

Retention data were analyzed from all rain events that occurred during temperatures above 0°C as a percentage of total rainfall for each rain event. Frozen precipitation was not physically removed from the platforms and melting precipitation was allowed into the data set if it fully occurred in temperatures above 0°C. Independent rain events were defined as precipitation events separated by six or more hours. In the event runoff was still occurring six hours after the first event, the two events were combined. Rain events were arbitrarily categorized as light (<2 mm), medium (2 – 6 mm), or heavy (>6 mm). The extent of each category was chosen to get rain event sample sizes that were similar across all three categories.

Data were analyzed as mean percent retention per rain event using an ANOVA model with roof slope, media depth, and rainfall category as fixed effects. Although original means are presented, all retention values were transformed prior to analysis using a power transformation (0.113) to stabilize the variance and normalize the data set. Significant differences between treatments were determined using multiple comparisons with Tukey-Kramer adjustments (PROC MIXED, SAS version 8.02, SAS Institute, Cary, NC). Total retention values for the study are presented, but were not subjected to statistical analysis due to the limited number of data points.

Results

Measurable precipitation (>0 mm) was recorded on 162 of the 430 days of the study (38%) (Figure 1). Daily precipitation amounts ranged from 0.08 to 53.59 mm. Of the 83 rain events measured during temperatures above 0°C, there were 26 light (<2 mm), 30 medium (2 – 6 mm), and 27 heavy (>6 mm) rain events. A histogram of measured rain events used in our analysis shows the distribution of the measured rain events (Figure 2). Generally, low rain events were more frequent than larger rain events.

Daily maximum and minimum ambient air temperatures are shown in Figure 3. Daily low temperatures ranged from -24.6°C to 20.8°C and daily high temperatures ranged from -9.9°C to 34.2°C.

Representative hydrographs (Figure 4) and cumulative hydrographs (Figure 5) from a selected rain event within each rainfall category show the effect that slope and media depth had on quantity of runoff, as well as their ability to delay runoff. Initial runoff from all four treatments occurred within 10 minutes of each other for both the medium and heavy representative rain events. During the representative light rain event, runoff from both treatments with 4 cm of media was delayed 30 to 40 minutes compared to the 2% - 2.5 cm and 6.5% - 6 cm treatments. Runoff was not only delayed during the representative heavy rain event, it was spread out over time; the last measured runoff from the platforms occurred 14 hours after the rain event ended.

Over the 14 month period, the roof platforms retained over 68% of the 556 mm of the measured rainfall. Individually, the 6.5% sloped platforms containing 4 cm of media retained the least amount of rainfall (65.9%), followed by the 6.5% - 6 cm (68.1%), 2% - 2.5 cm (69.8%), and 2% - 4 cm (70.7%). During light rain events (25 mm total), 94% of the rainfall was retained. Retention ranged from 82.9% (2% - 2.5 cm) to 85.5% (2% - 4 cm) for medium rain events (113 mm total) and from 59.5% (6.5% - 4 cm) to 65.1% (2% - 4 cm) for heavy rain events (418 mm total).

When total rainfall was separated into distinct rain events and retention percentages were averaged together, overall retention percentages ranged from 83.8% (6.5% - 4 cm) to over 87% (2% - 4 cm) when light, medium, and heavy rain events were combined (Figure 6). Overall, the greatest retention percentage (87%) occurred at 2% - 4 cm.

When light, medium, and heavy rain events were categorized, the lowest retention percentage occurred during heavy rain events (69.2% - 75.6%). Light rain events resulted in the highest retention percentage where over 96% of the rainfall was retained regardless of roof slope or media depth. The lowest retention percentage recorded during the study was 22%, which occurred during a 2.37 mm rain event. One hundred percent retention occurred on several occasions with rainfalls up to 5.8 mm. The heaviest rain event, 73 mm, occurred on 3 – 5 Apr. 2003. Thirty percent of the rain from this event was retained when averaged over all four treatments.

Retention percentages for light and medium rain events were greatest on the 2% - 4 cm platforms ($P \leq 0.05$). The other three treatments were not different from each other in these rainfall categories. For heavy rain events, no difference was detected between treatments. The 2% - 4 cm treatment had the highest mean retention percentage when all rain events were combined across rainfall categories. The other treatments were again, not significantly different from each other.

Discussion

Although Schade (2000) found similar runoff coefficients between four roof slopes using a vegetated mat green roof system, we hypothesized that increasing roof slope would increase the quantity of runoff and that this occurrence could be off set by increased media depth.

As expected, platforms built on a 2% slope containing 4 cm of media retained a greater quantity of rain than the others on both a per rain event basis and for total rainfall. Retention percentage for this treatment was significantly greater than the others in all rainfall categories except heavy events. Although the difference was significant, the difference from other treatments was minimal. No treatment consistently yielded the lowest retention value in all rainfall categories.

Overall, at the 4 cm depth the treatments on a 2% slope retained significantly more water than the 6.5% slope treatments. This finding contradicts those of earlier studies. Schade (2000) reported nearly constant water retention rates for roof slopes ranging from 2% up to 58%. Liesecke (1999) generalized that annual retention rates of 55% to 65% on an 8.7% sloped roof are comparable to a 2% slope. The difference in findings between past and current studies could be due to differences in media composition among the studies.

Increasing media depth increased water retention at only one slope. Retention percentages for platforms with 6 cm of media were not different from platforms with 4 cm of media on the 6.5% roof slope. However, for the 2% roof slope, deeper media (4 cm) retained a significantly greater percentage of water for both the light and medium rainfall categories, but not heavy ($P \leq 0.05$). Together with past studies, we can establish that increasing media depth usually increases retention (Liesecke, 1998).

Media depth should be considered for reasons other than just stormwater retention. In Quebec, Boivin et al. (2001) found that substrate depth can influence freezing injury in certain herbaceous perennials. The researchers concluded that in their climatic region, a minimum substrate depth of 10 cm (4 in) should be used for the green roof system constructed for their study. Other studies found that media depth influences the growth, drought stress, and drought tolerance of green roof vegetation (Durhman et al., 2004; Lassalle, 1998; VanWoert, 2004).

Several studies have shown a delay in peak flow of runoff from a green roof when compared to a standard roof (Liesecke, 1999; Moran et al., 2003; Schade, 2000). However, Figure 5 shows that the effect of roof slope and media depth on runoff delay is minimal for rain events greater than 2 mm. This implies that once sufficient rainfall has occurred to reach the media's water holding capacity, additional rainfall will leave the roof as runoff regardless of media depth. The only observed runoff delay among treatments occurred during the representative light rain event. From the results of this and previous studies, we can speculate that roofs with deeper media provide a greater delay in runoff due to increased water holding capacity.

Past studies have indicated that media moisture content immediately prior to a rain event influences the amount of water retained (Monterusso et al., 2004; Moran et al., 2003). Rainfall intensity and duration also play a part in water retention. Media moisture content, rainfall intensity, and rain event duration likely explain differences between this study and others.

Conclusion

Media depth influenced water retention on our model-scale extensive green roofs at one of the tested slopes. Other studies that have considered the effects of media depth on water retention have found similar results. However, we can not draw definitive conclusions regarding the effect of roof slope on runoff levels. The fact that retention percentages were affected by the two slopes with equal media depths would lead us to think that slope would have an effect under any situation, although we can not be sure without further testing. Because of the mixed results regarding roof slope between Liesecke (1999), Schade (2000), and this study, further research is warranted.

One roof slope and media depth combination (2% - 4 cm) retained the most water out of the four treatments studied. However, the difference was minimal. The fact that one treatment did retain more than the other treatments becomes important for future building projects that will utilize green roofs. If the objective is to maximize rainfall retention on the roof, then different slopes and media depths should be explored. Although green roofs are not new to other parts of the world, they are a promising new technology to mitigate stormwater runoff in the United States. They are a technology that should be considered for all roofing projects, especially those projects in areas where stormwater management is a concern for city planners.

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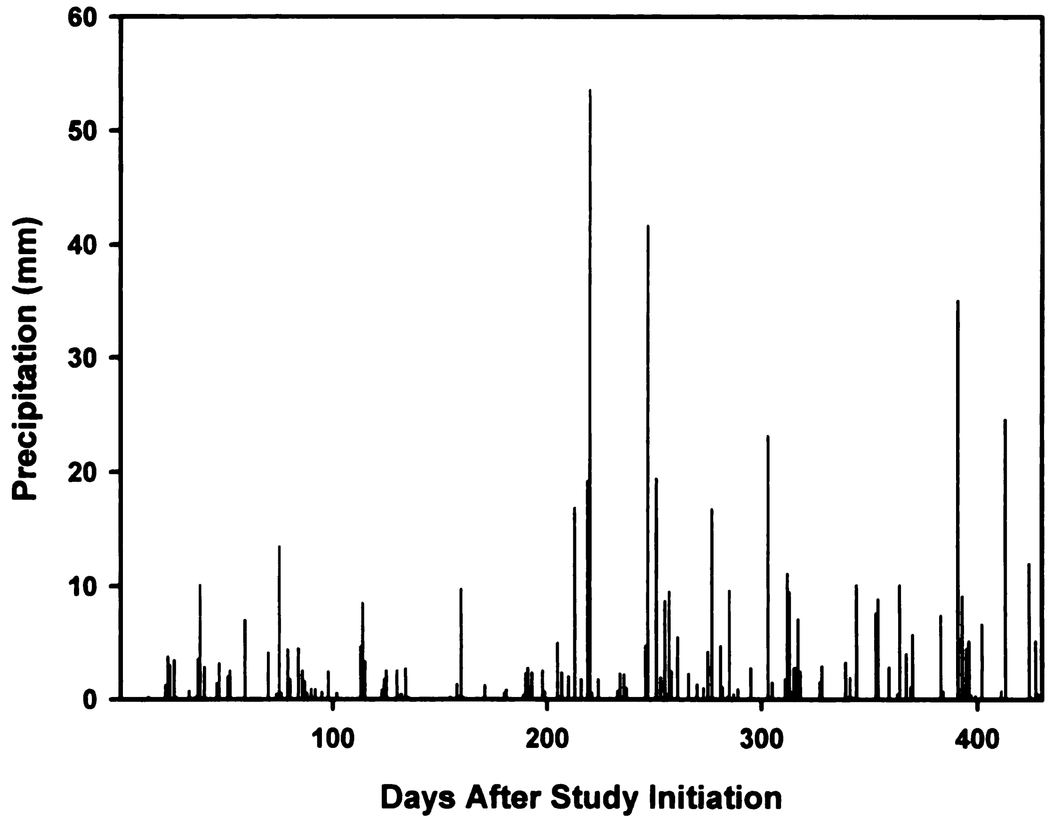
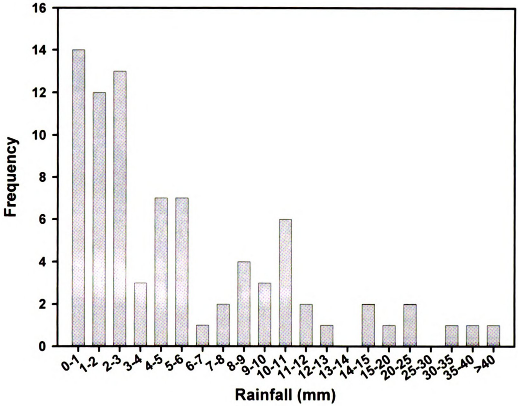
Figure 1.



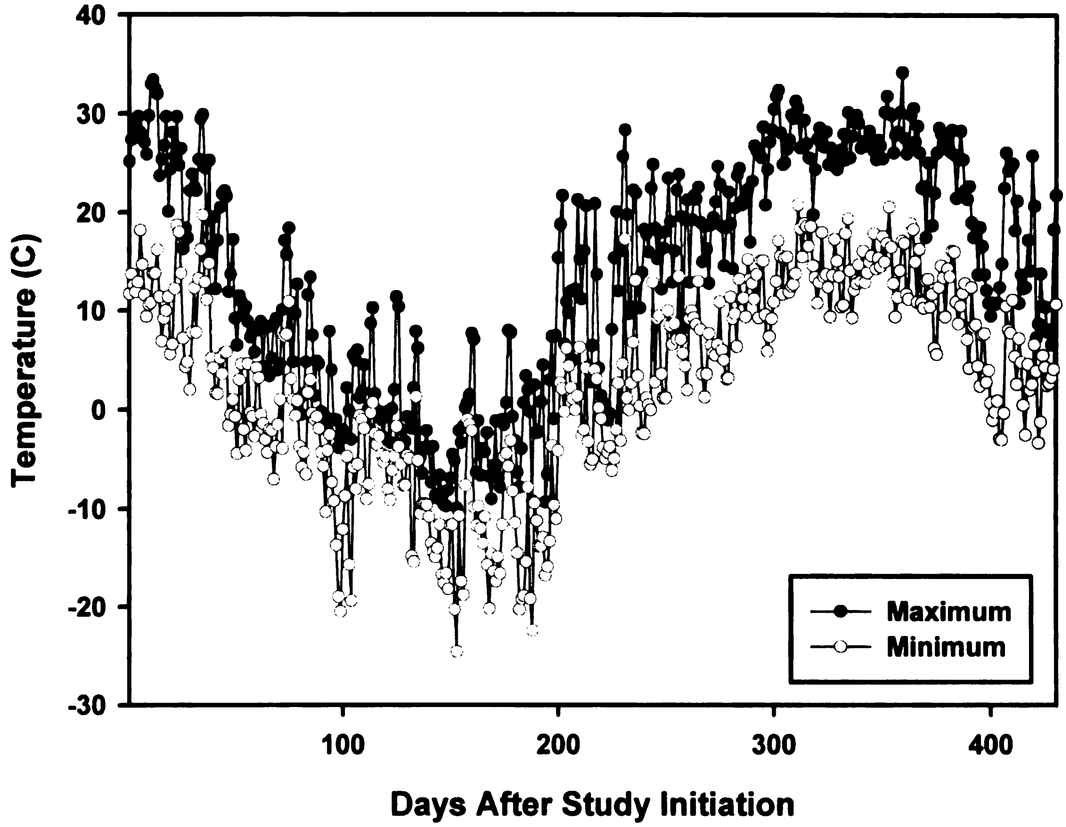
Daily precipitation (mm) during the experimental study (28 Aug. 2002 through 31 Oct. 2003). Values are averages of measurements taken using three tipping bucket rain gauges mounted at the research site.

Figure 2.



Frequency of rain events that occurred above 0 °C from 28 Aug. 2002 through 31 Oct. 2003. Rainfall measurements were averages from three tipping bucket rain gauges mounted at the research site.

Figure 3.

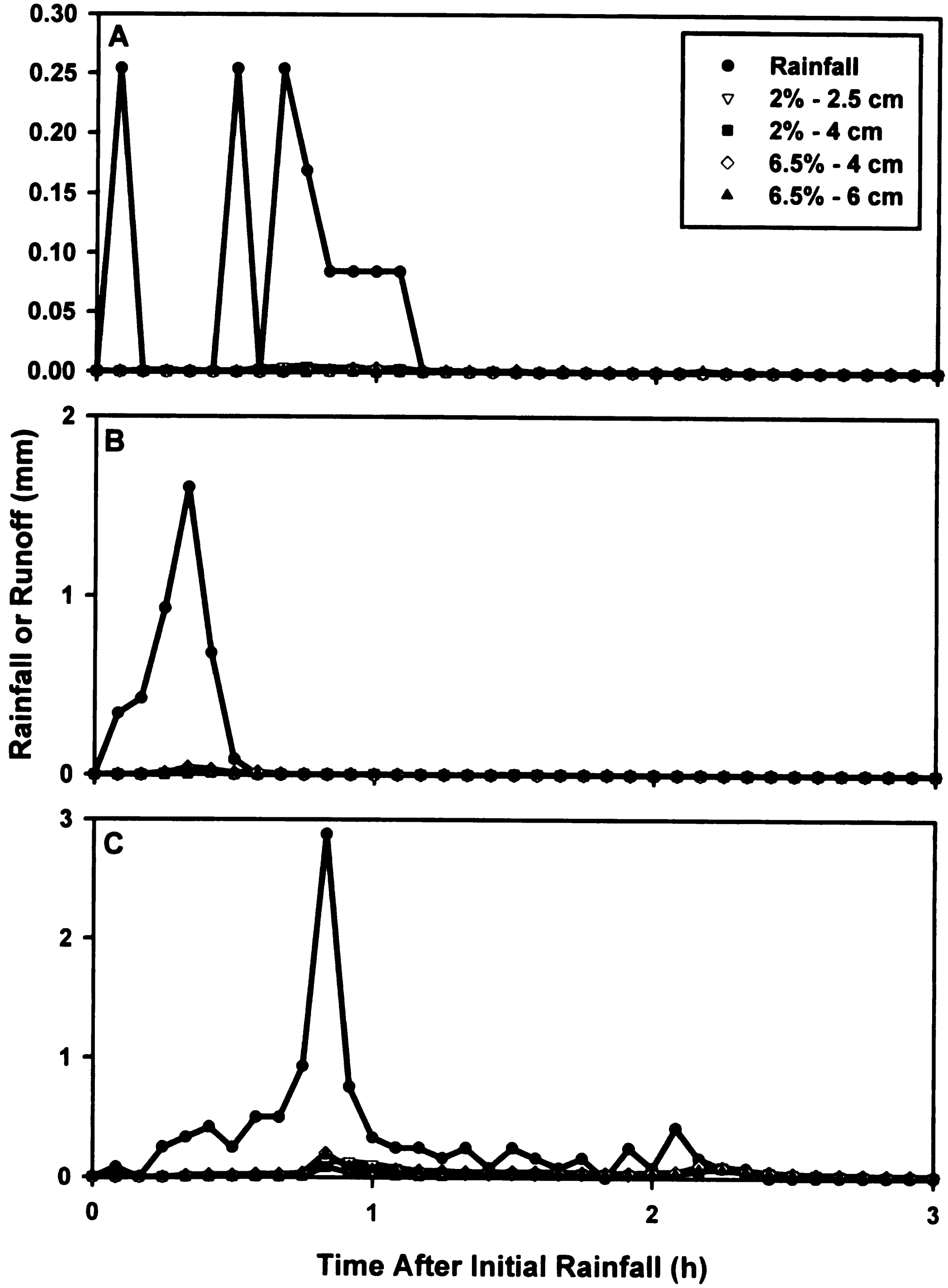


Daily maximum and minimum temperatures (°C) during the experimental study (28 Aug. 2002 through 31 Oct. 2003). Temperatures were taken using the Michigan Automated Weather Network's East Lansing weather station (located adjacent to the research site).

Figure 4.

Runoff hydrographs of selected representative (A) light (1.27 mm), (B) medium (4.06 mm), and (C) heavy (10.08 mm) rain events. Lines represent either rainfall (mm) or runoff (mm) from a 2% roof slope with 2.5 cm of media (2% - 2.5 cm), 2% roof slope with 4 cm of media (2% - 4 cm), 6.5% roof slope with 4 cm of media (6.5% - 4 cm), or 6.5% roof slope with 6 cm of media (6.5% - 6 cm). Values are averages of three replications measured using tipping bucket rain gauges mounted at the research site. Note the different y-axis scales.

Figure 4.



0.30
0.25
0.20
0.15
0.10
0.05
0.00
A
Rainfall
2% - 2.5 cm
2% - 4 cm
6.5% - 4 cm
6.5% - 6 cm
2
1
0
B
Rainfall or Runoff (mm)
3
2
1
0
C
0
1
2
3
Time After Initial Rainfall (h)

Figure 5.

Cumulative runoff hydrographs of selected representative (A) light (1.27 mm), (B) medium (4.06 mm), and (C) heavy (10.08 mm) rain events. Lines represent either rainfall (mm) or runoff (mm) from a 2% roof slope with 2.5 cm of media (2% - 2.5 cm), 2% roof slope with 4 cm of media (2% - 4 cm), 6.5% roof slope with 4 cm of media (6.5% - 4 cm), or 6.5% roof slope with 6 cm of media (6.5% - 6 cm). Values are averages of three replications measured using tipping bucket rain gauges mounted at the research site. Arrows denote the end of rainfall. Note the different y-axis scales.

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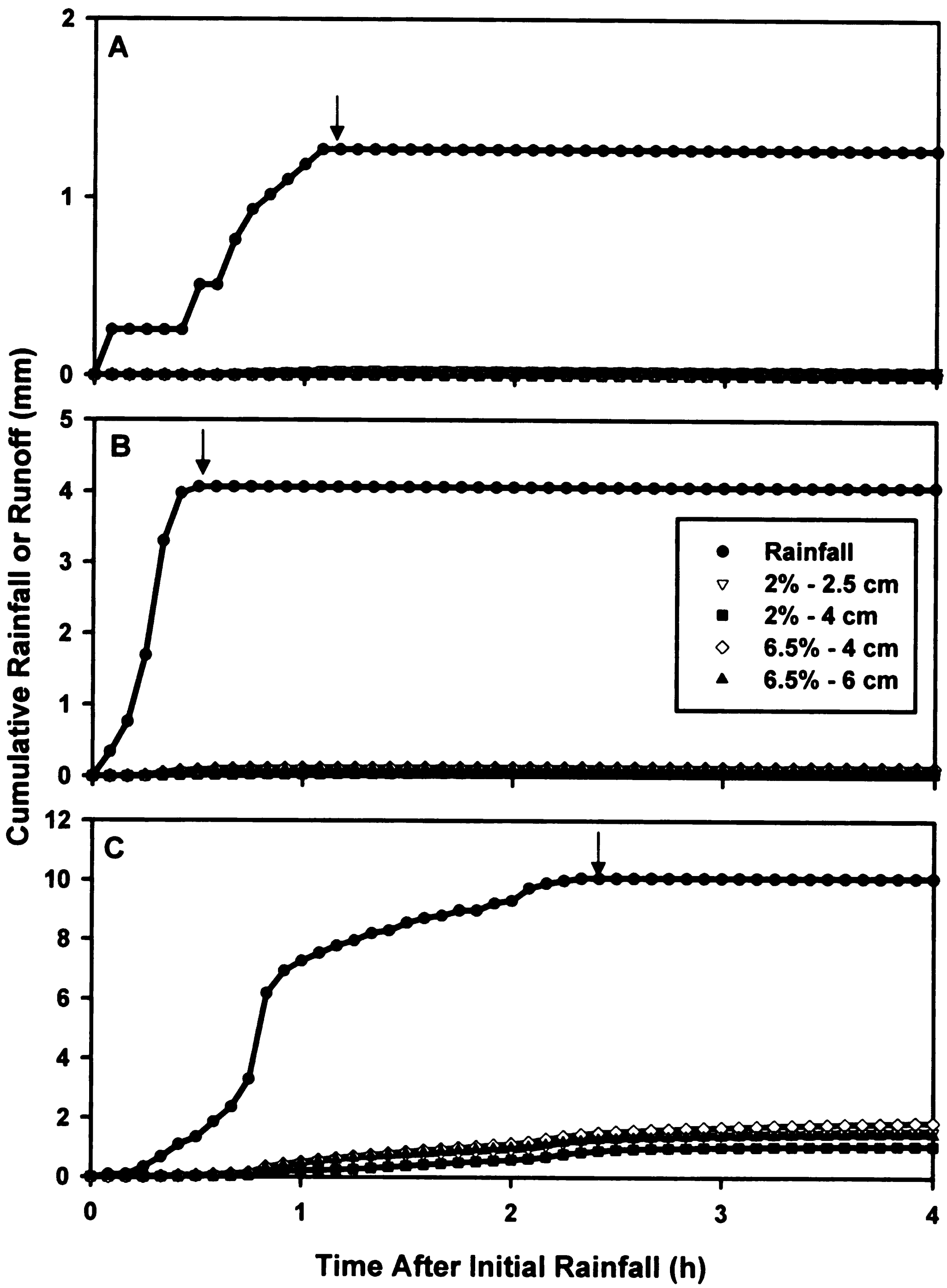
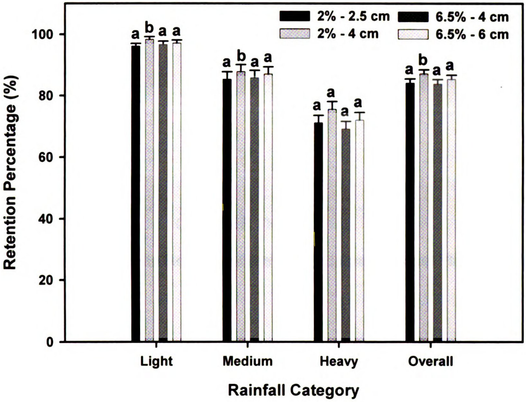

A
B
C
Rainfall
2% - 2.5 cm
2% - 4 cm
6.5% - 4 cm
6.5% - 6 cm
Cumulative Rainfall or Runoff (mm)
Time After Initial Rainfall (h)
0
1
2
3
4
5
6
8
10
12

Figure 6.



Retention percentage (%) for all measured rain events in respective categories (light, n=26; medium, n=30; heavy, n=27; overall, N=83) for each roof slope and media depth treatment. Treatments were as follows: 2% roof slope with 2.5 cm of media (2% - 2.5 cm), 2% roof slope with 4 cm of media (2% - 4 cm), 6.5% roof slope with 4 cm of media (6.5% - 4 cm), and 6.5% roof slope with 6 cm of media (6.5% - 6 cm). Mean separation among treatments within each rainfall category by Tukey's Studentized Range (HSD) test, $P \leq 0.05$, n=3. Error bars represent standard error.

CHAPTER THREE

Watering Regime and Green Roof Substrate Design Impact *Sedum* Plant Growth

Watering regime and green roof substrate design impact *Sedum* plant growth

Additional index words. ecoroof, evapotranspiration, extensive green roof, stonecrop, water management

Abstract

Green roofs are an increasingly common, environmentally responsible building practice that offer a new and growing market for the horticulture field. They require unique vegetation that is tolerant of harsh conditions. *Sedum* species have historically been the most commonly used plants because, with proper species selection, they are tolerant of extreme temperatures, high winds, low fertility, and a limited water supply. However, limited studies have been performed on the production requirements of the numerous *Sedum* spp. with results that could be applied to a production program for green roof vegetation. This study was conducted to determine the minimum irrigation requirements of a mixture of *Sedum* spp. on a green roof drainage system. Results indicate that substrate volumetric moisture content can be reduced to 0 $m^3 \cdot m^{-3}$ within one day after watering depending on substrate depth and composition. Deeper substrates provided additional growth with sufficient water, but also required additional irrigation due to an increased evapotranspiration rate. Over the 88 day study, water was required at least once every 14 days to support growth in green roof substrates with a 2 cm media depth. However, substrates with a 6 cm media depth could do so with a watering only once every 28 days. Therefore, we

determined that although the vegetation was still viable after 88 days of drought, water should be applied at least once every 28 days for typical green roof substrates and more frequently for shallower substrates to sustain growth.

Introduction

Green roofs are an increasingly common, environmentally responsible building practice. Originally, modern-day green roofs were installed to replace lost green space (Herman, 2003). Today, however, green roof installations are driven by several environmental and economic forces (Herman, 2003; Liptan, 2003). They can reduce the heat load on buildings (Niachou et al., 2001), aid in reducing the Urban Heat Island Effect (Dimoudi and Nikolopoulou, 2003; Wong et al., 2003), reduce air and water pollution (Dramstad et al., 1996; Liesecke and Borgwardt, 1997), and reduce storm water runoff from the roof (Liesecke, 1998; Monterusso et al., 2004; VanWoert, 2004). In addition, Relf and Lohr (2003) indicated that numerous studies have documented the positive influence of plants on human well-being and reduced stress; there is no reason why green roofs would not result in similar benefits if the roof is visible from surrounding buildings.

Although several plant taxa have been explored for potential green roof utilization, the favored plants often come from the genus *Sedum* (Boivin et al., 2001; Lassalle, 1998; Monterusso, 2003). Water use and drought tolerance among this genus has been well studied (Lee and Kim, 1994; Gravatt and Martin, 1992; Gurevitch et al., 1986; Ting, 1985). However, to our knowledge, only a few studies have examined plant water use while utilizing green roof drainage systems (Kirschstein 1997a; Kirschstein 1997b; Lassalle, 1998). Lassalle (1998) studied the effects of substrate depth and substrate water holding capacity (WHC) on drought stress for three potential green roof plant species. Utilizing media depths between 2.5 and 15 cm in the study, *Sedum album* L. outperformed *Festuca glauca* Vill. and *Chrysanthemum leucanthemum* L. in all treatments concerning visual appearance under drought conditions.

Drought tolerant *Sedum* spp. are ideal for extensive green roofs due to their method of photosynthetic carbon metabolism and their ability to store water. All *Sedum* spp. are succulents, and are categorized as crassulacean acid metabolism (CAM) plants, one of three mechanisms for plant uptake of CO_2. CAM plants have the ability to fix CO_2 in the dark for later use in photosynthesis. By opening their stomata at night for the uptake of CO_2, they limit water loss due to transpiration (Ting, 1985). Facultative CAM plants are a variation of CAM and are able to shift between C_3 metabolism and CAM depending on soil moisture conditions (Lee and Kim, 1994; Ting, 1985). This ability to shift from one method of metabolism to the other is very beneficial when water becomes available to the plant (Borland and Griffiths, 1990). Several *Sedum* spp. possess the facultative CAM trait, including *S. kamtschaticum* Fisch. (Lee and Kim, 1994).

One key to survival under drought stress is water use efficiency (WUE), which is increased in CAM plants. *Sedum* spp. have been shown to have greater WUE values than most C_3 and C_4 plants (Gravatt and Martin, 1992). Staats and Klett (1995) found that *S. acre* L. required less irrigation to maintain a pleasing leaf color when compared with C_3 and C_4 plants. They also found that the quality of this species with no supplemental irrigation was almost as good as that of irrigated plants.

Some *Sedum* spp. are able to store extra water in their leaves and shoots. Teeri et al. (1986) showed that apical portions of *S. rubrotinctum* R.T. Clausen could survive at least two years without supplemental water in a greenhouse due to its ability to reallocate water to vital plant tissues. Kirschstein (1997b) studied the root water potential of *Sedum* and concluded that this mechanism also helps the plant survive periods of drought. Kirschstein (1997a) explained that the frequency of rain was more important to succulent plants than the total amount of rain because they are able to recover with only small amounts of moisture. After a period of drought in a greenhouse, many *Sedum* spp. recovered within one week of rehydration.

If the green roof industry is to continue to grow in the United States, quantifiable data regarding *Sedum* water use are needed to aid green roof managers in making irrigation decisions. Therefore, a greenhouse study was conducted under controlled conditions to determine the minimum irrigation requirements of a mixture of *Sedum* spp. on a green roof drainage system. The results of this experiment will be instructive for future water management decisions through both the propagation and functional stages of extensive green roofs.

Materials and Methods

Potted green roof system design. Plastic pots (11 cm x 11 cm x 12 cm deep) were filled with one of three substrate types, all of which included a green roof drainage layer (XF108) and vegetation carrier (XF301) (Wolfgang Behrens Systementwicklung, GmbH, Groß Ippener, Germany) at the Plant Science Greenhouses at Michigan State University, East Lansing, Mich. The drainage layer consists of a geotextile fabric with nylon coils attached on the underside and has a total thickness of approximately 1.5 cm. The vegetation carrier was placed above the drainage layer. It included a recycled synthetic fiber fabric used for water retention sewn to an inverted version of the drainage layer that held media and vegetation. The water retention fabric holds up to 800 $g{\bullet}m^{-2}$ of water and is approximately 0.75 cm thick. It is composed of a recycled synthetic fiber mixture consisting of polyester, polyamide, polypropylene, and acrylic fibers. Total thickness of the drainage layer and vegetation carrier is approximately 3.75 cm. The assembled system allows excess water from the retention fabric and planting media to drain through the nylon coils and exit the pot. A representative extensive green roof system similar to the one used for this study is shown in Figure 1.

Planting media. The planting media mixture consisted of 40% heat-expanded slate (gradation 3 mm to 5 mm) (PermaTill®, Carolina Stalite Company, Salisbury, N.C.), 40% United States Golf Association (USGA) grade sand (Osburn Industries, Taylor, Mich.), 10% Michigan Peat (Osburn Industries, Taylor, Mich.), 5% Dolomite (Osburn Industries, Taylor, Mich.), 3.33% composted yard waste (Kalamazoo Landscape Supplies, Kalamazoo, Mich.), and 1.67% composted poultry litter (Herbruck's, Saranac, Mich.) by volume. At time of planting, electrical conductivity (EC) and pH of the media were 3.29 mmho•cm^{-1} and 7.9, respectively. All treatments had 100 g•m^{-2} of Nutricote® type 100, 20N-$7P_2O_5$-$10K_2O$ controlled release fertilizer (Agrivert, Webster, Texas) hand-applied at the time of planting.

Plant material. A seed mixture of seven *Sedum* spp. was sown on 14 January 2003. The mixture contained seed of *S. acre* L., *S. album* L., *S. kamtschaticum ellacombianum* Fisch., *S. pulchellum* Michx., *S. reflexum* L., *S. spurium* Bieb. 'Coccineum', and *S. spurium* Bieb. 'Summer Glory', at a rate of 0.14 g•m^{-2} for each species. All seed was obtained from Jelitto Staudensamen, GmbH (Schwarmstedt, Germany). Due to its extremely small size, seed was mixed in dry sand prior to application to ensure even distribution within each pot. Eighty-three pots of each substrate type (249 total pots) were grown for an 85 d establishment period prior to use in the actual experiment.

Natural lighting in the greenhouse was supplemented with 400 watt incandescent lighting (Philips Lighting Co., Somerset, N.J.) for a 16 hour photoperiod. Average light meter (model LI-250, LI-COR, Inc., Lincoln, Nebr.) measurements at plant height were 338.4 μmol•s^{-1} m^{-2} on a selected representative cloudy day and 897.1 μmol•s^{-1} m^{-2} on a selected representative sunny day. Air temperature was controlled by a thermostat set at 21±1°C.

Once the plants were established, the study commenced on 10 April 2003. At this time a representative sample of 33 pots from each substrate type (99 total pots) was selected on the first day of the study. Shoots from each pot in the representative sample were harvested and dried for 6 d at 60°C to establish an initial mean shoot biomass dry weight.

Factors. Three substrate types were studied: (A) 80 mL of media (2 cm depth), (B) 80 mL of media (2 cm depth) with an extra moisture retention fabric layer capable of retaining 1200 g•m^{-2} of water (XF158, Wolfgang Behrens Systementwicklung, GmbH), and (C) 300 mL of media (6 cm depth).

Following the establishment period, watering regimes of 2, 7, 14, 28, or 88 days between watering (DBW) were randomly assigned to each pot. Watered pots received 157 mL of water on designated days with excess water allowed to drain. Upon completion of the study, all shoots were destructively harvested and dried at 60°C. The difference between the mean initial and final weights yielded a total shoot biomass production determination for each treatment.

Data collection. A lysimetric approach was used to measure water use over the course of this study. Prior to the first watering, pots were weighed to establish the dry weight of the pot, green roof components, dry media, sand-seed mixture, and fertilizer. On the first day of the study, pots were weighed after the initial watering; the difference between this weight and the dry weight reflected the water holding capacity of each pot. After the initial watering, pot weights were measured daily for the first week, then three times per week through week 4, after which measurements were taken once per week for the remainder of the 12 week study. Substrate moisture was monitored throughout the study by inserting a theta probe (ML2x, Delta-T Devices, Ltd., Cambridge, United

Kingdom) into the media until the points of the prongs contacted the vegetation carrier. Measurements were collected prior to watering on the same schedule as pot weights were measured. The theta probe instrument has a range of 0.0 to 1.0 $m^3 \cdot m^{-3}$. It should be noted that the accuracy of the theta probe was ±0.01 $m^3 \cdot m^{-3}$ for values from 0.05 to 0.6 $m^3 \cdot m^{-3}$ and likely less for values below 0.05 $m^3 \cdot m^{-3}$ and above 0.6 $m^3 \cdot m^{-3}$ (Delta-T Devices, 1999).

Experimental design and statistical analysis. The experiment was a completely randomized design with two factors, substrate design and watering regime. The study consisted of three substrate types, five watering regimes, and an unvegetated control treatment to characterize plant water use. There were ten replications of each treatment for a total of 300 pots. Pots were arranged with a single non-sampled border row consisting of vegetated and unvegetated control pots surrounding the study.

Shoot accumulation (final minus initial shoot dry weight) and total shoot dry weight comparisons were analyzed using an ANOVA model fitted with fixed effects of watering regime and substrate type. Although original means are presented, all differences were transformed prior to analysis using a log-linear hybrid transformation to stabilize the variance and normalize the data (Rocke and Durbin, 2003). Comparisons of initial versus final total shoot dry weight were made using a t-test within each substrate type. Differences between treatments for shoot dry weight accumulation were analyzed using multiple comparisons with Tukey-Kramer adjustments (PROC MIXED, SAS version 8.02, SAS Institute Inc., Cary, N.C.).

Evapotranspiration (ET) values were derived from the repeated measurements of pot weights over the first week of study for watering regimes of 2 and 7 DBW (7 DBW is representative of the other three watering regimes since none were watered over the first week). An assumption of the amount of water retained by each pot when watered was made based upon the pot weights before and after watering on the first day of study. Vegetated treatments within each of the two watering regimes were subjected to repeated measures analysis using an unstructured covariance structure (PROC MIXED). For substrate moisture analysis, all treatments were subjected to repeated measures covering the first 33 days of the study using an unstructured covariance structure (PROC MIXED). Values past 33 days were not used because the different watering regimes did not correspond to the days measurements were collected.

Results and Discussion

Shoot dry weight. Plants in all substrate compositions gained shoot biomass over the course of study when watered at least once every seven days (Figure 2). Under a 14 DBW regime, plants in substrates B (2 cm of media and additional water retention fabric) and C (6 cm of media) gained aboveground biomass, but plants in substrate A (2 cm of media) was not different from its initial biomass. Only plants in substrate C gained shoot biomass under a 28 DBW regime; the other two treatments were not significantly different from their respective initial dry weights.

When watered only once over the course of study (88 DBW), plants in substrates A and B did not gain biomass, however, an interesting occurrence was observed with substrate C. The aboveground biomass was actually 31% lower following the 88 day study when compared to the initial dry weight. This occurrence could be attributed to the larger vegetation, which had a higher water demand, found in the deeper substrate. Degradation of the non-structural carbohydrates within the plants was therefore greater (Taiz and Zeiger, 1998).

Shoot dry weight accumulation. Figure 3 depicts shoot dry weight accumulation. All substrate types accumulated more shoot biomass under the 2 DBW regime compared to the other watering regimes ($P \leq 0.05$) (Table 1). For substrates A and B, the other watering regimes were not significantly different from each other. However, watering regime did have an effect on growth for substrate C. Mean shoot accumulation was 2.63 g for the 7 DBW regime, followed by 14 DBW (1.30 g), 28 DBW (0.99 g), and 88 DBW (-0.28 g). All watering regimes were significantly different for substrate C except for the 14 and 28 DBW regimes. Data suggest that watering every other day is ideal for plant growth, but even those treatments that experienced 88 straight days of drought still had plants alive at the end of the study.

Comparisons of shoot accumulation under different watering regimes between substrate types are presented in Table 2. Substrate C accumulated the most dry weight in the three most frequent watering regimes. However, it was not different from the other substrates under the 28 or 88 DBW regimes and was not different from substrate B under the 14 DBW regime. Dry weight accumulation for substrates A and B was not different under any watering regime. This would suggest that the extra moisture retention fabric had minimal influence on plant growth.

Substrate moisture. Substrate moisture levels of the vegetated treatments were typically higher than those of unvegetated treatments in respective substrate designs. This is visible in watering regimes of 2 DBW and 7 DBW (7 DBW is representative of 14, 28, and 88 DBW over the first week) (Figure 4). When viewed over the first 33 days of study (Figure 5), the substrate C treatments consistently had the highest substrate moisture value across all watering regimes on successive days. However, the vegetated treatments of substrate C were only significantly different from the others under watering regimes of 2 and 7 DBW ($P \leq 0.05$). The higher substrate moisture levels for the vegetated treatments are presumably due to the shade provided by the plant canopy which lowered substrate moisture evaporation. The spikes in the substrate moisture figures correspond with the watering that occurred according to the regimes assigned to the treatments.

Substrate moisture averaged across all treatments for substrate C was greater than substrates A and B. However, substrate A and B substrate moisture values were not different. Vegetated and unvegetated treatments averaged across all other factors were only different from each other under the 2 DBW watering regime (data not presented). For substrate moisture comparisons within substrate design, the vegetated and unvegetated treatments were only different from each other for substrate C.

One particularly interesting finding of the substrate moisture monitoring was how rapid the values dropped after water application. Depending on substrate type and whether it was vegetated or not, values dropped to 0 $m^3 \cdot m^{-3}$ as quickly as one day after watering. For non-CAM plants growing in typical field soils, this would suggest a serious problem. However, *Sedum* spp. experience minimal adverse effects due to substrates with a low water holding capacity (Lassalle, 1998; Monterusso, 2003).

Evapotranspiration. ET rates under the 2 DBW regime were highest on the day of watering. Second day rates were always lower than the preceding day. The ET rates of all treatments were significantly different on all watering days the first week (days 3, 5, and 7) (Figure 6A). Substrate C experienced the highest ET rate on all days except day 4, on which it was not significantly different from the other treatments. On the final day of measurement the first week, substrates B and C experienced ET rates significantly higher than any previously measured rate. This can likely be attributed to the ambient weather. Although air temperatures in the greenhouse were maintained at 21±1°C using a thermostat, air temperatures at times were likely higher due to solar heating. According to Prazak et al. (1994), an increase in air temperature leads to an increase in potential ET.

After reaching a maximum ET rate on day 3 under the 7 DBW regime, ET for all substrates decreased daily until leveling off at 0 $mm \cdot d^{-1}$ (Figure 6B). This occurred two days after watering for the shallowest substrate (Substrate A) and after seven days for the other two substrates. Although ET rates were at zero, the plants were still viable as can be seen from the results of Durhman et al. (2004) in which chlorophyll fluorescence was measured in a study occurring simultaneous to the one reported here.

Overall, ET for substrates B and C was not significantly different under the 7 DBW regime, although substrate A was different from both. On individual days, substrates B and C were only different on days 3 and 4. However, by day 5, their ET rates were essentially the same and by day 7 the ET rate of all substrates was essentially the same. The ET rates given for both regimes, 2 and 7 DBW, are likely rather conservative due to the conditions in which they were collected. Had this study been performed outdoors under additional climatic variables, mainly wind and increased solar radiation, ET rates would likely increase.

Conclusion

Although the vegetation of all substrate treatments survived after reaching ET rates as low as 0 mm • d^{-1}, irrigation scheduling should be adjusted accordingly to prevent this during production. However, once the vegetation has been installed on a roof, the ability of *Sedum* to withstand extended drought conditions makes it ideal for shallow extensive green roof systems. If an extensive green roof is to be truly sustainable, that is, to not depend on supplemental irrigation, then it must tolerate all the harsh conditions presented, including extended periods of drought. Most *Sedum* spp. fulfill these requirements.

The deepest substrate treatment (6 cm of media), clearly performed the best in terms of substrate moisture retention and plant growth. The deeper substrate did not dry out as fast, so a greater amount of water was retained and available to the plants during periods of drought. Because of the fact that many *Sedum* spp. are not always negatively affected by drought, the vegetation in shallower substrates may perform equally as well once substrate moisture has lowered to zero when the vegetation has been installed on a roof. One way to extend the period of water availability to the plant would be to add a water retention fabric to the substrate. Although our results suggest that it is not necessary for green roof vegetation in the propagation stage, it may be worthwhile for an installed green roof because the extra fabric helped hold water lessening the length of drought periods. Even so, treatments subjected to drought for the duration of the study (88 days) was still viable at the end of the experiment.

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Table 1. Mean shoot dry weight accumulation (g) for each treatment over the course of the study. Values are treatment means of watering regimes of 2, 7, 14, 28, and 88 days between watering (DBW) within each substrate type [(A) 2 cm of media, (B) 2 cm of media with an extra moisture retention fabric layer, and (C) 6 cm of media].

	Substrate		
DBW	A	B	C
2	*1.82a	2.68a	5.54a
7	0.47b	0.63b	2.63b
14	-0.04b	0.27b	1.30c
28	0.10b	0.12b	0.99c
88	-0.05b	-0.01b	-0.28d

* Means within same column followed by the same letter are not significantly different ($P \leq 0.05$).

Table 2. Mean shoot dry weight accumulation (g) for each treatment over the course of the study. Values are treatment means of substrate types [(A) 2 cm of media, (B) 2 cm of media with an extra moisture retention fabric layer, and (C) 6 cm of media] within each watering regime.

	Days Between Watering				
Substrate	2	7	14	28	88
A	*1.82a	0.47a	-0.04a	0.10a	-0.05a
B	2.68a	0.63a	0.27ab	0.12a	-0.01a
C	5.54b	2.63b	1.30b	0.99a	-0.28a

* Means within same column followed by the same letter are not significantly different ($P \leq 0.05$).

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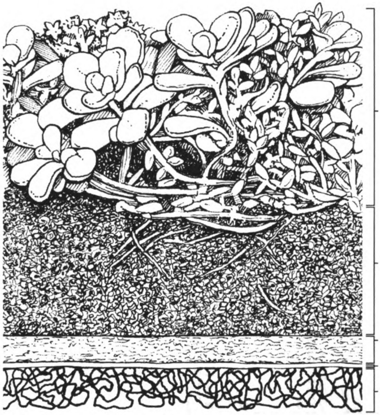
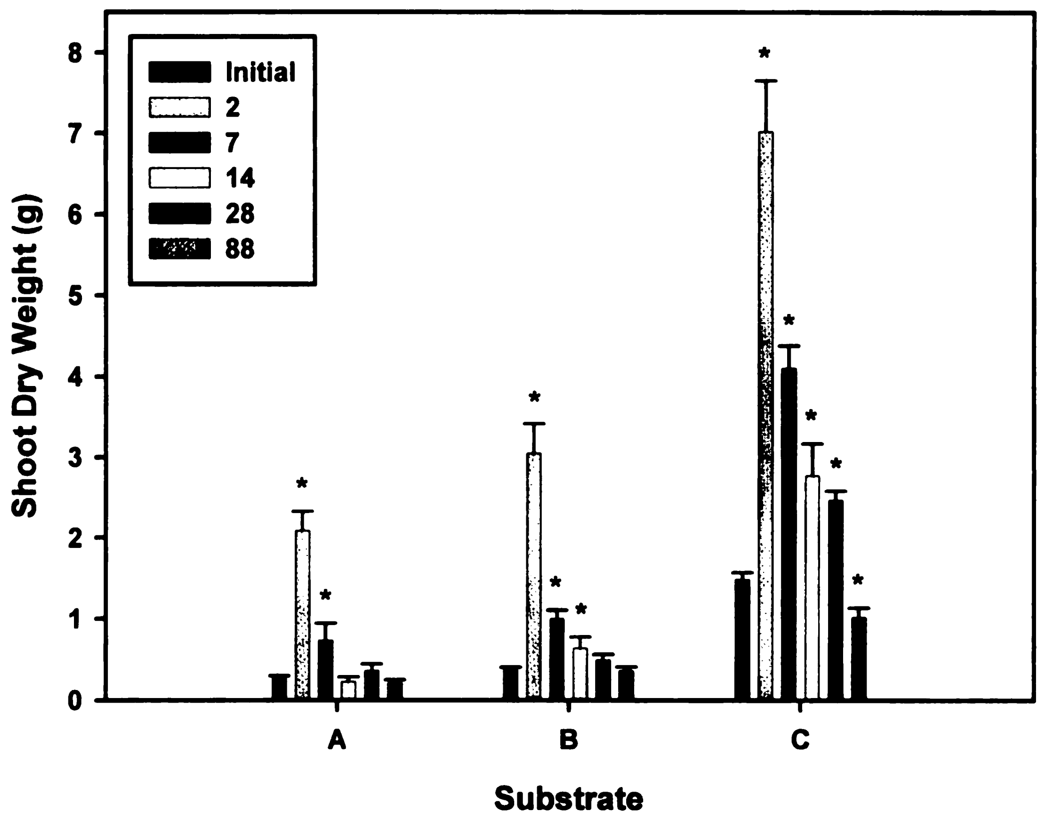
Figure1.



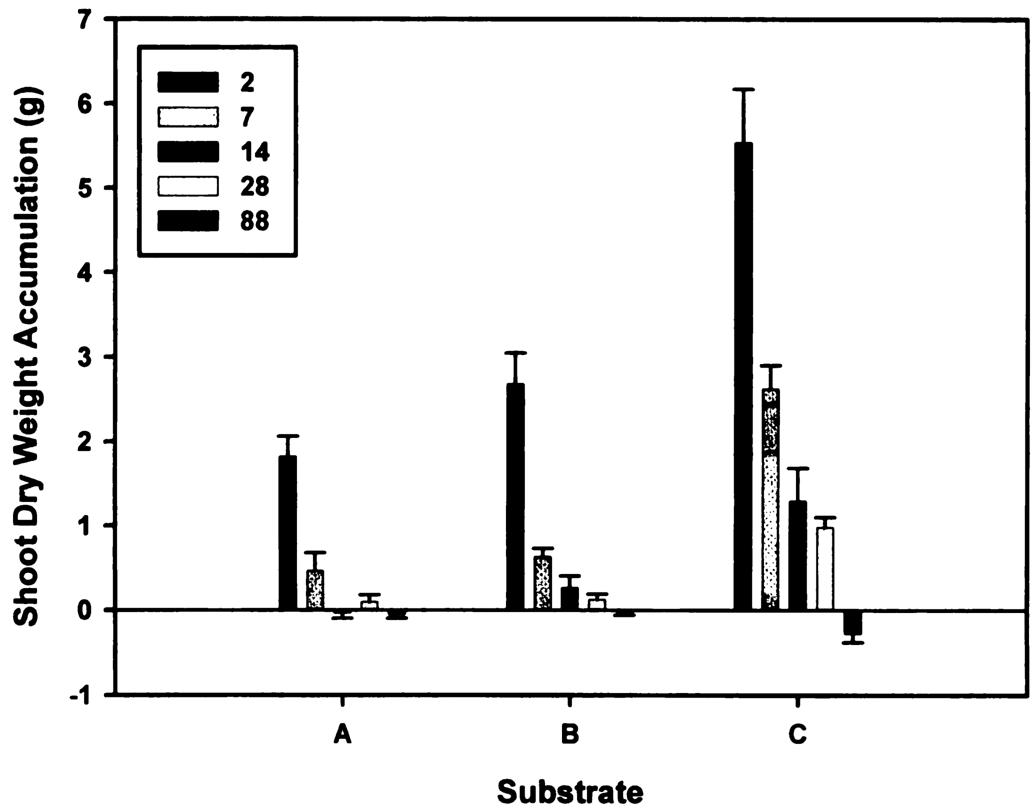
A cross section of a representative extensive green roof system. Substrate treatments for this study were modified as either: (A) 2 cm of media, (B) 2 cm of media with an extra moisture retention fabric layer, or (C) 6 cm of media.

Figure 2.



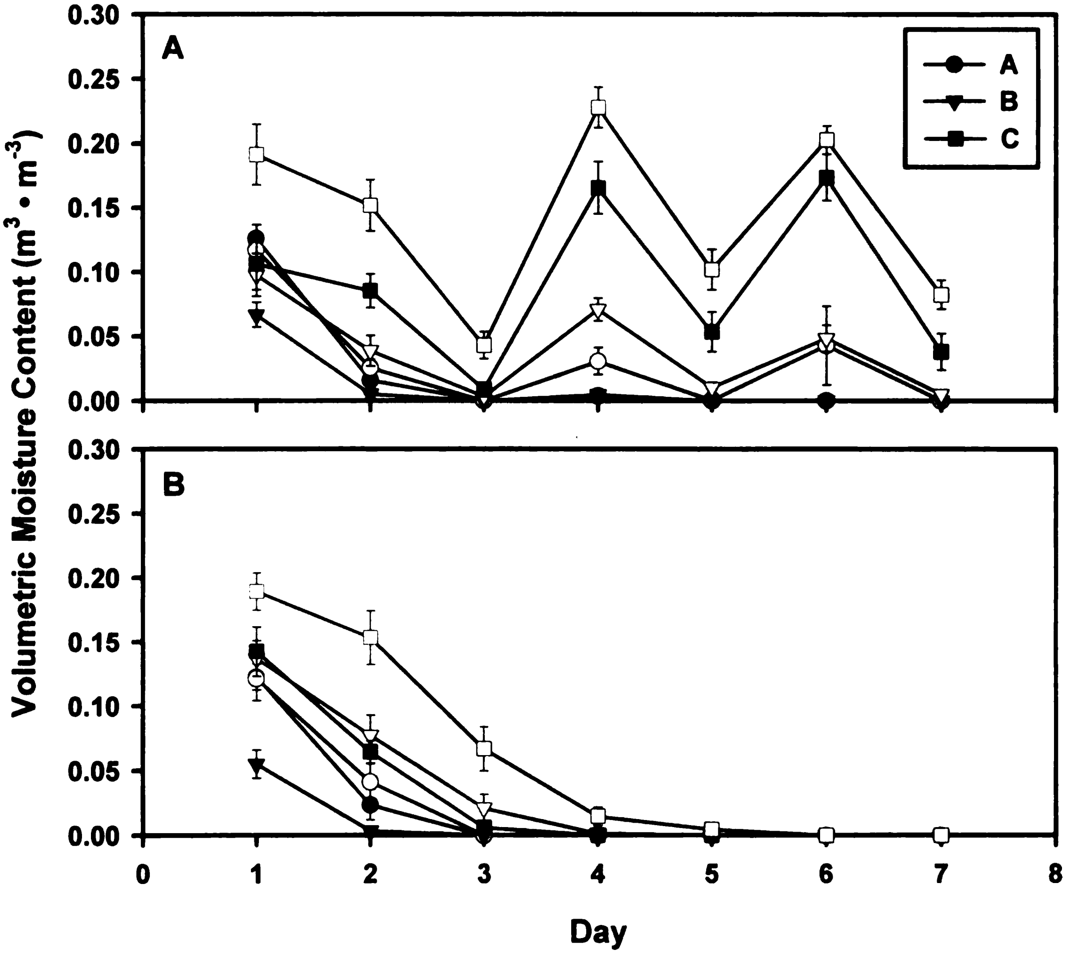
Shoot dry weights (g) for each substrate type measured either initially or after 88 days under a watering regime of 2, 7, 14, 28, or 88 days between watering (DBW). Substrate types for this study were: (A) 2 cm of media, (B) 2 cm of media with an extra moisture retention fabric layer, and (C) 6 cm of media. Bars with an (*) are significantly different from the initial dry weight of their respective substrate type ($P \leq 0.05$). Error bars represent standard error.

Figure 3.



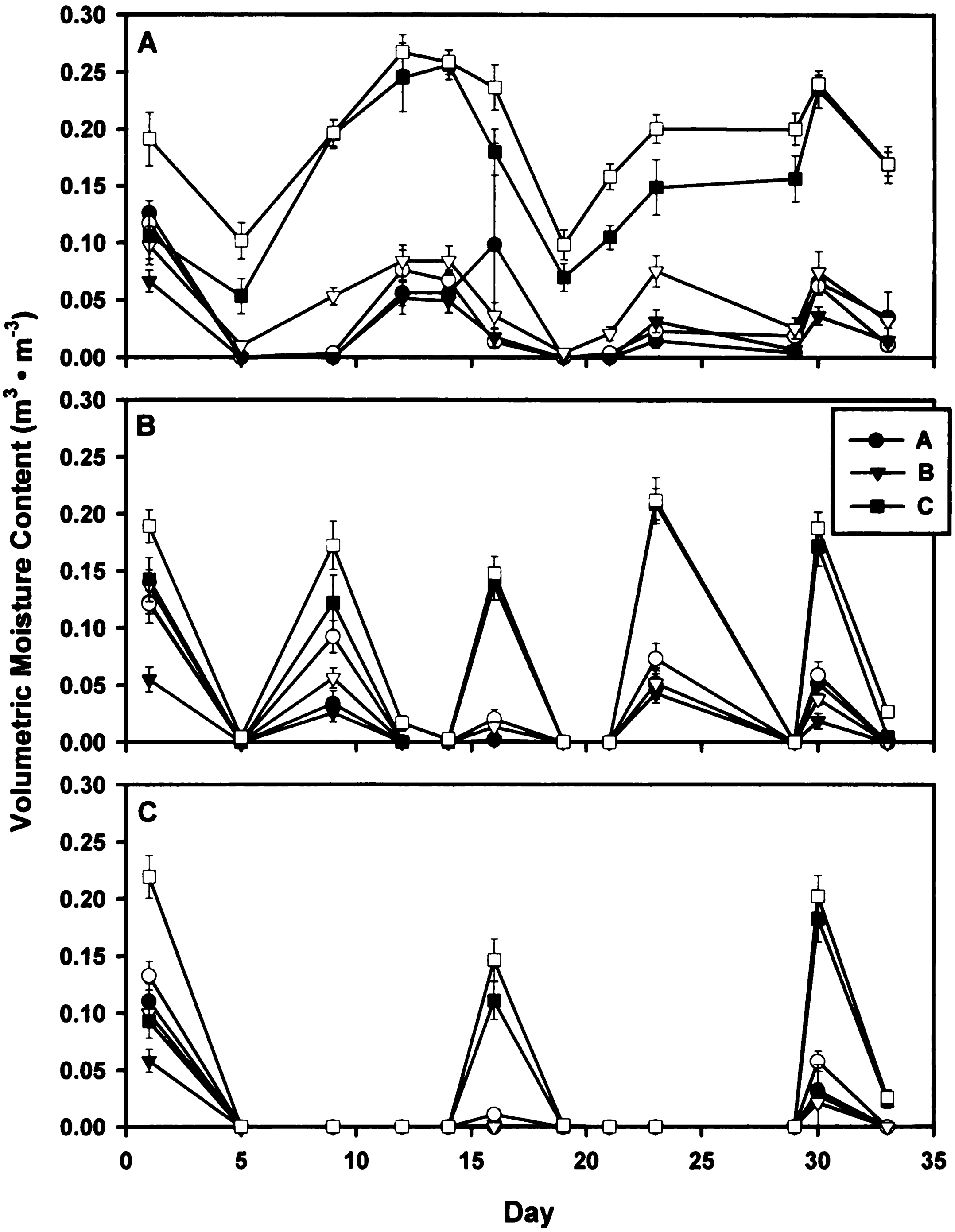
Shoot dry weight accumulation (g) following an 85 d establishment period and 88 d under a watering regime of 2, 7, 14, 28, or 88 days between watering (DBW) for each substrate type. Substrate types for this study were: (A) 2 cm of media, (B) 2 cm of media with an extra moisture retention fabric layer, and (C) 6 cm of media. Error bars represent standard error.

Figure 4.



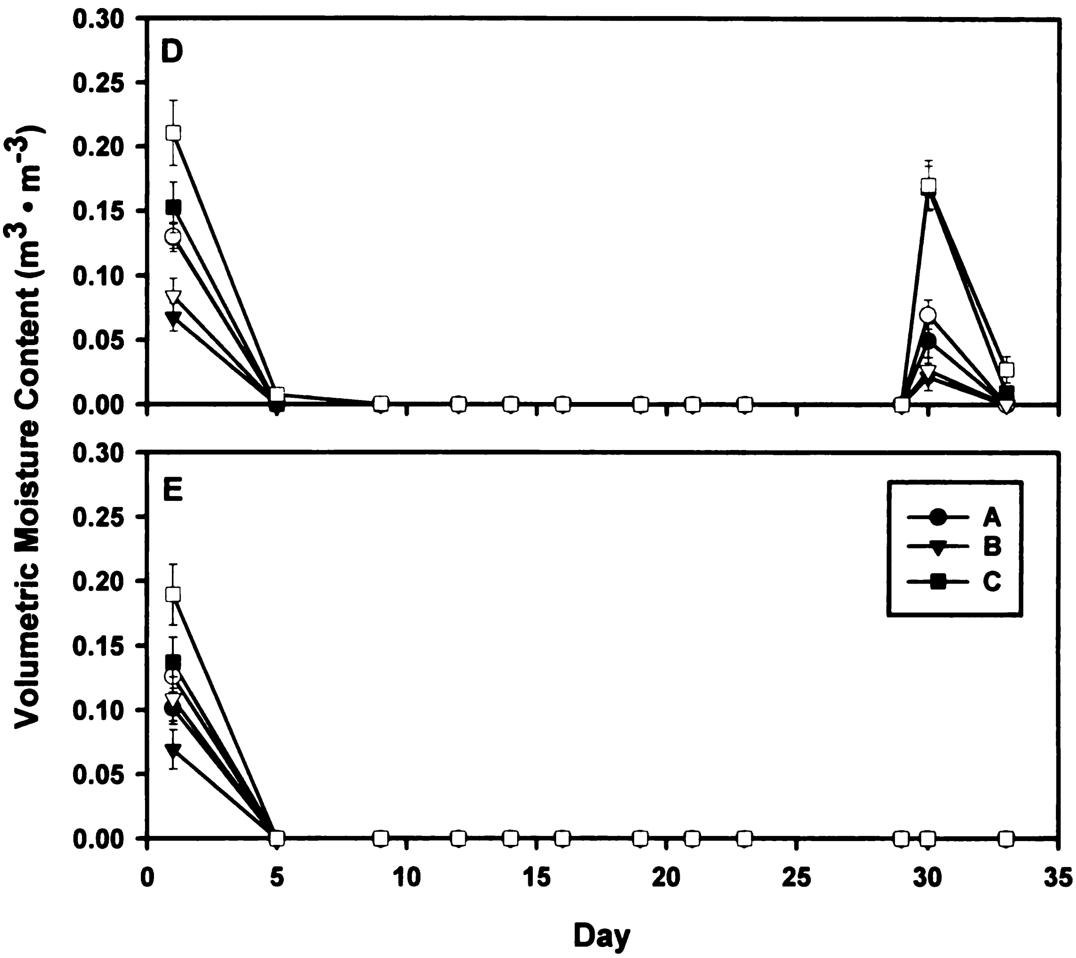
Substrate volumetric moisture content ($m^3 \cdot m^{-3}$) over the first week of the study for watering regimes of 2 days between watering (DBW) (A) and 7 DBW (B). Data points represent substrate types of (A) 2 cm of media, (B) 2 cm of media with an extra moisture retention fabric layer, and (C) 6 cm of media. Darkened symbols represent unvegetated treatments and open symbols represent vegetated. Error bars represent standard error.

Figure 5.



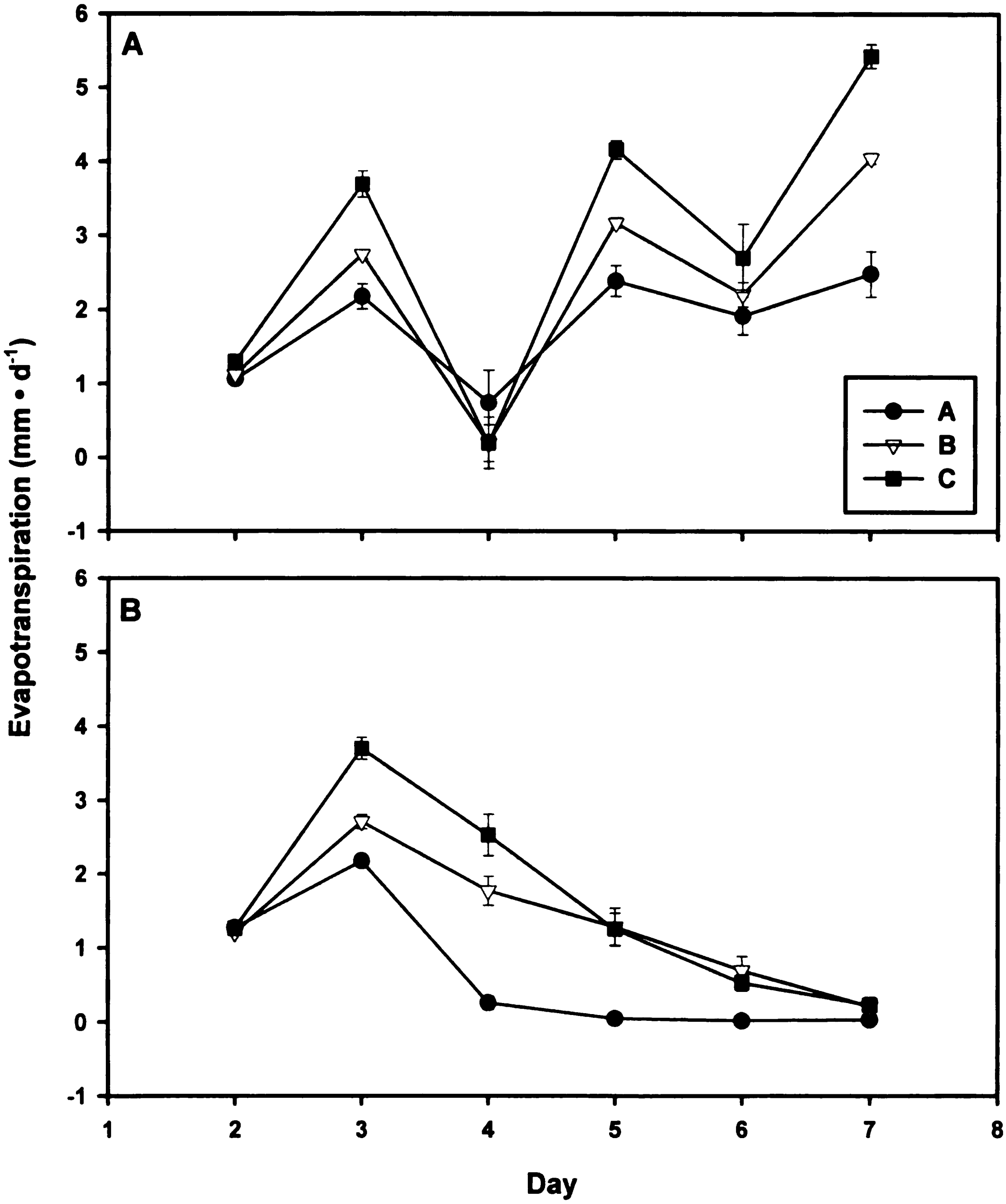
0.30
0.25
0.20
0.15
0.10
0.05
0.00
A
B
C
A
B
C
Volumetric Moisture Content ($m^3 \cdot m^{-3}$)
0
5
10
15
20
25
30
35
Day

Figure 5 continued.



Substrate volumetric moisture content ($m^3 \cdot m^{-3}$) over the first 33 days of the study for watering regimes of: (A) 2, (B) 7, (C) 14, (D) 28, and (E) 88 days between watering (DBW). Data points represent substrate types of (A) 2 cm of media, (B) 2 cm of media with an extra moisture retention fabric layer, and (C) 6 cm of media. Darkened symbols represent unvegetated treatments and open symbols represent vegetated. Error bars represent standard error.

Figure 6.



Evapotranspiration values (mm • d^{-1}) over the first week of the study for watering regimes of 2 days between watering (DBW) (A) and 7 DBW (B). Data points represent substrate types of (A) 2 cm of media, (B) 2 cm of media with an extra moisture retention fabric layer, and (C) 6 cm of media. Error bars represent standard error.

THESIS CONCLUSION

The preceding chapters represent three studies in the ongoing vegetative green roof research program in the Department of Horticulture at Michigan State University. Along with continuing stormwater runoff monitoring, current studies are exploring other species of the Crassulaceae family for their green roof potential in the Midwestern climate and the ecological interactions that occur with them on a roof surface.

Results of studies reported in this thesis support earlier claims that green roofs retain more stormwater than typical roofs currently found on most commercial buildings. The results also support claims that properly selected *Sedum* spp. are tolerant of the drought conditions that are often present on roof surfaces. These findings can now be utilized by decision makers in the building construction industry to make better educated decisions regarding the design and construction of extensive green roofs.

Specifically, results indicate that increasing growing media depth increases stormwater retention and vegetative growth. Optimally, media depth would be increased until 100% retention was achieved. However, increasing growing media depth also increases the load support requirements of the roof and therefore increases construction costs. This would likely make green roofs cost prohibitive for most projects. Increasing media depth can also lead to increased maintenance costs. While vegetative growth of the preferred plant taxa increases, *Sedum* spp. in our studies, establishment and growth of weed species also increases. With thin extensive green roof systems, weed seeds are able to germinate, but usually do not become established because of the lack of water on a roof. However, when media depth is increased, water availability may also increase enough to allow weeds to become established.

Further research is warranted to determine if green roofs are effective stormwater retention devices on roofs with slopes greater than those utilized in this series of studies. While green roofs have traditionally been utilized on relatively flat-sloped roofs, many roofs are constructed with slopes that have traditionally been considered too steep to utilize green roofs systems. These buildings offer another area where room exists for improvements in stormwater management.

Green roofs will likely become increasingly common in the future as green space continues to be developed and formed into vast expanses of impervious surfaces. Studies from other researchers have indicated that green roofs offer other environmental benefits beyond stormwater mitigation. Aiding the reduction of the Urban Heat Island Effect, decreasing energy demands of the building they cover, and providing more of a "natural" habitat for numerous organisms in urban areas are some of the other major benefits that justify green roof utilization if our communities are to ever approach sustainability.