National Decentralized Water Resources Capacity Development Project (NDWRCP) Research Project



QUANTIFYING EVAPORATION AND TRANSPIRATIONAL WATER LOSSES FROM GREEN ROOFS AND GREEN ROOF MEDIA CAPACITY FOR NEUTRALIZING ACID RAIN

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Abstract:

Green roofs are becoming increasingly common in North America, where they are being promoted as a stormwater management BMP. Although green roofs have been used in Europe, particularly Germany for over 30 years, the North American Industry is still relatively new and installation, management, and performance standards are relatively poorly developed. Research on the performance of North American green roofs has really only been done for the last decade, and although much has been learned, there are still many unanswered questions. There is ample evidence that green roofs can reduce stormwater runoff in Eastern North America by 40 - 60%, but the relative contribution of the media and plants to this stormwater retention has not been characterized or quantified. Further, for this retention and evapotranspiration to be of use to stormwater engineers and developers, tools to predict the retention and detention of stormwater on a green roof are needed. This project describes studies of the evaporation and evapostranspiration of water from green roof modules planted with three common green roof plant species. Green roof plants like sedum and delosperma used water quickly when it was available and reduced their water use rate when they were drought stressed. This makes sedums and delosperma ideal plants for green roof use. Plants contribute as much as 40% of the roof capacity to retain stormwater depending on the frequency and intensity of the storm events. This data and other runoff data from larger field study roofs provided the basis for models that describe and predict the function of a green roof described in this report. In addition to influencing the quantity of runoff, green roofs can also influence the quality of runoff. One of the most consistently reported benefits of a green roof for runoff quality is the neutralization of acid precipitation. It is clear however, that this is a finite property of the medium, controlled by the potential buffering capacity of the medium. To maintain this capacity and hence the water quality benefit, green roof maintenance should include periodic liming to replace the neutralized media buffer. This project describes the buffer potential of two commercial green roof media, and details a testing procedure. The testing procedure allows a green roof manager to estimate when lime will be needed, and what the potential buffering capacity of a green roof media will be. With the two media evaluated there were slight differences in total buffer potential, however the differences were not great and the response to acid addition was similar for both media, with both having sufficient buffering capacity to neutralize acid precipitation in Central Pennsylvania for at least 10 years before liming would be required.

Benefits:

The water use from green roof media of three common species of green roof plants was evaluated. The results of these evaluations dispel two common misconceptions about green roofs planted with sedums and other succulent species and support their use in green roof applications. The three plants used water freely immediately following irrigation and conserved water when media moisture was less available. This data disproved the common misconception that these plants conserve water all the time making them poorly suited for removing stored water from a green roof medium. The data also indicate that the contribution of the plants to the stormwater management function of a green roof can be considerable, up to 40% of the total function depending on storm intensity and frequency. This result calls into question the reports that the media

is really the only thing providing the stormwater management function in a green roof. The results provide new evidence that these plant species are in fact, very well suited for this use.

- The storm-based retention and detention simulation model was developed. Results have been published and presented at several conferences. This spreadsheet-based model has been distributed and is being used by a number of engineering and development firms to plan the use of green roofs in their stormwater plans.
- A test method to quantify acid rain buffering capacity for green roof media was developed and evaluated with two commercial media. The data suggest that common commercial media can neutralize acid rain for 10-30 years depending on acid deposition rates. The model developed can be used to determine when a roof should be tested to determine lime requirements. The results have also been used to suggest the amount of lime to add to a green roof media to raise the pH to a desired target. Leaching of cation metals from a green roof suggests that with relatively clean acid rain the roof will not reduce metal cation content in the leachate runoff compared to runoff from a non-greened roof. The ability of media to retain cation metals was however fairly large and if contaminated irrigation water is applied to a green roof the roof can adsorb some of these ions. The accelerated acid aging test has been presented at the International Green Roof congress in Basel, and the Green Roofs for Healthy Cities Conference in Boston as well as several other workshops and seminar programs.
- Five short manuscripts detailing the benefits and uses of green roofs are presented. These are being used as a part of the background for a college class in eco-roof technology.

Keywords: Green roofs, acid rain, green roof media, sedums, plant water use, green roof stormwater retention, green roof benefits.

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EXECUTIVE SUMMARY

Rooftop greening has been suggested as a method to reduce impacts of urbanization, reducing the impervious surface within a developed zone. The stormwater benefits offered by green roofs include not only direct retention of a portion of the rainfall, but also a delay in the runoff peak and decrease in the peak rate of runoff from the site as well as potential improvement in some runoff water quality parameters.

One of the major limitations to promoting this use of green roofs has been the lack of accepted design tools or models to predict the effects of the green roofs, and a major limitation in current models has been our lack of a good understanding of evaporation and evapotranspiration (ET) by the green roof systems. Many of the plants commonly used on an extensive green roof are drought tolerant succulent plant species. By their nature they conserve water, so it has been hypothesized that they will, by conserving water, provide relatively little recharge in the medium water storage capacity between rain events. This hypothesis, and data on medium water storage and potential evaporation rates has led to the conclusion that an unplanted roof may be nearly as effective as a planted roof for stormwater management. Data from this project demonstrate that plants can and most likely do, contribute to the stormwater management function of a green roof system. These plants use water relatively rapidly when it is available and conserve water when it

is not. When it rains the planted roof loses 2x the amount of water lost by an equivalent unplanted roof, recharging the media water storage potential much faster than could be achieved without the plants (Figure 1). If there is no rain for an extended period these plants conserve the remaining moisture in their tissues to survive where other species might quickly reach the permanent wilting point and die. The relative contribution of the plants to the stormwater function of a green roof is greatest (approximately 40% of the total stromwater retention response in this study) in areas with relatively



frequent, relatively small rains. This essentially means that these plants are ideally suited for a green roof in climates like that of the Northeastern U.S. The green roof stormwater models developed and refined during this project predict the potential of a sedum green roof to retain and detain 40-60% of the annual stormwater in the Northeast.

One of the major water quality benefits reported for green roofs has been their ability to neutralize acid rain. Acid precipitation is known to cause a number of problems in urban runoff including acidification of surface waters and potential acid leaching of metal ions from rooftop flashings, downspouts and other exposed metals on a roof. To manage a green roof to maintain

the ability to neutralize acid rain over the long term one must understand both the exchange capacity of the medium and the acid buffering capacity inherent in the green roof system. This understanding allows a maintenance manager of a green roof to predict the frequency and effects of routine procedures (liming) needed to maintain this capacity over the life span of the green roof. An accelerated acid addition (aging) test was developed. The procedure involves the addition of small aliquots of acid to a known volume of media. The media acid slurry is allowed to rest for a period of at least 24hr following each acid addition to let the system come to equilibrium with the media buffer. This slow titration should be continued to a stable end point of pH 6.0 or less. With the two media evaluated the buffering potential was similar in the desirable range for an extensive green roof (pH > 6.5), but was quite different at lower pH. The test results for the 2 media were described by a simple linear equation with a correction factor for the medium.

Medium pH = $7.18 - 50.36 \times H^+ + M$

Where H^+ is the acid added (meq / cc of media) and M is the media correction factor (0 for clay-based media and 0.3 for a slate-based medium). This equation can be modified and solved to predict the number of years before a medium will reach a target pH for a given rate of acid deposition and depth of media on the roof.

$$Yr = \frac{TpH - 7.18 + (M \times d)}{50.36 \times Hd \times 0.01}$$

Where Yr is the number of years to reach the target pH, TpH is the target pH, M is the media correction factor, d is the depth of the media in cm, Hd is the acid deposition rate in Kg H per hectare. With a target pH of 6.5, a medium depth of 8.6 cm, and a deposition rate of 0.495 Kg H per ha, a clay-based medium would be expected to reach the target pH in about 24 years. Since there are other potential sources of acidification in a normal roof including fertilizers, leaching, and plants, a manager of this roof should probably test pH after about 10-15 years.

Nine species of potential green roof plants were not adversely impacted by irrigation with acid irrigation water. In fact, the pH of the leachate from most of these plants was higher than from unplanted pots.

The pH of runoff from non-greened roofs without media was lower than that from green roofs, however metal ions (Fe, Cu, Mn and Zn) were higher in the runoff from the green roofs. Although there is ample cation exchange capacity to adsorb the metals if present in concentrations that exceed the media solution levels in the run on to the roof (eg. contaminated irrigation water), rain water in this study had lower concentrations of these ions than the medium solution so there was a net leaching of these ions from the media.

CHAPTER 1.0

INTRODUCTION

Significant water quality and quantity issues result from stormwater runoff from developed areas in North America. For the five-year period from 1997 to 2001 the rate of urban development averaged 890,000 ha/year (2,400 ha/day) (NRCS, 2003). Development results in water quality impairment and quantity management issues throughout the affected watershed. For example, nutrient loading (a widespread result of agricultural runoff) may be replaced as the critical impairment issue for a watershed by increased peak flows, flooding, and urban pollutant loads as runoff is collected from impervious pavement and roof surfaces.

Rooftop greening has been suggested as a method to reduce these impacts by reducing the impervious surface within a developed zone (Scholtz, 2001). The stormwater benefits offered by green roofs include not only direct retention of a portion of the rainfall, but also delaying the runoff peak and decreasing the peak rate of runoff from the site (PACD, 1998). Most extensive green roofs currently being installed in North America consist of four distinct layers: an impermeable roof cover or roofing membrane, a "drainage net," lightweight growth medium (about 8cm), and adapted vegetation (PACD, 1998). The drainage layer is an open, highly permeable material that quickly channels gravitational water off the roof. The growth medium, in addition to providing a suitable rooting zone for the selected vegetation, should be of low density and have high water-holding capability while also providing good drainage. A light weight medium allows for retrofit installation on older buildings, and also reduces the need for extra structural support in new buildings. Medium depth and porosity plays an important role in stormwater retention and plant growth. Plants provide shade to the surface below the foliage, intercept rainfall, and slow the direct runoff from sloped roofs (Miller, 1998).

The use of green roofs in Germany is widespread and has been promoted in many cities through financial incentives (Pederson, 2001). Economies of scale, contractor experience, and specialized equipment have reduced the cost of installing a green roof in Germany and throughout Europe. In contrast, installing a green roof in the U.S. can be very expensive, adding at least \$6 to more than \$30-40 per square foot to the cost of the roof. Other barriers also limit widespread use of green roofs in the U.S. Engineers, developers, and policy makers are unsure of the actual quantifiable benefits of a green roof. Although much anecdotal information exists detailing the benefits of green roofs, little scientifically based replicated data has been collected. Although water retention by the medium and evaporation from it can be fairly easily modeled and represented mathematically, the addition of plants, particularly drought tolerant crassulacean acid metabolism (CAM) plants, with their unique ability to close stomates during the day may greatly complicate predicting water retention.

The Center for Greenroof Research at Penn State, established in 2000, promotes greenroof research, education, and technology transfer. (http://hortweb.cas.psu.edu/research/greenroofcenter/index.html). It is the only facility of its type in the U.S. with replicated small buildings for the study of extensive green roofs. The center has

collected performance data from its green roof structures over the last three years. Data collected during 2002 and the very wet summer of 2003 indicates that the green roofs will retain approximately 40-50% of the annual precipitation (Denardo, 2005; Jarrett et al., 2004). Retention from individual storm events ranged from 0-100%. The green roofs also delayed runoff and reduced peak runoff rates. Water quality data collected in 2002 and 2003 show that green roofs can improve water quality in runoff, particularly in their ability to neutralize acid precipitation.

Our research programs focus on identifying potential benefits and limitations to adoption of green roofs and providing the data and professional training needed to demonstrate their effectiveness. Efforts to date suggest that the most likely cost effective driver for a developer or zoning board to promote the use of green roofs is their ability to retain and detain stormwater, thus reducing or eliminating the need for increased stormwater management infrastructure on the part of the municipality or watershed management board, and reducing or eliminating the need to set aside development land for onsite stormwater management basins. In either case the costs and benefits are direct, easy to understand, and easy to assign to an individual entity. One of the major limitations to promoting this use of green roofs is the lack of accepted design tools or models to predict the effects of the green roofs, and a major limitation in current models is our lack of a good understanding of evapotranspiration (ET) by the green roof systems. We have begun to address this need with this research by developing accurate and dynamic estimates of ET and green roof plant water use.

This project also addresses a major runoff water quality issue that our preliminary research suggests green roofs could effectively remediate. Our data demonstrates the ability of a green roof to neutralize acid rain and increase the pH of the runoff. Although the effects are clear and consistent, the potential benefit has not been fully explored or quantified. Acid precipitation is known to cause a number of problems in urban runoff including acid leaching of metal ions from rooftop flashings, downspouts and other exposed metals on the roof. A green roof has the potential to all but eliminate this pollution source. To manage a green roof for this purpose over the long term we must understand both the exchange capacity of the medium (ability to adsorb metal ions) and the acid buffering capacity (ability to neutralize acid rain) inherent in the green roof system and the frequency and effects of routine maintenance procedures (liming) needed to maintain this capacity over the life span of the green roof.

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CHAPTER 2.0

GREEN ROOF PLANT WATER USE

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2.1 Abstract

Extensive green roofs are being promoted as a stormwater best management practice in North America. Research and experience from Northern Europe and Northeastern North America has demonstrated that these roofs can retain 40-70% of the annual precipitation depending on medium depth and plant communities. Although the plants are clearly what makes a green roof "green", the relative contribution of plants to the stormwater function has been described as minimal, and it has been suggested that much of the function could be achieved with media alone. To investigate and quantify the role of common green roof plants like sedum and delosperma, a series of weighing lysimeters were constructed in a greenhouse at Penn State University in University Park, PA. Delosperma nubigenum, Sedum spurium, and Sedum sexangulare in green roof modules were subjected to a dry down period during which water loss from the roof module was recorded. The sedum and delosperma tested were found to use water rapidly when it was available. The water loss rate from planted roof modules was about 2 times that from unplanted modules during the first five or so days following irrigation. After five days the rate of water loss was similar for planted and unplanted roof modules. The relative effect of plants on the total water loss for the roof modules suggest that the plants could contribute as much as about 40% of the stormwater retention function of the green roof. The relative affect of plants would be greatest with relatively frequent (3-5 day) relatively small (12.7 mm, 0.5") storms. With longer dry periods the affect of the plants is less, i.e. the medium alone is capable of the same or nearly the same water retention as a planted system.

2.2 Introduction

Extensive green roofs are rapidly being accepted as a stormwater BMP in North America (PaDEP, 2006). A simple extensive green roof in North America designed as a stormwater BMP consists of a drainage layer covered with 2-6" of a lightweight growing medium and vegetation. Numerous studies have concluded that a green roof with about 4 inches of medium can retain 40-60% of the annual precipitation in the Northeastern U.S., with nearly 90% of many summer storms retained (Denardo, et al., 2005). In addition green roofs have been shown to detain runoff, reducing peak flows. It is no accident that this 40-60% retention is very similar to the amount of annual precipitation used by evapotranspiration in the Northeast. It appears that green roofs function in this sense, by restoring the evapotranspirative component of the hydrologic cycle

(Kramer and Boyer, 1995)). It has been suggested that most of this retention in a green roof is a function of the medium (VanjWoert et al., 2005). The lightweight media used are designed to retain as much as 50% water by volume (FLL, 2002), so a 4" roof in theory could retain 2" of precipitation if all the storage was available at the time of the rain. In practice this is seldom that case, event frequency, environmental conditions between events and tightly held matric water in the media reduce this figure to something closer to 0.5-1.25" retained in most summer storms by a 4 inch thick roof in Central Pennsylvania (Denardo et al., 2005). Media components also contribute to storage capacity in different ways. In a summary of test results from the Penn State Agricultural Analytical Testing Laboratory the average water holding capacity for 39 multicourse green roof media samples (standard extensive roof media test) was 46.1% with a low of 14.7% and high of 65.2% (Berghage, 2007). Although media water storage capacity obviously affects retention in any given storm, it has surprisingly little effect on total annual retention (Jarrett et al., 2006). Using a model based on ET and stormwater records Jarrett, et al., 2006 reported very little increase in annual retention as media storage capacity was increased from 40 to 79mm. In fact even with only 3mm of storage more than 30% of the annual precipitation was predicted to be retained in State College.

Although the majority of the water retention capacity of a green roof is contributed by the medium, plants also store water. The plants most commonly used on extensive green roofs are low growing succulents like sedum, delosperma, sempervivum, etc. (Snodgrass and Snodgrass, 2006). These succulent plants can store considerable water in their tissues. A mature population of *S. spurium* can weigh 1g/cm of roof surface of which 80-90% can be water. As with the soil storage only a portion of this is available for atmospheric exchange. Many of these succulent plants are well adapted to living in drought and have adapted a variety of strategies to reduce water loss including lignified, waxy tissues and CAM metabolism where stomata can remain closed during the day to reduce water loss and photosynthetic gas exchange can occur at night (Larcher, 1995). Sedums can live for weeks or months without rain (Snodgrass and Snodgrass, 2006). This ability to minimize water loss during drought and lose an appreciable percentage of stored water without plant death makes the concept of permanent wilting point difficult to define with these species and makes it difficult to place a value on the portion of the plant stored water that is exchangeable with the atmosphere.

The biggest contribution of plants to green roof water retention is most likely through the affects of evapotranspiration on media water storage. Plants use soil moisture both for growth and metabolism, and as a cooling system. Water is extracted from the soil by the root system, moves through the vascular system and exits through pores in the tissues called stomates (Kramer and Boyer, 1995). The driving force for this movement of water is the vapor pressure differential between the water saturated plant tissue and the relatively drier external air. The rate of water use is thus a function of the open surface area of the stomata and the vapor pressure of the surrounding air. Plant architecture therefore plays a large role in potential evapotranspiration and the ability of a plant community to use media water and recharge the media storage potential. Plants with large exposed surfaces and a high density of stomata have the potential to use far more water than plants with a high tissue volume to surface area ratio and few stomata. Low growing species with densely packed foliage present less exposed surface and hence lose less water. It would seem then, at first glance, that sedums and other succulents are poor choices for recharging media water storage because they are architecturally and metabolically adapted to reduce water loss, however a green roof is only green when the plants are alive. It would seem that the ideal plant for a non-irrigated green roof would have the ability to use water when

available, but to conserve when water was scarce.

Although we know that sedums and other succulents can tolerate drought, and are very good at surviving with very little water, and in fact have been outstanding plants on green roofs in Europe and the temperate Northeastern U.S., little is known about the rate these plants actually use water on a green roof when it is available. Are they always conservative, or do they use more water if it is readily available? Do different species contribute more or less to the recharge of the media storage capacity? What is the actual contribution of the plants to the total function of the roof and does a sedum roof in fact work significantly better than a medium roof without plants?

2.3 Materials and Methods

A series of eight weighing lysimeters were constructed in a greenhouse at The Pennsylvania State University in University Park, PA (Figure 1). Each lysimeter consisted of a load cell (LCEB-150, Omega Engineering Company) connected to a data logger (Campbell Scientific). Green roof modules were constructed from wood and suspended from the load cells with metal cable. Modules attached to each load cell could be changed by releasing the suspension cables and installing a different module. Modules were 1.05 x 0.54 x 0.10 m (LxWxH) with a 10 mm (0.5") drainage slit at one end. Each module was filled with a 12 mm (0.5") thick drainage layer (Enka drain 9715; Cold Bond, ENKA - North Carolina) and 89 mm (3.5") of a commercial green roof medium

Figure 1. Weighing lysimeters in PSU greenhouse. *S. sexangulare* planted modules are shown in this photo. Note suspension cables connecting roof modules to load cells.



(Gerick Corp., Ohio). The media had a bulk density of 0.534 g/cc and a volumetric water content at field capacity of 28%. The total water storage potential for the module was thus about 25 mm of water. A total of 16 modules were constructed. Four modules were planted with *Sedum spurium*, 4 modules were planted with *S. sexangulare*, 4 modules were planted with a mixture of 80% *Delosperma nubigenum* and 20% *S album*, and 4 modules were left unplanted with just the drainage layer and medium. Modules were grown until plants covered 95-100% of the surface of the module before any measurements were made. Delospoerma dominated the mixed vegetation modules when they had reached 90-100% coverage, so although some *S. album* was still present the responses reported are largely Delosperma, hence these roof modules will be referred to as Delosperma for the rest of this report. Vegetated roof modules were installed in the weighing lysimeters one species at a time. Modules were installed with a 1:12 slope (8%). The 4 unplanted modules were used as controls for each of the planted series. After each planted module change, load cell module units were recalibrated with standard brass weights between 100 and 2000g. A light meter (LI-COR quantum sensor Q25338), and 6 copper-constantan (Omega) thermocouples were also installed.

Modules were fully saturated followed by a dry-down period of 14-21 days. Each species was subjected to multiple saturation and dry-down cycles at different times of the year (different

environmental conditions). Saturation to field capacity was achieved by irrigating the roof modules to runoff, allowing gravitational water to drain for 24-48 hours followed by another irrigation to runoff. This process was repeated at least 2-3 times before each measurement period. After the final irrigation, modules were allowed to drain for 2-4 hours (until dripping stopped) before measurements were collected. During the measurement period module weights were recorded every 10 minutes. Weight changes were converted to mm of water. Analysis of variance was used to compare planted and unplanted water loss and least squares regression was used to fit linear and log functions to dry down curves.

2.4 Results

Evapotranspiration rates varied between species in the modules and with environmental conditions in the greenhouse, however the general form of the responses were remarkably consistent across species and climatic conditions. In every evaluation with non-dormant plants the rate of water loss was rapid for the first 5-6 days, with planted modules losing significantly more water than unplanted modules. This rapid loss phase was followed by a slower more or less linear rate of loss where the rate of water loss was not statistically different between planted and unplanted roof modules.

2.4.1 Species Responses

2.4.1.1 S. spurium

The rate of water loss was about two times greater for planted roof modules than unplanted for the first 6 days (Figure 2a,b). After 6 days the planted modules had lost on average, 13 mm of water compared to 7 mm for unplanted modules (Figure 2a). After 6 days the rate of water loss rapidly converged between planted and unplanted roof modules (Figure 2b) with both loss rate curves approaching zero after about 20 days. The difference in water loss rates between planted and unplanted roof modules also decreased rapidly with time from about 1.4 mm/day immediately after irrigation to less than 0.2 mm/day by day 10 (Figure 2c). The hourly water loss rates from planted and unplanted roof modules immediately after irrigation (day 2) were similar during the night (0:00 hours to 07:00 and 18:00 to 0:00) (Figure 3a,b). Planted roof modules lost more water during the morning and early afternoon (07:00 to 14:00), similar amounts during mid afternoon (15:00), and more during the late afternoon (16:00-18:00) than unplanted modules. The difference in hourly water loss rates peaked in the early afternoon (13:00hr) (Figure 3c). Greater water loss from planted compared to unplanted modules resulted in about 47% more water loss from planted modules (2.6 mm compared to 1.8 mm, respectively). Ten days after irrigation planted green roof modules were losing only slightly more than unplanted modules (Figure 4a) and these differences were no longer significant (Figure 4b,c).

2.4.1.2 D nubigenum

The rate of water loss was about two times greater for planted roof modules than unplanted for the first 5 days (Figure 5a,b). After 5 days the planted modules had lost on average, 8 mm of water compared to 6 mm for unplanted modules (Figure 5a). After 6 days the rate of water loss rapidly converged between planted and unplanted roof modules (Figure 5b) with both loss rate curves approaching zero after about 10 days. Two equations were fitted to each line to describe the function, a quadratic equation was used to describe water loss for the first 5 days and a log equation was used for the remaining period. The equations for the fitted lines were [Water loss (mm/day] = $3.41 - 1.12 \text{ x Day} + 0.102 \text{ x Day}^2$] for the unplanted roof boxes during the first 5 days; [Water loss (mm/day) = $3.41 - 0.76 \text{ x Day} + 0.049 \text{ x Day}^2$] for planted roof modules during the first 5 days; [Water loss (mm/day) = $0.636 \times 0.94^{\text{Day}}$] for unplanted modules after the first 5 days and [Water loss $(mm/day) = 0.794 \times 0.911^{Day}$] for planted roof modules after day 5. The difference in water loss rates between planted and unplanted roof modules also decreased rapidly with time from about 1 mm/day immediately after irrigation to close to 0 mm/day by day 10 (Figure 5c). The hourly water loss rates from planted and unplanted roof modules immediately after irrigation (day 2) were similar during the night (0:00 hours to 07:00 and 20:00 to 0:00) (Figure 6a,b). Planted roof modules lost more water during the morning and early afternoon (07:00 to 14:00), similar amounts during mid afternoon (15:00-17:00), and more during the late afternoon (18:00-20:00) than unplanted modules. The difference in hourly water loss rates peaked around noon (11:00-13:00hr) (Figure 6c). Greater water loss from planted compared to unplanted modules resulted in about 80% more water loss from planted modules (2.0 mm compared to 1.1 mm, respectively). Ten days after irrigation planted and unplanted green roof modules were losing very little water (Figure 7a) and differences were no longer significant (Figure 7a,b,c).











Figure 5.

a. Cumulative water loss(mm) from roof modules planted with *D. nubigenum*;

b. Daily water loss (mm/day) rates from roof modules planted with *D. nubigenum*;

c. Difference in water loss rate (mm/day) between planted (*D. nubigenum*) and unplanted media only modules.

Average temperature during the measurement period was 26.8C, with a minimum temperature of 13.3°C and a maximum temperature of 41.1°C.



Figure 6.

a. Water loss on day 2 after irrigation for green roof modules planted with *D. nubigenum* and unplanted modules;

b. Hourly water loss rates on day 2 after irrigation;

c. Difference in hourly water loss rates between planted and unplanted *D. nubigenum* roof modules on day 2 after irrigation.





Figure 8.

a. Cumulative water loss (mm) from roof modules planted with *S. sexangulare*;

b. Daily water loss (mm/day) rates from roof modules planted with *S. sexangulare*;

c. Difference in water loss rate (mm/day) between planted (S. sexangulare) and unplanted (media only) modules. Average Temperature during the measurement period was 27°C with a minimum of 21°C and a maximum of 38°C





2.4.1.3 S. sexangulare

The rate of water loss was about two times greater for planted roof modules than unplanted for the first 5 days (Figure 8a,b). After 5 days the planted modules had lost on average, 4.2 mm of water compared to 2.7 mm for unplanted modules (Figure 8a). After 6 days the rate of water loss converged between planted and unplanted roof modules (Figure 8b) with both loss rate curves approaching 0.2 mm/day after about 15 days. The difference in water loss rates between planted and unplanted roof modules also decreased rapidly with time from about 0.4 mm/day immediately after irrigation to 0.1 mm/day by about day 10 (Figure 8c). Two equations were fitted to each line to describe the function one to describe water loss for the first 5 days and a second for the remaining period. The equations for the fitted lines were [Water loss (mm/day)] = $1.08 \times 0.829^{\text{Day}}$] for the unplanted roof boxes during the frst 5 days; [Water loss (mm/day) = $1.87 - 0.611 \text{ x Day} + 0.078 \text{ x Day}^2$ for planted roof modules during the first 5 days; [Water loss $(mm/day) = 0.633 \times 0.94^{Day}$ for unplanted modules after the first 5 days and [Water loss] $(mm/day) = 1.01 \times 0.932^{Day}$ for planted roof modules after day 5. The hourly water loss rates from planted and unplanted roof modules immediately after irrigation (day 1) were similar during the night (0:00 hours to 08:00 and 22:00 to 0:00) (Figure 9a,b). Planted roof modules lost more water during the morning and early afternoon (08:00 to 16:00), and similar amounts during mid afternoon and evening (17:00-22:00) than unplanted modules. The difference in hourly water loss rates peaked around noon (12:00-13:00hr) (Figure 9c). Greater water loss from planted compared to unplanted modules resulted in about 56% more water loss from planted modules (1.3 mm compared to 0.9 mm, respectively).





Ten days after irrigation planted and unplanted green roof modules were loosing very little water (figure 10a) and differences were no longer significant (Figure 10a,b).

2.4.2 Seasonal Effects

In the winter, with cool temperatures and dormant plants, there was little difference in water loss rates between planted and unplanted roof modules until the surface of the unplanted media became visibly dry. For example with *D. nubigenum* roof modules about 8 mm was lost from both planted and unplanted modules in 10 days following irrigation. The rate of loss was essentially linear. Over the next 11 days the planted modules lost more water than the unplanted, media only modules presumably because the plants accessed water from deep in the media which was less available to evaporation from the dry media surface (Figure 11). With active plants cooler temperatures had very little effect on the pattern of water loss with rapid losses in the first 5 days following irrigation, about 2 times as much water loss from planted compared to unplanted and most of the differences occurring in the morning and early afternoon of the first 5-6 days (Figure 11a-c; Figure 12a,b; Figure 13a,b).



2.5 Discussion

At the onset of this study it was not known if the drought-tolerant succulent plants used for green roofs would conserve water, maintaining a slow water loss rate to protect against the effects of drought regardless of water availability. With the three species studied this was clearly not the case. When water was readily available the plants used it at a relatively rapid rate compared to evaporation from the media of the control roof modules. As water became more limiting, the water loss rate of the planted modules was reduced to a rate not significantly different than the unplanted modules. Water loss during the day when water was readily available followed the expected pattern for ET (Larcher, 1995) with water use exceeding evaporation in the morning or early afternoon, reduced relative to evaporation or equal to evaporation during the heat of the day, and higher again in the evening. This is an interesting and very promising result for the use of green roofs planted with succulents for stormwater

management. These species seem by their nature to be very well suited for this use. When it rains, water is rapidly used and released back to the atmosphere, when it doesn't rain the plants conserve remaining water to ensure survival until the next rain. Although sedums are reported to be CAM plants there was no evidence to support higher water loss in the evening/night under water limiting conditions observed in this study. This may have been due to the resolution limits of the weighing systems used. The minimum weight change measurable by the system was between 100 and 200g (0.17-0.35 mm) depending on wind and other vibrational noise in the greenhouse. Under water limiting conditions average hourly water loss rates were often well below this threshold. Although the pattern of water loss was consistent for all the species studied, the total water loss rate, followed by *D. nubigenum* and finally *S. spurium*. This result is not surprising given the differences in plant architecture between these species. *S. sexangulare* is a low growing species with very small cylindrical leaves tightly packed in six-sided whorls around the stem axis (Figure 13), *D. nubigenum* also is low growing and has cylindrical leaves, however



they are much larger and more exposed (Figure 14), while *S. spurium* is the most upright of the species and has relatively flat broad leaves (Figure 15). Thus the differences observed in rate of water loss were likely a function of exposed surface for evaporation. The results of this study suggest that the contribution of plants to green roof stormwater management potential is largely a function of rain event size and interevent interval. For example if one were to consider a typical 12.7 mm rain (0.5") in calculating the retention using the log equations for water loss for *S. spurium* (Figure 1b). The maximum relative effect of the plants would be about a 40% reduction in runoff compared to an unplanted roof (just media) which would occur

about 6 days after the last saturating rain event. At that time the planted roof would retain 100% of the rain event while the medium without plants would only retain about 60% of the rain (Figure 16a). Plants would only contribute a 10% increase in retention for the same rain event occurring 1 day after the last saturating rain (23% retained by the planted roof and 13% retained by the media) and 10% after about 23 days (100% retained by planted roof and 90% retained by an unplanted media roof). Compare this to a 6.35 mm rain (0.25") (Figure 16b). With this rain the maximum affect of the plants is a 38% greater reduction in runoff from planted roofs compared to plain media roofs occurring 2 days after the last rain (87% retained by the planted roof and 49% retained by the medium roof). In this case there will be no affect of plants for rain events that occur 5 or more days after the last saturating rain (both planted and media roofs will retain 100%). It seems clear then that the contribution of plants to the green roof as a stormwater management tool are greatest when numerous small rain events are spaced in time to maximize the difference between planted roof evapotranspiration and potential evaporation from unplanted media or an equivalent ballast (3-6 days). This research suggests that the maximum contribution of sedums and other similar plants under these conditions will be about a 40% increase in rain retention compared to an unplanted media or ballast on the roof. The other way to look at this is that 60% or more of the function of a green roof for stormwater management can be obtained with media and no plants. It follows then that planted green roofs will be most effective in a

climate like the northeast U.S. or Northern Europe with frequent (but not too frequent) relatively small rain events. In a drier climate with infrequent rain events the contribution of plants to the system will be relatively diminished and more of the stormwater function will be attributable to the media alone. Of course without plants other benefits of the green roof, particularly the aesthetics will be impacted. The benefits of a green roof for temperature reduction will also be clearly reduced without plants. Since the temperature reduction is largely a function of evaporation and the latent heat required, the temperature reductions from a planted roof will be roughly double those of a wet unplanted medium for the first 5 or so days following a saturating rain or irrigation event.

2.6 Summary and Conclusions

In summary, green roof plants like sedums contribute to the potential of the green roof to function as a stormwater management tool. These plants (like other less drought tolerant species) use water relatively rapidly when it is available. The affect of plants is thus greatest for the first 5 or so days following a rain event when the plants essentially double the rate of recharge of the media moisture holding capacity allowing more of the next rain event to be stored and less to run off. The pattern of water use by the plants examined was similar, however the total water loss rate varied with species and was likely related to plant architecture. Additional plants, and plant communities should be evaluated to examine the potential to select individual species and communities to maximize the effectiveness of planted green roofs for stormwater management.


Figure 16a. Calculated water retention for a 12.7 mm rain (0.5") occuring following various dry periods for unplanted (media only) and vegetated (S. spurium) green roofs and the relative contribution of S. spurium to total retention; 16b. Calculated retention from a 6.35 mm (0.25") rain.

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CHAPTER 3.0

ANNUAL AND INDIVIDUAL-STORM GREEN ROOF STORMWATER RESPONSE MODELS

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3.1 Abstract

The departments of Agricultural and Biological Engineering and Horticulture at the Pennsylvania State University and Biological and Agricultural Engineering at North Carolina State University have combined efforts to quantify the stormwater attenuation capabilities of extensive green-roof systems. This green-roof system consisted of a conventional flat-roof covering, a 12-mm thick Enka-drainage layer, 89 mm of porous medium, and Sedum spurium planted 75 mm on center. The combined layers of this green roof had a retention storage capacity of 40 mm and a saturated hydraulic conductivity of 11 mm/s.

The green roof system was modeled using a checkbook approach with daily rainfall depth as an input along with daily ET rate and roof runoff as the output. The Annual Model was applied to 28 years (1976-2003) of rainfall data in State College, PA and Raleigh, NC and showed that 45-55% of the annual rainfall volume (depth) can be retained on the green roof. Increasing the volume of storage (roof media depth) does not improve the roofs ability to retain rain water. Providing only 3 mm of roof storage will still cause 25-40% of the annual rain to be retained on the roof.

The green roof system was also modeled using the modified Puls routing model with inputs of the rainfall hyetograph, roof size, and daily ET rate and runoff as the output. The model was applied to 16 storms measured at the Green Roof Research Center in Rock Springs, PA and to a variety of synthetic type II 2-, 25-, and 100-year rains under summer and dormant-season conditions. The Storm Model simulated the experimental results well (runoff volume r2 = 0.906; peak runoff rate r2 = 0.847). The model also showed that this green roof can attenuate the design stormwater events to the level of the pre-development runoff rates expected from the building foot print.

3.2 Introduction

Green roofs are a surface treatment for rooftops involving the addition of layers of growth media and plants to create a controlled green space. Widespread use of roof vegetation has developed since the early 1970s, with Germany leading in the use of green roofs, specifically in cities (Peck et al., 1999).

A green roof consists of four distinct layers: an impermeable roof covering that serves as a root barrier, a drainage net or layer, lightweight growth media, and adapted vegetation (PACD, 1998), see Figure 1. The drainage layer is an open, highly drainable material that quickly channels gravitational water to the roof discharge point(s). The growth medium performs several functions. In addition to providing a suitable rooting zone for the selected vegetation, the medium should be of low density and have high water-holding capability. The lighter weight allows for retrofit installation on older buildings, and also reduces the need for extra structural support in new buildings. The thickness of the medium and its capillary and gravitational water holding capacity play an important role in stormwater retention and attenuation of extreme rainfall events. The plants intercept rainfall, slow its movement into the rooting medium, and are a measurable portion of the green roof's water storage capacity (Miller, 1998).

Topics addressed by European green roof researchers include air quality, stormwater runoff attenuation, plants as building insulation, sound insulation, and building envelope protection. Current research planned and ongoing in North America includes modeling the impact of green roofs on the urban heat island, modeling the amount of stormwater retained annually, and urban agriculture. The majority of these projects are ongoing in Toronto, Canada. (Overview of Current and Planned Research, 2001). Other ongoing research has focused on the survival of plant species in varying substrate depths in northern latitudes (Biovin et al., 2001). Some of this research stems from environmental concerns with air quality and water quality. It is thought that the vegetation will filter dust particles and greenhouse gasses and serve to clean the



Figure 1. Typical Green Roof Profile.

air in urban areas.

Green roofs, as stormwater management devices, must be viewed in two different ways; 1) their ability to retain stormwater from day-to-day rainfall events, 2) their ability to attenuate the runoff expected from extreme rainfall events. From a practical, layman's perspective stormwater management is most often viewed as not having excess water to deal with from the day-to-day rainfall events. These are storms with varying depths, from a trace to the rain expected once every year that do not tax the capacity of the engineered stormwater system, but create nuisance flooding. From an engineering and land development perspective, stormwater BMPs are implemented because they have the ability to attenuate peak runoff rates from storms having frequencies ranging from 2- to 100-years. In Central Pennsylvania, these design storms have rainfall depths ranging from 66-150 mm for a 24-hour event (Aron et al., 1986). PACD (1998) and Jarrett et al. (2004) report that the stormwater benefits offered by green roofs include increasing the time of concentration, thus delaying the runoff peak, and decreasing the peak rate of runoff from the site. Also, green roofs intercept and retain stormwater, thus reducing the volume of water running off a roof, thereby contributing greatly to the NPDES II recommendation of infiltrating the two-year return period runoff event.

Stormwater research on green roofs has included both model simulations and actual trials with full-scale and pilot-scale installations. Miller (1998) and Scholz-Barth (2001) reported annual runoff reductions of 38 to 54% and 38 to 45%, respectively for a 76-mm thick green roof media. Peak flow rate reductions approximated 50%. Moran et al. (2003) reported that based on six April to May 2003 rain events in Goldsboro, NC, a 100-mm thick green roof was able to retain approximately 13-15 mm of rain. They also observed up to 90% reduction in peak flow from their experimental roofs. Additionally, Michigan State University has initiated a large green roof research program that includes measuring stormwater retention on the Ford Motor Company's 11 acres extensive green roof on their new assembly plant in Dearborn, MI and the City of Portland is encouraging the placement of green roofs on all new construction within the city. Their Design Guidelines for Green Roofs specifically states that some jurisdictions may reduce water and sewer charges or may provide financial incentives to developers who retain stormwater on site and that green roofs can help reduce the size of stormwater management ponds, thus recognizing the importance of water retention on green roofs. DeNardo et al. (2005) reported that green roofs retained 100% of rains smaller than 15 mm and 25% of larger rains in October and 43% of larger rains in November. Jarrett et al. (2004) reported that green roofs retained 48, 53, and 78% of larger rains in May, June and July in central PA, respectively. These benefits, in combinations with limited open space in cities make green roofs a practical method for easing the pressure on storm sewer systems.

The research reported herein provides the results of a stormwater modeling study designed to determine the ability of a green roof to attenuation extreme rainfall events and the results of a second model designed to predict the annual depth of rain that can be retained on a green roof in central PA and Raleigh, NC.

3.3 Green Roof Hydrologic Response Models

Following the experimental green roof research conducted on six 4.4 m2 buildings at the Russell E. Larson Research Center of the Pennsylvania State University (DeNardo et al., 2005; Jarrett et al., 2004) we began to extend these results to include modeling the green roof and its influence on hydrologic events. To this end two independent models were developed to assess

the influence of green roofs on the stormwater response to local rainfall events. These included 1) an Annual Green Roof Response (AGRR) Model that predicted annual roof runoff as the sum of the daily roof responses using daily rainfall depths and daily ET as input, and 2) a Storm Green Roof Response (SGRR) Model that routes individual storm hyetographs through the green roof to predict the roof's runoff rate and volume on a routing interval basis.

The green roofs modeled in this work consisted of the waterproof membrane, a drainage layer, the growth medium, and green-roof plants. Above the roof membrane was a 0.5-in thick layer of plastic/geotextile Enka-drain material designed to facilitate drainage of the overlying green-roof medium, Figure 1. Above the drainage layer was 89 mm of growth medium consisting of 12.5% sphagnum peat moss, 12.5% coir (coconut fiber), 15% perlite, and 60% hydrolite with a saturated weight of 1.20 kg/mm-m2. The vegetation used was Sedum spurium.

3.3.1 Annual Green Roof Response (AGRR) Model

The AGRR model was based on three assumptions; 1) that a daily (24-hour) rainfall record was available to be used as input, 2) that a reliable estimate of daily evapotranspiration (ET) was available, and 3) that the maximum water retention available within the roof and its vegetation is known or available. This "checkbook-type" model computed the depth of water storage available in the green roof and its vegetation on a daily basis. This depth of available storage, or water deficit, Dgr is defined as the pore-space available in the drainage layer and roof media below field capacity plus the water holding capacity of the plants. Both the capillary and hygroscopic water in the drainage layer and roof media were considered to be part of the retention storage and could be depleted by evaporation and transpiration. In addition, the deficit, Dgr included the water within the plants used as vegetation on the roof. These plants are ideal for use on green roofs because, like other arid climate plants their stomata close during the hot, dry daylight hours to limit transpiration and conserve water. One unique feature of these plants is that they increase and decrease in size depending on the amount and availability of water. When water is readily available (it has rained or the soil is well watered) the plants swell to maximum size and provide excellent cover to the green roof. When water is not readily available (during drought conditions) the plants actually take a portion of their needed water from within themselves for plant functions and transpiration, thus from day to day they decrease in physical size. By the later stages of an extended drought, these plants may only contain 70 to 80% of the plant mass (and volume) they had when fully watered. When a drought period is followed by a wetter period, these plants quickly (within a day or so) re-expand to their full size. Therefore the plants used on our green roofs actually provided up to 10 mm of water retention roof storage.

The daily roof deficit, Dgr can be expressed as

$$Dgri = Dgri-1 + ETi - Ri$$
 (1)

where Dgri-1 is the roof water deficit on Day i-1, ETi is the evapotranspiration on Day i, Ri is the rain on Day i, and Dgri is the roof water deficit on Day i. The daily deficit is not permitted to exceed the retention capacity in the roof (Dgri may not be larger than Dmax). Rain on the roof decreases the daily deficit, but the daily deficit may never be less than zero (0), the condition that represents the green roof system filled to field capacity. If, on any day, the daily deficit reaches zero (0), any remaining water is water the green roof cannot retain and thusly becomes runoff. This logic was applied to each day during the year in question to estimate how much of each day's rain was expected to runoff the green roof. Rainy days following several days without rain had more storage available, thus less runoff. Rainy days following other rainy days yielded a large portion of the rain as runoff.

3.3.2 Storm Green Roof Response (SGRR) Model

The SGRR model is based on three assumptions; 1) that a storm hyetograph is available with uniform times steps between 6 and 60 minutes to be used as input, 2) that a reliable estimate of daily evapotranspiration (ET) can be provided, and (3) that the month of the storm and the number of days since the last rain is known. The SGRR model is a Modified Puls Reservoir Routing Model (Jarrett, 2000) adapted to a green roof.

The rainfall hyetograph input can either be rainfall intensities for a series of uniform time steps during an actual rain event or rainfall intensities from a synthetic rainfall distribution similar to those used to estimate pre- and post-development stormwater hydrographs for ungaged development sites. These rainfall intensities must have a uniform time step between 6 and 60 minutes.

The stage-storage relationship for the green roof was developed from the green roof drainage layer and roof media characteristics reported by DeNardo et al. (2005). The influence of water stored in the green roof plants was developed from data reported by Rezaei et al. (2005). The 12-mm thick drainage layer had a porosity of 78% and field capacity of 5.2%. The 89-mm growth media had a porosity of 55% and field capacity of 34%. The plants growing in the media were able to give up and then recover 10 mm of water. The daily ET rate was used to reduce the water in the green roof starting at field capacity prior to each annual simulation. The ET was estimated for each month based on the experimental ET results of Rezaei et al. (2005) and the number of days since the last rain event.

3.4 Results and Discussion

3.4.1 Annual Green Roof Response (AGRR) Model

Twenty eight years (1976-2003) of daily rainfall data in State College, PA and Raleigh,

NC were evaluated using the AGRR model. The State College input rainfall series had an average annual rainfall depth of 1024 mm of which 527 mm, or 52.8%, was retained on the green roof. The Raleigh, NC rainfall series had an average rainfall depth of 1084 mm of which 483 mm, or 45.4%, was retained. The Log Persson Type III return periods were determined for the annual rainfall depths and these are plotted against the percent of rain retained on the green roof in Figure 2. Percent retention, R was



related to return period, T as R = 71.0T-0.0947; r2 = 0.578 in State College and R = 50.4T-0.117; r2 = 0.678 in Raleigh.

These results can be viewed very positively by considering that 53% of the rain falling on a green roofed building in State College, PA (45% in Raleigh, NC) will be retained on the roof and this portion of rainwater does not require any stormwater attention. The stormwater piping infrastructure can be smaller. Forty-five to sixty-five percent less water will runoff from development sites than from similar development sites without green roofs.

Another, less positive way of looking at the stormwater impacts of green roofs, is to remember that rain water that falls on and is retained on a green roof has no opportunity to infiltrate into the soil profile and becoming part of the local water supply.







daily rain depths and the associated runoff depths for each rainfall event in 1999 in State College. 1999 was a typical year with average rainfall. It should be noted that only larger rain events produced runoff from the green roof. Though the runoff results vary greatly, green roof runoff is usually limited to larger events and rains that occur immediately following rainy days, when the roof media has not had sufficient time to recover its retention storage capacity.

Before leaving the AGRR Model, it is very useful to note that this model was setup so that the green roof's retention storage capacity could be varied. The green roof modeled to produce the results shown above had a retention storage capacity of 40 mm. We varied the roof's retention storage capacity, which was equivalent to making the green roof (primarily the media depth) thicker (> 89 mm) of less thick (< 89 mm). The roof's retention capacity was varied from a low of 3 mm to a high of 76 mm. The percent of the annual rainfall depth retained on the roof for each retention capacity is shown in Figure 4. There are two rather striking results that come

from this evaluation. First, when the roof's retention capacity was increased (simulating a green roof with thicker media) there was not a great deal of decrease in the runoff expected from the roof. In other words making the roof thicker did not greatly improve the roof's ability to retain rain on the roof. Secondly, when the roof's retention capacity was decreased, in our case to as

low as 3 mm, there was still an important reduction in annual runoff caused by this small amount of roof storage. The horticulture professionals make it clear that these plants (most plants in fact) need at least 70-90 mm of media to provide adequate rooting and support. Thus a roof with only 3-6 mm of retention storage would no longer be a green roof, but this analysis shows that placing one or two layers of a heavy-weight geotextile or providing only a few millimeters of roof storage would



cause the roof to retain 25-40% of the annual rainfall.

3.4.2 Storm Green Roof Response (SGRR) Model

For engineers responsible for creating stormwater management plans for individual development sites, the primary focus is not so much on the portion of rainwater captured and retained annually, but on how a BMP will attenuate the peak runoff rates from large storms that often cause flooding and considerable damage. To more fully understand how a green roof will attenuate a specific rain event, the SGRR model was developed as described earlier. This flood routing based model was applied to two groups of storms; 1) a series of 16 actual rain events that occurred at the Russell Larson Research Center 10 miles southwest of State College, PA, and 2) several synthetic 2-, 25-, and 100-year return period rain events developed for use in a local stormwater management plan.

3.4.2.1 Actual Storm Simulations

Sixteen rain events that occurred between October 2002 and July 2003 were inputted into the SGRR model. The actual rainfall hyetograph, each with a 1-hr time step, was used as input in each case. The other input parameters were the month of the event and the number of days since the last rain. The model assumed up to 1 mm of interception. The interception was decreased as the time between events increased because the plants were assumed to reduce in size as the availability of water decreased. The stage-storage relationship used in the routing model assumed no runoff was possible until the rain had increased the water content in the media and drainage layer to field capacity. The experimentally observed and modeled depth results for the 28.7-mm June 2, 2003 storm are shown in Figure 5. The rain and observed results were collected on an hourly basis. The modeled results were, likewise, computed on an hourly basis. The runoff collected from this storm totaled 22.6 mm and the modeled runoff total for this storm was 20.5 mm. The model was able to correctly show the delay in the start of runoff until the fourth-hour after the start of the rain event. It also was able to track the runoff in time as it came from the green roof. The comparison of the predicted versus observed runoff depths for all 16 storms evaluated are shown in Figure 6. This figure shows that for storms ranging from 3 to 41 mm of rain over the months

of October to November 2002 and May to July 2003, the SGRR model predicted the observed runoff very well (r2 = 0.906). The model predicted the runoff responses best for rains smaller than 21 mm. There was greater scatter for larger rains. These results clearly establish the validity of the SGRR model.





The 2-, 25-, and 100-year design storm hyetographs were developed for the State College, PA area. During most stormwater design procedures, these hyetographs would have been used with the USDA-SCS Soil Cover Complex method or a similar algorithm to compute pre- and post-development runoff hydrographs for the site being developed. These hydrographs would then be used in a flood routing procedure to design a stormwater basin and its spillway system to properly attenuate the post-development hydrograph peaks to the specified level related to the pre-development peak rates of runoff for all return periods. Because in the case of green roofs the rain falls directly on the green roofs, the intermediate runoff hydrograph step was unnecessary.







roof after a 5-day dry period in July.

In our simulations we applied each rainfall hyetograph directly to the green roof and routed the rain through the green roof to yield the runoff event in time. Figure 7 shows the rainfall and runoff rates as well as the cumulative rainfall and runoff depths for our green roof on a 70- by 270-ft roof subjected to (1) a 2-year simulated rain following 5 dry days in February. This synthetic storm had a peak rainfall rate of 58 L/s and a peak runoff rate of 27 L/s. The peak runoff rate for an undeveloped parcel of this size using a time of concentration of 5 minutes and a CN = 79 (HSG = C) is 17 L/s using TR-55 (USDA-SCS, 1986) and 22 L/s using TR-20 (USDA-SCS, 1983). Thus the green roof will adequately attenuate the 2-year storm even when the ET from the green roof is limited by February weather conditions.

Figure 8 shows the rainfall and runoff rates as well as the cumulative rainfall and runoff depths for our green roof on a 70' x 270' roof subjected to a 100-year simulated rain following 5 dry days in July. This synthetic storm had a peak rainfall rate of 119 L/s and a peak runoff rate of 50 L/s. The peak runoff rate for an undeveloped parcel of this size using a time of concentration of 5 minutes and a CN = 79 (HSG = C) is 59 L/s using TR-55 (USDA-SCS, 1986) and 76 L/s using TR-20 (USDA-SCS, 1983). Thus the green roof will attenuate the 100-year storm under, what could be considered the best ET weather conditions.

The green roof's ability to attenuate the peak runoff rates was evaluated for the 2-, 25-, and 100-years return period storms in State College, PA. These storms were evaluated for four different climatic conditions including; February ET conditions with 1 and 5 dry days before the design event and July ET conditions with 1 and 5 dry days before the design event. In all cases the runoff rates from the green roof were less than the pre-development peak runoff rate for the same sized parcel of land. Figure 8. Rainfall and runoff rates and cumulative rainfall and runoff depths for a 100-year rain applied to our green roof after a 5-day dry period in July.

Because of the way a green roof temporarily detains excess water in its gravitational pore spaces and the rate at which this water is released from the media as runoff, green roofs have the ability to adequately attenuate high intensity rains and considerably reduce the volume of runoff from large volume rains.

The results of the SGRR Model have shown that a Modified Puls routing model can be adapted to simulate the hydrologic response of a green roof. In the large-storm cases examined

the green roof was able to attenuate the peak roof outflow rates to or below the pre-development runoff rates expected from these parcels.

3.5 Summary and Conclusions

The water retention and detention properties of extensive green roof have been demonstrated to greatly improve stormwater conditions on developing sites. The AGRR Model showed that an 89-mm thick green roof with 40 mm of retention storage capacity will retain between 45 and 55% of average annual rainfall depth in State College, PA and Raleigh, NC. This simple check-book model was also able to show that roofs with more retention capacity will not greatly improve the roofs ability to retain rainwater. In addition this model also showed that roofs with smaller retention capacities can have an important effect on retaining annual rainfall depth; even to the point where 3 mm of retention storage capacity can retain as much as 25 to 40% of the annual rainfall depth. The SGRR Model, based on the Puls Modified routing routine was able to account for 90% of the variability between measured and simulated results from individual storms. This model also showed that peaks runoff rates from 2-, 25-, and 100-year storms will be adequately attenuated to the level of the pre-development runoff peaks; thus making green roofs a substitute for traditional stormwater basins.

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CHAPTER 4.0

GREEN ROOF CAPACITY TO NEUTRALIZE ACID RUNOFF

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4.1 Abstract

Acid precipitation is common in many parts of the Northeastern and Midwestern United States. Average pH of rain in much of this region is well below a pH of 5 and in many cases may be pH 4.5 or less. One of the key runoff water quality benefits offered by a green roof is the neutralization of acid rain. This benefit is of course limited by the buffering potential of the green roof media. If this benefit is to be maintained for the 50+ year life span of a green roof it will be necessary to replenish the media buffer through liming, much as we do with ground level gardens and agricultural fields. We have developed and demonstrated a relatively simple test procedure to evaluate the potential of a green roof media to neutralize acid rain. The procedure involves the addition of small aliquots of acid to a known volume of media. The media acid slurry is allowed to rest for a period of at least 24hr following each acid addition to let the system come to equilibrium with the media buffer. This slow titration should be continued to a stable end point of pH 6.0 or less. The resulting response curve, combined with acid deposition data, provides the basis for estimating the time a roof will neutralize acid precipitation before liming is required. A clay based green roof medium and a slate based medium were used to develop the test. The response of the 2 media to acid additions was very similar in the range of pH desirable on an extensive green roof. The best fit was obtained with a linear equation [media pH = 7.18 - 7.1850.36 x meq (acid added / cc media) + (media correction factor)] $R^2 = 0.82$. The medium correction factor for the slate based media was 0.3. Nine green roof plant species were grown in these media and subjected to acid irrigation for six months. There was little effect of the acid irrigation on plant growth. The leachate from planted containers had a higher pH than unplanted controls for most species. Runoff from green roofs had higher concentrations of several common plant nutrient metal ions (Cu, Fe, Zn, Mn) than runoff from non-green roofs. The medium solution concentrations of these ions were much higher than what was leached from metal downspouts and gutters by the acid precipitation. Green roof media can however reduce the concentration of leachate of metal ions from high concentration water filtered through the medium. Green roof medium cation exchange is similar to that of other soils and like other soils they can adsorb these ions removing them from solution.

4.2 Introduction

Acid precipitation is common in many parts of the Northeastern and Midwestern United States. Average pH of rain in much of this region is well below a pH of 5 and in many cases may be pH 4.5 or less (NADP, 2007) (Figure 1). For example in central PA the average annual pH of precipitation was about 4.4 from 2002 – 2005 (NADP 2007). The average total acidity in precipitation from 2000 – 2005 in central PA was 0.495Kg/Ha (NADP, 2007). Acid precipitation can have major impacts on surface waters and streams and can damage forests, and buildings (U.S. EPA, 2007). Episodic acidification of surface waters caused by runoff can cause short-term problems even in areas where soil buffering capacity may protect base flows. Episodic acidification may be even more problematic in urban areas where impervious surfaces increase runoff even from relatively small storms.

The use of extensive green roofs has been proposed as a means to reduce runoff from flat roofs in highly developed urban areas. An extensive green roof is characterized by a relatively shallow, usually less than 6" deep media (manufactured soil) layer topped with drought resistant plants like sedums and sempervivums. The medium is composed primarily of a highly porous, lightweight aggregate, most often an expanded clay, slate or shale, and a small amount of organic compost (Beattie et al., 2005). The medium is designed to provide an appropriate chemical and physical environment for root growth, and yet be sufficiently lightweight that building structural



costs remain reasonable. Most green roof media hold about 35-45% moisture by volume at field capacity and have a high rate of hydraulic conductivity (FLL, 2002). A 4" extensive green roof will retain roughly 60% of the annual rainfall it intercepts (Denardo et al., 2005). During the summer months nearly 90% may be retained while in the winter 20-30% retention is common.

Precipitation runoff from the roof passes through the medium and flows off most roofs through a drainage course installed below the planted medium. The drainage course may be a course

aggregate similar to the medium but without organic material or fine particle sizes, or a synthetic geotextile (usually plastic). The practical result of this is that runoff is influenced by the medium and the medium has the potential to affect the quality of the runoff from a green roof. Among the water quality parameters green roofs have been reported to influence, the buffering of runoff pH is one of the most consistent (Figure 2) (Berghage et al., 2007; Van Seters et al., 2007). Although the affects of a green roof on acid runoff are clear and consistent, the potential



Figure 2. pH of runoff from green roofs and non-green asphalt roofs at the Center for Green Roof Research in Rock Springs PA.

benefit has not been fully explored or quantified. Acid precipitation is known to cause a number of problems in urban runoff including acid leaching of metal ions from rooftop flashings, downspouts and other exposed metals on the roof. A green roof has the potential to all but eliminate this pollution source. To manage a green roof for this purpose over the long term we must understand both the exchange capacity of the medium (ability to adsorb metal ions) and the acid buffering capacity (ability to neutralize acid rain) inherent in the green roof system and the frequency and effects of routine maintenance procedures such as liming needed to maintain this capacity over the life span of the green roof. The objective of this study was to better quantify the potential for green roofs to neutralize the acidity in runoff from acid rain.

4.3 Materials and Methods

4.3.1 Media Titration

A commercial clay based aggregate green roof media was titrated with sulfuric acid. A 250 cc sample of media was placed in a 1-liter container and saturated with 500 ml of deionized water. pH was measured directly in the media slurry. Incremental acid additions (0.02M sulfuric acid) were made to the media slurry. After each addition the pH was measured when the pH became stable (about 4-7 minutes). The first 15 additions were 1 ml of acid, followed by 10 additions of 5 ml and 3 additions of 10 ml , 1 of 15 ml, and 1 of 20 ml, for a total of 130 ml of acid added. The final pH was 4.41. The sample was left on the lab bench and after 24, 48, and 72 hours the media slurry was stirred and pH was measured. The test was repeated with a 40 cc media sample in 400 ml of deionized water. Incremental additions of 0.5, 1, and 2 ml of acid were used with the smaller sample.

4.3.2 Accelerated Media Aging Test

Two commercially available green roof aggregates were evaluated using an accelerated aging test. The aggregates were an expanded clay and an expanded slate. Ten 200 cc samples of each aggregate were placed in individual 1-liter containers and saturated with 500 ml of deionized water. pH was measured directly in the media slurry after 1 hour. Acid (2 ml of 0.05M sulfuric acid) was added to each sample, the samples were stirred and allowed to equilibrate for 1 hour, stirred again and the pH was measured in the media slurry. After 24 hours samples were stirred again and pH was measured again in each media slurry and then 2 ml of 0.05M sulfuric acid was added to each, stirred, and allowed to equilibrate, and pH was again measured. This process was repeated daily until the sample pH became relatively stable, 47 days for the clay aggregate and 75 days for the slate aggregate. This procedure was repeated with acid additions every 4 days and once per week to further evaluate the affects of recovery time. All acid additions were converted to meq/cc of media for presentation in this report. Data were analyzed with least squares regression and Analysis of Variance (EXCEL, Microsoft)

4.3.3 Simulated Acid Precipitation and Planted Green Roof Media

Plants of nine species suitable for use on an extensive green roof were planted in each of the two media (expanded slate based and expanded clay based) used in the accelerated aging test. Five plants of each species were planted in each media in 10 cm nursery pots. Plants evaluated were *Artemisia stelleriana*, *Agastache rugosa*, *Potentilla argentea*, *Dianthus deltoides*, *Sedum album*, *Sedum spurium*, *Talinum parviflorum*, *Delosperma nubigenum*, and *Festuca idahoensis*. In addition 5 pots were filled with each media but not planted. Plants and unplanted media were irrigated using an acidified irrigation water on an as needed basis (every 2-5 days). The acidified irrigation water was made with deionized water adjusted to pH 4 with sulfuric acid. Irrigation was applied to runoff (~200 ml). At various intervals after planting leachate was collected from an irrigation and pH was determined. Data were analyzed with least squares regression and Analysis of Variance (EXCEL, Microsoft)

4.3.4 Metals in Runoff and Media Cation Exchange

Runoff samples from small buildings, three with green roofs and two with flat asphalt roofs were collected and analyzed by ICP (inductively coupled plasma) for metals in the runoff. Runoff from the buildings was collected through standard metal gutters and down spouting. Runoff from five rain events were sampled and analyzed for Cu, Zn, Mn, and Fe. Green roof media samples were sent to the Penn State Agricultural Analytical Lab and tested for total CEC using standard lab procedures (PSU Ag analytical laboratory, 2006).

4.4 Results and Discussion

4.4.1 Media Titration

Green roof media (expanded clay based) pH dropped from 7.5 to 4.1 as the media was titrated with 0.013 meq of sulfuric acid. There was a little initial buffering for the first 2-3 steps in the titration (0.0003 meq), followed by a relatively rapid drop to pH 6.3 (0.0013 meq), followed by another relatively stable pH zone and then a more or less linear decline in pH with additional acid added (Figure 3). After titration the pH of the media slurry increased back up to

6.5 over 72 hours (Figure 4). This suggests that a simple rapid titration is not an adequate method to estimate the buffering potential of a green roof media. The pH recovery indicates some of the potential buffering capacity of the green roof media depends on a slower process than can be measured with a simple titration so a slower accelerated ageing test was developed to better evaluate the total buffering potential.

4.4.2 Accelerated Aging Tests

When acid was added daily with a 24-hour recovery period an interesting pattern in pH affects was observed with each media. With the clay-based media, the initial pH (after recovery and before the next acid addition) remained relatively stable for the first 4-5 days (0.01meg acid added per cc of media) (Figure 5). The drop in pH with the daily acid addition was about 0.4 pH units and recovery was complete in 24 hours. After 5 days the pH in the media began to drop in a more or less linear fashion with a pH difference between before and after acid addition of about 1pH unit. This response occurred from acid additions of 0.01 meg to about 0.05 meg. Beyond acid additions of 0.05 meg, the change in pH was reduced and the difference in pH between before and after acid addition was smaller (0.4 pH units). The general response of the slate based media to acid additions was similar (Figure 6). The system was well buffered initially with little change in pH as acid was added up to about 0.01 meq. This was followed by a more or less linear decrease in pH with a large response to the acid addition and a large recovery. The difference in pH from before to after acid addition was greater than in the clay based medium (about 1.5 pH units) and the recovery in pH from acid addition continued for a longer period in the slate passed medium (0.01 meg acid /cc media added through 0.14 meg acid added). For the first 0.028 meg of acid added the pH response of the two media after recovery from each acid addition was about the same, with the slate based medium having a slightly higher pH throughout. After 0.028 meg of acid added, the pH of the clay-based media after recovery dropped faster than the pH of the slate based media (Figure 7). This difference was a difference in the recovery rather than the response to daily additions (Figure 8). The pH of the media was lower after 24 hr recovery than the pH after 96 hours or 168 hours (4 days, 1 week) for both media (Figure 9, 10). Although the difference was significant, it was fairly small (0.25 pH units or less), and the difference between 96 and 168 hours of recovery was smaller and in fact was not significant in either media. Although the response appears to be quadratic, the best-fit least squares regression line for this data was a simple linear equation. Polynomial and log functions did not significantly improve the fit of the prediction line. For the clav based media the equation for the line was media pH = 7.24-53.95 x (meg acid added / cc media) with an R² of 0.84 (Figure 9). For the slate based media the equation was media pH = 7.42 - 46.78 x (meg acid added / cc media) with an R² of 0.77 (Figure 10).

















4.4.3 Simulated Acid Precipitation and Planted Green Roof Media

The pH of leachate collected decreased with time and was significantly influenced by the species of plant. There was little difference between the pH of leachate from slate or clay based media with any of the plant species or the unplanted blank sample (Figure 11) so data for slate and clay were combined for statistical analysis. Plant performance was not influenced by the simulated acid precipitation over the course of the experiment (Figure 12a,b) with the exception of Talinum which had died by the end of the experiment. It was however not clear that the acid irrigation water was the cause of the death of the Talinum which could just as easily have died from other environmental considerations. By the end of the experiment many of the herbaceous plants were showing effects of low winter light (the experiment was terminated in February). The pH of the leachate from planted containers of green roof media followed 2 basic patterns. For Delosperma and Talinum the leachate pH was statistically different but the differences were so small that leachate was basically the same as leachate from unplanted containers (Figure 13, 14). With the other species, pH of the leachate from planted containers was similar to pH of leachate from unplanted containers early in the experiment, but was significantly higher than that from unplanted containers in later measurements (Figures 15-21). For example, pH of leachate from containers planted with Agastache was more or less constant through out the measurement period (Figure 16), resulting in about a 1 pH unit higher leachate pH from the planted than the unplanted containers. Other species generally showed similar responses although the magnitude was different. Leachate from S. spurium and Festuca planted containers, for example, was only about 0.5 pH units higher at the end of the trial than leachate from unplanted containers. In contrast to this general pattern, leachate from Artemisia planted containers had a lower pH than



Figure 11. pH of acid irrigation water leachate from pots of green roof media but no plants. Pots were irrigated as needed (every 3-5 days) with water adjusted to pH 4.

leachate from unplanted containers initially but higher pH by the end of the trial.

Figure 12 a and b. Plants growing in green roof media irrigated with pH 4 adjusted water. Photos taken after 5 months of acid irrigation.









Figure 13. Leachate from Delosperma in green roof media irrigated with pH 4 acid adjusted irrigation









Figure 19. Leachate from Sedum album in green roof media irrigated with pH 4 acid adjusted irrigation

Figure 20. Leachate from Sedum spurium in green roof media irrigated with pH 4 acid adjusted irrigation water.





4.4.4 Metals in Runoff and Media Cation Exchange

The concentration of Cu, Zn, Mn, and Zn, was higher in most samples from green roofs compared with samples from a standard asphalt roof (Figure 22). Detection limits for the ICP analysis were Cu < 0.002 mg/L, Fe < 0.005 mg/L, Mn < 0.001 mg/L, and Zn < 0.005 mg/L and many of the 15 samples analyzed for each ion from non-green roofs and quite a few from green roofs were below these limits. Average concentrations of Fe, Mn and Zn in runoff from green and non-green roofs were not different from each other or zero. While there was more Cu in the runoff from green roofs the average concentration was very small (just over 0.08 mg/L). The total cation exchange in the green roof media was 17.56 (meq/100g) and 16.22 (meq/100g).



4.5 Discussion

The ability of a soil, or in this case a green roof media to buffer pH change is a function of the potential buffers in the medium, the relative solubility of these buffers, and the structure of the medium, particularly as it relates to the accessibility of the media components to the soil or medium solution. Since one of the potential runoff water quality benefits of a green roof is to neutralize acid rain it is important to understand the total potential of these manufactured soils to buffer pH. This is even more important since many of the sedums used on green roofs grow best in neutral to alkaline soils (Brickell and Zuk, 1996). While it is possible to use an acid digestion procedure to estimate the total exchangeable buffer in a medium, this test tells you little of how the pH in the medium will gradually change with long term small acid additions as occur in a green roof medium exposed to acid rain. In reality the goal for successful green management is to understand how much acid can be neutralized before the pH of the medium drops below an appropriate level for plant growth or water quality considerations, rather than the total buffering

capacity of the medium. A better approach might be to do a simple titration where small amounts of acid are added in sequential aliquots and allowed to come to equilibrium in the medium. With both the green roof media evaluated in this study a simple quick titration proved inadequate. Although the pH of the medium slurry was "stable to read" within about 5 minutes of an acid addition (Figure 3), substantial pH recovery (medium buffering) occurred when longer equilibration times were allowed. Additional buffering was observed as equilibration times were increased from 24 hours (1 day) to 96 hours (4 days) and 168 hours (1 week) although the differences were relatively small, particularly as equilibration time increased from 96 to 168 hours (Figures 9,10). These small differences suggest that an accelerated acid aging test for green roof media can be successfully done using an equilibration time between 1 day and 7 days and that an equilibration time of 24 hours is probably adequate. There were clear differences in the nature of the buffering capacity of the two media tested (Figure 5-8), however it is important to keep in mind that the desirable range of pH for a multi-course intensive green roof media is pH 6.5-8.0 (FLL, 2002). It is interesting to note that nearly all of the differences in media buffering occurred after the medium pH had dropped below the desirable range. In fact most of the differences between the media were observed below a pH of 6.0. This is further demonstrated by the very similar regression functions that describe the response between medium pH and meg of acid added / cc of media. The 95% confidence intervals for these two regression lines overlap so it seems reasonable to use a single pH response model rather than individual models for each media. The difference between the two media was however, statistically significant so a media correction factor was added to the combined regression equation. The result was a the following equation [media pH = 7.18 - 50.36 x meg (acid added / cc media) + (media correction factor)].



The medium correction factor for the slate based media was 0.3 which essentially means that the pH of the slate based media was 0.3 pH units higher than the clay based medium. This combined function had an R^2 of 0.82. The 95% confidence intervals for the model parameters were 7.01-7.36 for the intercept, -55.88 to -45.14 for the slope and 0.2-0.4 for the media correction factor. Using this function a simple equation can be developed relating annual acid deposition to predicted medium pH. This function can then be easily used to determine when a green roof would drop below the recommended pH and should be tested to determine the need for lime additions and can suggest how much lime is needed to restore the lost buffering capacity. The function for this predictor is: [Years = (((Target pH - (7.18 + medium correction factor))) x(medium depth in cm)) / (50.36 x ((H deposition kg/ha/yr) x 0.01))]. For example, in Central Pennsylvania acid deposition from 2000 to 2005 averaged 0.495 kg H / ha / yr (NADP, 2007) (Figure 23). Using this average rate of deposition a 3.5 inch deep (8.6cm) clay based medium would be predicted to reach a target pH of 6.5 in 24 years and a slate based medium in 35 years. The 95% confidence interval on the regression coefficients indicates that for the clay medium there is a 95% probability that pH 6.5 will be reached in between 13 and 38 years in the clay medium, and between 19 and 54 years for the slate. The same evaluation for Eastern North Carolina where the average H deposition from 2000-2005 was .28 kg H / ha / yr results in reaching the predicted pH of 6.5 in 43 years in a clay based medium and 62 years with slate. The lower 95% confidence interval for this calculation is 23 years for clay and 34 years for slate. A standard testing protocol for these media on a green roof might be to test pH based on the predicted lower confidence interval, i.e. 13 years and 19 years for clay and slate based media in Central PA, and 23 and 34 years in Eastern North Carolina. This of course presumes that no other sources of acidification are at work in either location. It is likely that any fertilizer added will be acidic in reaction (many are), and it is quite possible that some of the plants used may either directly acidify the media or may acidify the media as they decompose. In this study the planted media was in fact better buffered, had a higher pH at the end of the acid irrigation trial, than unplanted controls. With few exceptions, i.e. Delosperma and Talinum, the pH of leachate from planted pots was as much as 1 pH unit higher than from the unplanted pots. This outcome is slightly surprising, however it might be explained if you consider that the plants were using some of the irrigation water, and hence reducing both the quantity of acid and time of exposure to the medium. This would suggest that the largest plants, and plants with the highest transpiration rates, should have had the highest pH. The Agastache was the largest plant at the end the experiment and had the highest pH in the media leachate. Plant roots may have provided access to media buffer constituents or may have directly modified the media solution pH. Some plants like Pelargonium, are known to acidify their root zone making nutrients more available. There is no evidence in this study to suggest that this is the case with any of the potential green roof plants studied in this evaluation. Since many of the plants used on green roofs, particularly sedums, are known to prefer neutral to alkaline soils, we were concerned that these plants would suffer from exposure to acidified irrigation. None of the sedums suffered ill effects of the acid irrigation over the period evaluated. Although the total acidity applied to the pots was not measured, it is likely that the total volume of irrigation applied was equivalent to approximately 2-3 years of rain and that the total acidity of the water greatly exceeded a normal rain. It seems then that there is little reason to be concerned with direct effects of acid irrigation on sedums in a green roof until the pH drops below problematic levels.

Acid runoff from a roof frequently comes in contact with metal devices and conveyances like flashings, gutters and downspouts. Acid in the runoff might contribute to leaching of metals from these materials. Since the green roof neutralizes the acidity in the runoff, (at least for some

number of years) if the leaching of these materials from the medium was less than the leaching from the metal gutters and downspouts, there would be a net improvement in runoff water quality. Our data suggests that leaching from the media exceeds any acid induced leaching from gutters and downspouts. The average pH of the runoff from the storms measured was 6.9 from the green roofs and 5.3 from the non-green roofs, but despite the increased acidity in the nongreen runoff, the runoff from the green roofs had higher concentrations of iron, copper, zinc and manganese. The medium cation exchange for the green roof media was similar to that which might be expected in a relatively fertile soil rich with organic matter (NRAES, 1995) especially if you consider the lightweight nature of the green roof medium. It is therefore possible to trap metals on the exchange of the medium, however since the concentration in the precipitation is lower than that in the medium solution (in equilibrium with the media exchange) the runoff contains more of these material than the incoming rain. If the precipitation were to become significantly more polluted with a metal cation, or if a contaminated irrigation water source were used for irrigation the medium would, like any other soil remove some of the metal ions through exchange. For example when we used a simulated acid rain with a heavy copper load, 0.138 mg applied in 2" of water on a column filled with 4" of roof medium 79% of the copper was retained by clay based medium and 66% was retained by a slate based medium.

4.6 Summary and Conclusions

One of the key runoff water quality benefits offered by a green roof is the neutralization of acid rain. This benefit is of course limited by the buffering potential of the green roof media. If this benefit is to be maintained for the 50+ year life span of a green roof it will be necessary to replenish the media buffer through liming, much as we do with ground level gardens and agricultural fields exposed to acid fertilizers and rain. We have developed and demonstrated a relatively simple test procedure to evaluate the potential of a green roof media to neutralize acid rain. The procedure involves the addition of small aliquots of acid to a known volume of media. The media acid slurry is allowed to rest for a period of at least 24hr following each acid addition to let the system come to equilibrium with the media buffer. This slow titration should be continued to a stable end point of pH 6.0 or less. The resulting response curve, combined with acid deposition data, provides the basis for estimating the time a roof will neutralize acid precipitation before liming is required. The response curves for the two media evaluated in this study were remarkably similar even though one was based on an expanded clay aggregate and the other on an expanded slate. The model response developed for these two media presented in this report has a correction factor for the difference in pH between the media, with the slate having a pH of about 0.3 pH units higher than the clay based media. Although the difference was significant and is included in the model developed in this study, the function was nearly as robust $(R^2 = .75 \text{ vs } R^2 = .82)$ for a simple linear model without a media correction (data not presented). The model suggests that a green roof in Central PA should have the medium pH evaluated after about 13 to 19 years for clay based and slate based media respectively, and will likely need to be limed at that time. Additional media should be evaluated using this procedure to determine if the general model described here has broader application.

Acid irrigation of green roof plants (simulated acid rain) did not cause plant injury over the 6-month study period. In fact nearly all the green roof plants evaluated had increased leachate pH relative to unplanted containers. Although other species might not respond the same way, these nine species which represent a variety of plant habits and forms, are not likely to be adversely impacted, or to adversely impact the media if used on green roofs in areas with acid precipitation at least in the short term. It remains to be seen, however if long-term impacts would be greater.

The acid runoff from non-green roofs did not result in increased leaching of metals from metal gutters and downspouts compared to runoff passing through a green roof which had a neutral pH. In fact the runoff (leachate) from the green roof had higher concentrations of the metals tested. In effect the metals on the media exchange in equilibrium with the medium soil solution were much higher than anything leaching from the gutters and downspouts. This doesn't however mean that the media cannot act as an ion exchange filter if challenged with high concentration rain or irrigation water. The media cation exchange is similar to that of other soils and if a solution with, for example high copper, is filtered through the media a significant percentage of the Cu can be retained (60-70% in this study). This suggests that the roof might be used as a part of a wastewater treatment program to remove metals, but because the concentration in normal rain is so low, rainwater passing through the media is bound to pick up additional ions from the media exchange.

4.7 Appendix A

4.7.1 Green Roof Acid Rain Buffer Test

Background and General Description:

One of the key runoff water quality benefits offered by a green roof is the neutralization of acid rain. This benefit is of course limited by the buffering potential of the green roof media. If this benefit is to be maintained for the 50+ year life span of a green roof it will be necessary to replenish the media buffer through liming, much as we do with ground level gardens and agricultural fields exposed to acid fertilizers and rain. This relatively simple test procedure can be used to evaluate the potential of a green roof media to neutralize acid rain. The procedure involves the addition of small aliquots of acid to a known volume of media. The media acid slurry is allowed to rest for a period of at least 24hr following each acid addition to let the system come to equilibrium with the media buffer. This slow titration should be continued to a stable end point of pH 6.0 or less. The resulting response curve, combined with acid deposition data, provides the basis for estimating the time a roof will neutralize acid precipitation before liming is required.

Materials:

Green roof media samples (200 cc) (The test should be run in triplicate to provide an estimate of the error) Deionized water Sulfuric acid solution (0.05M) Clean 1L beakers Burette or pipette capable of 2 ml measurements pH meter and electrode Spatula or spoon

Procedure:

- 1. Measure 3 (or more) 200 cc media samples. Place each sample in a 1L beaker.
- 2. Add 500ml of DI water to each beaker with the media sample, stir to mix completely.
- 3. Measure pH on the slurry record
- 4. Add 2 ml of 0.05M Sulfuric acid. Stir to mix completely. Measure pH and record.
- 5. Allow the media water acid slurry to rest at least 24 hours.
- 6. Repeat steps 3-5 until 3 or more consecutive samples are below the target pH (suggested value of 6)

Calculations:

Convert daily acid additions to meq acid / cc media (for the procedure described above the conversion is 0.002 meq acid added / cc of media each day).

Plot meq acid / cc vs. media pH

Determine the linear regression for the response

Use this regression to determine the number of years of acid deposition required to reach the target pH (use NADP data for H deposition; the conversion from Kg H/ha to meq/cc is (H Kg/ha/yr x 0.01)/(medium depth in cm)).

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CHAPTER 5.0

BACKGROUND EDUCATIONAL AND PROMOTIONAL MATERIALS FOR GREEN ROOFS: A SERIES OF ARTICLES TO PROMOTE UNDERSTANDING OF THE BENEFITS OF USING GREEN ROOFS

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5.1 An Introduction to Green Roofs: What They Are, Where They Originated, and Why They are Still Relevant Today

Green roof systems are extensions of existing roofing systems that allow plants to be grown on a rooftop. Generally, the components of a green roof include a waterproofing layer, a root repellant layer, a layer of drainage material, and a filter membrane topped with the growing medium and plants (Green Roofs for Healthy Cities, 2005). This basic formula can be modulated based on the purpose and type of green roof being installed, either an extensive or intensive green roofing system (Green Roofs for Healthy Cities, 2005). Extensive green roofing systems are not accessible or built to withstand human traffic, as they typically consist of low-growing plants, such as Sedum album or Sedum sexangulare as well as other species and cultivars, in a shallow, lightweight media less than six-inches deep (R.D. Berghage, personal communication, (Wong et. al., 2003). Intensive green roofs, on the other hand, can be planted with deeply rooted plants such as trees and shrubs, and are usually designed to withstand human traffic (Wong et. al., 2003). Typically, green roofs built exclusively for environmental benefits are extensive, as these require lower initial investment than intensive green roofs. Extensive green roofs also require less structural loading capacity, and frequently do not require additional support to be added when converting an existing roof to a green roof (Wong et. al., 2003). An intensive green roof provides additional benefits since it can be tailored to provide an area for the community to socialize, garden, grow food, and enjoy water features such as fountains and ponds. Intensive roofing systems tend to provide more social benefits than extensive roofing systems because they are designed to withstand foot traffic and can provide areas for social interaction (Huang, 2005; Wang et. al., 1999; Yuen et. al., 2005.)

5.1.1 History

Green roof technology is not a new concept. Throughout history, many cultures have utilized green roofs in some form. The first historical reference to gardens built above ground level are the ziggurats of ancient Mesopotamia, which were built beginning in the fourth millennium up until approximately 600 B.C. (Wark et. al., 2003). They were built in the courtyards of temples located in major cities, and consisted of stepped pyramids made from

stone, spiraling upwards towards the zenith. Archaeological evidence suggests that plantings of trees and shrubs on landings of these stepped terraces provided resting areas for those climbing the pyramid (Osmundson, 1999). Evidence of plants growing on rooftops can also be traced back to the Hanging Gardens of Babylon (approximately 500 B.C. to 90 B.C.). In ancient Babylon, terraced structures were built atop beams on which soil and plant material were placed over waterproofed layers consisting of tar and reeds (The Garland Company, 2005). The Hanging Gardens of Babylon were constructed by Nebuchadrezzar II to mimic the mountain scenery of the native land of his homesick wife, Amytis. A Greek historian, Diodorus Siculus, provided detailed descriptions of the gardens, making it clear that they were built in part on terraces over vaults, the highest of which was approximately 70' and carried the entire weight of the garden (Osmundson, 1999).

In the 13th century, some Benedictine abbeys in France utilized rooftop gardens (Wark et. al., 2003). Rooftop gardens were also built in at least three Italian cities from the 1300s to 1500s, namely Pienza, Lucca, and Careggi. Other European countries occasionally used green roofs, and from 1600 to 1875 greened roof space could be found in several places in Germany and Russia. Even regions in South America had ancient rooftop gardens. The major Aztec city of Tenochtitlan had many roof gardens, although none survived the Spanish invasion. Cortes, himself, wrote a letter to King Charles I of Spain wherein he described the rooftop gardens on native dwellings. In his letter, Cortes stated, "… there are many rich citizens who also possess very fine houses. All these houses, in addition to having very fine and large dwelling rooms, have very exquisite flower gardens both on the upper apartments as well as down below" (Osmundson, 1999).

Centuries ago, Norwegians designed sod roofs to help insulate their buildings against temperature extremes. Use of sod roofs as insulation also occurred in North America, as settlers of the Great Plains utilized sod roofs during the mid to late 1800s. Settlers constructed dwellings that were built into the side of a hill or had sod roofs. The soil covered rooftops provided insulation from temperature extremes (Osmundson, 1999). These roofs were planted with grasses to prevent erosion, but leakage was a problem when it rained so most buildings were abandoned with the advent of modern heating technology.

More recently, in the early 1900s, rooftops were used for summer entertainment in major cities of the United States. The term roof gardens was coined around 1893 and referred specifically to the theater roof plantings of the period, in fact a number of theaters, such as Madison Square Gardens in New York City, derived their names from their rooftop gardens (Osmundson, 1999). The Rockefeller Center in New York City also installed rooftop gardens during the early 1900s. A total of five rooftop gardens were installed between 1933 and 1936, designed to provide pleasant views to high-rise tenants at premium prices (Wark et. al., 2003). Frank Lloyd Wright and Le Corbusier, two influential architects, designed buildings that incorporated rooftops as functional and garden space. In many of his designs, Wright used roof areas as an extension of indoor living space, and although not true gardens, these rooftop living areas incorporated plantings. The Midway Gardens building, designed by Frank Lloyd Wright, and built in Chicago in 1914, utilized rooftop plantings. Unfortunately, Midway Gardens met a fate similar to other Frank Lloyd Wright buildings, such as the Larkin Building in Buffalo, NY and the Imperial Hotel in Tokyo, Japan, all of which were destroyed in the mid to late 1900s. Le Corbusier, a Swiss architect, also believed in using rooftops as an additional living space, and therefore many of his designs incorporated plants. Some of his buildings, such as the Villa Savoye in Poussy, France, the Domino houses, the Pessac workers' housing estate, the Unite
d'Habitation apartments in France, and his government building in Punjab, India, incorporated plant material as an incidental part of his rooftop design (Osmundson, 1999).

5.1.2 The Current State of Green Roof Technology

Currently, green roofs are starting to come back into favor and are being installed on roofs of new buildings. While green roof technologies are well established in Europe, the benefits and construction are poorly understood in North America (Penn State, 2004). Green roof technology is successful in Europe due in part to supportive legislation and financial benefits for building owners who choose to install a green roof (Green Roofs for Healthy Cities, 2005). In Germany, it is estimated that 10% of roofs are greened, and the Penn State Center for Green Roof Research stated, "between 1989 and 1999, German roofing companies installed nearly 350 million square feet of green roofs" (Penn State, 2004). Green roof technology is also well established in France, Austria, Norway, and Switzerland (Wong et. al., 2003).

The city of Chicago has been innovative in its early acceptance of green roof technology in the U.S. (Walsh, 2004/2005). Chicago's City Hall has a green roof, and the city's government has adopted policies encouraging, and in some cases requiring, green roofs for new developments (Walsh, 2004/2005). Chicago currently has more than 80 green roofs totaling more than 1 million square feet. In 2005, Chicago started offering \$5,000 grants to residential or small commercial property owners to green their rooftops, encouraging a wider population to use green roof technology (City of Chicago, 2005). Currently green roofs in general, although more specifically extensive green roofs, are experiencing a nationwide surge in popularity, and that trend can be expected to continue. Recent press coverage has hailed the green roof as an environmental benefit, a trendy design element, and an economic building decision. Pennsylvania State University, University Park Campus, has plans to install a green roof, and has committed to building another green roof on a new student medical center (R.D. Berghage, personal communication). Other educational institutions have also embraced green roofs. Swarthmore College's Alice Paul Dormitory, Swarthmore, PA; Carnegie Mellon's Hamerschlag Hall, Pittsburgh, PA; U.S. Naval Academies' Chauvenet Hall, Annapolis, MD; Wayne Community College, Goldsboro, NC; Harvard University, Cambridge, MA; and MIT, Cambridge, MA, constitute part of a growing list of educational facilities that utilize green roofs on one or more buildings on their campus. The growth of green roof usage extends beyond the world of academia (Green Roof Plants, 2006; The Green Scene, 2005). Data from a recent survey of the green roof industry indicated that total green roof square footage in the U.S. grew 81% between 2004 and 2005 (from 1,186,738 installed in 2004 to 2,149,585 installed in 2005) (Green Roofs for Healthy Cities, 2006). As this market grows, it provides opportunities for growers, landscapers, landscape designers, wholesalers and retailers to market to a new customer base and fill niches in a growing industry still in its infancy. In order to continue to expand this market, it is important to fully understand the benefits of green roofs, including environmental, economic, and human, all of which will be presented in future articles.

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5.2 Green Roofs: How They May Be a Benefit to Businesses and Industry

In order to maintain and expand their businesses, large and small companies need to: operate efficiently, minimize waste, maximize resources, increase employee productivity, increase their customer base, create brand/company recognition, provide memorable and convenient service, and lastly, be innovative and competitive with the goods and/or services they offer. Green roofs offer several advantages to businesses that utilize them, which may include increased employee productivity, higher employee retention, increased retail sales, higher building occupancy, and other benefits (Gilhooley, 2002; Lohr, 1996).

5.2.1 Improved Working Conditions

There are potential benefits, through increased worker satisfaction and retention, for businesses which install green roofs and provide employees with views of natural landscape (Lohr, 1996). Although the effects of green roofs on worker satisfaction, worker productivity, and the office environment have not been directly studied, other research indicates the importance of green spaces to these subjects. Employee's wages and benefits are the most expensive business assets a company will acquire, therefore employee retention, satisfaction, and productivity are paramount to business success (Gilhooley, 2002).

In one study that illustrates the importance of plants in the working environment, participants were given a timed computer task to complete. During the task, the participant's emotional states were surveyed using questionnaires. The control group completed the task in a windowless room without plants, while the test group performed the same task in a room with plants. Pre-task surveys showed no significant difference between the two groups, but after completion of the task, those in the presence of plants had attentiveness scores significantly higher than participants in rooms without plants. In the same study, participants who completed the task in the presence of plants were more productive, with a reaction time 12% faster than participants in a bare room (Lohr, 1996).

A study conducted at Surrey University in the United Kingdom examined the stress levels of participants completing a complex task in the presence of plant material. Participants were allowed to rest in a room for 10 minutes, during which a baseline measure of stress was recorded prior to beginning the task. After the task, participants rested for another 10 minutes in the office to allow for the collection of post-task stress measurements. Participants who completed the task in the office with plants experienced lower stress levels throughout the task and recovered from stress faster after the task than those in the office without plants (Russell, 1999). Results from another study showed that participants were more vigilant in proofreading a document after a break in a room with plants (Oxford Brooks University, n.d.).

At the BMW headquarters in Munich, Germany, administrators received high levels of employee complaints related to the workplace. In an attempt to alleviate employee dissatisfaction, BMW sponsored an internal study that compared planted areas to non-planted areas in regards to employee well-being, health, motivation, and absenteeism. Administrators found that employees experienced increased well-being in the greened areas, with 93% of those working in the planted areas feeling healthier and more motivated than they did prior to the installation of plants. BMW stated, "The human factor is the No. 1 criterion in determining a company's relative success" (Plantscapes, n.d.).

Increased worker productivity and attentiveness saves businesses time and money, and in addition, workplace stress plays a major role in worker retention and absenteeism. Surveys have shown that one out of every five workers in the U.S. has left a job in the past year due to workplace stress. Data also shows that one out of every eight workers in the U.S., or 12%, have taken time off due to stress in the workplace (Gilhooley, 2002). It is possible that the presence of green spaces could increase worker satisfaction and reduce workplace stress, which could increase worker retention, decrease absenteeism, and potentially save money.

5.2.2 Increased Retail Sales

The presence of plants and landscapes can affect a person's perception of the quality of products a retailer offers. Consumers perceive a building with interior planting as having a more expensive appearance, and as such, research has shown that perceptual responses in humans are related to price acceptance and patronage behaviors (Oxford Brooks University, 1999). Researchers investigating the perceived quality of different shopping districts found that product quality ratings were 30% higher in districts with tree-lined sidewalks versus those with barren sidewalks. Customer service was also perceived as being better in landscaped shopping districts. These perceptions of higher quality translate into a customer's willingness to shop and spend. Respondents reported a willingness to drive farther to shop at the landscaped shopping areas, and reported a desire to shop for a longer period of time. Similarly, respondents also reported that they were willing to pay more for equivalent goods in business districts with trees. According to survey results, landscaped shopping districts could charge 11.95% more than districts with bare sidewalks for the same goods (Wolf, 2002). By including the use of green spaces in a retail atmosphere, retailers can create an environment that promotes shopping and spending.

Use of green building technology, such as green roofs, can help a business increase sales and improve public perception. Giant Eagle, a grocery chain based in Pittsburgh, PA, used enough green building technology at their Brunswick, OH location to earn an LEED (Leadership in Energy and Environmental Design) certification, yet the building cost only 2% more to erect. Since being built, the Brunswick, OH Giant Eagle has become one of the chain's best performers, with sales exceeding projections by 20%. A Giant Eagle executive speculates that the high sales can be attributed to the environmentally friendly building technology used at the Brunswick store (Dinardo, 2005). This phenomena is not limited to businesses in the U.S. J. Bryson, manager of an extensively planted shopping center in the United Kingdom, said, "The annual cost of maintaining the planting of the center is just under 25,000 pounds (44,600 dollars), or 4.3% of the annual service charge. The fact that this massive sum of money has never been queried...implies a complete acceptance of the existence of plants...as a fundamental factor in the success of the center." He also stated, "Through the medium of plants the center...relaxes almost everybody, all ages and types of people relate to the atmosphere." This extensively planted shopping center also has the second highest net profit per square foot in Britain (Bryson, 1992).

5.2.3 Increased Occupancy Rates

It has also been observed that the presence of a green roof can increase interest from prospective guests and tenants of a given property, and thus increase the value of a building. In Portland, OR an affordable housing complex, Hamilton West Apartments, reported higher levels of interest from prospective tenants due to the installation of a green roof. Sean O'Neill, building manager for Hamilton West Apartments, said, "Everyone loves the eco-roof, not just tenants but

prospective tenants. I think it is a major selling point for the building, and it's been very helpful in attracting new tenants" (Walsh, 2004/2005).

Building owners and managers are often in competition to find occupants for their living units and office spaces. It is well documented that interior plantings can help attract and retain tenants. Reduced operating costs, improved environment, and the 'feel-good factor' that is associated with green buildings makes them more attractive to potential occupants (Freeman, 2005). Numerous case studies, including one involving the Opryland Hotel in Nashville, Tenn., have shown that tenant occupancy and retention improved 17% with the addition of interior plantings (Evans, 1992).

The Opryland Hotel is one of the most financially successful hotels for meetings and conventions in the U.S. It has earned multiple awards including the Golden Key Award from Meetings and Conventions magazine, the Mobil four-star award, the AAA four-diamond award, and was named one of the 10 best hotels in the country by readers of Corporate Meetings and Incentives magazine. The Opryland Hotel has over one million dollars invested in interior and exterior landscapes in America, boasting of 25 acres of outdoor garden space and over 18,000 interior plants. Fifty-two employees are responsible for maintaining the plants with access to a budget of about 1.2 million dollars. Results from the study at Opryland concluded that rooms overlooking the gardens are the first to be reserved by repeat visitors to the hotel, even at a premium cost. For example, a single night in a double occupancy room with two double beds reserved for June 10, 2006 costs \$199 for a 'traditional' view and \$264 for a view of the 'atrium' garden'. In addition to getting premium rates for garden suites, the occupancy rate for Opryland Hotel has exceeded 85% every year, whereas the occupancy rate in general for hotels in the U.S. only averages 68% (Evans, 1992). There is evidence that the effect of a green roof on occupancy may be similar to the increase in occupancy rates at the Opryland Hotel. The Ritz-Carlton Hotel and Towers located in Boston, Mass. adjacent to the Commons, has reported that many guests request a room overlooking the green roof on one of their rooftops (Reidy, 2004).

5.2.4 Public Relations

Large corporations are also investigating the benefits of a green building. Wal-Mart has built an experimental store in McKinney, Texas that incorporates multiple sustainable building technologies, including a green roof. Wal-Mart spokeswoman Tara Stewart stated, "We wanted to learn how [we] could improve in the area of sustainability." Wal-Mart has experienced failing public perception over the past 10 years, and it has been stated that the current experimentation with eco-friendly stores is simply a good public relations effort (Dinardo, 2005). It cannot be denied that green roofs have garnered the attention of journalists and become the subjects of newspaper articles in New York, Chicago, Seattle, and areas of California. This constitutes free publicity advertising the environmental initiative of the businesses installing the eco-friendly technology.

There are other economic benefits of green roofs that could potentially benefits builders, building owners, business owners, and homeowners. Green roofs have been effective in reducing energy usage, increasing roof life, and reducing heating/cooling costs. A future article will discuss these additional economic benefits of green roofs.

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5.3 Green Roofs: Longer Roof Life and Reduced Energy Consumption Yields Valuable Economic Benefits

Green roofs, aside from possibly benefiting businesses, may also provide economic benefits by providing a longer roof life, and allowing for savings on heating and cooling costs (Pennsylvania State University, 2004). Installing a green roof reduces heat flux through the roof, reducing cooling costs in summer, and lowering heating costs in the winter. A study in Ottawa, Canada, found that a green roof reduced heat losses by 26% and heat gains were reduced by 95% (Liu et. al., 2003). Other economic benefits that occur in some green roof installations include reducing the amount of insulation used, reducing or eliminating the need for roof drains, the ability to incorporate cooling or water treatment functions, receiving positive media exposure, meeting regulatory requirements for stormwater management, and reducing community resistance to new development (Green Roofs for Healthy Cities, 2005). The city of Chicago is creating an expedited, consolidated permit approval process for developers utilizing green building technologies. This expedited approval process will save time and money for building owners and developers by bypassing stages of approval that may postpone construction (City of Chicago, 2005). The American Society of Landscape Architects cited economics as one of the reasons they installed a green roof on their downtown Washington, D.C. headquarters. They stated that their choice was economically efficient since a green roof lasts longer and requires less maintenance than a regular roof, helps reduce heating and cooling costs, and decreases the amount of insulation required (Greener World Media, 2005).

5.3.1 Longer Roof Life

Some studies reported that green roofs last more than twice as long as regular roofs, and despite significantly higher initial costs, studies have shown them to be similar to, or less expensive than, traditional roofs over time (Wong et.al., 2003). There is a general lack of understanding of both the direct and indirect benefits of green roof, making the expense of a green roof less appealing. Another difficulty in quantifying the cost of green roofs is assigning a dollar value to the environmental benefits of green roofing systems, such as stormwater retention and a cooler microclimate. In some European countries entire service industries, such as green roof maintenance and installation companies, have been formed around green roofs, reducing the initial costs (Wong et.al., 2003).

It has been proven that green roofing systems last at least three times longer than their traditional counterparts. This longevity is in part due to the effect of the plants and media shielding the roof from solar exposure and temperature extremes often reached on traditional roofs. Protection offered from vegetative cover neutralizes the thermal intensity of rooftop exposure and minimizes temperature fluctuations. In Singapore, thermal intensities of up to 100°C were reduced and temperature fluctuations were decreased to 5°C due to the cover afforded by a green roof. Increasing the lifespan of the roofing system means that future maintenance and replacement costs are minimized. Singapore, like the U.S., does not benefit from a widespread use of green roof technology, and since economies of scale are not present, the initial cost of installation can be a barrier to utilization. The similarity between Singapore and the U.S. in regards to the high initial cost of a green roof makes it an applicable comparison for economic studies of green roof usage.

The National University of Singapore examined the initial cost implications of a green roof compared to a flat roof (Wong et.al., 2003). Two types of life cycle cost analysis were

undertaken to compare green roofs to an exposed flat roof; the first does not account for energy cost savings, while the second does. When energy cost savings are not accounted for, both intensive and extensive green roofing systems have a higher life cycle cost than an exposed roof; however, the cost difference between the extensive green roof and the bare roof was marginal (less than 2.4%). When the life cycle cost analysis was completed and accounted for energy cost savings, the extensive green roof was more cost effective than the traditional flat roof (Wong et.al., 2003). Although no studies have been reported on the life cycle costs of green roofs versus traditional roofing systems in the U.S., the U.S. EPA stated that, "future summertime energy savings brings the price of a green roof closer to that of a traditional roof." The U.S. EPA has also recognized that green roofs may be more affordable over the life of a building due to a longer life span (Walsh, 2004/2005).

5.3.2 Insulation/Heating and Cooling Benefits

Green roofs have a long history of being used as a means of insulation against temperature extremes, such as sod roofs used by Norwegians and settlers of the Great Plains, U.S. (Osmundson, 1999). Although roofing technology is far more advanced than it was in the days of the early U.S. settlers, green roofs still have the ability to moderate temperature extremes. Lower energy costs are seen as one of the advantages of green roof technology. Another advantage stated by architects is the possibility that the lack of heat buildup on a green roof leads to more efficient operation of air-cooling and ventilation systems (Reidy, 2004). During a U.S. energy crisis in the 1970s, there was a massive rise in earth-shelter (houses and buildings located underground) technology and research due to the rise in the cost of heating fuels. Green roofs can serve a similar purpose by reducing the temperature fluctuations within a building and reducing the need for heating and cooling (Osmundson, 1999). Being able to better control temperature within buildings, thereby saving energy, can also lead to additional savings for the business. In 1993 a study was completed illustrating that slight reductions in office temperature, of about 1.5°C, reduces worker absenteeism due to health complaints, thereby boosting workplace productivity (as reported in Bergs, 2002).

Along with U.S. cities, Chicago and Portland, OR, the city of London in the United Kingdom is looking into the widespread and legislated use of green roofs since they reduce energy use thereby cutting costs, are an asset to stormwater management programs, and provide environmental benefits. It is widely recognized that green roofs have the potential to reduce the energy consumption of cities, especially when more than one roof in the same area are greened. Reduction of energy consumption and the lowering of urban temperatures have become a major topic of discussion among policy makers in large cities. The urban heat island effect can increase temperatures by 12°C compared to suburban temperatures, increasing the need to provide energy-driven artificial cooling during hot weather (Murray, 2005). A study conducted by the City of Toronto, Canada, and Environment Canada (a weather forecasting and environmental inspection provider) states that if half of all roofs in Toronto were greened, a reduction of at least 1-2°C would occur in the urban heat island (as reported in Green Roofs for Healthy Cities, 2005). According to Leslie Hoffman, executive director of Earth Pledge (the organization leading the Silvercup Studios project which will put the largest green roof in New York on the building made famous by "The Sopranos"), the benefits of green roofs in reducing temperatures on the rooftop and in the surrounding environment, as well as reducing energy use, is increased when more roofs exist in one area. When large areas of greened rooftops are clustered in one area, it creates a microclimate that reduces the temperature further than isolated areas of greenery would, thereby increasing the energy cost savings, air pollution reduction, and other benefits derived from the installation of eco-roofs (as reported in Chamberlain, 2005).

Possible energy savings from the use of green roofs vary depending on a multitude of factors such as climate, building size, media depth, vegetation used, humidity, location, and season changes. This makes developing a satisfactory model for the purposes of estimating energy and cost savings difficult (R.D. Berghage, personal communication; Chamberlain, 2005; Niachou et.al., 2001; Onmura et.al., 2001). Dr. Brad Bass of Environment Canada's Adaptation and Impacts Research Division (at the University of Toronto's Centre for Environment) stated that the projected annual energy saving for an eight-story building in Madrid, Spain would be 6.4%, but that estimated energy savings based a simulation conducted for a single hot day would be closer to 10% (as reported in Murray, 2005). Using the Micro Axess Simulation model, Environment Canada estimated a one-story building with 3.9" of media would experience a 25% reduction of summer cooling needs. Dr. Bass believes the reduction of urban temperatures and the reduction in temperature fluctuations resulting from green roof implementation would reduce the demand on the power grid during a heat wave, making green roofs appealing to power companies (as reported in Murray, 2005). Supporting evidence indicates temperatures are measurably more stable on a green roof than on a traditional roof. Green roof surface temperatures during peak davtime hours in July are 19-31% cooler (Chamberlain, 2005).

Researchers have continued to explore and develop models which evaluate performance of green roofs in regard to the thermal protection of buildings. A green roof system is difficult to model due to the many variables that affect its performance. For instance, evaporative cooling and evapotranspiration of vegetative material greatly improves the effectiveness of a green roof. In times of drought or minimal rainfall, the amount of cooling from plant material and evaporation will be lower. An improved model found, in one simulation, an average of 7.2°C reduction in indoor air temperature due to the addition of an eco-roof with the maximum reduction observed during the hottest period of the day, 12:00 to 15:00 hours. This model also presumed that the heating flux entering a green roof was four times less than that entering a bare roof. Green roofs also have very little fluctuation in the amount of heat flux when compared to traditional roofing systems. One aspect this model carefully considered is the affect of L.A.I. (leaf area index, or the amount of leaf tissue per a given amount of space) on the amount of heat flux and the efficiency of a green roof. A green roof exhibits peak performance when the L.A.I. is high, as the vegetative material acts as insulation and a cooling system (Kumar et.al., 2005).

One researcher investigated the performance of green roof thermal properties and the variations in energy savings using a model. It was demonstrated that some of the variation in energy savings experienced are due to vegetation, building construction (greater savings are possible in older building with less existing insulation), and other factors, although it was focused on how the amount of insulation a building affects the added benefits of installing a green roof. The model was used to study energy savings pertaining to three different building types: heavily insulated (as might be expected in modern buildings built to be energy efficient), moderately insulated, and minimally insulated (as is often the case in older buildings) (Niachou et.al., 2001). Buildings with minimal insulation would most likely experience a 45% energy savings when a green roof was installed, conversely, a building that was heavily insulated received only a 2% benefit. Retrofitting older buildings, and buildings with poor insulation, could provide a true benefit to business owners in regards to energy savings (Niachou et.al., 2001).

Green roofs may provide cost savings, but in the U.S. initial costs remain high. While the price may be a source of hesitation for some building owners, there are laws and subsidies in several areas of the U.S. that necessitate or provide monetary incentives for businesses or private property owners to install a green roof. Since major cities are experiencing overburdened wastewater management systems, green roofs are one way to provide relief and minimize the impact of new development on existing water management systems (R.D. Berghage, personal communication). Currently, the concept of green roofs is receiving more attention from city authorities in the U.S. in part because they help mitigate stormwater. In addition, green roofs are used in some areas to promote biodiversity and other environmental benefits. These functions of green roofs will be featured in the next article of the series.

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5.4 Green Roofs: Reducing the Impact of Urbanization and What is Being Done to Encourage Usage

Cities throughout the world are showing high levels of interest in increasing the use of green roofs. Green roofs manage the effect of rain water falling on the increasing amount of nonporous surface area in cities and thereby reduce the impact of runoff on wastewater management systems. Managing the effect of additional buildings on wildlife populations (e.g., the Black Redstart, a bird common to Britain, U.K.) might also be achieved by the use of green roofs. Birds, insects, and reptiles, etc., could use the green roofs as habitat or breeding grounds (Evans, 2005). For these and other reasons, some U.S. cities are seriously considering how they can promote the use of green roofs on buildings by offering grants and subsidies.

5.4.1 Stormwater Mitigation

The majority of attention regarding green roofing systems has focused on its major contribution to the urban environment, primarily stormwater mitigation. Since many major cities are experiencing overburdened wastewater management systems, green roofs are one way to provide relief and minimize the impact of new development on existing systems. Currently, green roofs are getting more attention from city authorities in the U.S. because of potential energy savings and stormwater mitigation. For example, in New York City there are drainage basins where as little as one-twentieth of an inch of rain could cause overflow (Murray, 2005). Some cities, including Seattle, WA., Portland, OR., and Chicago, IL., are already including green roofs as part of their stormwater management programs (Walsh, 2004/2005). Although some of the other benefits of green roof technology may be difficult to assign dollar figures, the savings in sewage treatment costs are more tangible as they have the potential to be measured in dollars per gallon.

Green roofs absorb water during a rainfall event, delaying and reducing the run-off. When this run-off is unabsorbed and a stormwater or sewage system overflows, the overflow becomes an expensive management problem for the city as it can pollute waterways. This pollution has caused the U.S. EPA to pressure cities to initiate better stormwater management practices (Murray, 2005). Recently Balmori & Associates, a landscape design firm in New York City, conducted a comprehensive assessment of New York City's flat roofed buildings. They concluded that Long Island City alone has 667 acres of flat roof surfaces that are suitable for greening. If this amount of roof were greened in one area, substantial reductions in stormwater runoff, air pollution, the urban heat island effect, and energy grid loading could be expected (Chamberlain, 2005).

5.4.2 Biodiversity and Other Environmental Benefits

Green roofs can be used as alternative habitats for wildlife and threatened species (Evans, 2005; Frith et. al., 2005). Some buildings in Asia and Europe have unique amenities that attempt to attract, or facilitate migration of, wildlife to green roofs. For example, building owners have created networks of 'ladders' to enable lizards and other creatures to scale the building and reach the green roof, whereas other green roofs may consist of piles of rocks and woody debris that mimic the breeding habitat of birds (Berghage, personal communication). In London, U.K., much attention has been given to the possibility that green roofs may be able to increase the biodiversity in urban areas by providing wildlife habitat above the ground (Donald, 2005).

Green roofs also have the ability to neutralize acid rainfall and filter out some impurities and toxins (R.D. Berghage, personal communication; Oster, 2005), as the roof media can effectively neutralize acid rain and maintain a media pH that facilitates plant growth and development. After several years of exposure to such precipitation, the ability of the media to neutralize acid rain will decline. Based on results from soil tests, media can be recharged without replacement or major maintenance if a combination of quick acting and slow release lime is used to raise the pH to an acceptable level (R.D. Berghage, personal communication).

Green roofs may eventually aid in the reduction of the urban heat island effect in large cities. Long Island City, N.Y. has 667 acres (270 hectares), equivalent to more than 75% of Central Park, of empty flat-roof surfaces that could easily be converted to a green roof (Chamberlain, 2005b). If all of the suitable roofs in Long Island City, N.Y. were greened, a measurable reduction of the urban heat island effect would occur. An article by 'Look Japan' estimated the temperature in Tokyo, Japan, could be lowered by 0.11 to 0.84°C if 50% of all available rooftop space were greened, which would result in the savings of approximately \$953,380 each day for the city, just in electricity (as reported in Yuen et. al., 2005). By amassing large numbers of green roofs in one geographic area, the creation of a microclimate could reduce some of the environmental impacts of green space loss due to rampant urbanization.

5.4.3 Law and Subsidies

Laws, regulations, and subsidies that support or mandate the installation of green roofs are in place in several European countries, including Great Britain, Switzerland, and Germany. These regulations have various purposes, including habitat preservation, stormwater management, reducing the urban heat island effect, providing social areas, and energy conservation. In the U.K., the endangered Black Redstart, Phoenicurus ochruros (a bird), nests on the ground in abandoned industrial sites and are being displaced by reconstruction of former industrial areas. To encourage preservation of the bird's population, which is estimated to be less than 100 pairs still nesting in Britain, the bird and its habitat are protected under Schedule 1 of the Wildlife and Countryside Act of 1981 (Frith, 2005). Builders who want to obtain permits to reconstruct old industrial sites must first create new habitats for the birds if the building in question currently serves as a nesting area (Evans, 2005). Due to the high value of land, the most economical fashion of complying with this law is to install a green roof on the new building with the objective of creating habitat for this endangered species (R.D. Berghage, personal communication). In some areas of Germany and Switzerland, a green roof is required in order to get a permit to build, and in other areas a flat roof over certain dimensions must, by law, be greened (R.D. Berghage, personal communication; Donald, 2005).

Even in the U.S., regulations supporting the installation of green roofs are being created, as cities such as Portland, Chicago, Seattle, and Boston have issued green roof guidelines (Frith et. al., 2005). Municipal codes in the city of Chicago are currently under review, with changes already made to energy conservation requirements, and all new flat-roofed city buildings are being outfitted with green roofs. A 2005 pamphlet from the City of Chicago on green building states, "The city has adopted a policy that encourages and, in some cases, requires green roofs and adherence to green building standards in developments undergoing Department of Planning and Development review." The pamphlet outlines some specifics, including the stipulation that discount mass merchandisers must cover at least 50% of their roof surface in greenery if they receive LEED certification, and 75% of the roof must be greened without LEED certification (City of Chicago, 2005a). The city of Toronto, Canada is also beginning to adopt policies

requiring the installation of greenery on all new city buildings with a suitable roof. It is also going to require that green roofs be installed as a provision of certain types of low-interest loans that support eco-friendly buildings (City of Toronto, 2005).

Various grants have also been able to help defray the costs of green roof installation. A \$500,000 grant was recently awarded to aid in the design and construction of a 35,000-square foot green roof on Silvercup Studios in Queens, New York (Chamberlain, 2005a). Chicago's Department of Environment began offering \$5,000 grants for residential and small commercial building owners to aid in the planning and installation of green roofs (Merritt, 2005). Chicago is also exploring other financial and policy incentives that can be utilized to further green building initiatives. Current and developing incentives for green buildings are not targeted at the developing community alone, but also benefit business owners, homeowners, financial institutions, and insurance providers (City of Chicago, 2005). Toronto is also creating grant programs to support the implementation of green roof systems, where such pilot programs will be focusing on retrofitting existing buildings with an eco-roof. Other incentives are being developed to encourage the use of green roofs in Toronto, they include reduced water rates for buildings with green roofs, certain building permit processes will be hastened or simplified, and free training will be provided (City of Toronto, 2005). Portland has been developing a stormwater discount program since 2000, and expects to implement it in 2006. This program will provide discounts to home and business owners that reduce water runoff from their rooftops, or use alternative management methods (Portland Bureau of Environmental Services, 2004). Grants from the City of Portland, the Portland Development Commission, and the Energy Trust of Oregon are also being made available as financial incentives for various green building initiatives (Portland's Office of Sustainable Development, 2005).

In addition to making cities better through decreased loads on the wastewater management system and additional habitat for flora and fauna, green roofs may provide significant human benefits. While there exists a rich body of evidence that plants and views of nature serve to calm the human psyche and enrich human well-being, there is no direct research on the effect of green roofs on human health and well-being (Fjeld, 2005). In the last article of the green roof series the potential benefits of greened rooftops on human health and well-being will be discussed along with the potential for future research.

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5.5 Green Roofs: Potential Benefits to Human Health and Well-being

Questions arise as to whether green roofs, like other studies conducted with interiorscapes, gardens, and natural settings, could improve human quality of life, social interactions, health event outcomes, stress levels, and moods. There exists a rich body of evidence that plants and views of nature serve to calm the human psyche and enrich human wellbeing (Fjeld, 2005). Increased urbanization and the high value of land in some parts of the world make setting aside large tracts of land for parks, stormwater mitigation, and natural habitat impossible. By utilizing unused rooftops, the amount of available green space can be extended (R.D. Berghage, personal communication). The use of intensive green roofing systems makes the existence of rooftop parks and public areas possible, thereby enriching the urban social environment (Yuen et. al., 2005).

Substantial evidence exists illustrating that the environment has a substantial affect on stress levels, recovery, and immunization (Bergs, 2002; Freeman, 2005; Gilhooley, 2002; Lothian et. al., 2005; Oxford Brookes University, 1999; Parsons, 1998; Plants-in-buildings, 2005; Plantscapes, (n.d.); Ulrich, 1984). One theory that explains the relationship between the natural environment and human psychological health hints at a long history of human/nature interaction. Plants and nature represent part of the ecosystem in which mankind evolved as a species. It is believed that human evolution (pre-Homo sapiens) began 4.5 million years ago, and it is also estimated that plant life has existed for 150 million years. This sequence of events means that the evolutionary history of humans has been closely linked to the natural environment. Modern human species, Homo sapiens, has existed for about 100,000 years, and the characteristics of human kind have changed little in the past 10,000 years. Mankind today is almost biologically identical to those who lived thousands of years ago, long before the creation of an industrial society which occurred about 250 years ago. While Homo sapiens have not changed considerably in the recent past, the living environment has. Within the last century humans interactions with nature have been reduced or severed in industrialized nations, meaning humans spends a large portion of their time in an artificial environment (Fjeld, 2005). Artificial environments can pose a risk to human psychological welfare; studies in the field of environmental psychology have shown that our surroundings have a significant effect on emotional stability, stress limits, and the sense of well-being (Bergs, 2002; Craig, 2003; Parsons, 1998; Whitehouse et. al., 2001). An explanation for the link between human well-being and environment is psychological identity. The concept of psychological identity is that human minds, as well as human bodies, adapted to ensure survival in the wild. In a natural setting, the human psyche may switch into an automatic mental state that recognizes nature and natural components as something familiar. Conversely, placed in an unfamiliar environment more mental energy is expended to maintain a higher state of awareness, thereby increasing stress levels (Fjeld, 2005). Expanding the amount of exposure mankind has to nature and natural elements could have significant impacts on stress levels and psychological health.

While there is no direct body of evidence which supports the reduction of stress from the view of a green roof, there is evidence that views of natural environments can differentially affect stress levels and stress recovery in varying contexts. Studies have shown that psychological and physiological stress recovery is hastened by views of nature. In one study, participants were exposed to mild stress while viewing environments dominated by natural or urban scenery. Those who viewed the videotapes of nature-dominated habitats recovered more quickly and completely than those who viewed videotapes dominated by urban artifacts (Ulrich et. al., 1991). Another study compared the affect of roadside environment on stress reduction and

immunization. Participants were evaluated for stress response by measuring: three channels of facial electromyographic activity; two channels of electrooculographic activity; and the results of electrocardiogram, blood pressure, and skin conductance tests. This study videotaped typical landscaped roadside environments (this constituted the nature dominated drive scenery), and roadside environments dominated by buildings, road signs, and construction (which constituted the simulated drive dominated by urban artifacts). After viewing a video of either the urban or landscaped scenery, a passive or active stressor was administered to analyze stress immunization. Results indicated that observing environments dominated by natural elements, as they would be viewed by the driver of a vehicle, reduced stress and helped immunize against future stressors when compared to drivers viewing roadside environments dominated by urban elements (Parsons, 1998). It could be inferred that the effect of roadside scenery on stress levels might be similar to the effect of a green roof on stress levels.

There is substantial evidence that some portion of a motorist's attention is devoted to non-task oriented environmental factors (Parsons, 1998). Studies on human interaction with workplace, medical, retail, and social environments provide evidence that a portion of their attention is also devoted to non-task oriented aspects of the environment (Bergs, 2002; Bryson, 1992; Craig, 2003; Evans, 1992; Freeman, 2005; Gilhooley, 2002; Lothian et. al., 2005; Milligan et. al., 2004; Ousset et. al., 1998; PLANET, 2005; Plants-in-buildings, 2005a, b; Russell, 1999; Sherman et. al., 2005; Ulrich, 2000; Ulrich, 1984; Westphal, 1999; Whitehouse et. al., 2001; Wolf, 2002; Yuen et. al., 2005). This indicates that the incidental or indirect view of green roof space could reduce stress.

Reductions in stress may be responsible for better health outcomes that have been observed among patients with views of nature. Hospital environments are stressful in part due to the fact that they are complex, technical, and unfamiliar (Kiecolt-Glaser et. al., 1998). It is thought that sustained exposure to a hospital environment can result in mental fatigue and cognitive dysfunctions. Evidence also suggests that significant distress or anxiety before and after surgery resulted in a more complicated and prolonged postoperative recovery (Kiecolt-Glaser et. al., 1998). Studies have shown that patients with a view of nature have lower rates of infection, require fewer analgesics, and may have shorter hospital or intensive care stays (Ulrich, 2000; Ulrich, 1984). One study observed surgical patients in a suburban Pennsylvania hospital matched based on age, pre-surgical health, gender, and other qualities after surgery. Hospital confinements for surgical patients often limit their access to the outdoors entirely to views from a window. Records of patients assigned to rooms on the second and third story were divided into two groups: those patients who had a room on the side of the hospital wing that overlooked a stand of deciduous trees, and those who had a room on the side of the wing with a window view of a brick wall. All patients on a given floor received care from the same nurses, and their rooms were nearly identical with a window placed in such a way that patients lying in a hospital bed had an unobstructed view of the outdoors. For the purposes of this study only records of patients that underwent a cholecystectomy, a surgery for gall bladder ailments, during the months that trees had foliage (May 1 through October 20), were used. Patient's records were then placed into matching pairs, based on sex, age, smoking status, weight, nature of previous hospitalizations, the year of surgery, and floor level. These records were then compared and analyzed for the number of days of hospitalization, number and strength of analgesics a day, number and strength of doses of anxiety medication each day, minor complications, and the nurses' notes on the patient's condition and recovery. Negative comments written by nurses about a patient's recovery were more common in those with a view of the brick wall than in those with a view of trees (3.96 per patient viewing the wall compared to 1.13 per patient with a view of trees).

Moderate and strong doses of painkillers, on days two through five of the hospital stay, were used significantly less by those with a view of nature than those with a view of the brick wall. Conversely, the group who viewed trees used more doses of weak painkillers, such as aspirin and acetaminophen while the group who viewed the wall was given more doses of potent narcotics. Shorter hospital stays were observed in the tree group: those with a view of the deciduous trees spend an average of 7.96 days in the hospital, and those with a view of the brick wall spent an average of 8.70 days in the hospital. Patients who had rooms looking out on a natural area required fewer painkillers, slightly fewer minor complications, and left the hospital sooner than participants with a view of other hospital areas. Reducing the amount of drugs used and the length of hospital stays has the potential to boost human well-being and lower the cost of healthcare. By influencing the patient's emotional state and stress level, a patient's recovery can be hastened (Ulrich, 1984). Hospital outcomes, staff morale, patient satisfaction, and the impressions of hospital visitors are all positively impacted by the addition of interior and exterior landscapes (Plants-in-buildings, 2005a).

Investigators who studied the use of healing gardens in a pediatric cancer center observed the number of people who visited the hospital's gardens and the number of patients with views of these areas who either chose to keep their window blinds open or closed. It was found that there was an inverse relationship between the number of people in the garden and the number of open blinds. It appears that the desire for privacy was more important than the ability to receive natural light and have access to natural views. By using green roofs, patients could have access to the view of a garden-like natural setting without sacrificing privacy (Sherman et. al., 2005). Another study researched the utilization and consumer satisfaction of visitors to a children's hospital garden. Reasons for visiting the garden were related to relaxation, coping mechanisms, and stress reduction (a combined 64% of responses); furthermore 90% of the participants reported positive mood changes, resulting from visiting the garden (Whitehouse et. al., 2001). The increased well-being may be related to the positive effects of a natural setting which may promote rest and relaxation.

In a study designed to discover the landscape and design preferences of assisted living residents, it was found that residents consistently chose interior and exterior designs that provided views. Using paired photographs: 1) a view digitally altered to include more plant material; 2) another exterior view (e.g., into another yard, onto a porch, or beyond a fence), or 3) a view that included less plant material, but included additional features (e.g., more walkways, benches, or a swing), assisted living residents were asked to choose which scene they preferred. In all cases where participants were shown an unaltered view or the digitally altered photograph with the added greenery or features, the scene with the additions was chosen (Rodiek et. al., 2004). Ability to view additional areas and see a natural or landscaped setting is important to assisted-living residents who spend a majority of their time in a confined setting.

A study by Amanda Read, a student of The Royal Agricultural College, Cirencester, England illustrated that the presence of plants in a classroom can encourage student attendance and in-class attentiveness. A group of 34 students was observed over the course of an academic year during weekly lectures. Class was alternately held in a room with plants and in a room without plants. In order to make accurate observations, the students (audience) actions were recorded and the tapes were later analyzed for signs of inattentiveness such as talking, yawning, or fidgeting. Results showed that in the planted room student inattentiveness was reduced by 70%. Class attendance was also higher for lectures in the planted room, with an attendance rate of 97.8% compared to 86.4% for the lectures in the unplanted classroom (as reported in Plants-inbuildings, 2005b). Results of this study further the conclusions of a study done by Virginia Lohr in which interior plantings were found to reduce stress and increase productivity in office workers (Lohr et. al., 1996).

In an urban environment, greening rooftops may be one of a few options left to increase green space. Research has shown that greenery helps to make an urban environment more livable for residents, and reduces the negative effects of living in urban centers. As a population's way of living becomes more urban, the desire and need for contact with nature increases. It has been postulated that people will visit urban green spaces on a regular basis when it is within a three to five-minute walk of home or work (as reported in Yuen et. al., 2005). In Singapore, some city officials are pushing architects and developers to include rooftop gardens to extend the amount of park space available to city residents. A study there used focus group discussions and surveys to explore city residents perceptions and expectations of rooftop gardens. A household survey was conducted of 333 residents living near (less than a five-minute walk) and further away (greater than five but less than or equal to a 20-minute walk) from a rooftop garden. Survey results showed a high awareness level of the rooftop garden, but low rates of utilization. Residents voiced some concerns over the utilization of rooftop park space, namely the high heat, the need to climb stairs to gain access to the garden, and safety concerns (Yuen et. al., 2005). Data also suggested that rooftop garden usage was more prevalent among those 35-54 years old, and that men were more likely to visit the roof gardens than women. Reasons residents visited the garden were also investigated, and the primary reasons included taking the children out to play, getting exercise, and finding peace and quiet. A possible reason for the low usage rates of rooftop gardens in Singapore may be related to the lack of amenities. Survey respondents and focus group members suggested the addition of more landscaping, areas for fitness routines/classes, barbeque pits, snack areas, garden statues, water features, and outdoor exercise equipment. When asked about benefits of green roofs and rooftop gardens in Singapore, respondents included better air quality, land use optimization, beautifying the environment, and the addition of greenery and nature views (Yuen et. al., 2005). T. Osmundson has concisely summed one benefit of rooftop gardens in urban settings in his book entitled Roof gardens: history, design, and construction, stated, "A feeling of isolation from the...general confusion of the typical downtown city street can be sensed in most roof gardens above ground level. It is one of their major attributes and one which a downtown park at street level can rarely achieve."

Part of the reason for the need to increase green space in an urban environment is related to the social breakdown that occurs in highly populated areas and high-density housing. Research has illustrated that negative effects of residential crowding are due in part to the collapse of social support systems. In fact, Lin reported that residents of high-rise housing in Taipei do not desire close relationships with their neighbors, and many believe the opportunity for social contact is unnecessary (as reported in Huang, 2005). The breakdown of a social construct in urban residents concerns social psychologists, and could create significant social problems over time. A study on behavior in high-rise buildings showed that 51.67% of the residents of high-rise complexes are not satisfied with their living environments. Of the nine reasons stated for resident's dissatisfaction, the lack of open spaces ranks number one (Wang et. al., 1999). Research conducted on the number of social interactions taking place on green roofs in Taiwan shows that the second highest percentage of social interaction takes place in planted areas (25.63%). To increase the quantity of social interaction by the use of intensive green roof space, the study concluded that areas of visual focus, plants, play areas, and open areas encourage social behavior (Huang, 2005). Provision of greenery and open spaces increases the opportunity for social interaction and thereby enhances the social construct. Creation of open spaces, park-like settings, and scenic views may significantly increase the quality of life for urban dwellers. Both

intensive and extensive green roofs can help fulfill the need of urban dwellers for green spaces. Studies are needed to discover what types and features of green roofs best fit urban needs.

Despite the fact that the green roof industry is still in its infancy in the U.S. and many other countries around the world, there has been considerable research into many aspects of green roofs including possible environmental benefits, energy benefits, stormwater management benefits, the water quality of green roof runoff, media formulas, and plant selections. Several questions remain that have not been answered by research to date: Economic impacts of green roof installations need to be quantified for the U.S. market, human benefits of green roofs (both extensive and intensive) have yet to be investigated, and in-depth studies of wildlife utilization of green roofs needs to be researched. With very strong evidence of the effect of views of nature on human health, well-being, and happiness, it can be postulated that green roofs may have a significant benefits of green roofs is needed to quantify the possible benefits to human well-being. Once the benefits to human well-being, actual or perceived, are investigated, further studies can be done to research the possibility of increased productivity, concentration, and attentiveness that are critical in the workplace environment.

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