AN ABSTRACT OF THE THESIS OF

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Abstract approved

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An alternative to traditional roofing, extensive green roofs are contained ecosystems consisting of a drainage layer, a thin media profile which is planted with hardy plant species. Extensive green roof plants must maintain multiple functions while growing in a highly aggregate media at a depth of ≤ 15.25 cm. The shallow media depth weighs less and can often be used when retrofitting an existing building with a green roof. Maximizing functions such as stormwater mitigation requires designing for the purpose of the green roof goal and for the maintenance plan that will ensure plant health in extreme environments. However, our understanding of these complex and dynamic ecosystems on rooftops is still very limited and management of green roofs is often an afterthought, rarely taking into account regional differences in climate.

The establishment period of an extensive green roof is a critical time to promote plant coverage, which often requires irrigation during dry periods. The Pacific Northwest (PNW) climate is challenging for green roof management

because plants experience cool wet conditions for much of the year yet must survive warm, nearly rainless summers. However, extensive green roof maintenance is generally minimal unless aesthetics are the primary goal. Maintenance in the second year and the years following includes irrigation during dry periods to keep plants healthy or to enhance green roof function. The removal of competitive weeds and tree seedlings is also recommended throughout the life of the green roof.

Extensive green roofs are increasingly being used to help improve stormwater management. The vegetative portion of an extensive green roof design is often steered by the structural load that a building can hold along with availability of local products and materials such as media and plants. A lightweight, high aggregate media planted with *Sedum* species and other succulents is often selected as these components have been successful and work well together. However, with the drive to increase the functional role of extensive green roofs, media and plant selection must be further investigated to fully understand how we can optimize green roof efficiency—in our case, stormwater management efficiency, the most requested function of commercial green roofs.

In this study green roof plants were provided adequate irrigation in the first summer and throughout establishment. At the start of the second summer, we tested how the eight taxa performed under three different management regimes in the PNW: (i) non-irrigated, ii) irrigated in compliance with Portland, Oregon's floor area ratio (FAR) bonus requirement and iii) according to out horticultural decision resulting in the highest watering regime. We also measured weed pressure across the irrigation treatments. We selected plant taxa based on their potential functional attributes (habitat quality, aesthetic quality, stormwater management proficiency) as well as their availability through the regional nursery trade.

Plants selected were *Camassia quamash, Cistus creticus* ssp *creticus* 'Lasithi', *Delosperma cooperi, Eriophyllum lanatum* var *lanatum, Festuca idahoensis* var *roemeri, Iris chrysophylla, Sedum spathulifolium* 'Cape Blanco' and *Sisyrinchium idahoense*. Within selected seasons the mean relative growth rate (MRGR) of each plant was analyzed and survivorship was recorded throughout this study.

Throughout the first year of establishment, all plants grew and survival was high. Exceptions were that *I. chrysophylla* declined in mean relative growth rate (MRGR) and *D. cooperi* had a twenty five percent loss in survival during a cold winter spell.

Plant growth and overall plant performance varied considerably among taxa throughout establishment and across the summer irrigation treatments. Weed pressure also varied across treatments. The highest watering regime provided the greatest plant survivorship and plants generally had a positive increase in MRGR. Exceptions were *F. idahoensis* var *roemeri,* which decreased in MRGR and *S. spathulifolium* 'Cape Blanco' which did not change in size. The irrigation regime compliant with the City of Portland provided increased plant survivorship over the non-irrigated regime, yet plant aesthetics were less for the same species compared to the highest watering regime. Plant survivorship in the non-irrigated regime included succulents, *D. cooperi* and *S. spathulifolium* 'Cape Blanco', and the summer-dormant bulb, *C. quamash*. Plant aesthetics within each irrigation regime varied considerably and mean aesthetic ratings declined as the summer season progressed.

These results suggest that tailoring green roof management more precisely to plant choices and the regional environment will improve function and reduce overall costs. Maintenance costs are less (water costs and weeding labor) with a non-irrigated green roof however, plant aesthetics are compromised when plants experience three to five days without water.

Overall the collected runoff from rainfall throughout this study, planted green roofs retained 45% of roof runoff verses 40.5 % retained by media only roofs ($p < 0.001$). Of the significantly different comparisons ($\alpha = 0.05$), the vegetated plots had a higher mean retention of runoff over media only roofs nine times out of ten. Green roof runoff retention varied considerably throughout the collection period depending on season, rainfall amounts and saturation of media. Climatic variations and increased plant growth may explain these varying results of stormwater runoff retention of the green roofs.

Results from this study suggest that we need to explicitly design green roofs to maximize the ecological goal, which in the case of this research is to mimic nature and allow for rainwater infiltration, retaining a percentage of runoff and detaining the rest so that it enters into stormwater systems at a manageable speed after the peak of the storm. The vegetative layer plays an important role in mitigating stormwater runoff; proper design influenced by regional climate, rooftop microclimates and plant needs as well as the subsequent maintenance regimes will optimize the intended green roof function while providing a suite of additional benefits.

Plant Selection, Irrigation Requirements and Stormwater Management of Pacific Northwest Extensive Green Roofs

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Erin Shroll, Author

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CONTRIBUTION OF AUTHORS

Dr. John Lambrinos assisted with experimental design, data analysis and the writing of each chapter. Dr David Sandrock assisted with experimental design and implementation of this research project. Marilyn Jordan assisted with the development and editing of Chapter 2.

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Chapter 1

General Introduction

Extensive green roofs also known as ecoroofs or vegetative roofs along with other plant-based technologies are increasingly being used to help mitigate stormwater runoff, replace otherwise lost habitat, reduce urban heat island effect, filter harmful air particulates and reduce energy use (Brenneisen, 2006; Dunnett and Kingsbury, 2004; Snodgrass and Snodgrass, 2006; VanWoert et al., 2005). Green roofs do not require additional land and replace an impervious surface with a vegetative layer that has the ability to retain rainwater, attract insects and cool ambient air temperatures (Scholz-Barth, 2001).

We have a limited understanding of how to enhance these complex and dynamic systems on rooftops in effort to maximize their intended ecological function. Horticultural components of an extensive green roof consist of a drainage layer, a lightweight media and a hardy plant palette. However, the environment of an urban rooftop bares no resemblance to plant habitat.

Extensive green roof plants are required to maintain multiple functions while often growing in a highly aggregate media at a depth of ≤ 15.25 cm, so that they are lightwieght. Maximizing these functions requires maintaining plant health in extreme environments.

To design green roofs for maximum ecological function, differences in regional climates, rooftop microclimates and plant needs must be considered. Other considerations include timing of installation, planting method, aesthetic needs and management requirements such as irrigation.

Green roof establishment is a critical time period to promote plant coverage which often requires irrigation during dry periods. Current guidelines suggest that with proper green roof design, permanent irrigation is not necessary after plants become established (Dunnett and Kingsbury, 2004; Getter and Rowe, 2006; Miller, 2003; Snodgrass and Snodgrass, 2006). The Pacific Northwest (PNW) climate is challenging for green roof management because plants experience cool wet conditions for much of the year yet must survive warm, nearly rainless summers. Not only may irrigation be important for plant survival but it may be important for increased efficiency of functional goals of green roofs.

In years subsequent to green roof establishment irrigation is provided primarily during extended dry periods. Using minimal irrigation based on plant needs can save money on maintenance costs. A full cost analysis is necessary to understand the payback of green roof benefits verses increasing maintenance needs that may allow for higher functional efficiency.

One of the most requested functional attributes of an extensive green roof is stormwater management. Research has shown that extensive green roofs have the ability to retain and detain stormwater runoff both of which reduce stress on stormwater systems.

Extensive green roofs in outdoor studies at a range of sites were able to retain 39 to 100 percent of rainfall in their respective location (Carter and Rasmussen, 2006; Hutchinson et al, 2003; Monterusso, 2005). This amount is influenced by the season, saturation of the roof, media type and media depth. Until a recent study (Dunnett, et al., 2008), little research showed that stormwater retention is influenced by green roof vegetation type.

Our study evaluated stormwater retention of extensive green roofs in the PNW during the first year of establishment. We also assessed nutrient loading of stormwater runoff periodically throughout this study. When assessing nutrients in total runoff total Kjehldahl nitrogen maintained a low and level concentration yet total phosphorus did. Water quality parameters of planted roofs showed that concentrations dropped after the initial watering.

This study was designed to determine how candidate PNW native plants and recommended succulent green roof plants establish and perform under three different summer irrigation regimes throughout our xeric summers. Plant species suitable for each irrigation regime are reported along with weed pressure, aesthetic ratings and estimated costs associated with total water use.

Explicit green roof components and lists of considerations vary within and across regions. Whether they arise from structural constraints, seasonal dry periods or client needs, there are many factors to consider when selecting media, plants and a maintenance regime for an extensive green roof. In fact, all of the factors and considerations listed interact to affect the health and success of an extensive green roof.

My goal is to influence extensive green roof design by taking into consideration regional climatic differences, rooftop microclimates and plant needs to increase green roof efficiency, in particular, stormwater management.

Chapter 2

Horticultural Considerations when Designing Extensive Green Roofs for Stormwater Management

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Many of us have seen mosses and sometimes weeds growing atop the garage roof or atop the neighbors' tool shed, but did you know that rooftops are being intentionally planted with aesthetic and functional plant species?

Extensive green roofs are contained ecosystems with a soil depth of less than 15.25 centimeters– the shallow depth resulting in a lighter-weight roof. Increasingly, researchers, horticulturalists and commercial developers are designing extensive green roofs that accomplish specific ecological services, such as stormwater management, reduction of urban heat-island effect or habitat creation (Brenneisen, 2003; Dunnett et al., 2008; Simmons et al., 2008; Wolf and Lundholm, 2008).

Creating an extensive green roof that provides ecological services is not necessarily easy. Structural constraints limit soil types, which influences plant selection. Extensive green roofs are harsh environments, often with prolonged periods of drought, high temperatures and intense wind. Green roof plants are expected to maintain multiple functions while growing in a thin aggregate media. In some cases, green roof management practices conflict with the goal of the green roof. For instance, in the Central City District of Portland Oregon, extensive green roof managers are expected to abide by an irrigation regime that will only support summer dormant native bulbs throughout our xeric summers.

While design goals increasingly require green roofs to provide multiple benefits our understanding of these complex and dynamic ecosystems is limited. Successful extensive green roofs result from a holistic design approach influenced by regional climates, rooftop microclimates, plant needs and, most importantly, the green roof goal.

Green roof layers include the waterproofing membrane, drainage layer, planting media and plants. Each layer of a green roof interacts with the other layers and components to influence functional performance. In many ways these interactions mimic the functioning of natural ecosystems. For instance, in natural systems soil structure and type, slope angle, plant composition, and climate all influence the pattern of waterflow in a landscape. In the engineered ecosystem of a green roof, the drainage layer, media, roof pitch, and plants interact to affect a green roof's ability to mitigate stormwater, reduce urban heat-island effect, replace otherwise lost habitat, filter harmful air particulates and reduce energy use, among other functional goals (Dunnett and Kingsbury, 2004; Snodgrass and Snodgrass, 2006; VanWoert et al., 2005).

Considerable effort and thought has been put into the engineering and architectural consideration for green roofs, but many of the issues in functional design are inherently horticultural in nature.

The different arts

Green roofing has been described as a combination of “black” and “green” arts. The black arts are performed by professional roofing contractors and involve all of the roofing components; the most important being roof structure. Extensive green roofs add a minimum saturated weight of 48 to 170 kg per square meter (GRHC, 2007). The weight bearing capacity for the roof fundamentally constrains green roof design options such as media type and depth, which in turn influences plant selection.

As with traditional roofs, important components of the black arts include a waterproofing membrane and drainage details that facilitate water movement off of the roof. Green roofs are compatible with most traditional waterproofing; the only important difference is that certain waterproofing membranes have organic components such as rubberized asphalt that requires a root barrier.

Root barriers protect particular waterproof membranes with organic components such as asphalt from breaking down as they come in contact with plant roots. Cities such as Portland, Oregon are banning the use of any root barriers that are chemically impregnated because the manner in which these chemicals break down is not known (Tom Liptan, personal communication). Alternative root barriers are often a tightly woven fabric or an inorganic barrier such as PVC sheets (Dunnett and Kingsbury, 2004).

A retention mat is an additional layer that may be included to increase water-holding capacity of the green roof. If used, the retention mat is usually placed below the drainage layer. This is not designed to provide the plants with more water; rather it is to increase stormwater runoff retention.

The green arts involve the living portion of the green roof. Every green roof has these five horticultural issues: drainage, planting media, plant choice, planting method and maintenance often issues within the two arts overlap.

Drainage

The slope of a commercial building can vary yet ‘flat roofs’ usually have slopes of around 1 to 2 percent and can be a little as ¼ percent which does not allow for quick movement of water off the roof. A drainage layer is placed at the bottom of the vegetative profile and can consist of either a prefabricated plastic layer resembling egg cartons or a 5 cm layer of pure aggregate such as pumice. This layer helps facilitate movement of water away from plant roofs once the green roof profile is saturated. Prefabricated plastic layers may provide an air layer inhabitable for plant roots during dry weather, yet can be designed to hold water for added retention. An aggregate drainage layer has the potential to provide an added space for plant root growth. Charlie Miller of Roofscapes has reported better plant growth with an aggregate layer (http://www.roofscapes.com/).

Just as with a traditional flat roof, water may be inclined to pool in certain areas, often around drains and at the bottom of slight slopes. These areas become microclimates for plant species that need more water than others. In the same vein, any dry areas such as those at the top of slopes are good sites for the hardiest plants on the roof. It is important to understand the plant needs when it comes to drainage. Either suit the drainage needs to the plant or the plant needs to the drainage.

Planting media

Extensive green roof media compositions vary widely across regions depending on local materials as well as the regional green roof goals. Extensive green roof media typically contains little organic matter (5-20 percent) and has a high mineral content (up to 90 percent), consisting of a lightweight aggregate such as pumice, expanded slate or expanded clay (GRHC, 2008).

Media standards have been developed by the German Landscaping and Landscape Development and Research Society (FLL). These standards known as the FLL were developed in 1982 to provide guidelines for professionals. This German standard has influenced media selection for North American green roofs. FLL compliant media is designed to be lightweight and reliably supports *Sedum* species and other succulents (FLL).

Although green roof media is typically low in organic matter, people have been trying alternatives with native soils and engineered lightweight media with higher organic matter for better water retention and increased plant palettes that replace otherwise lost plant habitat.

Although these media types have been used successfully on extensive green roofs, using native soils and engineered green roof media with high organic matter content is still a topic of debate. Skeptics believe that media high in organic matter is likely to decompose and decrease in depth unless the green roof is amended. Amending is a practical maintenance operation yet it can change the media composition and is not recommended on roofs with specific weight constraints.

Installing green roofs since 1995, Rick Buist has become an advocate for using medias higher in organic matter and planting green roofs with grasses to enhance stormwater management function. He has not seen any loss in media depth on existing green roofs, and when grasses are mowed once or twice a year, the clippings contribute organic matter back into the system (Bioroof seminar, April 2009).

At the other extreme, soil-based medias have also been successful. Originally covered in native soil to help moderate temperatures within the building, the Zurich MOOS Water Filtration Plant (Seewasserwerk Moos) in Switzerland is now a nine-acre roof meadow with 175 different plant species including nine orchid species (Werthmann, 2007). Constructed in 1914, the original media composition was five cm of sand and 15 - 20 cm of topsoil (Werthmann, 2007). It has become common practice in cities of Switzerland to green rooftops with native soils and call on an ecologist to assist with designing rooftop habitat (Brenneisen, 2006).

Regardless of media choice, professional laboratory testing of organic percentages, pH, and nutrients, weight, porosity, drainage capacity and water retention is recommended prior to mixing soils and components for a commercial green roof (Snodgrass and Snodgrass, 2006).

Planting method

Extensive green roofs can be planted in a variety of ways. In the order of increasing cost these include: seeds, cuttings, plugs, containers (10.16 cm squares or larger), sedum mats or sod and modules (Snodgrass and Snodgrass, 2006). Seeds and cuttings take more time to establish whereas modules are often fully planted at the time of installation (Snodgrass and Snodgrass, 2006).

The planting season also plays an important role in extensive green roof establishment. Depending on regional differences and season, supplemental irrigation and regular weeding may be needed to ensure plant establishment.

Plant selection

Extensive green roof plants are primarily mat-forming groundcovers that can withstand heat, sun, wind and cold along with being low maintenance and relatively pest resistant (Snodgrass and Snodgrass, 2006). Traditionally these mat-forming plants are succulents (often *Sedum* species) because they are drought-tolerant, low growing, fibrous rooted and most often evergreen (Snodgrass and Snodgrass, 2006). Germans have been researching green roofs since the 1950s. To date, most extensive green roofs in North America and Germany have been planted with succulents (Getter and Rowe, 2006). While accent plants such as bulbs provide added interest, they do not provide the same type of coverage as standard groundcovers (Snodgrass and Snodgrass, 2006).

Research in North America has also demonstrated that succulents perform well in green roof settings (Getter and Rowe, 2006; Monterusso, 2005; Nagase and Thuring, 2006). Succulents such as *Sedum, Sempervivum* and *Delosperma* are successful in aggregate media mixes throughout many regions and often survive in non-irrigated extensive green roofs (Getter and Rowe, 2006). There are many examples where drought tolerant *Sedum* species have performed well. *Sedum album* can survive more than 100 days without water and *Sedum acre, S. kamtschaticum ellacombianum, S. pulchellum, S. reflexum, S. spurium* 'Coccineum' and *S. spurium* 'Summer Glory' all survived 88 days without water (Getter and Rowe, 2006). *Sedum rubrotinctum* has survived two years without water in a greenhouse (Getter and Rowe, 2006). *Sedum spathulifolium* 'Cape Blanco' and *Delosperma cooperi* survived throughout a dry PNW summer without supplemental irrigation (Schroll et al., 2009).

The green roof industry is now emphasizing plant choices that increase the ecological function of a green roof. Simmons et al., (2008) reported that green roofs vary so widely that they must be designed according to the desired functional green roof goal. There is a great deal of interest in expanding the plant palette available to green roof designers to include regionally native species. This has been driven by a desire for green roofs to serve a habitat function either for the plant species themselves or for the animals that are associated with them. Regional research of plant taxa suitable for green roofs throughout North America's range of climates has been limited (Monterusso et al., 2005). Michigan State University (MSU) has conducted several research projects involving native plants and evaluated eighteen native Midwest plant taxa (Monterusso et al., 2005). *Allium cernuum, Coreopsis lanceolata, Opuntia humifusa* and *Tradescantia ohiensis* were the four native plants recommended for non-irrigated extensive roofs (Monterusso et al., 2005). The remaining fourteen are potential choices if irrigation is available (Monterusso et al., 2005).

In a study I conducted looking at the suitability of native PNW plants for use on extensive green roofs, the selected natives reliably survived when provided with enough summer irrigation. Optimal survival and growth was seen under an irrigation regime in which plants received a total of 171.45 mm (irrigation and summer precipitation) of water over 90 days (Schroll et al., 2009). Plant species included *Camassia quamash*, *Eriophyllum lanatum* var *lanatum, Festuca idahoensis* var *roemeri, Iris chrysophylla, Sedum spathulifolium* 'Cape Blanco' and *Sisyrinchium idahoense* (Schroll et al., 2009)*. Camassia quamash* and *Sedum spathulifolium* 'Cape Blanco' survived the non-irrigated regime, receiving only summer precipitation (38.1 mm) (Schroll et al., 2009). Although survival of *Sedum spathulifolium* 'Cape Blanco' was high, its aesthetics were compromised with less water. This could be in part due to planting method but overall, plant aesthetics declined with decreasing irrigation amounts (Schroll et al., 2009).

Complications for plant selection can arise from conflicts between different functional goals. For instance plant species that improve cooling or stormwater function through high transpiration rates may require large amounts of supplemental irrigation to thrive in a green roof environment. Wolf and Lundholm (2008) are assessing the potential trade-offs between drought tolerant species and plants with potential for cooling ambient air temperatures through transpirative cooling. *Poa compressa* lost the most water through evapotranspiration and researchers conclude that enhancing a green roofs' ability to cool roofs may require planting multiple species (Wolf and Lundholm, 2008).

A green roof design for stormwater management must include a plant palette that can walk a fine line between adequate drainage and saturation. In some parts of North America such as the PNW, plants must remain wet for several consecutive days throughout the rainy season.

Dunnett and colleagues (2008) evaluated plants to determine which are most useful for improving the management of stormwater. Plants were separated into functional groups and the grasses performed better than forbs, which performed better than succulents (Dunnett et al., 2008). Aside from this study, there is limited research evaluating plant species or functional groups to determine which mitigate stormwater best. However, there is increasing emphasis toward selecting plants that are suited for both regional climate and rooftop microclimates while working to increase efficiency of their ecological function.

Potential plants for stormwater management include grasses, herbaceous perennials and mosses. Facultative wetland plants that occupy vernal ponds may be likely candidates as well. Grasses successful at mitigating stormwater runoff include *Anthoxanthum odoratum and Trisetum flavescens,* which allowed the least amount of runoff within the grasses selected (Dunnett et al. 2008). *Festuca idahoensis* var *roemeri* is a facultative wetland species suitable for PNW extensive green roofs, requiring minimal irrigation for survival through xeric summer conditions (Schroll et al., 2009).

A successful herbaceous perennial researched in terms of mitigating stormwater is *Silene uniflora,* which allowed the least amount of runoff (Dunnett et al., 2008). *Sisyrinchium idahoense* is a facultative wetland species suitable for PNW extensive green roofs (Schroll et al., 2009). Other potential facultative wetland species include *Carex* spp and *Juncus* spp, yet neither has been tested for use on green roofs. Small bulbs such as *Crocus* spp, *Allium* spp and *Muscari* spp are suitable accents plants for extensive green roofs (Snodgrass and Snodgrass, 2006). In the PNW, *Camassia quamash* is a native summer-dormant bulb that often grows in locations that are wet throughout the winter and spring rainy season. *Camassia quamash* had 100 percent survival throughout a typical PNW summer under three different irrigation regimes including non-irrigated (Schroll et al., 2009).

Malcolm Anderson, a researcher at Oregon State University, has been working on the stormwater retention capabilities of three mosses. Anderson has found that mosses retain more water than vascular plants, and are able to withstand the seasonally dry summers, as they are native to the PNW (Anderson, 2009 unpublished).

Succulents are often selected on extensive green roofs for stormwater management. In some cases, they are well suited for non-irrigated green roofs with a highly aggregate media. They have the ability to take up and store a great deal of water, but they have a small fibrous root system that may allow more runoff compared to grasses and herbaceous perennials (Dunnett et al., 2008).

Maintenance

Extensive green roofs require minimal maintenance; in some cases they are only accessible for maintenance and in some cases they are not visible (Getter and Rowe, 2006). As with any roof a yearly inspection is recommended—clean gutters, remove debris from drainage areas and in the case of a green roof, scout out and remove any competitive weed species and monitor plant survival. Any green roof can be low maintenance if it is designed properly.

Irrigation requirements on a green roof depend on several variables, including planting method, design (substrate depth and composition, plant selection), local climate and the goals of the green roof (Getter and Rowe, 2006). A thorough watering is required immediately after planting and irrigation can be critical in the establishment phase of a green roof, which can take 6 to 18 months (Dunnett and Kingsbury, 2004; Getter and Rowe, 2006; Miller, 2003; Scholz-Barth, 2001; Snodgrass and Snodgrass, 2006). Irrigation will be most frequent initially, tapering off as plants acclimate to the media type and a dry climate (Getter and Rowe, 2006; Miller, 2003; Snodgrass and Snodgrass, 2006). The amount and frequency of each watering varies depending on climate, rainfall events, planting season and planting method.

Many current guidelines suggest that, with the exception of arid and semi-arid climates, irrigation is needed only for plant establishment. There is often no need for permanent irrigation (Dunnett and Kingsbury, 2004; Getter and Rowe, 2006; Miller, 2003; Snodgrass and Snodgrass, 2006). However, permanent irrigation may be necessary to achieve certain green roof goals. Maintaining aesthetic value, high plant biodiversity, reducing ambient air temperatures, and storing rainwater all require actively growing and transpiring plants (Dunnett and Kingsbury, 2004; Getter and Rowe, 2006). An irrigation system may need to remain in place in case of periodic drought, which can cause costly plant dieback (Snodgrass and Snodgrass, 2006).

During the years subsequent to establishment, irrigation requirements for extensive green roofs are low. With a media depth of less than 15.25 cm, media becomes quickly saturated and roof runoff occurs; there is no need to water beyond that point. In the irrigation trial I conducted, green roof plants living in 12.7 cm of aggregate media reliably survived with less than 174 mm of water (irrigation and summer precipitation combined) over the 90-day experimental period throughout a typical xeric summer in the Willamette Valley of the PNW (Schroll et al., 2009). That is less than 58 mm a month or less than 14.5 mm each week.

Weeds move into bare places in the media and increase in biomass with increasing irrigation amounts (Schroll et al., 2009). During establishment it is important to keep plant competition down by removing any aggressive weed species so that intended plant species can increase in size and provide coverage. In some cases, the aesthetic value of an extensive green roof is important and regular weeding of non-aggressive weeds may be necessary depending on what the horticulturalist and the client decide is a weed. Aggressive weed species and trees should always be removed throughout the life of the green roof.

Designing extensive green roofs within this new horticulturally slanted trend means explicitly selecting plants to fit with regional climates, rooftop microclimates, plant needs and, most importantly, the goal of the green roof. The composition of a green roof along with its list of considerations, vary within and across regions. Whether they arise from structural constraints, seasonal dry periods or client needs there are many considerations to make when designing an extensive green roof to maximize a specific ecological goal.

Literature Cited

Brenneisen, S. 2006. Space for urban wildlife: designing green roofs as habitats in switzerland. Urban Habitats. 5:27-36.

Dunnett, N. and N. Kingsbury. 2004. Planting green roofs and living walls. 1st ed. Timber Press, Portland, Ore.

Dunnett, N., A. Nagase, R. Booth and P. Grime. 2008. Influence of vegetation composition on runoff in two similar green roof experiments. Urban Ecosystems. 11:385-398.

FLL: Guideline for the Planning, Execution and Upkeep of Green-Roof Sites. 2002. Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau E.V. 4th ed. Bonn, Germany.

Getter, K.L. and D.B. Rowe. 2006. The role of extensive green roofs in sustainable development. HortSci. 41(5): 1276-1285.

Green Roofs for Healthy Cities. 2007. Green roof infrastructure: design and installation 201. Green Roofs for Healthy Cities, Toronto, ON.

Green Roofs for Healthy Cities. 2008. Green roof plants and growing medium 401. Green Roofs for Healthy Cities, Toronto, ON.

Miller, C. 2003. Moisture management in green roofs. Proc. Greening Rooftops for Sustainable Communities Conference, Chicago, Ill.

Monterusso, M.A., D.B. Rowe, C.L. Rugh and D.K. Russell. 2004. Runoff water quantity and quality from green roof systems. Acta Hort. (ISHS) 639:369-376.

Nagase, A. and C. Thuring. 2006. Plant responses to drought on extensive green roofs: the effects of temperature, substrate type and substrate depth. Proc. Fourth Annual Greening Rooftops for Sustainable Communities Conference. Boston, 11-12 May 2006.

Scholz-Barth, K. 2001. Green roofs: stormwater management from the top down. Environmental Design and Construction. Tremco Consultant Ser. Bul.

Schroll, E. J. Lambrinos and D. Sandrock. 2009. Irrigation requirements and plant survival on northwest green roofs. Proc. Seventh Annual Greening Rooftops for Sustainable Communities, Atlanta, Ga. 3-5 June 2009.

Simmons, M.T., B. Gardiner, S. Windhager and J. Tinsley. 2008. Green roofs are not created equal: the hydrologic and thermal performance of six different extensive green roofs and reflective and non-reflective roofs in a sub-tropical climate. Urban Ecosystems. 11:335-337.

Snodgrass, E.C. and L.L. Snodgrass. 2006. Green roof plants: a resource and planting guide. 1st ed. Timber Press, Portland, Ore.

VanWoert, N.D., D.B. Rowe, J.A. Andresen, C.L. Rugh, R.T. Fernandez and L. Xiao. 2005. Green roof stormwater retention: effects of roof surface, slope and media depth. J. Environ. Qual. 34:1036-1044.

Werthmann, C. 2007. Greener green roofs. Architecture Week. 12 May 2009. <http://www.architectureweek.com/2007/1107/environment_1-1.html>

Wolf, D. and J.T. Lundholm. 2008. Water uptake in green roof microcosms: effects of plant species and water availability. Ecological Engineering. 33:179-186.

Chapter 3

Plant Performance and Irrigation Requirements on Northwest Extensive Green Roofs

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Abstract

Extensive green roof plants are required to maintain multiple functions while growing in a highly aggregate media at a depth of 15.25 or fewer centimeters. Maximizing these functions requires maintaining plant health in extreme environments. However, management and maintenance of green roofs is often an afterthought, rarely taking into account regional differences in climate.

The Pacific Northwest (PNW) climate is challenging for green roof management because plants experience cool wet conditions for much of the year yet must survive warm, nearly rainless summers. Supplemental irrigation may be required for some roof designs and plant selections. Irrigation is often necessary during the early establishment of a green roof, which is a critical period to promote plant coverage.

This study explored the extent to which supplemental irrigation improves plant performance in a typical extensive green roof design in the PNW. We tested how eight taxa perform under three different water management regimes (increasing in water availability from i to iii) in the PNW: (i) non-irrigated, ii) irrigated in compliance with Portland, Oregon's floor area ratio (FAR) bonus requirement and iii) our horticultural regime for irrigation using runoff measurements as a tool. We also measured weed pressure across the irrigation treatments. We selected plant taxa based on their potential functional attributes (habitat quality, aesthetic quality, stormwater management proficiency) as well as their availability through the regional nursery trade.

Plant growth and overall plant performance varied considerably among taxa throughout establishment and across the summer irrigation treatments. Certain species showed signs of transplant shock and many species exhibited different growth patterns throughout the establishment period. Across summer irrigation treatments, plant survival and growth increased with increasing irrigation with many species not surviving at all under no irrigation. Three notable exceptions were *C. quamash*, *D. cooperi* and *S. spathulifolium*, which had 100%

survival under no irrigation. All plant species survived and maintained aesthetic quality within the regime supplying the highest amount of irrigation.

Weed pressure also varied across treatments, increasing in the abscence of plants and with increased irrigation amounts illustrating that green roofs with high percent plant cover have less weed pressure irrespective of irrigation regime.

Plant aestheics within each irrigation regime varied considerably and native herbaceous plants showed signs of water stress as early as 14 and 21 days after the initation of irrigation regimes. Mean aesthetic ratings of all plants including succulents, declined with less water and as the summer season progressed.

These results suggest that designing green roofs for functional efficiency requires tailoring management precisely to plant choices and the regional environment; these will improve function and may reduce overall costs associated with maintenance.

Introduction

Extensive green roofs are subject to extreme environmental conditions, including prolonged periods of drought, high temperatures and intense wind (Dunnett and Kingsbury, 2004). Plant species that are drought tolerant are often selected for potential use on green roofs. However, many drought-tolerant plants are able to survive in their native habitat because their roots grow deep into the soil to extract water (Dunnett and Kingsbury, 2004; Getter and Rowe, 2006). Shallow, extensive green roof substrates (typically 5.08 to 15.24 cm) do not allow for deep root penetration and exhibit more extreme temperatures than ground-level plantings (Dunnett and Kingsbury, 2004).

On non-irrigated extensive green roofs, succulent species of *Sedum, Sempervivum* and *Delosperma* are often selected (Getter and Rowe, 2006). Several *Sedum* species have been tested and proven drought tolerant on green roofs (Getter and Rowe, 2006). *Sedum album* can survive more than 100 days without water, and *S. acre, S. kamtschaticum ellacombianum, S. pulchellum, S. reflexum, S. spurium* 'Coccineum' and *S. spurium* 'Summer Glory' all survived 88 days without water (Getter and Rowe, 2006). *Sedum rubrotinctum* has survived two years without water in a greenhouse (Getter and Rowe, 2006). To date, most extensive green roofs in Germany and in North America have been planted with a variety of succulent species, most of which are non-native (Getter and Rowe, 2006).

Despite the shallow, porous media and the harsh conditions of an extensive green roof, there is a drive to use native plants. The decline of wildlife habitat, the threat of invasive species and the increased interest in providing biodiversity in the urban environment has led to native plants being specified for green roof design (Dunnett and Kingsbury, 2004; Snodgrass and Snodgrass, 2006). Native plants adapted to the local climate can co-exist with indigenous pests and may provide habitat for native insects (Dunnett and Kingsbury, 2004; Snodgrass and Snodgrass, 2006; Tallamy, 2007). Native species have been successfully used on green roofs in Switzerland where design criteria incorporate natural soils to enhance their similarity to native habitats (Brenneisen, 2006).

Despite the potential benefits of using native plants, the extreme rooftop conditions and the shallow media depths of extensive green roofs impose serious constraints on plant selection. When considering native plants for use on green roofs, it is ideal to look at the plant community along with its soil type (Snodgrass and Snodgrass, 2006). Plants that display suitable traits in their native contexts may not do so in the context of an extensive green roof. For instance, many prairie plant species survive well in drought conditions without inputs as a result of deep soils with specific microbial symbionts (Snodgrass and Snodgrass, 2006). Alpine plants experience extreme conditions yet air temperatures are often cooler at higher altitudes compared to those on an urban rooftop.

Ultimately, green roof plant selection will vary among geographic regions and green roofs must be designed to achieve specific goals while considering client needs (Simmons, et al., 2008). In many green roof contexts annuals, flowering herbaceous perennials and grasses require irrigation or deeper substrates to ensure plant survival and achieve desired aesthetics (Getter and Rowe, 2006).

Irrigation requirements on a green roof are dependent on several variables, including planting method, design (substrate depth and composition, plant selection), local climate and the goals of the green roof (Getter and Rowe, 2006). Current guidelines suggest that, with the exception of arid and semi-arid climates, irrigation is needed only for plant establishment, and with proper design, plant selection, substrate type and depth, there is no need for permanent irrigation (Dunnett and Kingsbury, 2004; Getter and Rowe, 2006; Miller, 2003; Snodgrass and Snodgrass, 2006). Semi-arid and arid climates cover more landmass than any other climate grouping, yet we have very little information about proper water management for green roofs under these conditions.

Despite its rainy reputation, the PNW is dry through most of the summer. For example, Portland, Oregon has an average rainfall of 952.5 mm with an average of 76.2 mm of precipitation throughout the months of July, August and September (Hale, 2009). Irrigation may be necessary to maintain roofs throughout this dry period. However, no studies have investigated the efficacy of current water management practices or evaluated the performance of green roof plant selections within the context of a specific water management regime. Ground level maintenance practices often don't translate well to green roof soils, environmental conditions or plants. For example, deep watering is often recommended when landscaping at ground level but deep watering of green roofs causes unnecessary runoff once the media becomes saturated. Tom Liptan (City of Portland, Bureau of Environmental Services) has noted that, in general, Portland green roofs are being watered beyond media saturation during the summer months.

With conservation in mind, Portland’s Bureau of Environmental Services has instated an irrigation limit on green roofs receiving an incentive known as the Floor Area Ratio Bonus (FAR bonus). The FAR bonus applies to the Central City District of Portland, a 3.6 hectare area that has a building height restriction. Building owners with green roofs that meet FAR bonus requirement are awarded an increase in building height, in-turn increasing revenue (Tom Liptan, personal communication).

Building owners that have been awarded the FAR bonus are permitted to apply 12.7 mm of irrigation to their extensive green roofs every 10 days during plant establishment and once it is established, to apply 6.35 mm every 10 days. This irrigation amount was selected based on Tom Liptan's experience monitoring Portland's first green roof, which was installed in 1996. Liptan calculated the flow onto the roof and monitored the runoff to determine that 6.35 mm of irrigation is sufficient for an established extensive green roof (Liptan, personal communication).

This study was designed to determine how effectively candidate PNW native plants and recommended succulent green roof plants establish and perform under three different summer irrigation regimes throughout a xeric summer customary to the Willamette Valley of Oregon. We identify suitable plant species and estimate water use of each irrigation regime and how water amounts affect the amount of weed biomass, plant survival and aesthetic quality of candidate species.

Method and Materials

Site description. Twenty-four 1.2 m X 2.4 m green roof prototypes were constructed at a height of 1.98 m at the Oregon State University (OSU) Oak Creek Center for Urban Horticulture in Corvallis, Ore. (latitude 44° 30'N longitude, 123° 17'W latitude, elevation 71 m). Each prototype was lined with a single-ply 0.045-mm thermal polyolefin (TPO) thermoplastic waterproof membrane (Firestone Building Products Indianapolis, Indiana) loose-laid with heat-welded seams. Each prototype had a uniform, lengthwise 2% slope. Twenty-one roofs were outfitted with a 6.35 mm thick standard drainage mat with a geocomposite fabric bonded to one side, placed fabric side up to provide a filter cloth between drainage mat and media (Tremco, Ashland, Ohio). Twelve were planted and nine contain media only. Extensive green roof media (screened pumice, Fiber Life compost and paper fiber; Pro-Gro, Sherwood, Ore.) was selected and uniformly applied to 18 prototypes at a 12.7 cm depth. The remaining three roofs (experimental controls) were lined with the waterproof membrane only.

Plant trial. On 25 July 2007, twelve prototypes were planted with the following eight species in a randomized complete block design: *Camassia quamash, Cistus creticus* ssp *creticus* 'Lasithi', *Delosperma cooperi*, *Eriophyllum lanatum* var *lanatum, Festuca idahoensis* var *roemeri*, *Iris chrysophylla*, *Sedum spathulifolium* 'Cape Blanco', *Sisyrinchium idahoense* (Table 1). Each green roof prototype consisted of four blocks (blocked across the drainage gradient) and each block contained a single-plant replicate of each species for a total of 48 single-plant replicates per prototype. Plants were purchased in 10.16 cm nursery pots from Oregon, Washington and British Columbia growers.

Although there is overlap, the following lists potential functional attributes of plant taxa evaluated in this study; habitat quality (*C. quamash, E. lanatum* var *lanatum*, *I. chrysophylla),* stormwater management proficiency (*C. creticus* ssp *creticus* 'Lasithi', *F. idahoensis* var *roemeri* and *S. idahoense)* and currently used in green roof trade (*D. cooperi* and *S. spathulifolium* 'Cape Blanco'). Aesthetic qualities of all plant taxa were taken into consdieration as well as their availability through the regional nursery trade as certain native species of interest were not obtainable.

Irrigation. Irrigation to the green roof test plots was supplied via short-radius (1.21 m) nozzles with head to head coverage set to an ACC controller (Hunter, San Marcos, Calif.). Nine can tests (three cans placed on each roof to collect and measure irrigation amounts) were conducted and averaged to determine that irrigation heads are consistently applied 6.63 cm per hour at 1.76 kgf/cm^2 kilograms –force per square centimeter. All planted prototypes were irrigated uniformly for establishment during the first year, receiving 2.18 mm everyday between the morning hours of 0400 and 0500 starting on 25 July 2007 and ending on 25 September 2007.

On 25 June 2008, three different, randomly applied irrigation treatments were initiated and applied over the 90 day study period: i) Non irrigated regime, receiving only summer precipitation which totaled 38.1 mm (Table 2). ii) Portland regime: irrigated in compliance with irrigation requirements for Floor Area Ratio Bonus awarded by Bureau of Environmental Services, City of Portland, Oregon totaled 57.15 mm in addition to summer precipitation (3.175 mm applied every 5 days) and iii) Horticultural regime: our horticultural decision made using roof runoff as a diagnostic tool, to provide adequate water to plants yet minimize water use. Irrigation was applied when media was dry to the touch in the top 10.16 cm (total aggregate media depth, 12.7 cm), which consistently occurred in approximately 2 days during the summer weather conditions. Irrigation amounts totaled 133.35 mm in addition to summer moisture (2.97 mm applied every two days). Irrigation was again consistently applied between the morning hours of 0400 and 0500.

Plant performance. Plant sizes were recorded on planting day (6/25/2007) and then measured on the 25th of each month through the following spring. Plant sizes were estimated as idealized spheres taking the longest width by the longest perpendicular width and the height of each plant. Blooming of fully opened flowers and plant mortality were also recorded during each sample period. *Camassia quamash* showed immeasurable signs of emergence on 25 February 2008, which initiated collection of size data every 15 days throughout the remainder of the spring and summer months of 2008. Monthly data collection resumed at the end of the irrigation trials (9/25/08).

Individual plant sizes were measured every 2 weeks throughout the summer irrigation trials (6/25/2008 to 9/25/2008).

At the start of the irrigation regimes (6/25/08), plant cover percent was calculated for each planted green roof prototype by placing three 0.25 square meter quadrats across lengthwise in the middle. Within each quadrat, thirty-two point counts were taken and percent plant cover was recorded. The total point count was averaged to determine overall percent plant coverage.

Weeds. At the start of the irrigation trials (6/25/08), each green roof test plot (media only and planted plots) was weed free. Once a month throughout the irrigation trials (7/25, 8/25 and 9/25), weeds were collected from each roof. Weeds were collected and weighed wet, dried at 41 C° for 48 hours, reweighed and dried for another 24 hours and final dry weight was used to compare total weed biomass within irrigation regimes and across planted and media only plots.

Aesthetics. Three times (6/25, 8/10 and 9/25) throughout the irrigation trials, the same four volunteers visited the research site and rated each green roof plant on a scale of one to five (one being the worst and five being the best) based on each plant's aesthetic value. Ratings were based on individual perceptions of volunteers. They were recorded and averaged for a mean rating for each individual plant. Throughout this experiment, we did not prune or fertilize the plants.

Flow amounts. Irrigation amounts were calculated over the 90-day irrigation season. Ninety-day totals for an extensive rooftop were: horticultural regime = 157 l/m^2 and Portland regime = 63 l/m^2.

Data analysis. Plant performance. The influence of irrigation treatments on plant performance was evaluated using the mean relative growth rate (MRGR) of individual plants over the course of the study. MRGR was calculated as: MRGR= (logW2-logW1)/ (t1-t2), where W= size of plant in cubic centimeters, t=time (day) (South, 1995). Only those plants that survived throughout the summer were included in the analysis, therefore the number of observations at each census varied. We used a one-way ANOVA to test for the effect of irrigation regime on growth rate within each species. (*C. creticus* ssp *creticus* 'Lasithi', *D. cooperi*, *E. lanatum* var *lanatum, I. chrysophylla* and *S. spathulifolium* 'Cape Blanco'). The MRGR *for F. idahoensis* var *roemeri* and *S. spathulifolium* were log transformed to comply with the normality assumption of ANOVA. A Kruskal-Wallis test was used to analyze *S. idahoense* because the data did not meet normality assumption. A planned comparison with Tukey adjustment for multiple comparisons was used to determine differences across irrigation regimes for *D. cooperi*. *Camassia quamash* is a native summer bulb which emerges early to mid March and has its full growth period before going dormant mid to late July therefore, only survivorship is reported in this study.

Weeds. We used a two-way ANOVA to test for differences in weed biomass across irrigation regimes and across planted and media only plots within those regimes. Planned comparisons using a Tukey multiplier were used to test for differences in weed biomass between each of the irrigation regimes.

Aesthetics. Kruskal-Wallis tests were used to determine a ranking of aesthetic means for surviving plants within each irrigation regime.

Results

Plant performance. Plant species displayed varying seasonal growth patterns during the establishment phase. Throughout the first summer of establishment, *F. idahoensis* var *roemeri*, *I. chrysophylla*, *S. spathulifolium* 'Cape Blanco' and *S. idahoense* had negative MRGRs while those of *C. creticus* ssp *creticus* 'Lasithi', *D. cooperi* and *E. lanatum* var *lanatum* were positive (Table 3). During the winter months of establishment *C. creticus* ssp *creticus* 'Lasithi' and *S. spathulifolium* 'Cape Blanco' were the only two that had a positive MRGR while the remaining species had negative MRGRs (Table 3). Throughout the first spring on the green roofs all seven species had a positive MRGR (Table 3). Over the course of the establishment year *E. lanatum* var *lanatum* had the highest MRGR and *I. chrysophylla* had the lowest (Table 3).

With the exception of *S. idahoense*, all plants increased in size over the course of the first year. *Cistus creticus* ssp *creticus* 'Lasithi' and *S. spathulifolium* 'Cape Blanco' had a steady mean size for much of the establishment period, increasing in size just before the start of spring (3/10/08) (Fig 1). *Delosperma cooperi* and *E. lanatum* var *lanatum* exhibited fluctuating mean sizes with decreases in size over the winter months and increases at the start of spring growth (3/25/08) (Fig 1). *Festuca idahoensis* var *roemeri, I. chrysophylla* and *S. idahoense* declined in size after initial planting and started to increase in size in spring; *I. chrysophylla* was the latest to begin spring growth on 5/10/08 (Fig 1).

We divided the first year of establishment into three seasons to examine survivorship of species. Overall plant survival was high throughout the first year of establishment (Table 4). Exceptions were *D. cooperi,* which experienced a 25 percent decline over the winter season (9/25/07 to 3/25/08) and *E. lanatum* var *lanatum*, which lost 19 percent over the spring season (3/25/08 to 6/25/08) (Table 4).

Irrigation. Plant performance on the roofs varied across species and irrigation treatments (Table 5, Fig 2). Some but not all species exhibited significantly greater growth rates under higher irrigation.

Across the horticultural and Portland irrigation regime, MRGR of *C. creticus* ssp *creticus* 'Lasithi' was significantly greater within the horticultural regime (one-way ANOVA p=0.004; d.f=24) and there was also difference in the ranking of MRGR for *S. idahoense* between the two regimes (Kruskal Wallace; p=0.001; d.f. =1) (Table 5) with the horticultural regime having a greater ranking.

The MRGR for *D. cooperi* was significantly greater on the two irrigated regimes compared with the non-irrigated treatment (Table 5, one-way ANOVA; p=0.001; d.f. =33). Planned comparisons with a Tukey-Kramer adjustment showed that the MRGR of *D. cooperi* was significantly different between both the horticultural (p=0.027) and the Portland (p=0.001) compared to the non irrigated regimes (Table 5).

There was not a significant difference in MRGR for *S. spathulifolium* 'Cape Blanco' across all irrigation regimes (one-way ANOVA; p=0.289, d.f. =45) (Table 5). Across the horticultural and Portland irrigation regime there was no difference in MRGR for F. idahoensis (one-way ANOVA; p=0.634; d.f. =28), *E. lanatum* var *lanatum* (one-way ANOVA; p=0.404; d.f. =12) and *I. chrysophylla* (one-way ANOVA; p=0.99; d.f. =11) (Table 5). *Eriophyllum lanatum* var *lanatum* and *I. chrysophylla* had low survivorship across irrigation regimes (Table 5).

In general plant survival increased with increasing irrigation with many species not surviving at all under no irrigation (Table 5). Three notable exceptions were *C. quamash*, *D. cooperi* and *S. spathulifolium*, which had 100% survival under no irrigation (Table 5).

Weeds. Total weed biomass provided convincing evidence of an effect of both the irrigation treatment (two-way ANOVA, p=0.008, d.f. =2,15) and the planting treatment (p<0.0001, d.f. =1,15). However, the interaction between irrigation and planting treatments was not significant (p=0.157; d.f. = 2,15).

Planned comparisons indicated a significant difference in weed biomass between the horticultural and the non-irrigated regimes (p=0.006). There were not significant difference in weed biomass between the horticultural and Portland regimes (p=0.2) or the Portland and non-irrigated regimes (p=0.187). There was significantly greater weed biomass on the media only roofs relative to the planted plots and there was a convincing difference in weed biomass between the non-irrigated plots and the plots irrigated the most in the Horticultural regime (Fig 3). The non-irrigated plots had the least weed biomass over the course of the experiment (Fig 3).

Aesthetics. Aesthetic ratings proved to be very variable as rankings changed at each collection period (Table 6). *Camassia quamash* was almost completely dormant at the start of the irrigation regimes and is not included in plant aesthetic ratings. Just two weeks after initiating irrigation regimes *E. lanatum* var *lanatum* and *F. idahoensis* var *roemeri* showed signs of water stress within both Portland and non-irrigated regimes while the remaining species maintained aesthetic quality.

After one month, *C. creticus* ssp *creticus* 'Lasithi' had begun to uniformly turn brown within the non-irrigated regime. Within the Portland regime many of its leaves on terminal branch ends had turned brown, yet *C. creticus* ssp *creticus* 'Lasithi' remained green and flowered within the horticultural regime. On non-irrigated plots, *D. cooperi* shrunk in size (Fig 2) due to shriveled leaves while remaining succulent and flowering in Portland and horticultural regimes. *Eriophyllum lanatum* var *lanatum* became wilted on the non-irrigated plots and the Portland plots at one month, while it maintained some aesthetic quality on the horticultural plots. *Iris chrysophylla* had yellowing leaves with brown tips in both the Portland and non-irrigated regime and remained green within the horticultural regime. *Festuca idahoensis* var *roemeri* turned brown and fell apart from the middle on the non-irrigated plots; it was partly brown on the Portland plots and remained green on the horticultural plots. *Sedum spathulifolium* 'Cape Blanco' experienced some chlorosis within all plots at the one-month mark; on all non-irrigated plots it browned out in the center. *Sisyrinchium idahoense* had yellowing on leaves within all three regimes, with consistently more yellow with less irrigation.

Throughout the remainder of the irrigation trials, on the horticultural and Portland plots *C. creticus* ssp *creticus* ‘Lasithi’ dropped all brown leaves developed earlier and maintained relatively high survivorship (Table 4). *Cistus creticus* ssp *creticus* ‘Lasithi’, *E. lanatum* var *lanatum*, *F. idahoensis* var *roemeri*, *I. chrysophylla* and *S. idahoense* all declined in aesthetic quality and eventually died within the non irrigated regime. Overall, surviving plants within the horticultural regime had higher aesthetic means than in the Portland regime, which were higher than the non-irrigated regime respective to individual species (Table 6).

Discussion

Plant performance. Over this study plant species ultimately established well but there were differences among them in their growth patterns after being planted. Some species may have experienced transplant shock or merely exhibited their seasonal growth patterns, such as *S. idahoense* and *F. idahoensis* var *roemeri,* both of which are facultative wetland species that have mechanisms to protect against drought in seasonally dry weather.

Cold temperatures probably explain some of the growth patterns seen in *D. cooperi.* Its decrease in growth was directly related to a period of five days in which the mean low and high ambient temperatures were -8.43 °C and 2.62 °C respectively with snow. *Eriophyllum lanatum* var *lanatum* typically has resting buds throughout the winter months therefore it remained small until spring growth began.

Iris chrysophylla had difficulty becoming established, experiencing transplant shock and, in some cases, it was not planted deep enough in the media. In some cases, *Iris chrysophylla* did not fully recover from this initial decline.

Cistus creticus ssp *creticus* 'Lasithi' and *S. spathulifolium* 'Cape Blanco' did not appear to suffer from either transplant shock or winter temperatures; instead, they maintained a steady size throughout early establishment and began to grow well in the spring

It has been documented that green roof plants have a higher survival rate when supplemental irrigation is provided during establishment (Nagase and Thuring, 2006). Most of the plants evaluated had high survival rates, varying growth habits and did not increase in growth until the end of the establishment year, coinciding with spring. Maintenance during the establishment period appears to be the most important time to promote plant growth and coverage.

Plants were in good health at the start of the irrigation regimes. Planted green roof plots had an average of 83% plant cover and the plants had become integrated into the media profile. Plant cover of 80 to 85 percent commonly defines an established green roof (Snodgrass, personal communication).

Plant species responded differently to each of the irrigation regimes. Most species suffered from restricted water and this was noted at fourteen, twenty-one days and one month after initiating the irrigation regimes; their size over time reflects this observation.

The only surviving species on the non-irrigated test plots were *C quamash*, a Northwest native summer dormant bulb and the succulent species, *D. cooperi* and *S. spathulifolium* 'Cape Blanco'. Receiving just 38.1 mm of summer precipitation these species had 100 percent survivorship. These results coincide with other studies (Nagase and Thuring, 2006; Getter and Rowe, 2006) that conclude succulents are reliably able to survive with very little water.

However the aesthetic appearance of *S. spathulifolium* 'Cape Blanco' was jeopardized with less water; plants showed browning in the center and, in many cases, the center turned black. This browning out is probably a result of an incompatible interface between the nursery production media in which transplants arrived and the highly aggregate green roof media. This affect appears to be amplified with less water. Once the finer, highly organic nursery production media dries out it becomes difficult to provide adequate water to that area again. Less water is needed to saturate green roof media therefore the area that is contains nursery production media becomes inhabitable. Tom Liptan of City of Portland's Bureau of Environmental Services and Ed Snodgrass of Green Roof Plants have both noted center plant die-out to occur with green roofs plants installed in 10.16 cm square nursery containers (Portland green roof tour, August 2008). This may indicate that *S. spathulifolium* 'Cape Blanco' needs supplemental irrigation on extensive green roofs in the PNW to maintain aesthetic value if it has been planted from a nursery container.

It has been suggested that bulbs work well in non-irrigated green roofs (Snodgrass and Snodgrass, 2006). *Camassia quamash* is a PNW native bulb that grows well in moist areas and it was not necessarily expected to survive without any supplemental summer irrigation. *Camassia quamash* had 100 percent survival in all irrigation treatments. This summer dormant bulb, which emerges early to mid March, has a full growth period before going dormant mid to late July and did not need irrigation on green roofs within a 12.7 cm media profile yet, survivorship was not jeopardized by up to 133.35 mm of supplemental irrigation.

Within the Portland regime *C. creticus* ssp *creticus* 'Lasithi', *F. idahoensis* var *roemeri* and *S. idahoense* had fifty percent or better as did *C. quamash* and the succulent species. This regime provided 57.15 mm more water than did the non-irrigated regime. This regime provided 57.15 mm more water than did the non-irrigated regime. *Cistus creticus* ssp *creticus* 'Lasithi' slowly increased in size over time within this regime. However, its aesthetic value decreased as many leaves turned brown and dropped, leaving the branch ends bare. This may be a natural drought tolerance mechanism because it recovered with 73 percent survivorship within the Portland regime. In this regime, *Festuca idahoensis* var *roemeri* incurred a great deal of browning and it did not increase in size throughout the remainder of the irrigation trials. *Sisyrinchium idahoense* had the lowest survivorship and its decrease in size is attributed to its growth habit: actively growing in the spring and early summer months and essentially dormant through the later summer, autumn and early winter months. *Delosperma cooperi* maintained the highest MRGR yet its size fluctuated with summer precipitation events. Between the growth measurements on August 10th and August 25th Corvallis received 19.56 mm of summer precipitation and *D. cooperi* put on growth throughout this period and regained its succulent nature. *Sedum spathulifolium* 'Cape Blanco' had less die out in the center within the Portland regime compared to those on in non-irrigated regime.

These results suggest that when designing an extensive green roof for a climate similar to that studied here and that must comply with Portland's irrigation regime of 6.35 mm every ten days it would be best to select primarily succulents and summer dormant bulbs in high aggregate media. Though other species survived, their aesthetics were greatly compromised; they could however be considered for use on green roofs that are not visible. Overall, the native herbaceous plants evaluated are not reliable green roof plants for the Portland irrigation regime with this highly aggregate media type. These results suggest that an increase of irrigation amounts for green roofs in the PNW beyond what is allowed with the FAR bonus requirement will increase the plant palette beyond succulents and summer dormant bulbs. Tom Liptan and other members Portland's Bureau of Environmental Services Stormwater team are considering revising this irrigation requirement to allow for 12.7 mm every 10 days once the green roof is established (Liptan, personal communication).

The horticultural regime had the highest survivorship for all selected species. Again, this regime is specific to an extensive green roof media depth of 12.7 cm, primarily composed of pumice aggregate. The intent of this regime was to keep plants alive, green and aesthetic without over watering, allowing for minimal roof runoff. Finding an irrigation amount that minimizes runoff yet is applied before the green roof media dries out completely was the best means to calculate irrigation needs for maintaining plant health and increased plant performance. The installation of a rain shut-off valve on the irrigation system would increase efficiency and reduce irrigation during times with precipitation.

Under the horticultural regime most species displayed some growth, although only *C. creticus* ssp *creticus* 'Lasithi' and *D. cooperi* grew significantly more than in other irrigation treatments. *Eriophyllum lanatum* var *lanatum* and *I.*

chrysophylla had positive MRGRs as well. *Sedum spathulifolium* 'Cape Blanco' did not increase in size and *Festuca idahoensis* var *roemeri* was the only species that decreased in size under this regime.

The horticultural regime provides a guideline for the amount of irrigation necessary to satisfy plant needs in a high aggregate media of 12.7 cm. Site specific irrigation needs for an extensive green roof can be determined if those managing the water can monitor the amount of water applied until runoff occurs. This is likely a sufficient amount of irrigation for plants when media is dry to the touch. Adequate, but not extraneous irrigation amounts are not difficult to determine and result in high plant survivorship and increased aesthetics for green roof plants. This irrigation regime and method of establishing irrigation amounts is recommended for green roofs designed with native plants and other herbaceous perennials in high aggregate media.

In areas with extended cold and below freezing temperatures, *D. cooperi* is not a reliable green roof plant. Tom Liptan reported that some *D. cooperi* on Portland green roofs also died over December of 2008 (personal communication).

Weeds. Considering that weeds are often a primary part of green roof management, it is important to understand that with increased irrigation, weed species are likely to move into the bare spaces of a green roof. It was no surprise that there was a significant difference in weed biomass across irrigation regimes and between the planted and media only plots. The planned comparisons allowed us to see that the significant difference in weed biomass was between the media only plots and the planted plots within the horticultural regime. These results suggest that green roofs with good establishment and high percent plant cover have negligible differences in weed pressure relative to irrigation regime.

Aesthetics. Overall, lower irrigation amounts resulted in lower aesthetic ratings. Aesthetics are important to consider for green roofs with high visibility from other buildings or accessibility from residents. Although, there may be a regional acceptance to green roofs of lower aesthetic quality in the PNW considering that residents are accustomed to our dry summers, reflected in surrounding landscapes. Comment was made that in the Northeast region of the

United States, people have a higher standard of aesthetics for green roofs than that of the PNW (Snodgrass, personal communication).

Relative water use costs. The applied irrigation totals can be used to estimate relative water usage for each of the irrigation regimes in this study. The Portland regime water use totaled 0.69 liters for each square meter, each day. Extrapolated to the size of the Portland Building (1120 SW 5th Street, Portland, Oregon) with 1,668.4 m^2 (40.8 m X 40.8 m) a total of 105,457 liters of water used over 90 days or 1,172 liters each day. This total can then be used to estimate the monthly water bill during the irrigation season. The current cost of water in Portland, Oregon is $2.07 per unit or 2,832 liters. Therefore the Portland regime would cost an estimated $77 dollars for the entire 90-day season or $0.85 each day.

We can also estimate water costs associated with the horticultural regime although the amount applied in this case was suited for the particular plants selected with a media depth of 12.7 cm. Using the flow totals generated from this study, 0.163 liters of water a day was applied to each square meter. Again using the example of the Portland Building green roof, this would result in 2913 liters a day or a total of 262132 liters over a 90-day period. The horticultural regime would cost an estimated $192 dollars over 90 days or $2.13 each day in Portland, Oregon. Irrigating over a 90-day season in compliance to the Portland FAR bonus restriction saves the building owner $115 compared to the horticultural regime.

Conclusion

Plant performance during the establishment year was variable reflecting differences in growth form and seasonal growth patterns. *Delosperma cooperi,* which is a cold sensitive species and *I. chrysophylla,* which began to decline not long after the initial planting. When planted properly, *I. chrysophylla* may be a fine choice as an accent plant on PNW extensive green roofs yet it is not a candidate that will provide coverage.

Many sources have stated and confirm that green roofs need supplemental irrigation during establishment more than after plants have been established (Dunnett and Kingsbury, 2004; Getter and Rowe, 2006; Miller, 2003; Nagase and Thuring, 2006; Snodgrass and Snodgrass, 2006). We have found that weeds are likely to become established in bare areas of the media and increase with increasing irrigation. This study illustrates that plants may take up to a year to increase in growth (until the end of the establishment year) and our case, the end of establishment coincided with spring. Green roof managers will want to increase maintenance during the establishment period to remove aggressive weeds and promote plant coverage. Once plants establish a high percentage of cover, the effect of irrigation amounts on weed growth is negligible.

It is clear that green roof plant performance differs with varying irrigation amounts in addition to summer precipitation in the PNW. When designing an extensive green roof it is important to consider the goal of the green roof as well the needs of the client. Often the building's structural load bearing capacity will steer a green roof design and can restrict the amount of media that can be installed. If media depth must be limited and the green roof goals incorporate plants other than succulents, irrigation must be installed to maintain plant survival and increase plant performance in the PNW. In the absence of structural restrictions, the designer and client can consider a deeper media profile or one of natural soils to support a native plant palette.

We conclude that an aggregate media depth of 12.7 cm will likely not support many PNW native plants other than succulents and summer dormant bulbs unless supplemental irrigation is provided. It is also unwise to include certain native plant species while restricted by the FAR bonus irrigation regime in the Central City District of Portland, Oregon. It is important for planners to realize that irrigation restrictions also restrict plant choices, and not necessarily in favor of natives. It may be sufficient to increase the irrigation amount to 12.7 mm every ten days, which is currently being considered. Our study proves that an increase to approximately 15 mm every ten days will provide enough water for Northwest natives to survive on green roofs throughout our xeric summers.

Integrated green roof design requires a more comprehensive cost to benefit analysis for green roofs, assessing the costs associated with weeding, plant loss, and irrigation along with the benefits of biodiversity, stormwater management, energy savings or aesthetics. It is imperative that we consider the green roof design goal(s) and constraints alongside a management regime to ensure successful green roofs.

Table 1. Plant species evaluated in this study

Species	Family	USDA zones	Native range	Habitat type	Exposure	Plant type	Notes
Camassia quamash [1]	Liliaceae	3 to 8	Norhtwest: BC, CA, MT, WY, UT	grassy meadows & rocky crevices	sunny sites to part shade	perennial bulb	summer dormant; must dry out after flowering
Cistus creticus ssp. *creticus* 'Lasithi' [2]	Cistaceae	to 8	Eastern Mediterranean	degraded dense scrub	sunny & south-facing	prostate growing shrub	does not tolerate high clay or high organic matter soils
Delosperma cooperi [3]	Aizoaceae	6 to 10	southern Africa	short-grass prairies and north-facing cliffs	sun to light shade	succulent; mat-forming	salt tolerant and drought toerant
Eriophyllum lanatum var. *lanatum* [4]	Asteraceae	5 to 9	Pacific Northwest; BC to southern OR, east to MT	prairies, glacial deposits, disturbed sites	sun to light shade	mat-forming perennial	grows in locations from sea level to 11,500 ft
Festuca idahoensis var. *roemeri* [5]	Poaceae	5 to 9	fragmented populations: WA, OR, CA	prairies, serpentine sites, pine savannahs	sun	bunchgrass; facultative wetland species	part of the endangered Fender's Blue Butterfly habitat
Iris chrysophylla [6]	Iridaceae	6 to 9	WA, OR, CA	steep slopes, open areas near coniferous forests	sun to light shade	clump-forming, rhizomatous perennial	grows on Mary's Peak, 30 miles southwest of Corvallis, OR
Sedum spathulifolium 'Cape Blanco' [7]	Crassulaceae	5 to 8	Pacific Coast Ranges of CA, OR and WA	rocky cliffs & crevices; sandy, well-drained soil	sun to shade	succulent; spreads by rosettes	commonly used as a green roof plant in the PNW
Sisyrinchium idahoense [8]	Iridaceae	to 3	Central OR	sagebrush steppe communities	sun to shade	monocot; facultative wetland species	actively growing in spring and early summer months

REFERENCES: Armitage 2006[1,7]; Darris, Johnson & Bartow 2007[5]; Evans 2004[3]; Evans 1983[7]; Ewing 2002[4,5]; Fiegener et al 2004[5]; Amer Rock Garden Soc 1979[4]; Germishuizen 1982[3]; eds. Huxley, Griffiths & Levy 1992[4]; Kelaidis 2006[3]; Kohlein 1987[6]; Matthew 1981[6]; eds McGary 2001[1]; Page 2006[2]; Pettinger 1996[1]; Stephenson 1994[7]; USDA 2008[8]; eds. Warburton & Hamblen 1978[6]; Wilson 1999[5]; compiled by Wilson 2007[4]

Table 2. Summer precipitation from 6/25 to 9/25/2008 at green roof research site, Corvallis, Oregon.

Date	Rainfall (mm)
7/5	1.27
8/1	0.51
8/9	0.51
8/17	4.57
8/18	2.03
8/19	3.30
8/20	3.81
8/21	1.02
8/24	4.83
8/31	7.11
9/21	0.76
9/22	3.30
9/24	4.83
9/25	0.25
Total	38.10

Weather station installed and maintained by OSU College of Oceanic Science (http://skor.coas.oregonstate.edu/weather/netscape/weather.htm)

Table 3. Mean relative growth rate of seven species throughout establishment period 6/25/07 to 6/25/08

	6/25/07 to 9/25/07	9/25/07 to 3/25/08	3/25/08 to 6/25/08	6/25/07 to 6/25/08
	MRGR (log(g)/month)	MRGR (log(g)/month)	MRGR (log(g)/month)	Total MRGR (log(g)/month
Cistus creticus ssp. *creticus* 'Lasithi'	0.049	0.036	0.271	0.083
Delosperma cooperi	0.224	-0.251	0.640	0.091
Eriophyllum lanatam var. *lanatum*	0.458	-0.117	0.648	0.305
Festuca idahoensis var. *roemeri*	-0.038	-0.072	0.609	0.096
Iris chrysophylla	-0.090	-0.473	0.779	-0.076
Sedum spathulifolium 'Cape Blanco'	-0.006	0.050	0.301	0.110
Sisyrinchium idahoense	-0.413	-0.242	1.039	-0.011

MRGR (mean relative growth rate) is a calculated growth index (Log(END SIZE)-Log(BEGIN SIZE))/time. Scaled up to provide MRGR of 30 days. ~ MRGR of *Camassia quamash* is not included due to its seasonal growth (mid March to late July) and extended dormancy period.

Table 4. Percent survivorship of eight species throughout establishment period 6/25/07 to 6/25/08

	6/25/07 to 9/25/07	9/25/07 to 3/25/08	3/25/08 to 6/25/08	6/25/07 to 6/25/08
	Survivorship (%)	Survivorship (%)	Survivorship (%)	Total Survivorship (%)
Camassia quamash	100	100	100	100
Cistus creticus ssp. *creticus* 'Lasithi'	100	100	98	98
Delosperma cooperi	100	75	100	75
Eriophyllum lanatam var. *lanatum*	96	98	81	81
Festuca idahoensis var. *roemeri*	100	100	100	94
Iris chrysophylla	100	96	98	96
Sedum spathulifolium 'Cape Blanco'	100	100	100	100
Sisyrinchium idahoense	100	100	100	100

Table 5. Growth and survivorship of eight species across irrigation treatments

	Horticultural		Portland		Non Irrigated	
	MRGR (log(g)/month)	Survivorship (%)	MRGR (log(g)/month)	Survivorship (%)	MRGR (log(g)/month)	Survivorship (%)
Camassia quamash	~	100	~	100	~	100
Cistus creticus ssp. *creticus* 'Lasithi'	0.20 a	94	0.05 b	73	~	0
Delosperma cooperi	0.22 a	100	0.30 a	100	0.08 b	100
Eriophyllum lanatam var. *lanatum*	0.07 a	90	0.00 a	32	~	8
Festuca idahoensis var. *roemeri*	-0.03 a	100	-0.03 a	94	~	0
Iris chrysophylla	0.17 a	85	0.17 a	13	~	0
Sedum spathulifolium 'Cape Blanco'	0.00 a	100	-0.07 a	100	-0.08 a	100
Sisyrinchium idahoense	0.10 a	100	-0.06 b	88	~	0

MRGR (mean relative growth rate) is a calculated growth index (Log(END SIZE)-Log(BEGIN SIZE))/time. Scaled to provide MRGR of 30 days. ~ MRGR of species that died and *Camassia quamash* are not included due to its seasonal growth (mid March to late July) and extended dormancy period. Letters that are different across irrigation treatments within a speceis have different means using a Tukey-Kramer adjustment for a planned comparison.

Survivorship in percent survival from 6/25/08 to 9/25/08.

Table 6. Aesthetic ranking and means for surviving plants within each irrigation treatment. Aesthetic ranks are ordered with 1 = poor and 5 = excellent.

	Aesthetic ratings 6/25		Aesthetic ratings 8/10		Aesthetic ratings 9/25	
Species and irrigation regime	Rank	Means	Rank	Means	Rank	Means
Horticultural regime						
Festuca idahoensis var *roemeri*	1	4.69	3	2.76	1	3.11
Sedum spathulifolium 'Cape Blanco'	2	4.61	5	2.52	5	2.46
Sisyrinchium idahoense	3	4.55	1	3.02	4	2.56
Delosperma cooperi	4	4.26	2	2.84	2	2.76
Cistus creticus ssp *creticus* 'Lasithi'	5	3.77	4	2.56	3	2.67
Portland regime						
Sedum spathulifolium 'Cape Blanco'	1	4.52	4	1.69	4	1.64
Cistus creticus ssp *creticus* 'Lasithi'	2	4.16	3	1.83	3	2.15
Festuca idahoensis var *roemeri*	3	4.13	2	2.00	1	2.82
Delosperma cooperi	4	3.19	1	2.18	2	2.78
Non irrigated regime						
Sedum spathulifolium 'Cape Blanco'	1	4.25	1	1.41	2	1.44
Delosperma cooperi	2	3.97	2	1.26	1	2.26

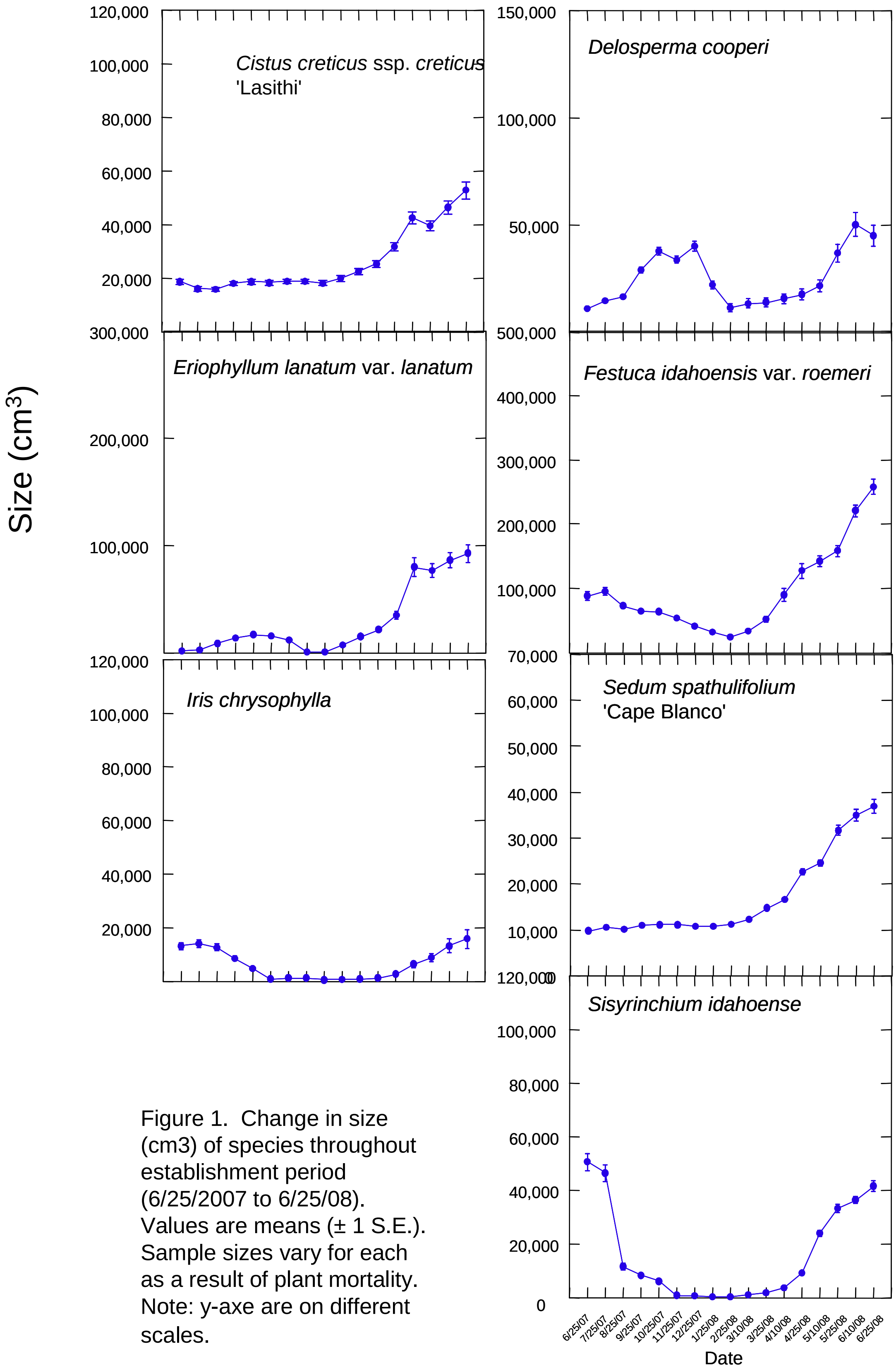

Figure 1. Change in size (cm3) of species throughout establishment period (6/25/2007 to 6/25/08). Values are means (± 1 S.E.). Sample sizes vary for each as a result of plant mortality. Note: y-axe are on different scales.

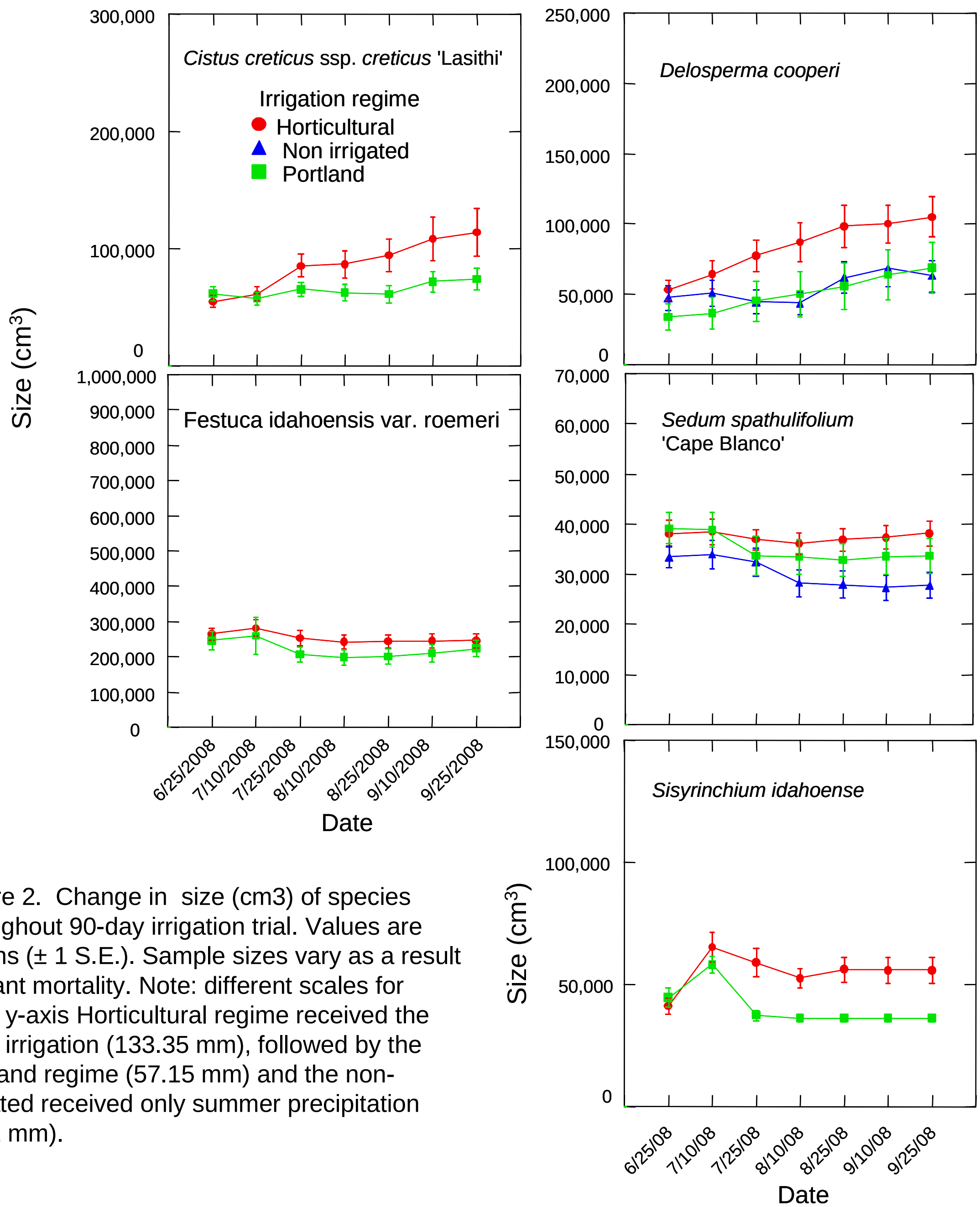

Figure 2. Change in size (cm3) of species throughout 90-day irrigation trial. Values are means (± 1 S.E.). Sample sizes vary as a result of plant mortality. Note: different scales for each y-axis Horticultural regime received the most irrigation (133.35 mm), followed by the Portland regime (57.15 mm) and the non-irrigated received only summer precipitation (38.1 mm).

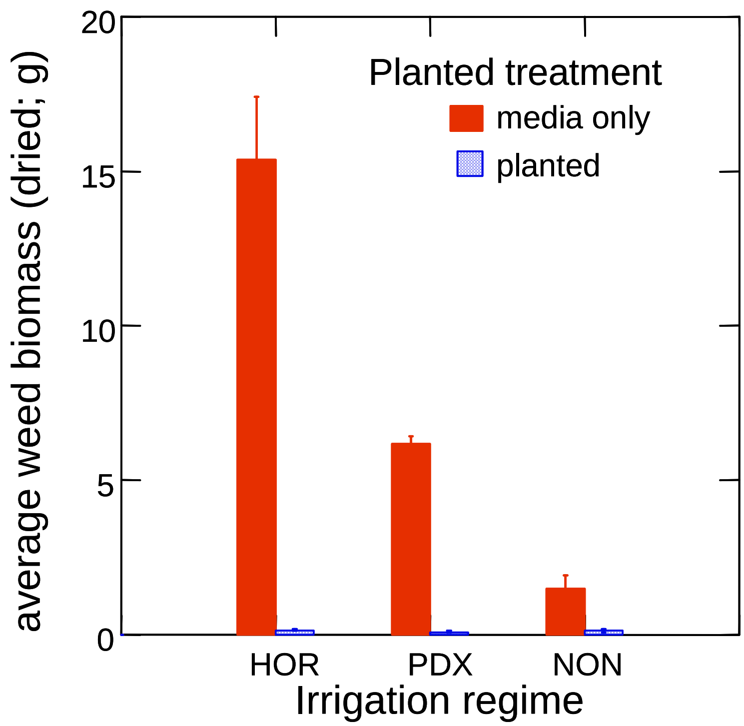

Figure 3. Total dry weight of weed biomass (g) collected from planted and media only plots three times throughout irrigation trails (7/25, 8/25 & 9/25/08). Values are means (± 1 S.E.); n=21. (Irrigation regimes: HOR= horticultural; PDX= Portland; NON= non-irrigated). All planted plots had less than 0.1 grams of dry weed biomass. Over the summer irrigation trials there was convincing evidence of an effect of both the irrigation treatment (two-way ANOVA, p=0.008, d.f.=2,15) and the planting treatment (p<0.001, d.f.=1,15) on total weed biomass. The interaction between irrigation and planting treatment was not significant (p=0.157; d.f.=2,15).

Literature Cited

Amer. Rock Garden Plant Conf. 1976. Alpines of the americas. The American Rock Garden Society: NW Chapter and the Alpine Garden Club. British Columbia and Settle.

Armitage, A.M. 2006. Armitage's native plants for north american gardens. 1st ed. Timber Press, Portland, Ore.

Brenneisen, S. 2006. Space for urban wildlife: designing green roofs as habitats in switzerland. Urban Habitats. 5:27-36.

Darris, D., S. Johnson, A. Bartow. 2007. Roemer's fescue plant fact sheet. USDA, NRCS Plant Materials Center. Corvallis, Ore.

Dunnett, N. and N. Kingsbury. 2004. Planting green roofs and living walls. 1st ed. Timber Press, Portland, Ore.

Evans, E. 2004. Plant Fact Sheets, NC State University. 8/21/2007. http://www.ces.ncsu.edu/depts/hort/consumer/factsheets/groundcover/delosperma_cooperi.html.

Evans, R.L. 1983. Handbook of cultivated sedums. 1st ed. Northwood, Middlesex, Science Reviews.

Ewing, K. 2002-1. Effects of initial site treatments on early growth and three-year survival of idaho fescue. Restoration Ecol. 10:282-288.

Ewing, K. 2002-2. Mounding as a technique for restoration of prairie on a capped landfill in the puget sound lowlands. Restoration Ecol. 10:289-296

Fiegener, R., B.L. Wilson, D. Darris, R. Johnson, K. Kuykendall. 2007. Festuca roemeri common garden study. Institute for Applied Ecology. Corvallis, Ore.

Germishuizen, G. 1982. Transvaal wild flowers. 1st ed. MacMillan, Johannesburg, South Africa.

Getter, K.L. and D.B. Rowe. 2006. The role of extensive green roofs in sustainable development. HortSci. 41(5): 1276-1285.

Hale, Cadee. 2009. Oregon Climate Service, Oregon State University. 12 January 2009. < http://www.ocs.oregonstate.edu>.

Huxley, A., M. Griffiths, M. Levy, eds. 1992. The New Royal Horticultural Society of Gardening. 1st ed. The Stockton Press, New York.

Kelaidis, P. 2006. Ice plant on skis. Cactus and Succulent J. 78:190-194.

Köhlein, F. 1987. Iris. 1st ed. Timber Press, Portland, Ore.

Kozloff, E.N. 1976. Plants and animals of the pacific northwest. 1st ed. University of Washington Press, Seattle.

Mattew, B. 1981. The iris. 1st ed. Universe Books, New York.

McGary, J., ed. 2001. Bulbs of north america. 1st ed. Timber Press, Portland, Ore.

Miller, C. 2003. Moisture management in green roofs. Proc. Greening Rooftops for Sustainable Communities, Chicago, Ill.

Monterusso, M.A., D.B. Rowe, C.L. Rugh and D.K. Russell. 2004. Runoff water quantity and quality from green roof systems. Acta Hort. (ISHS) 639:369-376.

Mosquin, D. 2006. Botany photo of the day: eriophyllum lanatum var. lanatum. 12 Sept 2007. http://www.ubcbotanicalgarden.org/potd/2006/02/eriophyllum_lanatum.php.

Page, R. G. 2006. The cistus and halimium website. http://www.cistuspage.org.uk/. Rawdon, Leeds, West Yorkshire, England.

Pettinger, A. 1996. Native plants in the coastal garden. 1st ed. Whitecap Books. Vancouver, B.C.

Scholz-Barth, K. 2001. Green roofs: stormwater management from the top down. Environmental Design and Construction. Tremco Consultant Ser. Bul.

Simmons, M.T., B. Gardiner, S. Windhager and J. Tinsley. 2008. Green roofs are not created equal: the hydrologic and thermal performance of six different extensive green roofs and reflective and non-reflective roofs in a sub-tropical climate. Urban Ecosystems. 11:335-337.

Snodgrass, E.C. and L.L. Snodgrass. 2006. Green roof plants: a resource and planting guide. 1st ed. Timber Press, Portland, Ore.

South, D.B., 1995. Relative growth rates: a critique. South African For. J. 173:23-26.

Stephenson, R. 1994. Sedum: cultivated stonecrops. 1st ed. Timber Press, Portland, Ore.

Tallamy, D. 2007. Bringing Nature Home. 1st ed. Timber Press, Portland, Ore.

USDA, NRCS. 2008. The plants database. National Plant Data Center. Baton Rouge, La. http://plants.usda.gov/. 26 Jan 2008.

Warburton, B. and M. Hamblen, eds. 1978. The world of iris. 1st ed. Publisher's Press, Salt Lake City.

Wilson, B. L. 1999. Fescue taxonomy in the pacific coast states. Oregon State University. Corvallis, Ore.

Wilson, M. V., compiler. 2007. Willamette valley prairie plant trait database. Department of Botany and Plant Pathology, Oregon State University. Corvallis, Ore.

Chapter 4

Stormwater Management of Northwest Extensive Green Roofs

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Abstract

For ten years or more, urban planners, architects, horticulturalists, engineers and stormwater specialists have been exploring the use of extensive green roofs in North America to mitigate stormwater. Many cities in North America such as Portland, Oregon require extensive green roofs or an alternative management tool such as bioswales and rain gardens to direct urban runoff away from combined stormwater and sewage systems.

Despite considerable research documenting the stormwater mitigation benefits of green roofs, almost no research has investigated the degree to which the vegetative component influences this important function. The design of the vegetative portion of an extensive green roof is often driven by non-functional criteria such as the structural load of a building or the availability of local products and materials such as media and plants. For instance, typical designs consist of lightweight, high aggregate media planted with *Sedum* species and other succulents, mostly because these components are widely available and are known to work well together. A more explicit understanding of the functional roles of vegetation and media will help us better optimize green roof efficiency.

This study assessed the contribution of the vegetative component of green roofs to stormwater mitigation using replicated extensive green roof test plots in the Pacific Northwest (PNW). We compared patterns of stormwater runoff and retention for plots containing only media and plots planted with a suite of vascular plants. Results varied depending on storm characteristics and perhaps other factors related to plant performance such as season and age of green roof. However, overall results indicated an effect of vegetation on the percent of roof runoff retained.

Planted green roofs retained 45 percent of the total runoff from rainfall collected within this study while media only roofs retained 40.5 percent supporting our hypothesis that vegetation can enhance efficiency of stormwater management.

Water quality was not the focus of this study; however, periodic water samples were analyzed. High phosphorus levels occurred in green roof runoff ranging from 8.67 to 31 mg in total runoff from planted prototypes. In runoff from planted prototypes, concentrations of total Kjehldahl nitrogen, total phosphorus, total suspended solids, alkalinity and conductivity were all high at the start of the experiment, most of which leveled out in the last three water quality samples. We address a question that green roofers ask; should we divert the first flush?

Introduction

North America's traditional building practices in the urban environment and increased development are causes of stream and watershed degradation (Carter and Rasmussen, 2006; Richards, 2006; Scholz-Barth, 2001). Impervious surfaces such as roofs, roads, and sidewalks prevent stormwater from natural soil infiltration and increase pollutant concentrations and flow rates into receiving bodies of water relative to those observed (Carter and Rasmussen, 2006; Scholz-Barth, 2001). Federal, state and local governmental agencies often require developers to mitigate these adverse effects by using stormwater Best Management Practices (BMP) (Carter and Rasmussen, 2006). Stormwater BMPs are systems designed to allow for infiltration, detain water before releasing it, or retain it all together (Carter and Rasmussen, 2006). In highly urbanized environments, impervious surface cover exceeds 50 percent of the total urban area and there is little area available for BMPs that utilize land, such as bioswales or bioretention ponds (Carter and Rasmussen, 2006; Monterusso, et al., 2004; Scholz-Barth, 2001).

Until recently, urban developers in the United States had completely overlooked using roof space as a tool for stormwater management (Carter and Rasmussen, 2006). A significant benefit and one of the most desirable traits of a green roof is the ability to mitigate stormwater (Long, et al., 2006; Monterusso, et al., 2004; Scholz-Barth, 2001, Simmons, 2008). Green roofs do not require additional land and replace an impervious surface with a vegetative layer that has its ability to filter, retain, detain and mitigate peak flow in a stormwater event (Carter and Rasmussen, 2006; Scholz-Barth, 2001). The type and depth of substrate, saturation level of substrate, the type of vegetation and the slope of the roof are all factors in a green roof's stormwater management efficiency (Monterusso, et al., 2004; Liu, 2005; Scholz-Barth, 2001). Across, and even within regions of North America, green roof design and performance varies (Simmons, et al., 2008).

To date, most research on stormwater mitigation functions of green roofs has been conducted in the Midwestern, Mid-Atlantic and Eastern States (Carter and Rasmussen, 2006; Monterusso et al., 2004; Hutchinson et al, 2003). At the University of Georgia, retention of individual storm events ranged from 39 to 100 percent, with retention decreasing as the precipitation amount increased (Carter and Rasmussen, 2006; Liu and Minor, 2005). At the Penn State Center for Green Roof Research, researchers estimate that green roofs can retain 55 percent of the annual average rainfall for Pennsylvania (Long, et al., 2006). Average stormwater retention was 49 percent at Michigan State University and 57 percent on the Eastview Neighborhood Community Centre in Toronto (Liu and Minor, 2005; Monterusso et al., 2004). Portland's Bureau of Environmental Services (BES) found that Hamilton West Apartment Building green roof in Portland, Oregon had retained 69 percent of the runoff averaged over the first 2 yrs of the green roof (Hutchinson et al., 2003).

As the green roof industry develops worldwide, researchers, engineers and green roof designers are investigating ways to maximize achieving the goal of stormwater management. Minimal research has asked explicitly how vegetation contributes to stormwater retention. Some report no difference in runoff retention between vegetated and non-vegetated green roofs (VanWoert et al., 2005; Monterusso et al., 2004). At University of Michigan, media only plots were compared to vegetated plots with six different *Sedum* species (VanWoert et al., 2005). The vegetative effect on runoff retention from this study may have been muted by either the plant selection or the fact that 40 percent of the substrate was retention mat added to increase water retention (VanWoert et al., 2005).

At Michigan State University an experiment primarily designed to compare four different commercial green roof systems with different media depths as well as different drainage layers did not provide statistically different results (Monterusso et al., 2004). When investigating the effect of vegetation on stormwater runoff, comparisons were made between three planted mixes (seven *Sedum* species, two sedum species and 18 Michigan native species) without comparing vegetation to a media only control (Monterusso et al., 2004).

Recently however, Dunnett, et al. (2008) found that green roofs planted to different vegetation types did not behave in the same way in terms of managing runoff under simulated rainfall in controlled conditions. Grasses performed better than herbaceous perennials, which performed better than *Sedum* species (Dunnett, et al., 2008). Thus, plant selection for increasing stormwater management efficiency is not a matter of simply increasing plant diversity, rather explicitly selecting plants based on their tested performance at retaining stormwater.

Rainfall patterns in most of the previously mentioned study areas do not match the Mediterranean climate of the PNW where most rainfall occurs from November through March. In the Willamette Valley the total rainfall averages range from 914.4 to 1168.4 mm; the driest months are typically June through September, with less than 12.7 mm of rainfall often occurring during July (Hale, 2009).

Considering the weather pattern in the PNW, green roofs must be able to manage stormwater during seasons with low plant transpiration and while some species are dormant. Plants that are actively growing during the rainy season, such as facultative wetland species, are potential stormwater mitigation choices for the PNW. In addition, the summer dry climate of the PNW often necessitates irrigation to maintain vegetative health and cover. Because of this, water conservation measures that limit irrigation could potentially influence plant selection and the stormwater function of green roofs.

In this study, we tested the degree to which the vegetative component of a green roof provided stormwater function in a climate typical of the Pacific

Northwestern U.S. We test vegetation composed of selected PNW native plants that are active during the spring and fall months, drought tolerant PNW natives, a drought tolerant non-native shrub, and succulents commonly used in the green roof industry. We compared stormwater retention between test roofs that were planted or media only during many natural and one simulated rain event. In addition, we tested whether different irrigation management practices during the summer months influence stormwater performance. While not a primary focus of this study, we also monitored quality concentrations of total phosphorus (TP) (mg/l), total Kjehldahl nitrogen (TKN) (mg/l), conductivity (uS/cm), total suspended solids (TSS) (mg/l), alkalinity (mg/l) in the runoff from planted roofs and liner only controls.

Methods and Materials

Site description. Twenty-four 1.2 m X 2.4 m green roof prototypes were constructed at a height of 1.98 m at the OSU Oak Creek Center for Urban Horticulture in Corvallis, OR (latitude 44° 30'N, 123° 17'W, elevation 71 m). Each prototype was lined with a single-ply 0.045-mm thermal polyolefin (TPO) thermoplastic waterproof membrane (Firestone Building Products Indianapolis, Indiana) loose-laid with heat-welded seams. Each prototype had a uniform, lengthwise 2% slope. Twenty-one roofs were outfitted with a 6.35 mm thick standard drainage mat with a geocomposite fabric bonded to one side, placed up to provide a filter fabric between media and drainage layer (Tremco, Ashland, Ohio). Twelve were planted and nine contained only media.

Extensive green roof media (PRO-GRO Mixes Inc, Tualatin, Oregon) was uniformly applied to prototypes at a 12.7 cm depth. Green roof media is primarily comprised of screened pumice (0.16 to 0.95 cm), with minor percentages of Fiber Life Compost (byproduct of an anaerobic digestive process) and paper fiber (clean cellulose based byproduct). This extensive green roof media has an estimated field moisture capacity of 732 kg/m^3, estimated saturated bulk density of 1017 kg/m^3 and an estimated weight of 546 kg/m^3 when received on site. This green roof media was selected to due its local availability and current use in the PNW green roof industry.

Rainfall and weather data were collected on-site by a weather station installed and maintained by Oregon State University's College of Oceanic Sciences (46 m from green roof test plots). Every 24 hrs, readings were provided for rainfall, temperature, time of high and low temperature, time, and speed of highest wind gust and percent sunlight. (http://skor.coas.oregonstate.edu/weather/netscape/weather.htm). Throughout the study year, the study site received 1035.4 mm (103.54 cm) of precipitation, only 38.1 mm of which fell form July through September.

Vegetation composition. On 25 July 2007, twelve prototypes were planted with the following eight species: *Camassia quamash, Cistus creticus* ssp *creticus* 'Lasithi', *Delosperma cooperi*, *Eriophyllum lanatum* var *lanatum, Festuca idahoensis* var *roemeri*, *Iris chrysophylla*, *Sedum spathulifolium* 'Cape Blanco', *Sisyrinchium idahoense* (Table 1*)*. Plants were purchased in 10.16 cm square nursery pots from Oregon, Washington and British Columbia growers.

Irrigation. Irrigation to the green roof test plots was supplied via short-radius (1.21 m) nozzles with head to head coverage set to an ACC controller (Hunter, San Marcos, California). Nine can tests (cans were placed on test roofs to collect and measure irrigation amount applied) were conducted and averaged to determine that irrigation heads are consistently applying 6.63 cm per hour at 1.76 kgf/cm^2 kilograms –force per cm^2. All planted prototypes were irrigated uniformly throughout the first summer (25 July 2007 to 25 September 2007), receiving 2.18 mm everyday between the morning hours of 0400 and 0500.

In year two, on 25 June 2008, three irrigation treatments were initiated and randomly assigned to green roof test plots over a 90 day study period: i) Horticultural regime: irrigated according to our decision, using roof runoff from planted roofs as a diagnostic tool. Plants received 133.35 mm applied every two days (2.97 mm) in addition to summer moisture ii) Portland regime: irrigated in compliance with requirements of Floor Area Ratio Bonus awarded by BES, City of Portland, Oregon, totaling 57.15 mm applied every 5 days (3.175 mm) in addition to summer precipitation and iii) Non irrigated regime, plants received 38.1 mm of summer precipitation. Irrigation was consistently applied between the morning hours of four and five.

Stormwater management. Each roof was outfitted with a 189.27 l vertical collection tank (JTI Supply, Albany, Oregon; originating company: Norwesco of St. Bonifacius, MN). Runoff volumes were measured after rain events during dry periods to determine stormwater retention of the three roof conditions (planted, media only, and liner only).

Runoff enters the collection tank through a custom-made 10.16 x 15.24 cm metal scupper (Anderson Roofing, Salem, OR) centered on the lower end of the 2 percent slope. A Rainwater Downspout Filter (SPEC-ALL Products, Austin Texas; originating from Nest Construction Pty Ltd Australia) is modified to directly fit the scupper end and a TPO lid is heat welded onto each roof, fitting tight over the downspout filter to prevent extraneous water form entering the tank.

The bottom center of each tank is fitted with a poly bolted “Bottom Drain” tank flange (part no. BF075BD 1.9 X 2.54 cm Threaded Flange EPDM; Banjo Liquid Handling Products, Crawfordsville, IN) and a 1.9 cm ball valve allows for collection. Water is collected in a 4000 ml container (Nalgene, Rochester, N.Y.).

Stormwater runoff volume was measured for a series of natural rainfall events from 11 November 2007 to 29 November 2008. During each event we collected total runoff leaving the roof from the start of precipitation up to 4 - 6 hrs after precipitation ceased. Defining the beginning and end of rainfall events can be difficult, particularly in the PNW where rainfall of varying intensity span several days and includes dry intervals of varying length (Liptan and Murase, 2000). We determined that some of our individual collections were in fact part of a single longer rain event and should be grouped as such. We retrospectively grouped our initial list of recorded events using the following grouping criteria: (1) at least 12 hrs of zero precipitation prior to closing ball valves and initiating rainfall collection and (2) commenced in a period of dry weather approximately 4 - 6 hrs after event. Grouping resulted in 18 individual rain events that varied in duration from 2-13 days (Tables 2-3). Prior to summer irrigation treatments, one simulated rainfall event was performed (June 25, 2008) to saturate green roofs and these runoff data are included (Table 2).

Stormwater collection events were categorized based on total volume over a rainfall period: small < 12.7 mm, medium = 12.7 to 25.4 mm and large > than 25.4 mm.

Eighty-one percent of storm events in Portland, Oregon are less than 25.4 mm (Liptan and Murase, 2000). We grouped rainfall events with totals of 25.4 mm and less (small and medium sized events) separately from large events over 25.4 mm to analyze retention totals for 81 percent of the storms that occur in Portland.

To calculate mean runoff retention of green roofs, liner only controls were assumed to retain four percent of the runoff, based on data from a literature review of German green roofs (Mentens, et al., in 2005). Conventional non-living roofs with a slope of 2 percent allowed 96 percent of rainfall to run off (Mentens, et al., 2005).

The runoff totals from liner only controls were used to determine percent runoff retained by media only and planted green roof test plots. Four percent was added to mean runoff totals of liner only roofs and this total was divided by the amount of runoff from each of the media only and planted green roofs to provide percent runoff. That final value was then divided by 100 to provide percent of runoff retained.

As a baseline measurement, gravimetric moisture content for all planted and media only plots was determined prior to the first two rainfall collections (November and December 2007). Gravimetric moisture content of the media was determined again prior to the simulated irrigation event on 25 June 2008.

Water quality. Water quality samples were collected throughout the experiment and analyzed by Central Analytical Lab (Oregon State University, Corvallis, Oregon). Concentrations of TP (mg/l), TKN (mg/l), conductivity (uS/cm), TSS (mg/l), alkalinity (mg/l) and pH were reported for runoff from planted roofs in the first two collections (25 June 2007 and 20 Jan 2008) and reported for planted roofs and liner only controls for the remaining three collections (10 April 2008, 24 June 2008 and 29 November 2008).

Statistical analysis. Using Kruskal-Wallis tests because data did not fit the normality assumption, we tested for differences in mean gravimetric moisture content between media only and planted plots for the first two rainfall events (November and December 2007) and for the June irrigation event.

Pre-irrigation storm events were grouped with rainfall totals that were less than 25.4 mm and all rain events that totaled more than 25.4 mm in rainfall. Within each we tested for differences in percent retention among media only and planted roof treatments using one-way ANOVA. Two-sample t test with Bonferroni correction were used to test for differences in percent retention between media only and planted roofs for each individual rain event. After the start of summer irrigation we tested for differences in percent runoff retention between planted and media only plots within each of the irrigation treatments using one and two-sample t-tests and Kruskal Wallis test was used when the normality assumption could not be met. In some cases a test was not performed due to lack of variation between treatments.

To estimate the chronic release of total nutrients from the planted and liner only roofs, nutrient concentration in runoff were multiplied by the total amount of runoff collected over the last three collection dates. Either a one-way ANOVA or Kruskal-Wallis analysis was used to determine the difference in mean total concentration of nutrients (TKN and TP), conductivity, TSS and alkalinity ($CaCO_3$) between planted roofs and liner only controls.

Results

Baseline data analysis proved that there was no difference in mean gravimetric moisture content between media only plots and planted plots for the first collection event in November (Kruskal-Wallis; p=0.076) and again prior to the December collection (Kruskal-Wallis; p=0.201).

Over this 1-yr study, runoff data were collected from rainfall events totaling 286.26 mm. The bulk of the stormwater runoff was collected from November 2007 through April 2008. The rainfall patterns were typical for the PNW. Rainfall was recorded every 24 hr with precipitation amounts ranging from 0.254 to 46.5 mm while collected amounts ranged from 0.254 to 25.15 mm within a 24-hr period. Total precipitation within a collection event ranged from 0.752 mm to 65.79 mm (Table 2, Table 3).

Across all rainfall volumes, seasons and irrigation regimes, roof treatment had a significant effect on total percent stormwater retained (one-way ANOVA; $p < 0.001$; d.f. = 2, 21). On average the planted roofs retained 45 percent of the total rainfall runoff collected while media only retained 40.5 percent.

However, the effect of vegetation on stormwater retention was highly variable across individual rain events (Table 2). There was no significant difference in retention rates between planted and media only roofs during five small rain events from January to April. In four of these events both planted and media only roofs retained one hundred percent of the rainfall (Table 2). However, vegetated roofs did retain more runoff (63%) than media only roofs (57%) during one small rain event on March 7th (two-sample t-test; $p = 0.007$) (Table 2).

Three of the recorded rain events were medium in size. The first occurred from 8 to 12 November 2007 during which planted roofs had a greater mean runoff retention than that of media only roofs (two-sample t-test; $p < 0.001$) (Table 2). Within the other medium rainfall events, media only roofs and planted roofs were not statistically different in mean runoff retention either in March (two-sample t-test; $p = 0.082$) or in early April (two-sample t-test; $p = 0.108$).

Three large rainfall events were collected. The first one, in December 2007 had the least amount of runoff retained by green roofs, yet planted roofs (8%) and media only roofs (7%) were different (two-sample t-test; $p = 0.044$) (Table 2). In the spring of 2008, a rainfall period occurring over 13 days totaled 61.976 mm and provided no evidence of a difference between ranking of mean runoff retention of media only and planted roofs (two-sample t-test; $p = 0.315$) (Table 2). However, the last large rainfall period occurred in April, during which 41.402 mm of rain was collected. Planted only roofs had a higher percent of mean runoff retention compared to media only roofs (two-sample t-test; $p = 0.001$).

When combining the total amount of runoff retained from all collection events of less than 25.4 mm of rainfall, planted roof roofs had the same mean retention of 65.6 percent as media only roofs (one-way ANOVA; $p = 0.984$; d.f.=1,19)(Fig 1). Similarly when large rainfall events were grouped, media only and planted roofs did not differ in retention (one-way ANOVA; p 0.435; d.f.=1,19)(Fig 1).

Prior to the irrigation event on 25 June 2008, the mean rankings of gravimetric moisture content of the planted roofs (43%) and media only roofs (47%) differed (Kruskal-Wallis; $p=0.013$).

For the June irrigated event, all plots, which provided 13.1 mm of water and after four hours had passed runoff, was collected. Planted roofs had a mean retention of 75 percent that was statistically different from media only plots that has a mean runoff retention of 60 percent (one-way ANOVA; $p < 0.001$; d.f.=1,19)(Table 2).

There was no consistent effect of irrigation treatment on stormwater retention during the five rain events that occurred after the start of the irrigation treatments (Table 3). Irrigation regimes ran from 25 June 2008 to 25 September 2008. In the summer, two small rainfall events were collected and each had a high mean percent retention of runoff (Table 3). Overall, planted roofs had a higher mean retention than media only roofs across all three irrigation treatments, but not all differences were statistically significant (Table 3).

In autumn, two small rainfall events and one large rainfall event were collected (Table 3). Aside from the last event in which all green roofs retained 100 percent of the precipitation, the planted roofs had higher mean retention than the media only roofs within each irrigation regime (Table 3). In the large rainfall event collected on October 9th, the planted plots had a greater mean retention of runoff than media only plots within each irrigation regime: non-irrigated regime (Kruskal-Wallis $p=0.034$); Portland regime (two sample t-test $p=0.002$) and horticultural regime (Kruskal-Wallis $p=0.034$) (Table 3).

Water quality. Periodically collected water samples from planted plots throughout the experiment showed than the mean concentration for TP, TKN, TSS, alkalinity, and conductivity declined dramatically from initial values (6/25/2007) and appeared to plateau over the remaining three collections (Figure 3).

When concentrations were multiplied by total runoff, there was no significant difference in TKN released by planted roofs relative to the liner only controls over all three collection periods (Table 4). In contrast, planted roofs released consistently more TP than liner only roofs over the sample periods (Table 4). Differences in runoff quality between planted and liner only roofs were more variable over collection dates for other parameters (Table 4).

Discussion

Overall, these results support our hypothesis that green roof vegetation has an impact on stormwater management efficiency. When combining all runoff collections, we found that planted green roofs had higher mean runoff retention of 45 percent over media only (40.5%) and planted roofs had a higher mean retention in nine of the ten significantly different ($\alpha < 0.05$) comparisons made throughout this study.

This mean runoff retention of vegetated green roofs was lower than reported in other studies including the Hamilton Building apartment green roof, which retained an average of 69 percent of annual rainfall in Portland, Oregon over its first two years. Other outdoor studies also reported higher average retention rates of 55 and 49 percent (Long et al., 2006; Monterusso et al., 2004).

Compared to previously mentioned studies, we report a broader range in overall mean retention (7 to 100 percent). However, in year one of the Hamilton Building green roof, mean runoff retention across January to March was 20 percent (Hutchinson et al., 2003). This pattern was not repeated in the second year; instead an average of 53 percent of the runoff was retained during that timeframe with similar climatic conditions (Hutchinson et al., 2003). The Hamilton Building green roof study showed seasonal variation in runoff retention and suggests that green roofs may have increased stormwater mitigation efficiency with age.

The greatest differences in runoff retention between planted and media only plots occurred in early fall, late spring and summer. During and after the summer irrigation treatments were initiated on test plots, the planted green roofs had a mean retention range of 64 to 100 percent while media only roofs had a mean retention range of 38 to 100 percent compared within their respective irrigation regimes (Table 3). These data are in agreement with the retention range of 39 to 100 percent, reported by the University of Georgia (Carter and Rasmussen, 2006; Hutchinson et al., 2003).

Overall, vegetation tended to decrease runoff compared to media only roofs, however there was variability in this effect during individual rain events throughout the seasons. How effective green roofs are at retaining stormwater depends on the size and intensity of the storm, the saturation level of the media, climatic conditions and age of the roof (Carter and Rasmussen, 2006; Hutchinson et al., 2003; Getter and Rowe, 2006; Monterusso, 2006). Whether it is due to plants' size and structure (Dunnett et al., 2008) or to active water uptake and transpiration by plants planted roofs retained significantly more mean runoff from than did media only roofs.

These data suggest that seasonal plant growth may have an effect on stormwater runoff retention, although further research is needed for conclusive evidence. It is difficult to tease seasonal plant growth apart from the variables in climatic conditions of a green roof field study. A climate controlled green house bioassay may help determine what effect growth patterns of certain species have on stormwater management of green roofs. In the PNW, potential green roof plants may include mosses, bulbs and facultative wetland plants, which are all active much of the autumn, winter and spring.

Continued assessment of regionally suited plant species must occur to select a plant palette proficient at retaining stormwater in a variety of conditions focused on when retention is needed most. Studies of individual species (e.g. Dunnett et al., 2008) will provide better understanding of how individual plant species (monocultures) and explicit plant matrices contribute to stormwater management.

Plant species with high transpiration rates may be able to optimize a green roofs' ability to reduce ambient air temperatures (Wolf and Lunholm, 2008). Increased water loss is because high plant transpiration rates can cause increased water use, species with high transpiration rates may also be good candidates for stormwater retention compared to species with low transpiration rates (Wolf and Lunholm, 2008). *Sedum* species seemed to be particularly good at retaining water (Wolf and Lunholm, 2008).

Quantifying green roof efficiency of stormwater management is not merely based on the amount of water that is retained. Green roofs are able to retain and detain runoff past the peak of the storm, both of which can minimize stress for stormwater systems.

Our study design makes it impossible to address some important questions about green roof stormwater mitigation potential. Continuous data collection of runoff from test plots would increase our understanding of how green roofs mitigate peak flow in the PNW. Despite low retention in seasons with relatively high rainfall, the peak of stormwater runoff can be delayed (Carter and Rasmussen, 2006; Simmons et al., 2008). This peak delay may be a critical green roof function to help decentralize runoff into stormwater systems.

Even in regions with seasonal rainfall, green roofs are functioning well at retaining stormwater. In Portland, Oregon 81 percent of the rainfall events are less than 25.4 mm (Liptan and Murase, 2000). Any storm event that exceeds 2.54 cm in depth causes CSOs (Tom Liptan, personal communication). If Portland green roofs are able to retain 66 percent of the runoff from these storm events each year, they could have a positive impact on reducing combined sewage overflows into the Willamette River.

To ensure that we promote an efficient BMP, investigations need to be made into the runoff quality of typical green roof media. In the planted plots, there was a clear drop in the mean concentrations of TP, TKN, TSS, conductivity and alkalinity between the first flush of runoff and the second collection. Concentration fluctuations leveled out over the last three water quality collections. TKN and other forms of N decreased with time (Moran, 2004). P and orthophosphate (OP) differed from P and OP which both increased in runoff over several weeks when media was saturated (Moran, 2004).

Green roofers often ask if the first flush of runoff should be diverted, knowing that runoff from a newly planted green roof would naturally be highest in nutrient concentrations from organic matter. Diverting the first flush is not widely practiced, likely due to the logistics of collecting runoff from tall commercial buildings that are directly tied into the stormwater systems.

Nitrogen does not appear to be a problem yet phosphorus levels remain a problem throughout the sampling. However, high levels of P in green roof runoff may be a result of the media saturation (Moran, 2004). Phosphorus anions can become reduced in saturated soils and released with added precipitation (Moran, 2004). During seasons in which transpiration is low and rainfall is high, green roofs will remain fairly saturated. This may be a problem in regions such as the PNW when seasonal rains often occur intermittently and sometimes continuously over six to nine months a year.

Liner only roofs release a large amount of potential pollutants considering the amount of runoff that is released from these control roofs (Table 4). Due to the fact that the planted green roofs have a significantly greater mean percent runoff retention, similarities are found between liner only controls and planted green roofs (Table 4).

Conclusion

Our study supports Dunnett et al. (2008) in that stormwater management can be improved with vegetation as plants likely intercept rainfall in a number of ways: within the plant canopy, plant uptake and storage and through evapotranspiration. Trends in current literature suggest that matching regional plants in the context of stormwater mitigation will increase this functional green roof goal. Our study suggests that planted roofs retain more stormwater than media only roofs, although, the differential was influenced by temperature, rainfall amount and intensity as well as the saturation level of the media prior to rain.

We found a wide range of mean runoff retention throughout the study period over several different types of rain events observed. Within light rainfall events, media only and planted roofs retained 100 percent of the rainfall, whereas in a period of plant dormancy and high levels of media saturation, roofs retained only 7 to 8 percent. Retention variability was exhibited yet, there appeared to be a seasonal trend, planted roofs retained a higher mean percent runoff, up to 15 percent more than media only roofs.

Optimizing the extensive green roof goal of stormwater management can be facilitated by isolating regional plants—in the case of the PNW, those that are active from October through May—to decipher how seasonal growth patterns can increase this functional goal and which plants are the most efficient stormwater managers.

Our study also supports the suggestion that the first flush from green roof runoff should be diverted to prevent high concentrations of nutrients (TKN and TP), TSS and alkalinity ($CaCO_3$) from entering into systems and potentially into waters downstream. Along with investigation into regional plant species in effort to maximize green roof goals such a stormwater management, research into runoff concentrations from green roof media must also be explored.

Table 1. Plant Species selected

Species	Family	Native range	Plant type
Camassia quamash [1]	Liliaceae	Norhtwest: BC, CA, MT, WY, UT	summer dormant bulb
Cistus creticus ssp. *creticus* 'Lasithi' [2]	Cistaceae	Eastern Mediterranean	prostate growing shrub
Delosperma cooperi [3]	Aizoaceae	South Africa	succulent; mat-forming
Eriophyllum lanatum var. *lanatum* [4]	Asteraceae	PNW; BC to southern OR, east to MT	mat-forming perennial
Festuca idahoensis var. *roemeri* [5]	Poaceae	fragmented ares: WA, OR, CA	bunchgrass; facultative wetland species
Iris chrysophylla [6]	Iridaceae	WA, OR, CA	rhizomatous perennial
Sedum spathulifolium 'Cape Blanco' [7]	Crassulaceae	Pacific Coast Ranges of CA, OR and WA	succulent; spreads by rosettes
Sisyrinchium idahoense [8]	Iridaceae	Central OR	monocot; facultative wetland species

REFERENCES: Armitage 2006[1,7]; Darris, Johnson & Bartow 2007[5]; Evans 2004[3]; Evans 1983[7]; Ewing 2002[4,5]; Fiegener et al 2004[5]; Amer Rock Garden Soc 1979[4]; Germishuizen 1982[3]; eds. Huxley, Griffiths & Levy 1992[4]; Kelaidis 2006[3]; Köhlein 1987[6]; Matthew 1981[6]; eds McGary 2001[1]; Page 2006[2]; Pettinger 1996[1]; Stephenson 1994[7]; USDA 2008[8]; eds. Warburton & Hamblen 1978[6]; Wilson 1999[5]; compiled by Wilson 2007[4]

Table 2. Comparison of mean runoff retention during sampled rainfall events between media only(MO) (n=9) and planted treatments (PL) (n=12). Collection events were categorized based on amount of rainfall: small < 12.7 mm, medium = 12.7 to 25.4 mm and large > 25.4 mm.

Collection	Date	Rainfall total (mm)	Categorical size	Duration (days)	Pre-dry (days)	Season	Treatment	Retention (%)	p-value
							MO	51	
1	11/12/2007	19.05	medium	5	2	Autumn	PL	59	< 0.001
							MO	7	
2	12/21/2007	65.79	large	10	3	Winter	PL	8	0.044
							MO	21	
4*	1/19/2008	0.76	small	3	0	Winter	PL	18	0.825
							MO	98	
5	2/13/2008	1.78	small	2	2	Winter	PL	98	0.684
							MO	100	
6	2/20/2008	1.52	small	2	5	Winter	PL	100	na
							MO	100	
7	2/25/2008	1.78	small	3	2	Winter	PL	100	na
							MO	80	
8	3/4/2008	12.70	medium	4	2	Winter	PL	77	0.082
							MO	63	
9	3/7/2008	6.86	small	1	2	Winter	PL	57	0.007
							MO	31	
10	3/24/2008	61.98	large	13	2	Spring	PL	28	0.315
							MO	78	
11	4/9/2008	17.53	medium	6	3	Spring	PL	76	0.108
							MO	100	
12	4/15/2008	1.52	small	2	4	Spring	PL	100	na
							MO	39	
13	4/24/2008	41.40	large	6	3	Spring	PL	44	0.001
							MO	60	
14**	6/25/2008	13.10	irrigation	1	2	Summer	PL	75	< 0.001

Two sample t-test; Bonferroni correction

* Two events were combined due to continued runoff from media only plots from one event to the next.

** Simulated irrigation event at the initiation of summer irrigaiton treatments.

na ~ There was no variation between media only and planted treatments; no test performed.

Table 3. Comparison of mean runoff retention between media only (MO) (n=3) and planted (PL) (n=4) treatments within irrigation treatments.

Collect	Date	Rainfall total (mm)	Categorical size	Duration (days)	Pre-dry days	Season	IRR TMT	Retention (%) Media only	Planted	p-value
							NON	87	100	0.023 †
							PDX	76	100	0.086 †
14	08/21/08	7.87	small	3	0	Summer	HOR	70	99	0.025 †
							NON	100	99	0.178 ††
							PDX	95	99	0.480 *
15	08/24/08	3.81	small	1	2	Summer	HOR	83	100	0.019 †
							NON	99	100	0.074 ††
							PDX	97	100	0.408 †
16	09/25/08	5.08	small	2	1	Autumn	HOR	75	98	0.107 †
							NON	54	76	0.034 *
							PDX	43	67	0.002 †
17	10/09/08	28.96	large	6	4	Autumn	HOR	38	64	0.034 *
							NON	100	100	na
							PDX	100	100	na
18	10/21/08	3.05	small	3	8	Autumn	HOR	100	100	na

† Two sample t-test

†† One sample t-test

* Kruskal Wallis

na~ There was no variation between media only and planted; no test performed.

Table 4. Comparison of runoff: water quality parameters between planted green roofs (PL) and liner only controls (LO) for three collection periods. These are the total amount leached (runoff concentration X total volume of runoff).

	Rain event			Irrigation events					
	Collection 3; 4/10/2008			Collection 4; 6/24/2008			Collection 5; 11/29/2008		
	LO	PL	p-value	LO	PL	p-value	LO	PL	p-value
Total phosphorus mg	1.56	26.79	0.050 *	4.03	8.67	0.180 *	0.38	30.94	0.008
Total Kjehldahl nitrogen mg	16.34	25.65	0.490	2.42	10.29	0.148	0.02	24.61	0.124
Conductivity uS/cm	464.72	3315.78	0.050 *	1883.70	909.39	0.271	1988.56	2415.50	0.356
Total suspended solids mg	774.14	3895.33	0.050 *	2771.50	2220.94	0.390	1323.92	2553.16	0.078
Alkalinity $CaCO^3$ mg	139.72	1813.15	0.050 *	442.75	160.36	0.180 *	572.18	934.81	0.028
pH	6.8	9	0.050 *	7.6	7.6	0.655 *	7.3	7.7	0.180 *

One-way ANOVA

* Kruskal-Wallis

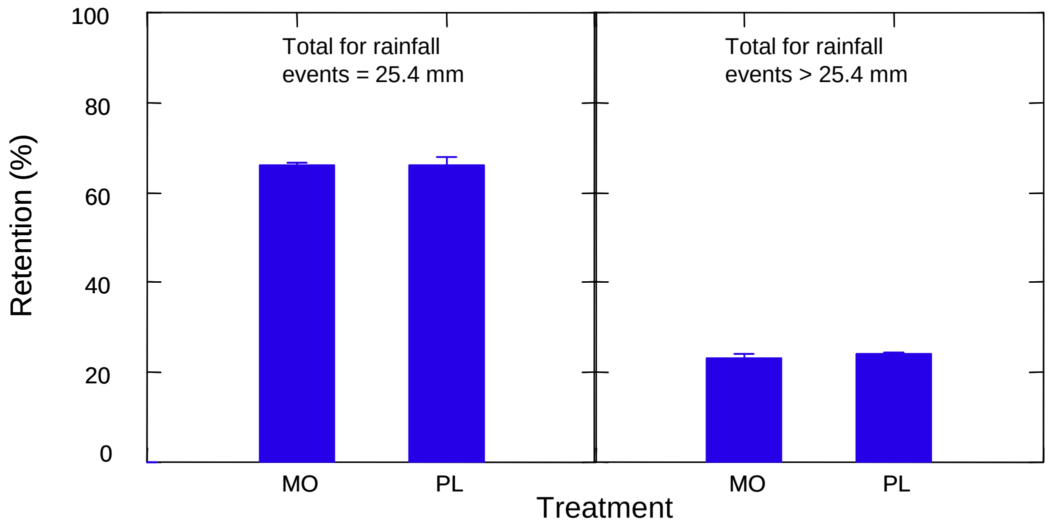
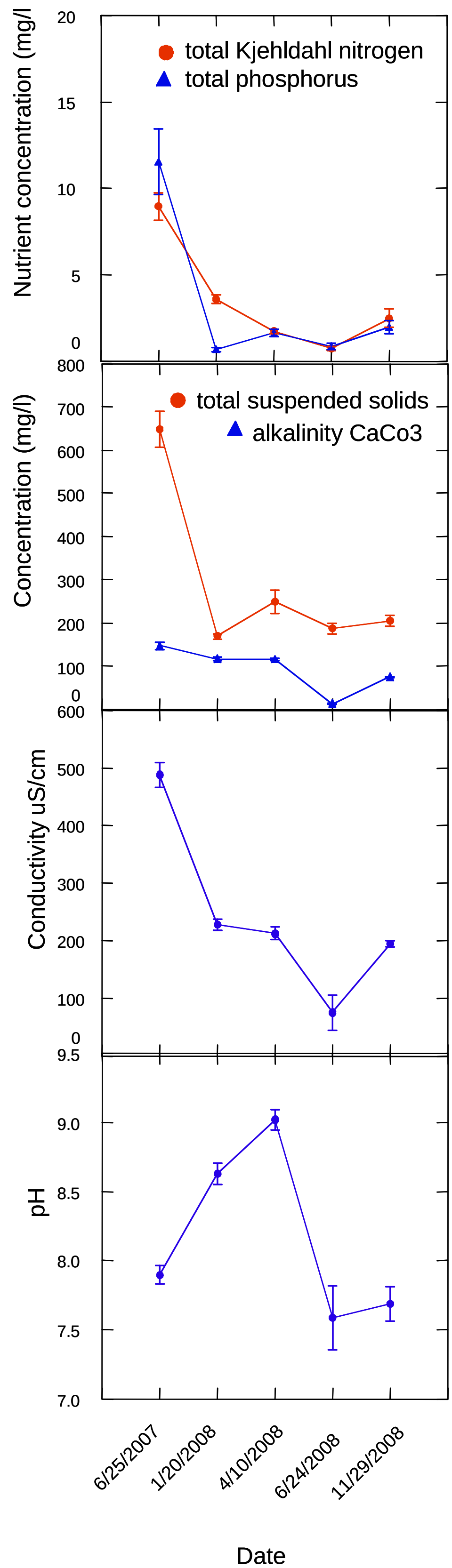


Figure 1. Comparison of percent retention across two roof treatments within grouped rainfall events; total for all rainfall events that are equal to or less than 25.4 mm in depth (one-way ANOVA; p=0.984; d.f.=1,19) and total for all rainfall events that are greater than 25.4 mm in size (one-way ANOVA; p=0.435; d.f.=1,19). Values are treatment means (± 1 S.E.); MO= media only (n=9) and PL= planted (n=12).

Figure 2. Water quality parameters of runoff from planted roofs over the course of the study (green roofs were not fertilized). Values are means (± 1 S.E.) Sample size for the first two collections was 6 and for the last three it was 3. Note: y-axis are different scales. The first collection (6/25/2007) corresponds with planting day and is the first flush of runoff.



Literature Cited

Berndtsson, J.C., T. Emilsson and L. Bengtsson. 2005. The influence of extensive vegetated roofs on runoff water quality. Sci. of the Total Environ. 355:48-63.

Carter, T.L. and C.R. Jackson. 2006. Vegetated roofs for stormwater management at multiple spatial scales. Landscape and Urban Planning. 80:84-94.

Carter, T.L. and T.C. Rasmussen. 2006. Hydrologic behavior of vegetated roofs. J. Amer. Water Resources Assn. 42:1261-1274.

Dunnett, N., A. Nagase, R. Booth and P. Grime. 2008. Influence of vegetation composition on runoff in two similar green roof experiments. Urban Ecosystems. 11:385-398.

Getter, K.L. and D.B. Rowe. 2006. The role of extensive green roofs in sustainable development. HortSci. 41(5): 1276-1285.

Hale, Cadee. 2009. Oregon Climate Service, Oregon State University. 12 January 2009. < http://www.ocs.oregonstate.edu>.

Hutchinson, D., P. Abrams, R. Retzlaff, and T. Liptan. 2003. Stormwater monitoring two ecoroofs in portland, oregon, u.s.a. Proc. Greening Rooftops for Sustainable Communities.

Liptan, T. and R.K. Murase. 2000. Watergardens as stormwater infrastructure in portland, oregon. Water Sensitive Ecol. Planning and Design Symp. Harvard Design School, Cambridge Mass., 25-26 Feb. 2000.

Liu, K. and J. Minor. 2005. Performance evaluation of an extensive green roof. Proc. Greening Rooftops for Sustainable Communities, Washington D.C.

Long, B., S.E. Clark, K.H. Baker and R. Berghage. 2006. Green roof media selection for the minimization of pollutant loadings in roof runoff. Penn State Harrisburg. Water Environ. Foundation.

Metens, J., D. Raes and M. Hermy. 2005. Green roofs as a tool for solving the rainwater runoff problem in the urbanized 21st century? Landscape and Urban Planning. 77:217-226.

Moran, A. 2004. A north carolina field study to evaluate greenroof runoff quantity, runoff quality, and plant growth. N.C. State Univ., Raleigh, MS Diss.

Monterusso, M.A., D.B. Rowe, C.L. Rugh and D.K. Russell. 2004. Runoff water quantity and quality from green roof systems. Acta Hort. (ISHS) 639:369-376.

Richards, L. 2006. Water and the density debate. Planning magazine, APA. June 2006.

Scholz-Barth, K. 2001. Green roofs: stormwater management from the top down. Environmental Design and Construction. Tremco Consultant Ser. Bul.

Simmons, M.T., B. Gardiner, S. Windhager and J. Tinsley. 2008. Green roofs are not created equal: the hydrologic and thermal performance of six different extensive green roofs and reflective and non-reflective roofs in a sub-tropical climate. Urban Ecosystems. 11:335-337.

VanWoert, N.D., D.B. Rowe, J.A. Andresen, C.L. Rugh, R.T. Fernandez and L. Xiao. 2005. Green roof stormwater retention: effects of roof surface, slope and media depth. J. Environ. Qual. 34:1036-1044.

Wolf, D. and J.T. Lundholm. 2008. Water uptake in green roof microcosms: effects of plant species and water availability. Ecol. Eng. 33:179-186.

Chapter 5

General Conclusion

Green roof designers and managers can reduce maintenance, save money, increase plant aesthetics and maximize green roof goals when tailoring green roof design to the regional climates and rooftop microclimates in respect to plant selection and maintenance. Researchers have started investigating ways to increase green roof efficiency in terms of stormwater management and reduction of ambient air temperatures. There is no one recipe for extensive green roofs due to the vast differences in climate across North America and distinct needs within the built environment.

A critical phase of an extensive green roof is establishment, in which irrigation needs are highest and weeds are most likely to move into bare spaces. Once the green roof was established with 80 to 85 percent plant coverage, weeds were minimal regardless of irrigation amounts in our PNW setting.

In areas with extended dry periods, such as PNW summers, irrigation is necessary to broaden extensive green roof plant palettes beyond succulents and summer dormant bulbs and to maintain plant aesthetics. In the years subsequent to establishment, irrigation requirements are rather low for extensive green roofs. Selected native plants to the PNW reliably survived with 171.45 mm of water throughout a 90-day period or ~14 mm of water each week. Understanding irrigation needs for the plants selected can help minimize water use and reduce costs.

The ability of green roofs to mitigate stormwater may depend not only on seasonal climate and media saturation but also on the seasonal growth of selected plants. Vegetative roofs generally retained more stormwater runoff than media only roofs, with a trend toward statistical differences during times of increased plant growth and lower precipitation. It is difficult to tease the effects of seasonal growth patterns from climatic variables. Further research is necessary to fully understand how plant species and plant matrices contribute to mitigating stormwater.

Water quality of green roof runoff is a concern during the initial stages of a green roof's life and green roof managers should devise a way to divert the first runoff from green roofs. Because phosphorous is a concern in green roof runoff, researching how to minimize such nutrient leaching will be important for continued extensive green roof development.

Designing for increased functionality of extensive green roofs requires a clear understanding regional climatic differences and plant needs. We need to continue to explore new ways to create efficient green roofs for each region of North America, tailored to its primary functional goal of course.

Bibliography

Amer. Rock Garden Plant Conf. 1976. Alpines of the americas. The American Rock Garden Society: NW Chapter and the Alpine Garden Club. British Columbia and Settle.

Armitage, A.M. 2006. Armitage's native plants for north american gardens. 1st ed. Timber Press, Portland, Ore.

Berndtsson, J.C., T. Emilsson and L. Bengtsson. 2005. The influence of extensive vegetated roofs on runoff water quality. Sci. of the Total Environ. 355:48-63.

Brenneisen, S. 2006. Space for urban wildlife: designing green roofs as habitats in switzerland. Urban Habitats. 5:27-36.

Carter, T.L. and C.R. Jackson. 2006. Vegetated roofs for stormwater management at multiple spatial scales. Landscape and Urban Planning. 80:84-94.

Carter, T.L. and T.C. Rasmussen. 2006. Hydrologic behavior of vegetated roofs. J. Amer. Water Resources Assn. 42:1261-1274.

Darris, D., S. Johnson, A. Bartow. 2007. Roemer's fescue plant fact sheet. USDA, NRCS Plant Materials Center. Corvallis, Ore.

Dunnett, N., A. Nagase, R. Booth and P. Grime. 2008. Influence of vegetation composition on runoff in two similar green roof experiments. Urban Ecosystems. 11:385-398.

Evans, E. 2004. Plant Fact Sheets, NC State University. 8/21/2007. http://www.ces.ncsu.edu/depts/hort/consumer/factsheets/groundcover/delosperma_cooperi.html.

Evans, R.L. 1983. Handbook of cultivated sedums. 1st ed. Northwood, Middlesex, Science Reviews.

Ewing, K. 2002-1. Effects of initial site treatments on early growth and three-year survival of idaho fescue. Restoration Ecol. 10:282-288.

Ewing, K. 2002-2. Mounding as a technique for restoration of prairie on a capped landfill in the puget sound lowlands. Restoration Ecol. 10:289-296

Fiegener, R., B.L. Wilson, D. Darris, R. Johnson, K. Kuykendall. 2007. Festuca roemeri common garden study. Institute for Applied Ecology. Corvallis, Ore.

FLL: Guideline for the Planning, Execution and Upkeep of Green-Roof Sites. 2002. Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau E.V. 4th ed. Bonn, Germany.

Germishuizen, G. 1982. Transvaal wild flowers. 1st ed. MacMillan, Johannesburg, South Africa.

Getter, K.L. and D.B. Rowe. 2006. The role of extensive green roofs in sustainable development. HortSci. 41(5): 1276-1285.

Green Roofs for Healthy Cities. 2007. Green roof infrastructure: design and installation 201. Green Roofs for Healthy Cities, Toronto, ON.

Green Roofs for Healthy Cities. 2008. Green roof plants and growing medium 401. Green Roofs for Healthy Cities, Toronto, ON.

Hale, Cadee. 2009. Oregon Climate Service, Oregon State University. 12 January 2009. < http://www.ocs.oregonstate.edu>.

Hutchinson, D., P. Abrams, R. Retzlaff, and T. Liptan. 2003. Stormwater monitoring two ecoroofs in portland, oregon, u.s.a. Proc. Greening Rooftops for Sustainable Communities.

Huxley, A., M. Griffiths, M. Levy, eds. 1992. The New Royal Horticultural Society of Gardening. 1st ed. The Stockton Press, New York.

Kelaidis, P. 2006. Ice plant on skis. Cactus and Succulent J. 78:190-194.

Köhlein, F. 1987. Iris. 1st ed. Timber Press, Portland, Ore.

Kozloff, E.N. 1976. Plants and animals of the pacific northwest. 1st ed. University of Washington Press, Seattle.

Liptan, T. and R.K. Murase. 2000. Watergardens as stormwater infrastructure in portland, oregon. Water Sensitive Ecol. Planning and Design Symp. Harvard Design School, Cambridge Mass., 25-26 Feb. 2000.

Liu, K. and J. Minor. 2005. Performance evaluation of an extensive green roof. Proc. Greening Rooftops for Sustainable Communities, Washington D.C.

Long, B., S.E. Clark, K.H. Baker and R. Berghage. 2006. Green roof media selection for the minimization of pollutant loadings in roof runoff. Penn State Harrisburg. Water Environ. Foundation.

Mattew, B. 1981. The iris. 1st ed. Universe Books, New York.

McGary, J., ed. 2001. Bulbs of north america. 1st ed. Timber Press, Portland, Ore.

Metens, J., D. Raes and M. Hermy. 2005. Green roofs as a tool for solving the rainwater runoff problem in the urbanized 21st century? Landscape and Urban Planning. 77:217-226.

Miller, C. 2003. Moisture management in green roofs. Proc. Greening Rooftops for Sustainable Communities, Chicago, Ill.

Monterusso, M.A., D.B. Rowe, C.L. Rugh and D.K. Russell. 2004. Runoff water quantity and quality from green roof systems. Acta Hort. (ISHS) 639:369-376.

Moran, A. 2004. A north carolina field study to evaluate greenroof runoff quantity, runoff quality, and plant growth. N.C. State Univ., Raleigh, MS Diss.

Mosquin, D. 2006. Botany photo of the day: eriophyllum lanatum var. lanatum. 12 Sept 2007. <http://www.ubcbotanicalgarden.org/potd/2006/02/eriophyllum_lanatum.php>

Nagase, A. and C. Thuring. 2006. Plant responses to drought on extensive green roofs: the effects of temperature, substrate type and substrate depth. Proc. Fourth Annual Greening Rooftops for Sustainable Communities Conference. Boston, 11-12 May 2006.

Page, R. G. 2006. The cistus and halimium website. http://www.cistuspage.org.uk/. Rawdon, Leeds, West Yorkshire, England.

Pettinger, A. 1996. Native plants in the coastal garden. 1st ed. Whitecap Books. Vancouver, B.C.

Richards, L. 2006. Water and the density debate. Planning magazine, APA. June 2006.

Scholz-Barth, K. 2001. Green roofs: stormwater management from the top down. Environmental Design and Construction. Tremco Consultant Ser. Bul.

Schroll, E. J. Lambrinos and D. Sandrock. 2009. Irrigation requirements and plant survival on northwest green roofs. Proc. Seventh Annual Greening Rooftops for Sustainable Communities, Atlanta, Ga. 3-5 June 2009.

Simmons, M.T., B. Gardiner, S. Windhager and J. Tinsley. 2008. Green roofs are not created equal: the hydrologic and thermal performance of six different extensive green roofs and reflective and non-reflective roofs in a sub-tropical climate. Urban Ecosystems. 11:335-337.

Snodgrass, E.C. and L.L. Snodgrass. 2006. Green roof plants: a resource and planting guide. 1st ed. Timber Press, Portland, Ore.

South, D.B., 1995. Relative growth rates: a critique. South African For. J. 173:23-26.

Stephenson, R. 1994. Sedum: cultivated stonecrops. 1st ed. Timber Press, Portland, Ore.

Tallamy, D. 2007. Bringing Nature Home. 1st ed. Timber Press, Portland, Ore.

USDA, NRCS. 2008. The plants database. National Plant Data Center. Baton Rouge, La. http://plants.usda.gov/. 26 Jan 2008.

VanWoert, N.D., D.B. Rowe, J.A. Andresen, C.L. Rugh, R.T. Fernandez and L. Xiao. 2005. Green roof stormwater retention: effects of roof surface, slope and media depth. J. Environ. Qual. 34:1036-1044.

Warburton, B. and M. Hamblen, eds. 1978. The world of iris. 1st ed. Publisher's Press, Salt Lake City.

Werthmann, C. 2007. Greener green roofs. Architecture Week. 12 May 2009. <http://www.architectureweek.com/2007/1107/environment_1-1.html>

Wilson, B. L. 1999. Fescue taxonomy in the pacific coast states. Oregon State University. Corvallis, Ore.

Wilson, M. V., compiler. 2007. Willamette valley prairie plant trait database. Department of Botany and Plant Pathology, Oregon State University. Corvallis, Ore.

Wolf, D. and J.T. Lundholm. 2008. Water uptake in green roof microcosms: effects of plant species and water availability. Ecological Engineering. 33:179-186.