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EVALUATION OF CRASSULACEAN SPECIES FOR EXTENSIVE GREEN ROOF APPLICATIONS

By

Angela Keri Durhman

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ABSTRACT

EVALUATION OF CRASSULACEAN SPECIES FOR EXTENSIVE GREEN ROOF APPLICATIONS

By
Angela Keri Durhman

Green roofs are an emerging technology in the United States that alleviate several environmental problems. Because environmental conditions are often more extreme on rooftops, many xerophytic plants are ideal for extensive green roofs. However, limited studies have been performed to determine the characteristics necessary to sustain plant life for green roof applications in the Michigan region. Therefore, a greenhouse experiment determined the effect of watering regime on plant stress for succulent and non-CAM plants. Results indicate even after the four month period, *Sedum* spp. were able to survive and maintain active photosynthetic metabolism, relative to the non-CAM species. Two field studies performed over 16 months on simulated roofing platforms evaluated 25 Crassulacean species. For both field studies, overwintering survival was dramatic, as only 47% survived in the deepest substrate of 7.5 cm. Results indicated deeper substrates promoted greater survival, growth, and faster coverage, however, in the shallowest depth of 2.5 cm, several species continued to persist. Relative abundance was highest for *Phedimus spurius* Raf. 'Leningrad White,' *Sedum acre* L., *S. album* 'Bella d'Inverno' L., and *S. middendorffianum* L. Subsidiary species included *S. hispanicum* diploid L., *S. kamtschaticum* Fisch., *S. sediforme* J., *S. spurium* Bieb. 'Summer Glory,' *S. dasyphyllum* 'Burnati' L., and *S. reflexum* L.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Figure | Page

CHAPTER ONE

CHAPTER TWO

CHAPTER THREE

A LITERATURE REVIEW

Evaluation of Crassulacean Species for Extensive Green Roof Applications

The next time you depart from an airplane at a municipal airport, look down at the landscape as you ascend into the sky. More than likely, the view will be filled with impervious surfaces created by roads, parking lots, buildings, and tar roofs. As you leave the city, the landscape changes towards more vegetation provided by forests, agricultural crops, and grasses. Now imagine the two landscapes merging into one. Vegetation growing on impervious surfaces. Vegetation growing on roofs. This literature review provides details regarding green roof applications, suggests how green roofs serve as a solution for environmentally sustainable designs for the urban environment, and describes what plant species are ideal candidates for extensive green roof systems.

History of Vegetative Green Roofs

The broadest description of a vegetative green roof is growing plants on rooftops. Green roofs, also referred to as eco-roofs, living roofs, vegetative roofs, or roof gardens, date back to ancient Mesopotamia from the fourth millennium through 600 B.C. The Hanging Gardens of Babylon, one of the Seven Wonders of the World, was constructed to reproduce mountain scenery (Osmundson, 1999). Ancient roof gardens are no longer in existence because the buildings have crumbled. However, more recently built gardens, such as the Tower of Guinigis in Lucca, Italy (built around 1660), can still be visited.

Green roof construction continued sporadically throughout the ages and across the Old World, for purposes such as entertaining guests, appeasing architectural demands by religious sectors, and revolting against local political rule. Roof gardens of the past were not only designed for aesthetics, but were also constructed to lessen environmental extremes. In the mid-to-late 1800's, sod roofs were added improve home insulation and prolong longevity of building materials by reducing wind and water erosion. In Scandinavia, turf grass, birch bark, and straw were considered inexpensive yet well functioning building material (Dunnett and Kingsbury, 2004). Vegetative roofs were popular throughout Europe and to the settlers among the Great Plains of North America (Osmundson, 1999).

Since the 1960s, green roofs have experienced a resurgence. To date, they are most prevalent in Germany, where 14% of flat roofs have been developed with green roofs (Herman, 2003). In the last decade, this number has grown three percent, increasing the total area to 13,500,000 m^2 of roofscape. It is uncertain how much green space occupies roofs in the United States, although American installations in have increased over the past few years. As demand for green space in cities and commercial areas increases, manufacturing facilities, hotels, residential complexes, hospitals, city halls, and other urban buildings, are incorporating green roofs to their infrastructure. Vegetative rooftops are not limited to flat roof buildings, but can also thrive on steeper sloped roofs like those seen on residential homes.

Benefits of a Green Roof

The numerous benefits that green roofs provide have helped to fuel their resurgence in industrial and urban settings. There are many environmental and economical benefits that can be realized such as stormwater retention, energy conservation, reduction in the urban heat island effect, increased longevity of the roofing membrane, the ability of plants to create biodiversity and filter air contaminants, and beautification of the surroundings by incorporating green space on previously barren sites (Dunnet and Kingsbury, 2004).

Conventional roof systems do not retain a significant amount of stormwater. Most stormwater quickly flows off the roof and enters municipal stormwater or sewer systems, often resulting in overflow and wastewater contaminants that are released into the environment (Thompson, 1998; Hunt et al., 2004). For this reason, stormwater management strategies (minimizing and retaining stormwater runoff during rain events) are often high priorities for city planners. Depending on vegetation type, substrate components and depth, and roof slope, a green roof system can slow the runoff from rooftops and spread stormwater runoff over a longer period of time by retaining as much as 60 to 100% of the rainwater (VanWoert, 2005; Hunt et al., 2004). In a study conducted in Michigan on roof platforms, VanWoert (2005) reported that in evaluated combined rain events, 87% retention occurred on platforms at a 2% slope with 4 cm media depth, and 84% retention on platforms at a 6.5% slope with 4 cm media depth.

Building heating and cooling costs can be reduced by roof vegetation because green roofs insulate and minimize temperature extremes. Green roofs protect the roof components from solar radiation thus reducing heat flux into the building during the summer, and insulate in the winter (Niachou et al., 2001). Stein (1990) reported that vegetative roofs decreased the inner air temperature of buildings by 5°C. Another study correlated a 50% reduction in heat flux into a room with a 30°C decrease of surface temperature on a roof slab (Onmura et al., 2001). Savings in energy costs are dependent on the regional climates and may be enough to pay for the extra cost of a green roof system over a certain number of years (Niachou et al., 2001).

The urban heat island effect is a phenomena facing many urban areas developed cities experience temperatures 20-30 °C higher temperatures than agricultural land in the surrounding areas (Liu, 2004; Peck et al., 1999). Liu (2004) compared differences in ambient air temperature above a conventional roof and a vegetative roof. As the ambient summer temperature exceeded 30°C on 10% of the days over the 22 month study, the reference roof exceeded 30°C over 50% of the days, whereas the green roof exceeded over 30°C only 3% of the days (Liu, 2004). Differences in temperature can be correlated to the plant's lower albedo and their ability to cool the surrounding air around plant leaves via evapotranspiration (Eumorfopooulou and Arvantinos, 1998; Lükenga and Wessels, 2001).

Vegetation also increases the lifespan of the roof membrane compared to a conventional roof. A green roof will last at least twice as long as a conventional green roof (Osmundson, 1999). Constant daily expansion and contraction of the roof membrane due to temperature extremes on a conventional roof ultimately leads to material failure. Vegetated roofs protect materials from UV radiation and are not exposed to extreme temperature fluctuations, subsequently extending their lifetime (Dimoundi and Nikolopoulou, 2003; Lükenga and Wessels, 2001; Liu, 2004).

Green roofs also have the potential to improve air quality. Minke and Witter (1983) calculated that a 1.5 m^2 grass surface produces enough oxygen for one human for one year. Liesecke and Borgwardt (1997) reported that green roofs filtered diesel and gasoline exhaust. A green roof system may absorb heavy metals, some of which may be taken up by the plant and used in growth processes. Additionally, urban dust and particulate matter can be retained on green roofs and filtered through during a rain event (Lükenga and Wessels, 2001).

Providing green space in urban areas supports greater ecological biodiversity. For example, residents in West Berlin, Germany, claim to see species of birds that were not present prior to the installation of green roofs in the neighborhood (Darius and Drepper, 1984). A recent evaluation on a 90-year-old naturalized roof meadow in Switzerland documented 175 plant species, including nine rare orchid species (Brenneisen, 2003). In London, biodiversity studies showed that an increase in substrate depth and plant structure increased species diversity, primarily for invertebrate communities (Gedge and Kadas, 2004). Additionally, green roofs in urban communities can be designed and planted to target specific wildlife for habitat mitigation (Gedge and Kadas, 2004). City parks and gardens, plant medians between roads and sidewalks, and plant other barren sites. Since land values are quite high and undeveloped land is rare in large cities, increasing biodiversity by placing vegetation on rooftops provides an alternative to planting at ground level.

Incorporating green space into the human built environment restores nature in urban and industrial settings. In general, plants have a positive influence on human well-being, so it is assumed that visible green roofs would also provide those benefits (Relf and Lohr, 2003). In industrialized nations, we spend up to 90% of our lives in buildings (Halliday, 1997), so why not make them more desirable to work and live? Views of a living roof are more aesthetically pleasing than conventional roofing systems. Because of this, offices and residential units overlooking a green roof can have a higher resale and economic value to urban areas (Osmundson, 1999). In Montreal, Canada, the Hilton Hotel constructed a rooftop garden in 1967. Since then, they have had a higher than average occupancy rate at 70%, compared to local hotels around 63% (Kongshaug and Bhatt, 2004).

Sustainability as a Goal for Environmental Management

Sustainable urban development and smart growth have gained more attention by urban planners in recent years (De Sousa, 2002), and installing green roofs answers the "green technology" demand to urban and industrial development by providing attractive benefits to those areas. Sustainable design is a very flexible concept, and is therefore defined using an array of terms and practices across environmental, economic, and social disciplines. Sustainability could be simply defined as creating lasting communities (Halliday, 1997). ASTM

International defines sustainability as "the maintenance of ecosystem components and functions for future generations," and sustainable development as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (ASTM E 2114).

Brief History of Sustainability

Why is Germany advanced in green roof technology and environmental attitudes? In contrast to American sprawl and unchecked development by the inception of the Industrial Revolution, Germans early in the 20th Century recognized the threat by industrial development to their landscape. Citizens appealed to government officials, and by 1914 transformed an environmental reform movement (Lekan, 2004). This movement, tens of thousands members strong, criticized industrial capitalism's destruction of the environment. By the 1920's organizations began regional landscape conservation, know as *Landschaftspflege*, which advocated future-orientated, environmentally sensitive planning. This laid the foundation for modern environmental regulation.

During the American Industrial Revolution (over the 18th and 19th centuries), little or no consideration was given to preserving the natural landscape as building infrastructure for cities and industrial areas took place. Industries developed capabilities that owed nothing to nature, but rather sustained growth by technological advances and social arrangements (Page and Walker, 1991). American citizens formed a distance between the farmland by working and living in cities, factories, and workshops that promised new growth and development.

A shift in consciousness surrounding the environment and long term sustainability of the natural world was initiated by essays written by philosophers such as Aldo Leopold during the late 1920's (Norton, 2003). However, it was not until the mid 1980's that incorporation of the human built environment with nature was largely considered by the public and private sectors in the United States as a concept to limit environmental degradation (Norton, 2003). Approaching sustainable design requires a conceptual shift that inevitably results in productive, socially beneficial, and ecologically intelligent framework (McDonough et al., 2003).

Today in the United States, tax incentives are being implemented to manage stormwater issues, reduce urban heating, and minimize the impact of the built environment. California, Maryland, Massachusetts, New York, and Oregon are all adapting these practices (American Council for an Energy-Efficient Economy, 2002). The City of Portland has restricted construction of new buildings of some maximum height to floor ratio, which can often not be achieved without bonuses (Liptan, 2003). Eco-roofs serve as one option to achieve the zoning codes necessary to maximize the height desired by building architects. A floor bonus is added if 30-60% of the roof is covered with vegetation. If roof vegetation is greater than 60%, then the square footage of the eco-roof is tripled to equal the amount of floor space granted to the new building. To date, Portland is the leader in the floor area ratio (FAR) bonus, however other cities are watching its success closely.

The Built Environment

Because we spend up to 90% of our lives indoors, we expect buildings to enhance our well-being by providing functional, comfortable conditions with regards to noise, heating, cooling, safety and security (Halliday, 1997). From the inception of a building project, the building owner, architect, and engineer must agree on the long-term and short-term functionality and maintenance of the building as well as the local impact it will have in order to achieve sustainability (Halliday, 1997). Site selection, choice of source for construction material, energy, and water, and replacement/recycling costs of materials can require holistic thought and must be considered in life-cycle cost of a building.

In 1992, the U.S. Department of Energy (DOE) Office of the Federal Environmental Executive published Executive Order 13123 which required federal agencies to "apply sustainable design principles to the site, design, and construction of new facilities." Greening projects for the Federal Energy Management Program (FEMP) include buildings within the Washington D.C. area such as the White House, the Pentagon, and the DOE Headquarters. Additionally, Grand Canyon National Park and Denali National Park, among others, were selected as greening projects. These projects evaluate existing structures and create a working strategy to improve the sustainability of the site for the building envelope, the surrounding landscape, and transportation and parking issues around the site. For example, a green roof was installed on the

Remote Delivery Facility (RDF) of the Pentagon. Other renovations on the RDF included window replacement (17% energy savings), alternate-current photovoltaic array (an alternative energy source), and a water efficient landscape design using xeriscaping. These examples show that there is a shift to more environmentally conscious actions that consider the life-cycle of the building and surrounding site.

As part of their master plans, many college campuses and public schools are incorporating sustainable technologies such as green roofs to help mitigate stormwater runoff and conserve energy of buildings. Elementary schools, the University of North Carolina- Chapel Hill and Michigan State University are some examples. A demonstration green roof (3,500 ft ^{2}) was recently installed on a portion of the Plant and Soil Science Building at Michigan State University. This roof was designed to compare roofing surfaces, evaluate plant species, and serve as a demonstration for building inhabitants and the general public.

Numerous government and non-profit agencies have the goal of creating environmentally responsible best management practices regarding the life-cycle cost of the built environment. For example, The U.S. Green Building Council (USGBC) leads the coalition representing industry on environmental building matters. The USGBC mission is to produce a new generation of buildings that deliver high performance inside and out: environmentally responsible, profitable and healthy places to live and work *(www.usgbc.org)*. Representing all segments of the building industry, USGBC members developed the Leadership in Energy and Environmental Design (LEED™) Green Building Rating System™. This system is a voluntary, consensus-based national standard for developing high-performance, sustainable buildings. Currently, a coalition of over 3,000 companies and organizations belong to the USGBC.

Building projects may be qualified for LEED™ certification at three levels, which are defined by the total points received for the project. For certification of a building, green roofs can count directly to two of the 69 points, written in LEED™ as "potential technologies and strategies" under the stormwater management and heat island effect categories. A green roof may accumulate points indirectly under the categories on energy efficiency and water efficient landscaping. Even though LEED™ promotes integration of green roofs, the green roof industry has to compete with credits in other building component alternatives in different categories.

Aside from industry and government sectors, public awareness of green roof technology at the local and national level has also vastly improved in the last several years. University courses are teaching the concepts of green roofs through engineering, architecture, horticulture, and landscape architecture departments. As sustainable buildings become mainstream, green roofs will be continually sought for their benefits.

Technical Components of a Green Roof

There are two main categories of green roofs: intensive and extensive. Intensive green roofs resemble the gardens people access at ground level, often designed for and open to the public. Plant taxa may be represented by a variety of trees, shrubs, bulbs, perennials, and annuals. Usually the plant materials require deeper rooting substrates (greater than 15 cm) and higher maintenance requirements of irrigation, pruning, and fertilizing (Osmundson, 1999). Intensive systems can incorporate walkways, benches, and hardscapes in the design. These factors add to the weight of the rooftop system that may require changes or additions to the building structure to account for the additional weight (roughly 290-970 kg/m^2) (Dunnett and Kingsbury, 2004).

Extensive green roofs are much lighter (70 to 170 kg/m^2) and are not intended for public access (Dunnett and Kingsbury, 2004). Plants that grow on extensive green roofs require relatively little horticultural maintenance after the first year. They are often prostrate in growth habit (under 40 cm in height), can survive in shallow rooting substrates (3 to 10 cm), and are commonly herbaceous perennials or self propagating annuals (Osmundson, 1999). Ideally, these plants should survive with minimal irrigation (often natural precipitation is the only source), little to no fertilizer, and require less maintenance to sustain healthy plant growth and coverage on green roofs.

Extensive green roofs are often established on low degree or flat-sloped roofs on new or existing buildings. Structural components of the building must be strong enough to support the weight of the vegetation system. Depending on the design scope of a green roof project, existing roofs may be retrofitted to support the weight of the living roof.

To create a successful and sustainable green roof, several layers of engineered material are required at installation. The existing roof surface is covered by a root barrier membrane that prevents plant roots from growing into the building. This is usually a plastic (HDPE) or rubber physical barrier as opposed to a chemical barrier such as copper. A drainage layer placed on top of the root barrier allows for some aeration and creates an area for water to escape off the roof. The green roof industry provides many types of drainage systems using a variety of materials including gravel, polymers, and metals. Some manufacturers have engineered water retention cups into the drainage layers to help retain moisture. Although differences in drainage system design had no effect on plant establishment and growth, Monterusso (2003) reported that they did influence runoff quantity and quality. A filter fabric may be used to eliminate media and other components from being lost or clogging drains. Sometimes, a water retention fabric is placed on top of the drainage layer. The fabric retains water and provides additional space for roots to grow. The visible top layer consists of the growing media and plants. Media depths vary depending on the loading capacity of the roof and what plant species will be grown (Dunnett and Nolan, 2004). Some manufacturers use a vegetation carrier to support media and plant growth. For example, Xeroflor, LLC, uses a nylon mat with 1 cm high coils that make it easier to transport prevegetated green roof mats from the field to the roof.

Green roof substrate, or media, must be lightweight, well-drained, stable, and strong (Osmundson, 1999). In general, the media should have components that will not blow away or decay in a short amount of time. The green roof industry typically uses media comprised of 40 to 70% of a porous material such as heat-expanded slate or clay, and 30 to 70% of a heavier material such as sand (Beattie and Berghage, 2004). Substrate containing as much as 80% PermaTill® and a fertilizer level of 50 g/m^2 per year were found to maintain adequate plant health (Monterusso et al., 2005). Mineral substrates are preferred over those high in organic material because the organic matter will degrade over time, which will require the addition of more substrate to maintain the same depth. Nutrient sources come from roughly 15% incorporated organic material, decaying plant material, and an optional slow release fertilizer.

Plant establishment can be accomplished directly on the roof or at an off-site location. Regardless of the location of establishment, cuttings, plugs, or seeds can be used. Plants may be grown on the ground in modular trays or pre-vegetative mats in an off-site location. Pre-vegetative mats of a desired coverage can be cut or rolled up for transport and placed on the roof, similar to sod production, whereas plants grown in modular units generally remain less disturbed during transporting. One benefit of off-site locations during establishment is the ease of maintenance at ground level and the instant greenery on the roof observed upon completion of the project. Planting plugs directly on a roof is an option for establishment, although it is more difficult to maintain during the critical establishment period and plant coverage is not optimized immediately after installation.

Plant Life-forms

Botanists have described most plant species in nature (Ricklefs, 1990). Within the last century, classifications have developed relating plant forms to climate. Raunkiaer (1934) classified plants by the location of their regenerative buds, which corresponded closely to climatic conditions. He described five major life-forms: chamaephytes, hemicryptophytes, cryptophytes, therophytes, and phanerophytes. Chamaephytes are small shrubs and prostrate herbs. Snow often protects the reproductive buds located close to the soil from the extreme cold winter. Hemicryptophytes are characteristic of cold, moist zones, whose persistent buds are protected at the soil surface even though the vegetative tissue dies back. Growth tends to be prostrate by horizontal runners. In general, most Central European herbs are classified as hemicryptophytes. Cryptophytes are also found in cold, moist zones; however their buds are completely underground (i.e. bulbs). Therophytes (annuals) do not have persistent buds, rather regenerate exclusively by seed in the natural world, and are most abundant in deserts and grasslands. The phanerophytes (most trees and large shrubs) dominate in moist and warm environments. Buds are located on the tips of their branches and are more exposed to the climate. However, a green roof does not necessarily mimic a typical natural ecosystem. In a non-irrigated extensive roof system we would not expect to see long term survival of phanerophytes (trees and shrubs), but there may be dominant species of chamaephytes, hemicryptophytes, and therophytes. These species may naturally produce a horizontal surface area by creeping with multiple stems, leaves, and adventitious roots.

What plants in nature are characteristic of a climate such as Michigan? Understanding Raunkiaer's system of plant form classification relative to microclimate is important when describing types of plants we should expect to see. We must observe natural surroundings for identifying plant candidates, especially rock outcroppings and alpine regions. Cooper (1961) surveyed vegetative communities in southeastern Michigan and found xeric environments to be dominated by hemicryptophytes.

Plant Performance on Rooftops

Rooftops present unique surroundings for plants to grow as rooftops are often more extreme than at ground level and horticultural inputs are often minimized. As a result, plants selected for use on green roofs must be able to tolerate drought, shallow root depths, sun exposure, extreme temperature fluctuations, low winter temperatures, and increased wind velocities (Boivin et al., 2001).

Due to climatic differences, plants that do well in Germany may not be appropriate for Michigan (Rowe, 2003). Over a 30 year period (1971-2000), the normal high and low temperatures for East Lansing were 27.7°C and –10.3°C, respectively; and averaged 785 mm of annual rainfall. Over the same 30 year period, Berlin, Germany reported normal high and low temperatures of 23.1°C and -2.9°C, respectively; and received 560 mm of annual rainfall.

Plant growth and development is not dictated exclusively by temperature extremes or environmental normals. Growing degree days are defined as the relationship between plant development rate and temperature (Bonhomme, 2000). For *Sedum,* plant growth and development will not occur at temperatures below 10°C. Growing degree day (GDD) units are recorded as the amount of time temperatures exceeded or equaled a target base temperature. Based on a 40 year period from 1961-1990, approximately 1517 GDD (° C) occurred annually in Michigan, beginning March through October (Michigan State Climatologist's Office). Würzburg, Germany reported an average of 1060 GDD (° C) (Pool, 2000).

On a roof platform study in Michigan, Monterusso et al. (2005) compared 18 native forbs and grasses and nine species of *Sedum* over three years. All nine of the *Sedum* thrived, but only four of the 18 native taxa were found to be acceptable on non-irrigated roofs. In another study, six herbaceous plant taxa grown commonly on German rooftops were tested over three years under three soil depths in Quebec, Canada (Boivin et al., 2001). Low temperature plant injury was more pronounced at the 5 cm depth than at either 10 cm or 15 cm and *Sedum* grown at 10 cm and 15 cm showed less injury than the other species grown at these depths. This is possibly due to rapid, frequent changes in substrate temperature that causes plants to constantly shift in and out of dormancy.

The ability to survive prolonged low winter temperatures, characteristic of Michigan, is one environmental criteria needed to naturalize a roof, but drought tolerance is equally important. Water availability is one of the most limiting factors for a green roof (Kirschstein, 1997; Dunnett and Nolan, 2004). Extensive systems generally rely on natural precipitation events, although irrigation systems are sometimes used during establishment or when plant health begins to decline.

However, when extensive green roofs are designed for long-term sustainability, watering frequency is minimized during and after plant establishment.

Many xerophytic plants are ideal for extensive green roofs because they are physiologically and morphologically adapted to withstand harsh environmental conditions (Gebauer, 1988). Some succulents have been documented to exhibit Crassulacean acid metabolism (CAM), a plant physiological pathway adapted to water-stressed environmental conditions (Ting, 1985). CAM plants usually have fewer stomata than C_3 and C_4 plants, and these stomata can open at night for the uptake of CO_2, thus reducing daytime water loss. Another drought resistant mechanism is the plant's capacity to store water in the succulent leaves (Sayed, 2001).

CAM is defined as a massive diurnal fluctuation of titratable acidity, accounted for by malic acid (Ting, 1985). Typically, the diurnal curve of CO_2 exchange can be divided into four phases: (1) malic acid is carboxylated and stored in large vacuoles, (2) CO_2 fixation produces malic acid and there is an increase in stomatal conductance, (3) malic acid is decarboxylated and CO_2 is accumulated, and (4) typical photosynthesis and carbohydrate synthesis occurs. Because stomata are closed during the day, plant gas exchange occurs at night. The nocturnal uptake and fixation of CO_2 produces oxalacetate, which quickly reduces to malate. Subsequently, malic acid accumulates and is stored in large vacuoles until the light period. During the light period, malic acid floods from the vacuole, and is decarboxylated to produce pyruvate, phosphoenolpyruvate

(PEP), or other storage carbohydrates such as starch. Generally, CAM activity directly related to water availability and temperature.

There is variability in the metabolic pathways of CAM plants. Facultative CAM (or C_3- C_4- intermediates or inducible) shift from C_3 pathway to CAM under stressed conditions of water, salinity, temperature, and/or photoperiod (Kluge, 1977; Lee and Kim, 1994). Facultative CAM was demonstrated in *Sedum acre*, *S. kamtschaticum ellacombianum, S. pulchellum, S. reflexum,* and *S. ruprestre* (Lee and Kim, 1994; Sayed, 2001). CAM plants are not limited to the Crassulaceae family, as other angiosperms (especially orchids and euphorbias), gymnosperms and some ferns exhibit CAM.

How long can *Sedum* remain alive without water? *Sedum rubrotinctum* survived under greenhouse conditions for two years without water (Teeri et al., 1986). Kirschstein (1997) reported that after 99 days without water, 78% of the plants of *S. album* and *S. ruprestre* recovered within one week of watering. *Sedum kamtschaticum*, known to thrive in moister conditions, was the least drought resistance, and had a 45% recovery rate (Kirschstein, 1997). VanWoert et al. (2005) reported that a deeper substrate of 6 cm required less frequent watering regimes (once every 28 days) to promote growth of *Sedum* than at shallower substrate depth 2 cm where water was needed once every seven days to promote growth. However, *Sedum* sustained photosynthetic activity over the course of the experiment without ever receiving water over the 89 day study. Of course, every species is unique and will vary in biological activity in response to environmental conditions.

Lassalle (1998) compared the effect of drought stress on three potential green roof taxa – *Chrysanthemum leucanthemum*, *Festuca glauca*, and *Sedum album* in substrate depths of 5 cm, 10 cm, and 15 cm. Regardless of substrate depths, *S. album* outperformed *C. leucanthemum* and *F. glauca* regarding vitality, water holding capacity, and potential evapotranspiration. Drought tolerance was greatly increased for *Festuca glauca* in deeper substrates (>5 cm). *Chrysanthemum leucanthemum* was not suitable for shallow substrates (<5 cm) and performed the poorest of the three at all depths.

In general, when water deficit develops slowly and affects plant developmental processes, cell volume decreases, and lowers turgor pressure (Taiz and Zeiger, 1998). Eventually, a decrease in root growth potential and inhibited leaf expansion, results in less plant transpiration, and water is conserved (Taiz and Zeiger, 1998). Drought stress can affect Photosystem II efficiency, decreasing the photosynthetic potential yield of the photochemical reaction (Krause and Weis, 1991). Chlorophyll fluorescence is an early indicator of various types of plant stress, and can be easily measured using less expensive equipment than traditional gas exchange measurements (Mohammed et al., 1995; Bolhar-Nordenkampf et al., 1989). This yield can be measured as chlorophyll fluorescence, a loss of light energy from the PS II reaction, known as the "Kautsky Effect". Chlorophyll fluorescence can detect direct effects on the photosynthetic apparatus and other physiological effects that feed back to photosynthesis (Bolhar-Nordenkampf et al., 1989). Chlorophyll fluorescence can be measured by a modulated light fluorimeter. When a leaf is dark adapted, the oxidation or reduction intermediates for the electron transport pathway return to a common level. As the leaf becomes illuminated, there is a rise in light emission from PS II fluorescence. The yield can be represented as a ratio of variable fluorescence to maximum fluorescence (F_v/F_m). The F_v/F_m is typically within a narrow range of 0.832 ± 0.004 among many different species and ecotypes (Krause and Weis, 1991).

Green roof plant populations will change over time. Remnant plant populations can persist, despite negative growth rates, due to long-lived life stages and life-cycles (Eriksson, 2000). In nature, when a disturbance occurs (such as prolonged drought or extreme cold) remnant populations may be able to re-colonize. The larger the roof area, species diversity can persist despite individual species displacement in smaller patches on the whole vegetative roof (MacArthur and Wilson, 1967; Collinge, 1996). Long term persistence on the roof is important, as is the ability to spread quickly for coverage. To maximize benefits, performance, aesthetics, and longevity of a green roof, rapid and complete coverage of plant material is desired.

Description of Plant Species for Evaluation

Species listed on the following page were selected for evaluation throughout this thesis. The genera *Graptopetalum, Phedimus, Rhodolia,* and *Sedum* reproduce easily by asexual means from stem or leaf cuttings without the use of commercial rooting compounds (Stephenson, 2002); additionally, some self-sow readily after initial establishment. Limited information was available for several species used in the study even though they were cross-referenced using Stephenson (2002), Eggli and Hartmann (2003), Armitage (1997), and the United States Department of Agriculture PLANTS National Database. Some botanical names are synonymous with others, so referencing species may be different depending on the author. For example, according to Eggli and Hartmann, *Phedimus spurius* is synonymous with *Sedum spurium*; and *P. kamtschaticus* is synonymous with *S. kamtschaticum*. Selected succulent plants researched for this thesis are creeping herbs or small subshrubs, and described by Raunkiaer (1934) as passive chamaephytes.

	WO	PR	LF	LS	LC	FT	FC
G. paraguayense subsp. *Bern.*	N	P			B	0	
P. spurius 'Leningrad White'	O	P	H	B	G	6-7	W
R. pachyclada	O	A		B,T	G	0	R
R. trollii				B,T	G	0	
S. acre	O	P	H	D,G,S	G	5-7	Y
S. album 'Bella d'Inverno'	O	P	H	D,G,U	G,R	6-8	W
S. clavatum	N	P	S	G,U	G	0	W
S. confusum minor form	N	P	S	G,U,T	G,R	0	Y
S. dasyphyllum 'Burnatii'	O	P	H	D,G,S	B	6-8	P
S. dasyphyllum 'Lilac Mound'	O	P	H	D,G,S	B	6-8	P
S. diffusum	N	P	H	L,S	B	7-8	P,W
S. hispanicum diploid	O	A/P	H	L,G	B	6-7	P
S. kamtschaticum	O	P	H	B,G	G	7	Y
S. mexicanum	N	P	H	L	G	0	Y
S. middendorffianum	O	P	H	B,G,T	G	7-9	Y
S. moranense	N	P	S	D,L,S	G	8	R
S. pachyphyllum	N	P	S	G,U	B	0	Y
S. reflexum	O	P		G,L	B	5-7	Y
S. sediforme	O	P	H	L,G	B	7-9	W
S. spurium 'Summer Glory'	O	P	H	B,G	G	7-9	R
S. surculosum var. luteum	O	P	H	B	G	8	Y
S. 'Rockery Challenger'	N				G	0	
S. 'Spiral Staircase'	N				G	0	
S. X luteoviride	N			G,U	G	0	
S. X rubrotinctum	N	P	S	G,U	R,G	0	Y

Key:
(WO) World: New=N, Old=O
(PR) Persistence: Perennial=P, Annual=A
(LF) Life Form: Subshrub=S, Herb=H
(LS) Leaf Shape: Broad=B, Dense=D, Glabrous=G, Linear=L, Succulent=S, Thin=T
(LC) Leaf Color: Blue=B, Green=G, Red=R
(FT) Flower Time [1]
(FC) Flower Color: Pink=P, White=W, Yellow=Y, Red=R

[1] Time of flowering in East Lansing, MI, during 2004. Numbers represent month of the year.

Existing Research About Extensive Green Roofs: North America

Most current, long term research evaluating green roof systems has originated from Germany and Japan, where government regulations managing greenspace are more strictly imposed. Germans have evaluated green roofs over the past few decades, including on some green roofs over 90 years old where naturalization occurred and biodiversity was reported (Brenneisen, 2004). Researchers have extensively evaluated technology and systems provided by the green roof industry and reported data on benefits to the general public. In order to progress the North American market, we must study previous research in order to improve our regional research. Climate differences and the desire to support local industries, and inform policy makers facilitate the need for regional testing centers in North America.

Currently, there is not a network of regional testing sites that evaluate green roof systems North America . However, research centers including Michigan State University, Pennsylvania State University, North Carolina State University, University of British Columbia- Vancouver, and the National Research Council of Canada publish green roof performance and collaborate with the roofing industry to supply data on thermal performance (Rowe 2003; Beattie and Berghage, 2004; Hunt et al., 2004; Pedersen, 2000; Liu, 2004). Green Roofs for Healthy Cities (GRHC) is non-profit agency that centralizes current data and activities from university and government research programs for policy makers and the industry in North America. GRHC disseminates information through their website (www.greenroofs.ca) and the Green Roof Infrastructure Monitor, holds green roof training courses, and organizes annual conferences.

Research Objectives

The Michigan State University Green Roof Research Program is among the leaders in green roof research and disseminating peer-reviewed information to green roof professionals, initiated in 2000 to recommend the optimal green roof technology for Ford Motor Company's 42,900 m^2 extensive green roof. Plant establishment, growth, drought tolerance, and hardiness of several plant species were evaluated on simulated roof platforms at the MSU Horticulture Teaching and Research Farm beginning in 2001 (Monterusso et al., 2005; Rowe, 2003). Other MSU studies focused on the effects of vegetation on stormwater runoff and water use efficiency by a mixture of *Sedum* spp. grown under different substrate types (VanWoert et al., 2005, Durhman et al., 2004).

Evaluations of potential green roof taxa for green roof applications include criteria such as propagation success, rate of establishment and subsequent growth, competition among species, drought resistance, and over-wintering survivability. The knowledge gained from these experiments will help in recommending a larger plant pallet for green roofs based on selective criteria. One goal of the research is to use outdoor platform and greenhouse trials to characterize the diversity of candidate plant species for use in extensive green roof systems. A larger plant selection palette provides the opportunity to enrich the plant community for the green roof industry, which in turn creates a more sustainable, dynamic green roof system.

This thesis describes three studies: an initial growth rate and index of 25 species under field conditions; a diversity and competition analysis of 25 species under field conditions; and drought tolerance of five plant species under greenhouse conditions;

The first study was an outdoor trial measuring initial plant growth and coverage at three substrate depths. Stem and leaf cuttings of 25 Crassulacean plant species were excised from stock plants and grown on simulated roofing platforms. Weekly digital images were taken to measure growth over time. An index was calculated to show vegetative groundcover relative to starting size.

A second experiment evaluated 25 Crassulaceaen plant species' competitive characteristics over two growing seasons on roof platforms. Weekly measurements documented leaf area presence using a point frame transect. The line-intercept method was chosen to obtain density indices, estimate coverage, and evaluate species evenness (relative frequency) within platforms. Persistence and competition were important in predicting the long-term stability of the planted communities and preservation of the aesthetic goals of the roof design.

The drought stress experiment compared two Michigan natives plants, *Schizachyrium scoparium* Nash and *Coreopsis lanceolata* L., and three species of *Sedum* L. *(S. acre, S. reflexum, S. kamtschaticum ellacombianum*) grown under greenhouse conditions using five different watering regimes. To characterize plant stress under various water regimes, chlorophyll fluorescence, evapotranspiration, and biomass accumulation were measured and compared against five species.

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CHAPTER ONE

Substrate depth influences growth, coverage, and survival of succulent green roof taxa

Substrate depth influences growth, coverage, and survival of plant species for green roof systems

Additional index words: vegetative roof, eco-roof, living roof, plant evaluations, *Sedum*, Crassulaceae

Abstract

Green roofs enhance urban and industrial development by providing attractive benefits to those areas. This study evaluated 25 succulent plant species not previously reported for suitability on green roofs applications in the Midwest. Initial growth, rate of coverage, and survival were compared for plants grown in three substrate depths (2.5, 5.0, 7.5 cm). Results indicated deeper substrates promoted greater survival and growth, however, in the shallowest depth of 2.5 cm, several species continued to persist. Of the 25 species initially planted, only 47% survived in the deepest substrate of 7.5 cm. Recommended species for climates similar to southern Michigan include: *S. hispanicum* L. diploid, *S. spurium* Bieb.'Summer Glory', *S. sediforme* J., *P. spurius* Raf. 'Leningrad White', *S. acre* L., *S. album* L.'Bella d'Inverno', *S.middendorffianum* L., and *S. reflexum* L. Subsidiary species that are present at specific substrate depths but may not exhibit an ability to cover large amounts of area include: *R. pachyclada* L., *S. dasyphyllum* L.'Lilac Mound', *S. dasyphyllum* L. 'Burnatii', *S. kamtschaticum ellacombianum* Fisch.

Introduction

Sustainable urban development and smart growth has gained greater attention by urban planners in recent years (De Sousa, 2002). Vegetative roofs provide various benefits to the built environment, including stormwater management, building insulation, and mitigation of the urban heat island effect (Dunnett and Kingsbury, 2004). As more vegetative roofs become established in the United States, it is critical to increase the number and geographic range of proven plant resources for long term survival on rooftops. As with an agricultural system, a rooftop plant community with limited plant diversity is susceptible to disease, pests, and environmental stresses such as drought, flooding, or temperature extremes which could eradicate species (Koehler, 2003). Plant diversity provides aesthetic benefits from capitalizing on unique seasonal botanical characteristics including variation in foliar color, flower time and color, persistence of inflorescence spikes, plant height, and the mechanism to survive dormancy, whether it be perennial evergreen, deciduous, or an annual (White and Snodgrass, 2003). Greater plant diversity also creates habitats for other wildlife (Gedge and Kadas, 2004).

Many extensive green roofs consist primarily of low maintenance succulent perennial species such as *Sedum* L., *Delosperma* N.E.Br., and *Sempervivum* L.; grasses like *Festuca* L.; and herbaceous plants such as *Allium* L. and *Dianthus* L. (Dunnett and Nolan, 2004; Koehler, 2003). Plant evaluations for extensive green roof applications have been conducted in cool temperate regions such as Germany, United Kingdom, Sweden, Pennsylvania, Oregon, Michigan, and southern Canada (Dunnett and Kingsbury, 2004).

German studies documented plant performance and presence on extensive green roofs that are older than 50 years (Darius and Drepper, 1984). Koehler (2003) related plant community development in Germany to characterizing aspects of green roofs based on the substrate's water holding capacity, vegetation cultivation method, building architecture, maintenance, and regional climatic data. In Madrid, Spain, *Sedum* spp. were evaluated to naturalize roofs and subjected to freezing temperatures grown at a substrate depth of 3.5 cm (Gómez-Campo, 1996; Gómez-Campo and Tortosa, 1994). In North America, Boivin et al. (2001) reported that, for the six species tested, more freezing injury occurred at shallow substrate depths of 5 cm, compared to 9 cm or 11.5 cm depths. Monterusso et al. (2005) compared 18 native forbs and grasses to nine species of sedum on a roof platform study in Michigan. All nine of the *Sedum* thrived, but only four of the 18 native taxa were found to be acceptable on non-irrigated roofs.

When considering potential taxa for green roofs located in the Midwest (USDA hardiness zone 4 and 5), likely candidates can be found in extreme environments such as rock outcroppings or under alpine conditions. Cooper (1961) surveyed vegetation in southeastern Michigan and recorded that in increasingly xeric environments, hemicryptophytes became more dominant. Hemicryptophytes are a classification of plants that consist mostly herbs where the shoot apices are at the soil surface, protected by the soil and the above ground vegetation during the unfavorable season (Raunkiaer, 1934). In contrast, species classified as chamaephytes grow in the alpine region, where snow cover protects the shoots and buds against water loss. Chamaephytes are sub-shrubs and herbs with vegetative shoots that lie along the ground and remain intact at the beginning of an unfavorable season. *Sedum* are classified as passive chamaephytes because response during unfavorable conditions results in shorter internodal length and reduced shoot lengths.

Many xerophytic plants are ideal for extensive green roofs because they are physiologically and morphologically adapted to withstand harsh environmental conditions (Gebauer, 1988). Some succulents have been documented to exhibit Crassulacean acid metabolism (CAM), a metabolic pathway that enables them to adapt to water-stressed environmental conditions (Gebauer, 1988; Ting, 1985; Sayed, 2001). CAM plants usually have fewer stomata than C_3 and C_4 plants, and these stomata can open at night for the uptake of CO_2, thus reducing daytime water loss. Another drought resistant mechanism of CAM plants is to store water in the succulent leaves (Sayed, 2001).

Successful candidates for extensive green roofs also need to exhibit characteristics such as easy propagation, rapid establishment, high groundcover density, tolerance to extreme environmental conditions, and successful winter recovery (Boivin et al., 2001; White and Snodgrass, 2003). German guidelines require at least 60% vegetative coverage to be approved as a green roof (FLL, 1995). Optimal and efficient planting density reduce costs. Therefore the objective of this study was to evaluate 25 succulent plant species for their suitability for green roof applications in the Midwest by measuring growth rates, rate of coverage, and survival.

Materials and Methods

An initial growth and coverage study was conducted on simulated roof platforms at the Horticulture Teaching and Research Center at Michigan State University (MSU), East Lansing, Mich. The study was a split-plot completely random design with substrate depth as the main plot factor and species as the sub-plot factor. Each species was replicated eight times within each substrate depth for a total of 600 plants.

Platforms. Twenty-four 123 cm X 123 cm raised roof platforms were constructed. Each pressure treated wood platform was built per the same ASTM International standards that would be required for a commercial building and equipped with layers of insulation, waterproofing, a green roof drainage system, root barrier, substrate, and a 2% slope for drainage. In each plot, excess water drained via three drilled holes at the base of the slope, approximately 3 cm in diameter and covered by a mesh filter screen. The tops of each individual wood frame plot were bordered with flexible meter tape for rescaling and orientating the images.

Platforms included a green roof drainage layer (XF108) and vegetation carrier (XF301) (Wolfgang Behrens Systementwicklung, GmbH, Groß Ipener, Germany). The drainage layer consisted of a geotextile fabric with attached nylon coil. The nylon coils faced down when installed and the total thickness of this layer was approximately 1.5 cm. A water retention fabric layer, approximately 0.75 cm thick, was added with the capacity to hold up to 800 $g \cdot m^{-2}$ of water. The water retention fabric layer was composed of a recycled synthetic fiber mixture of polyester, polyamide, polypropylene, and acrylic fibers. The vegetation carrier consisted of a geotextile fabric with nylon coils attached and filled with substrate (Figure 1).

Substrate. Substrate depths of 2.5 cm, 5.0 cm, and 7.5 cm were randomly assigned to the 24 platforms. Substrate consisted of 40% heat-expanded slate (gradation of 3 mm to 5 mm) (PermaTill®, Carolina Stalite Company, Salisbury, N.C.), 40% United States Golf Association (USGA) grade sand (Osburn Industries, Taylor, Mich.), 10% Michigan Peat (Osburn Industries, Taylor, Mich.), 5% Dolomite (Osburn Industries, Taylor, Mich.), 3.33% composted yard waste (Kalamazoo Landscape Supplies, Kalamazoo, Mich.), and 1.67% composted turkey litter (Herbruck's, Saranac, Mich.). At time of planting, electrical conductivity (EC) and pH of the media were 3.29 $mmho \cdot cm^{-1}$ and 7.9, respectively. All treatments had 100 $g \cdot m^{-2}$ of Nutricote® type 100, 18N-6P-9K controlled release fertilizer (Agrivert, Webster, Texas) hand-applied 47days after planting on 28 July 2003, and the following summer on 29 July 2004 at the same rate.

Plant species. Stem and leaf cuttings of 25 Crassulaceaen plant species (listed below) were excised from stock plants growing in the MSU Plant Science Greenhouses on 11 June 2003. Length of the unrooted cuttings ranged from 2 to 4 cm, but were uniform in size within species. Cuttings were stored overnight at

5°C and propagated the following day on the outdoor platforms. Cuttings were placed on 20 cm centers with 25 individual species per plot. The location of individual cuttings within each plot was randomly assigned.

Graptopetalum paraguayense subsp. *Bern.* Rose	*S. mexicanum* Britt.
Phedimus spurius Raf. 'Leningrad White'	*S. middendorffianum* L.
Rhodiola pachyclada L.	*S. moranense* Kunth
R. trollii L.	*S. pachyphyllum* Clausen
Sedum acre L.	*S. reflexum* L.
S. album L. 'Bella d'Inverno'	*S. sediforme* J.
S. clavatum C.	*S.* 'Rockery Challenger' H.
S. confusum minor form Hemsley	*S.* 'Spiral Staircase' H.
S. dasyphyllum L. 'Burnati'	*S. spurium* Bieb. 'Summer Glory'
S. dasyphyllum L. 'Lilac Mound'	*S. surculosum* var. *luteum* Cos.
S. diffusum W.	*S.* x *luteoviride* C.
S. hispanicum diploid L.	*S.* x *rubrontinctum* C.
S. kamtschaticum Fisch.	

During the first 22 days of the study, the platforms were covered with a shade cloth. To help acclimate the plants, the shade cloth was removed, except on bright sunny days, up until day 31, at which time it was removed permanently.

Irrigation. During the establishment period, plots were overhead irrigated with Rain Bird® Xerigation XS-180 spray heads fixed to 30.5 cm Polyflex risers. The risers were placed at increments measuring 120 cm. For the first 20 days, the plots were irrigated for five minute cycles at 7:00 A.M., 11:00 A.M., 2:00 P.M., 5:00 P.M., and 8:00 P.M. Each five minute cycle applied enough water to saturate each plot, misting approximately 4.0 mm (30 ml) per plot. Irrigation duration was reduced to two minute cycles from day 21 to 41. After day 41, automated irrigation terminated, but occurred periodically to maintain plant health the first year. In the second growing season, supplemental irrigation was not used.

Weed species. During the establishment period, numerous weed seedlings emerged (listed below). Emerging weeds were hand picked up to day 33. They were then allowed to grow until day 86, at which time all weeds were removed. Thereafter, plots were managed to remain weed free for ease of data collection to maintain the original goals of measuring growth rates for desired planted species.

Cirsium arvense L.	*Panicum capillare* L.
Eleusine indica L.	*Populus deltoides* Marshall
Eragrostis cilianensis All.	*Salix nigra* Marsh.
Mollugo verticillata L.	*Senecio vulgaris* L.

Data collection. Measurements of two-dimensional plant coverage were recorded by taking weekly digital images (32MB, 1800 X1200 pixel, fine quality). A portable camera stand was constructed to raise a camera approximately 163 cm above the platforms. A digital camera (FUJIFILM MX-2900 zoom, 2.3 mega pixels, Fuji Photo Film Co., LTD., Tokyo, Japan) equipped with a F3.3/F7.6 wide conversion lens was suspended on the camera stand. The focal distance was set at 22 mm; and the focal range set at 0.9 m. Although planted on 12 June 2003, images were taken beginning 8 July 2003 (week 1). Weekly analysis occurred during the initial growing season, defined as the time up until the plants entered dormancy in late fall and a hard frost occurred on 28 October 2003 (week 17). Data collection resumed the following spring on 24 March 2004 (week 38). This method was used until 19 May 2004 (week 46) when it became too difficult to distinguish individual species related to plant competition.

Survival rates were recorded during establishment, after the first growing season, the next spring, and at the end of the second growing season (Table 1). The establishment period was defined as the period up to seven days after supplemented irrigation terminated, when 90% of the individuals had rooted by week 4 (day 26). Persistence for the first year was scored on week 17, after a hard frost. To consider over-wintering success, presence of individuals at week 17 was compared to presence at week 45. A final assessment of persistence during the second growing season was made on week 67, after a hard frost on 5 October 2004.

Image analysis. Plant growth rates and horizontal vegetative coverage were determined in a non-destructive method by utilizing SigmaScan Pro 5.0 image analysis software (SPSS Science, Chicago, Ill.). Vertical height was not measured. Coverage (plant community development) in each plot was measured to compare growth relative to substrate depth. Digital images were analyzed to determine the percentage of the total horizontal vegetative canopy that attributed to each individual. Image area was delineated for the quadrat area using the two-point rescaling function, then individual plants were analyzed using the manual trace mode (Olmstead et al., 2004). Manual trace mode was necessary because the software program could not automatically distinguish color, intensity, and hue differences between plant materials and substrate. A preliminary test established the accuracy of the method of taking weekly images, analyzing them in an image analysis program, and converting to actual cm^2. By measuring paper images of a known area (10 cm^2), it was determined that the measurements were 94% accurate, relative to actual size.

Vegetative growth was recorded by weekly image analysis, beginning 8 July 2003, following the 26 day establishment period when individual cuttings rooted. Because of snow cover, analysis of weekly images resumed the following spring on week 38. As it became too difficult to distinguish individual species boundaries, image analysis collection was terminated on week 46.

Due to size variability among propagules after the 26 day establishment period, an area index was calculated to show vegetative groundcover relative to starting size. During the first growing season (2003), area index was defined as final (week 17) area minus initial (week 1) area for each individual plant. Area index for the second season (2004) was calculated from final (week 46) area minus the initial (week 38) area that spring. Measurements for each species were averaged across the 8 replications at each species depth. Growth rate was defined using the area of coverage graphs to measure the slope of area divided by time (Figure 1).

Statistical analysis. Data were analyzed separately for 2003 and 2004 years. Significant differences between species growth and depth on specific weeks were determined using multiple comparisons (least significant differences) with Tukey-Kramer adjustments (PROC MIXED, SAS version 8.02, SAS Institute, Cary, N.C.). Survival percentages were compared using a mixed model where time and depth were factors, and species was nested in depth (PROC MIXED, SAS version 8.02, SAS Institute, Cary, N.C.). Survival data did not require a log transformation because it was observed to be normally distributed. Overall coverage of vegetation analyzed at the end of the study was tested using least significant differences (PROC GLM, SAS version 8.02, SAS Institute, Cary, N.C.).

Results and Discussion

Survival. In general, plants grown in the deeper substrate depths of 5.0 and 7.5 cm exhibited higher survival rates than those grown at the 2.5 cm depth (Table 1). Not all individual cuttings survived the propagation interval, however no single species experienced complete mortality for all eight replications at any depth. Five species had less than 100% propagation survival on some substrate depths after supplemental irrigation was terminated: *Rhodiola pachyclada*, *Sedum clavatum, S. kamtschaticum, S.* 'Rockery Challenger' and *S. surculosum* var. luteum. Further, S. *clavatum* and *S. surculosum* var. luteum displayed less than 100% rooting survival at all three depths (Table 1).

Plant mortality was observed most prominently at the 2.5 cm depth where survival percentage declined for seven species (Table 1). At the 5.0 cm depth, four species exhibited mortality. Individuals grown in the 7.5 cm depth were least affected after the first season where only two species experienced decreased survival percentages, although not significant. Regardless of depth, *S. clavatum* did not survive the first growing season; additionally, *S. surculosum* var. *luteum* only survived at the 7.5 cm depth.

In addition to initial establishment and growth, plant hardiness is critical for longevity, stability, and appearance of extensive green roofs (Boivin et al., 2001; Rowe, 2003). Substrate depth influenced plant cold hardiness, with deeper substrate depths of 5.0 cm and 7.5 cm supporting greater overwintering survival than those grown at the 2.5 cm depth (Table 1). However, of the 25 species, only 47% survived winter when averaged across all plots. Even more dramatic, at the shallow substrate depth of 2.5 cm, only nine of the 25 species (36%) overwintered. Results for *S. acre, S. kamtschaticum, S. middendorffianum 'Diffusum'*, and *S. reflexum* supports previous research that these species can survive on extensive green roofs in Michigan (Monterusso et al., 2005). In addition, all *P. spurius* 'Leningrad White,' *S. album*, *S. hispanicum*, *S. sediforme*, and *S. spurium* ' Summer Glory' survived regardless of substrate depth.

Comparing persistence after two seasons among the three substrate depths, most change in survival occurred at the 5.0 cm depth. For example, two species, *S. dasyphyllum* 'Lilac Mound' and *S. kamtschaticum* exhibited some mortality, while three species, *S. dasyphyllum* 'Burnatii,' *S. diffusum*, and *S. hispanicum* diploid recovered individuals, therefore increasing survival percentage. This may be explained by the species' ability to regenerate readily by adventitious rooting of detached stems or leaves or by reseeding. At the 7.5 cm depth, original individuals either maintained or improved their abundance in the plots, with *S. diffusum* showing more survival than in the shallower substrates. The 2.5 cm depth resulted in the least differences among all depths in winter recovery or reemergence by the end of the second year, with a significant increase in survival by *S. hispanicum* diploid. *Sedum diffusum*, recovered at the 5.0 and 7.5 cm substrate depth, significantly improving its survivability. This may be due to its tender hardiness, defined as a plants ability to buffer itself against cold temperatures, which resulted in delayed regeneration of vegetative tissue not observed in May.

Tender perennials such as *R. pachyclada*, *S. dasyphyllum* 'Burnatii,' *S. dasyphyllum* 'Lilac Mound,' and *S. diffusum* were able to survive the deeper substrate of 7.5 and 5.0 cm, but not in 2.5 cm. Deeper substrates likely provided greater moisture retention and root protection from temperature fluctuations and allow for more vertical space for plant roots to grow before reaching the root barrier. A more stable environment allows plants to grow stronger and healthier, which affects their ability to survive harsh climatic conditions of drought and temperatures. However, even with deeper substrates, mortality during winter could be due to death of the root systems, which are generally not as cold tolerant as the tops of plants (Wu and Cosgrove, 2000).

Growth rate. Substrate depth affected growth rate, although not immediate (Figure 2). This is probably because the roots systems were not yet large enough to exploit the entire depth of the substrate. Growth after establishment varied across species. *Sedum acre, S. album* 'Bella d'Inverno' and *S. spurium* 'Summer Glory' established and grew quickly early in the season. In contrast, *S. dasyphyllum* 'Burnatii,' *S. dasyphyllum* 'Lilac Mound,' *S.*

kamtschaticum, and *S. middendorffianum* did not show an increase in growth until much later in the season. These differences could be attributed to individuals' propagation potential, aggressiveness to establish in an open area, and resource allocation.

Across all species, plant vigor (i.e. the fastest growth rates) was greatest at the deepest substrate depth of 7.5 cm. Though the 2.5 cm depth did not promote growth to the same extent as the deeper substrates, plants remained alive. Over time, growth rates within depths varied across plant species especially for some species including *S. acre, S. album* 'Bella d'Inverno' , *S. diffusum, S. hispanicum, S. mexicanum,* and *S. middendorffianum* (Figure 2). This is due in part to favorable growing conditions, such as amount and duration of rainfall and temperatures (Figure 3).

Following winter, growth resumed for most species the second season. There was no observable vegetation present on week 38 for deciduous species such as *S. kamstschaticum* and *R. pachyclada.* This resulted in sustained or negative growth rates, which is evident in Figure 1. However, as regeneration occurred later spring, growth rates improved. Some species had vegetative dieback in the plant's center (semi-deciduous), though surrounding tissues were actively recovering from winter injury and/or growing. For this observation, plant material that looked healthy (turgid and/or leaf color similar to previous year's growth) was recorded. Species that exhibited dieback included *S. dasyphyllum* 'Burnatii,' *S. dasyphyllum* 'Lilac Mound, *S. hispanicum,* and *S. album* 'Bella d'Inverno.' However, by May, winter injury was no longer observed. One interesting observation was *S. middendorffianum, S. spurium* 'Summer Glory,' and *S. kamtschaticum* had much faster growth rates in the second year, compared to their performance the prior year. *Sedum acre* and *S. album* 'Bella d'Inverno' had consistently increasing growth rates.

Coverage. Among species, increases in coverage were significantly different at each depth, resulting in the greatest area of coverage occurring for plants growing in 7.5 cm substrate (Table 2). In 2004, *S. middendorffianum, S. album* and *S. acre* exhibited greater coverage, than the other species at the 7.5 cm and 5.0 cm depth. In the 2.5 cm plots, *S. album* 'Bella d'Inverno' covered more horizontal area than *S. middendorffianum* and *S. acre*, although not significantly different. Growth rates varied widely for individual species. For example, *S. sediforme* growth was not significantly different at any depth, whereas *S. hispanicum* tripled its area in response to a substrate depth change from 5.0 cm to 7.5 cm.

In the first growing season, *S. mexicanum* exhibited high coverage values and a fast rate of establishment across all depths. However, it did not overwinter and therefore was not included in the following growing season. *Sedum mexicanum* may be more suited for green roofs in warmer climates.

Life form characteristics influenced species survival, growth, and coverage. Raunkiaer (1934) classified the genus *Sedum* as passive chamaephytes, meaning evergreen or deciduous vegetative shoots lay along the ground and remain intact at the beginning of the unfavorable season. Evergreen species such as *S. album, S. acre*, and *S. spurium* 'Summer Glory' retain their vegetation over the Michigan winter. Additionally, their vegetative shoots quickly root and grow in different areas of the plots early in the growing season. In the spring, they have an obvious spatial advantage by predominating a particular area within the plot. In contrast, deciduous plants like *S. kamtschaticum* are not frost tolerant and above ground shoot tissues die in late fall with adverse weather conditions, though new vegetative growth occurs from regenerative buds in the spring. However, this influences the coverage present early in the season. They are at a disadvantage as they must compete spatially against evergreen species, however, their growth rates are comparable later in the growing season (Figure 2).

Although not apparent in this study, improved coverage and presence at the end of the second growing season by *S. hispanicum* was due mainly to its prolific re-seeding ability in late summer, especially compared to other species tested. In the second year, *S. hispanicum* flowered throughout June and July, with seedlings emerging by the beginning of August. Other species that re-seeded in the second season include *S. acre* and *S. album* 'Bella d'Inverno.' Overall, plants selected for this trial generally reproduce easily by asexual means of stem or leaf cuttings, without the use of commercial rooting compounds (Stephenson, 2002). Over time, original plants could have easily reestablished themselves in the plots by vegetative means, thereby increasing their coverage and presence at the end of the study.

Analysis of vegetation in the whole plot, recorded as a one whole community, will continue to be measured for several years. This is important in comparing vegetative coverage and long-term pant competition across substrate depths. At the end of the second year, however, 100% coverage at any depth was not achieved. However, vegetative coverage was different for each depth: 46.7%, 74.0%, and 95.8% for the depths of 2.5 cm, 5.0 cm, and 7.5 cm, respectively ($P \leq 0.05$) (Figure 4).

Conclusion

Most of the species examined within this study have not been previously reported for use on green roofs in the Michigan climate. Furthermore, some of these species and cultivars do not have published USDA hardiness zones. Therefore, this study offers new information for recommending novel plant candidates for use on green roofs. Of the 25 species initially planted, only 47% survived in the deepest substrate of 7.5 cm. Recommended species for climates similar to southern Michigan include: *S. hispanicum* diploid, *S. spurium 'Summer Glory', S. sediforme, P. spurius* 'Leningrad White', *S. acre, S. album* 'Bella d'Inverno', *S.middendorffianum,* and *S. reflexum.* Subsidiary species that are present at specific substrate depths but may not exhibit an ability to cover large areas include: *R. pachyclada, S. dasyphyllum* 'Lilac Mound', *S. dasyphyllum* 'Burnatii', *S. kamtschaticum ellacombianum.* Deeper substrates promote greater survival and growth, however, in the shallowest depth of 2.5 cm, several species were observed to form stable communities. In choosing a green roof system, it is important to consider both substrate depth and plant species growth factors for sustained species growth.

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Table 1. Percent survival of 25 taxa (*Graptopetalum, Phedimus, Rhodiola,* and *Sedum)* cultivated at three substrate depths (2.5, 5.0, and 7.5 cm) over two growing seasons (2003-2004). Survival reported in weeks, where week 4=29 July 2003; week 17=28 October 2003; week 45=12 May 2004; week 67= 5 October 2004.

	Survival (%)											
	2.5 cm				5.0 cm				7.5 cm			
Taxa	**4**	**17**	**45**	**67**	**4**	**17**	**45**	**67**	**4**	**17**	**45**	**67**
G. paraguayense sbsp. *Bern.*	100 Aa	100 Aa			100 Aa	100 Aa			100 Aa	100 Aa		
P. spurius 'Leningrad White'	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa
R. pachyclada	62.5 Aa	37.5 Aa			100 Ab	87.5 Ab			87.5 Ab	87.5 Ab	12.5 Ba	12.5 Ba
R. trollii	100 Aa	62.5 Ba			100 Aa	100 Ab			100 Aa	100 Ab		
S. acre	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa
S. album 'Bella d'Inverno'	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa
S. clavatum	12.5 Aa				25 Aa				12.5 Aa			
S. confusum minor form	100 Aa	100 Aa			100 Aa	100 Aa			100 Aa	100 Aa		
S. dasyphyllum 'Burnatii'	100 Aa	87.5 Aa			100 Aa	100 Aa	50 Cb	87.5 Bb	100 Aa	100 Aa	100 Ac	100 Ab
S. dasyphyllum 'Lilac Mound'	100 Aa	50 Ba			100 Aa	75 Bb	25 Cb	12.5Cab	100 Aa	100 Ac	87.5 Ac	87.5 Ac
S. diffusum	100 Aa	100 Aa			100 Aa	100 Aa		25 Cb	100 Aa	100 Aa		75 Cc
S. hispanicum diploid	100 Aa	87.5 Aa	25 Ba	37.5 Ba	100 Aa	100 Aa	75 Bb	100 Ab	100 Aa	100 Aa	100 Ac	100 Ab
S. kamtschaticum	87.5 Aa	87.5 Aa	12.5 Ba	12.5 Ba	100 Aa	100 Aa	100 Ab	87.5 Ab	100 Aa	100 Aa	100 Ab	100 Ab
S. mexicanum	100 Aa	100 Aa			100 Aa	100 Aa			100 Aa	100 Aa		
S. middendorffianum	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa
S. moranense	100 Aa	100 Aa			100 Aa	100 Aa			100 Aa	100 Aa		
S. pachyphyllum	100 Aa	100 Aa			100 Aa	100 Aa			100 Aa	100 Aa		
S. reflexum	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa	100 Aa
S. 'Rockery Challenger'	87.5 Aa	87.5 Aa			100 Aa	87.5 Aa			100 Aa	100 Aa		
S. sediforme	100 Aa	100 Aa	75 Ba	75 Ba	100 Aa	100 Aa	100 Ab	100 Ab	100 Aa	100 Aa	100 Ab	100 Ab
S. 'Spiral Staircase'	100 Aa	100 Aa			100 Aa	100 Aa			100 Aa	100 Aa		
S. spurium 'Summer Glory'	100 Aa	100 Aa	75 Ba	75 Ba	100 Aa	100 Aa	100 Ab	100 Ab	87.5 Aa	87.5 Aa	87.5 Ab	100 Ab
S. surculosum var. luteum	50 Aa				87.5 Ab				62.5 Aa	25 Bb		
S. X luteoviride	100 Aa	100 Aa			100 Aa	100 Aa			100 Aa	100 Aa		
S. X rubrotinctum	100 Aa	100 Aa			100 Aa	100 Aa			100 Aa	100 Aa		

Mean separation in rows for each species by LSD (P≤ 0.05). Uppercase letters denote comparisons over time within individual substrate depths (n=8). Lowercase letters denote comparisons of different substrate depths on specific dates (n=8). Blanks denote no surviving plants for specific species.

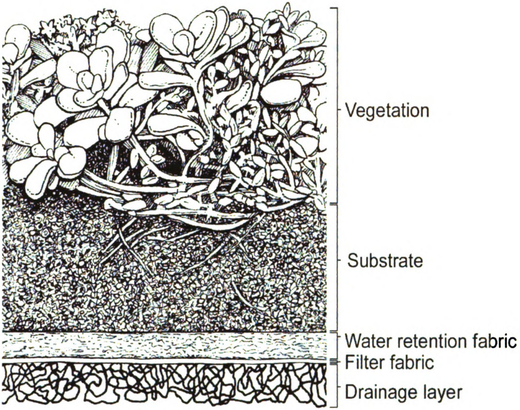
Table 2. Increase in coverage (cm^2) as calculated from image analysis. (8 July 2003 to 28 October 2003 and 24 March 2004 to 19 May 2004).

	Area (cm^2) 2003			Area (cm^2) 2004		
	Depth (cm)			Depth (cm)		
Taxa	**2.5**	**5**	**7.5**	**2.5**	**5**	**7.5**
G. paraguayense sbsp. *Bern.*	22.0 a	27.7 a	50.2 a			
P. spurius 'Leningrad White'	43.6 a	114.9 ab	264.1 c	110.0 a	236.9 ab	619.2 c
R. pachyclada		5.4 a	20.3 a			2.9 a
R. trollii			2.9 a			1.5 a
S. acre	139.4 a	320.0 b	491.8 c	218.9 a	599.5 b	1057.4 c
S. album 'Bella d'Inverno'	201.2 a	335.1 ab	656.4 c	334.0 a	601.4 b	1177.5 c
S. clavatum						
S. confusum minor form		28.7 a	85.0 a			
S. dasyphyllum 'Burnatii'	7.8 a	110.4 a	225.2 b		51.1 ab	231.0 b
S. dasyphyllum 'Lilac Mound'	142.6 a	399.4 a	371.0 a		2.00a	77.1 a
S. diffusum		19.2 a	44.4 b			
S. hispanicum diploid	83.1 a	250.7 b	355.2 c	7.9 a	195.2 ab	656.8 c
S. kamtschaticum	4.9 a	61.2 ab	107.9 b	2.0 a	220.0 b	381.6 b
S. mexicanum	**133.7 a**	**322.0 b**	**603.6 c**			
S. middendorffianum	50.8 a	137.8 ab	223.7 b	237.5 a	664.5 b	1237.0 c
S. moranense	40.0 a	55.6 ab	134.0 c			
S. pachyphyllum	10.1 a	68.1 a	99.0 a			
S. reflexum	55.2 a	151.2 ab	249.9 b	106.8 a	334.5 b	676.3 c
S. sediforme	82.1 a	165.8 ab	252.3 b	61.2 a	160.3 a	240.7 a
S. spurium 'Summer Glory'	27.8 a	123.0 a	160.4 a	61.1 a	348.9 b	373.2 b
S. surculosum var. luteum			3.1 a			
S. 'Rockery Challenger'	26.1 a	49.2 a	49.2 a			
S. 'Spiral Staircase'	16.4 a	44.1 a	80.4 a			
S. X luteoviride	8.2 a	51.0 a	96.2 a			
S. X rubrotinctum	35.6 a	99.3 a	137.4 a			

Mean separation in rows between depths within each taxa were tested using LSD with Tukey-Kramer adjustments ($P \leq 0.05$). Tests were separated by year prior to analysis. Blanks denote no surviving plants for specific species.

LIST OF FIGURES

Figure 1.



Cross section representative of an extensive green roof system used in the study. Substrate depths tested were 2.5 cm, 5.0 cm, and 7.5 cm.

Figure 2.

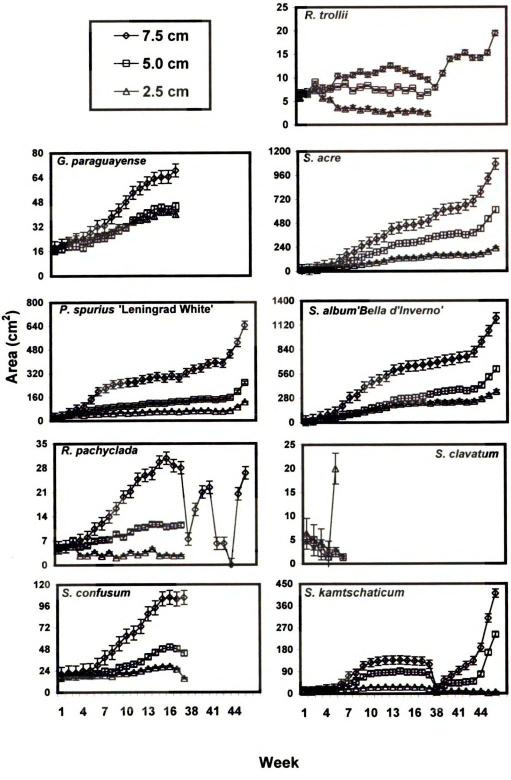

7.5 cm
5.0 cm
2.5 cm
R. trollii
G. paraguayense
S. acre
P. spurius 'Leningrad White'
S. album'Bella d'Inverno'
R. pachyclada
S. clavatum
S. confusum
S. kamtschaticum
Area (cm²)
Week

Figure 2 continued.

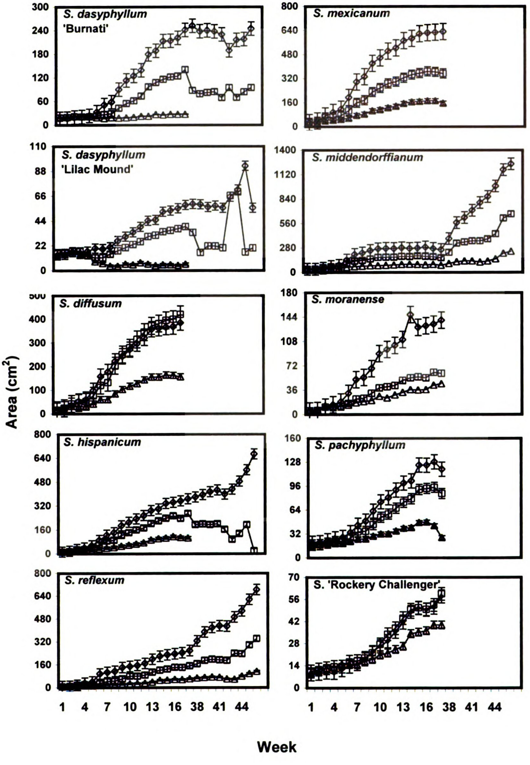
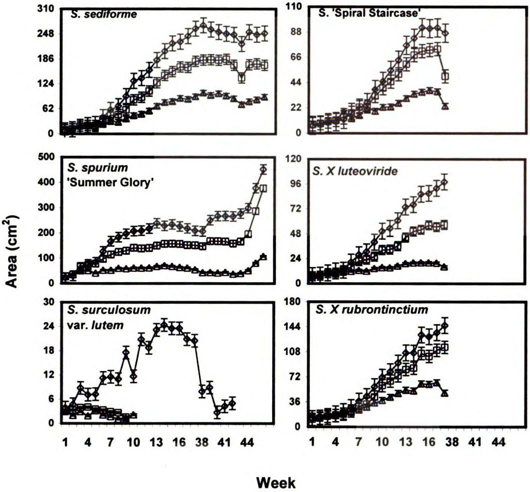
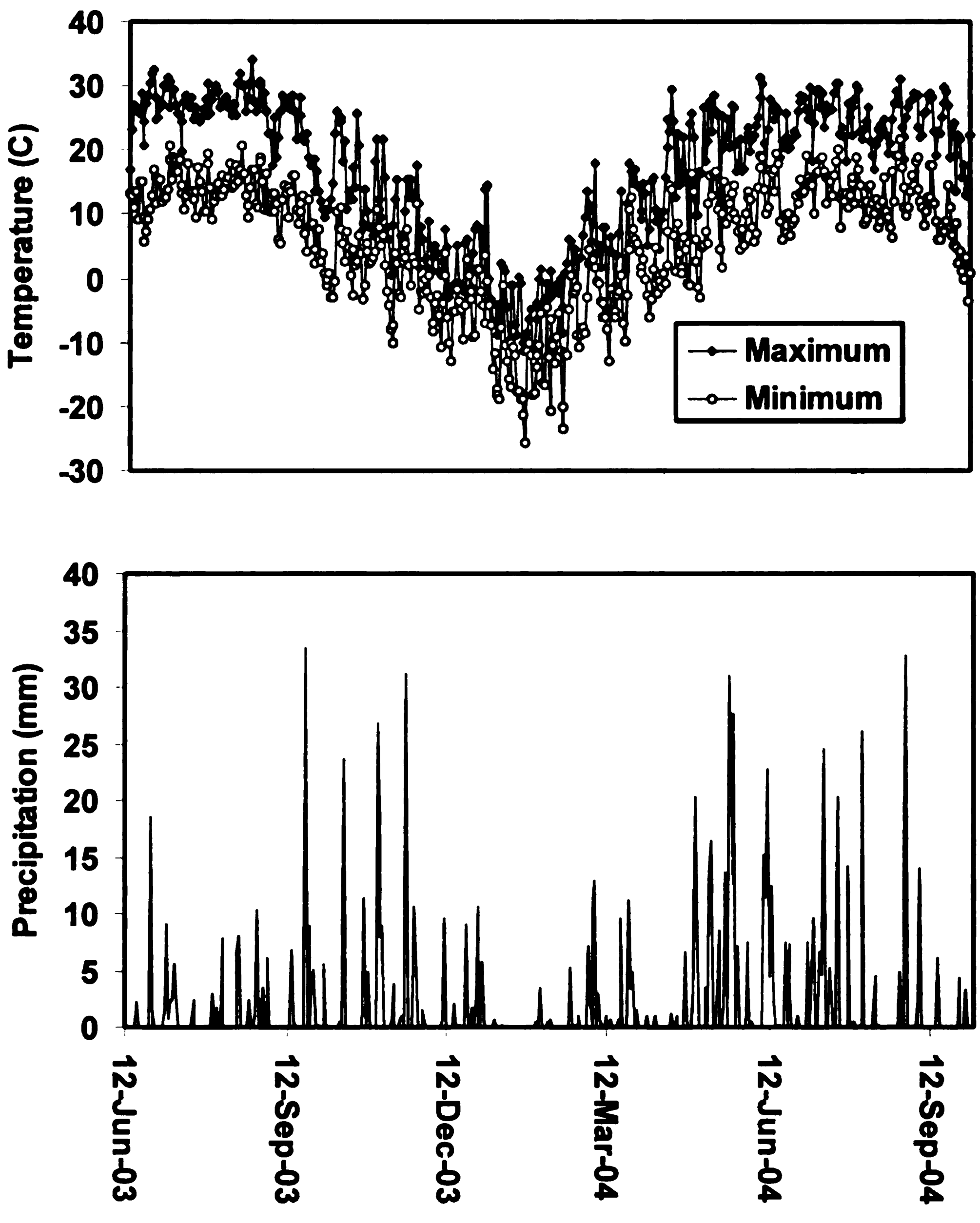


Figure 2 continued.



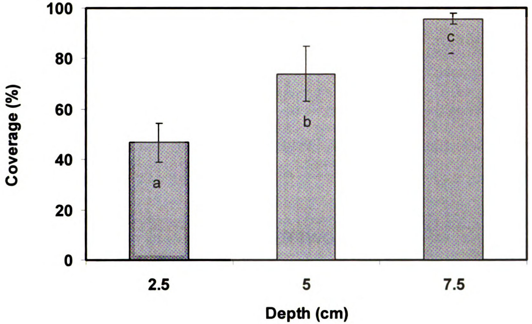
Growth of 25 taxa (*Graptopetalum, Phedimus, Rhodiola,* and *Sedum*) cultivated on green roof platforms at three depths (2.5, 5.0, 7.5 cm). Growth was calculated from digital image analysis. Data collected once a week for 17 weeks, and resumed the following spring on week 38, and terminated on week 46 when plants were too dense to discriminate. Break in x-axis to denote winter. Error bars represent standard error.

Figure 3.



Daily maximum and minimum temperatures (^{o}C) and precipitation (mm) during the experimental study (12 June 2003 through 06 October 2004). Weather data were taken using the Michigan Automated Weather Network's East Lansing weather station (located adjacent to the research site).

Figure 4.



Coverage of vegetation after two growing seasons (2003-2004) on green roof platforms at three substrate depths (2.5, 5.0, and 7.5 cm). Mean separation by LSD ($P \leq 0.001$) n=8. Error bars represent standard error.

CHAPTER TWO

Competition and diversity index of 25 Crassulacean species for potential application on extensive green roofs in Michigan

Competition and diversity index of 25 Crassulacean species for potential application on extensive green roofs in Michigan

Additional index words: living roof, vegetative roof, relative abundance, plant diversity, Sedum

Abstract

Green roofs are an emerging technology in the United States that alleviate several environmental problems in urban and industrial areas such as stormwater management, the urban heat island effect, and energy conservation. Initial plant selection and long-term survival is a major factor in success. No studies have been performed to predict long term plant composition and colonization of roofs in Michigan. Therefore, the objective of this study was to determine the effect of three substrate depths on plant diversity and relative abundance of 25 Crassulacean species growing on simulated roof platforms. Results indicate that substrate depth affected plant diversity and species behavior. Relative abundance was highest for *Phedimus spurius* Raf. 'Leningrad White,' *Sedum acre* L., *S. album* 'Bella d'Inverno' L., and *S. middendorffianum* L., compared to other species. Subsidiary species are those that may not be relatively abundant, but exhibited some level of success under rooftop conditions and included *S. hispanicum* diploid L., , *S. kamtschaticum* Fisch., *S. sediforme* J., *S. spurium* Bieb. 'Summer Glory,' *S. dasyphyllum* 'Burnati' L., and *S. reflexum* L.

Introduction

Vegetative or green roofs are an emerging technology that serves the concept of environmental sustainability. To maximize benefits, performance, aesthetics, and longevity of a green roof, rapid and complete coverage of plant material is essential. Non-vegetated portions of a roof may result in wind and water erosion, potentially contaminating air and water as substrates and other components erode off the roof. Vegetation shades roof materials from UV radiation, thus improving longevity, compared to conventional roofs. Additionally, extreme temperature fluctuations are reduced with vegetation; and heat flux into and out of the building is lessened during the summer and winter, respectively (Dimoudi and Nikolopoulou, 2003; Lükenga and Wessels, 2001; Liu, 2004; Niachou et al., 2001). Overall, non-vegetated portions of a green roof may reduce thermal protective properties of a green roof. Therefore total plant coverage, often initially achieved by planting species with high vigor, is encouraged.

Vegetated roofs are characterized as a cultivated system due to the human input that is required, especially during initial establishment. Extensive green roofs are intended to have minimum horticultural inputs, such as irrigation, fertilization, general plant maintenance, and infrequent replanting, so they could also be classified as an dynamic natural system located in an industrial or urban environment. Integrating observations and theories about natural events needs to be understood to explain the successional changes recorded on vegetated roofs both in the short term and long term.

Green roof plant populations evolve not only at the species level, but at the whole community level. In natural settings, succession on nutrient poor soils usually proceeds from species that were good colonists, but poor nutrient competitors; to species that were poor colonists, but good nutrient competitors (Tilman, 1990). The maximum growth rate-nutrient competition hypothesis describes this type of succession. Initially, the system is dominated by the fast growing plants that have low allocation of resources to the roots. However, over time vigorous plants will be replaced by slower growing plants that allocated more energy to the roots (Tilman, 1990). Ultimately, the species that can reduce the concentration of the limiting resource to the lowest level should competitively displace all other species (Tilman, 1990). Because extensive green roofs are generally low in nutrient content, one would expect similar results on a roof.

Over time, remnant plant populations can persist, despite negative growth rates, due to long-lived life stages and life-cycles (Eriksson, 2000). In nature, when a disturbance occurs via exposure to prolonged drought, extreme temperature, a lack of nutrients in the substrate, or allelopathic behavior; remnant populations may be able to re-colonize, therefore changing diversity in a given area. The distribution of individuals among the species in a given area is known as species evenness, or relative abundance (Brower et al., 1998). To colonize in a disturbed site, tradeoffs occur between the resource allocation to the seed bank versus the ability to compete for a limiting soil resource (Tilman, 1990). The ability to compete for resources can depend on dominant species evenness in a given area.

Certain micro-environmental criteria and regional limitations are key considerations as plants naturalize a rooftop. Water availability is a limiting factor when extensive green roofs are designed for long-term sustainability

(Kirschstein, 1997; Dunnett and Kingsbury, 2004). Many xerophytic plants are well suited for extensive green roofs because they physiologically and morphologically adapted to withstand harsh environmental conditions (Gebauer, 1988). Some succulents exhibit Crassulacean acid metabolism (CAM), a physiologic pathway that enables these plants to adapt to water-stressed environmental conditions (Gebauer, 1988; Ting, 1985; Sayed, 2001). Other adaptations include the ability to shift metabolic pathways in response to stress conditions (facultative CAM), fewer stomata that open at night for the uptake of CO_2, and the capacity to store water in the succulent leaves (Sayed, 2001). Another criteria needed to naturalize a rooftop is the ability to withstand low winter temperatures in some regions. In Michigan, if the species is not classified as USDA Hardiness zone four or five, it must have the ability to reproduce annually by seed. On a roof platform study in Michigan, Monterusso et al. (2005) compared 18 native forbs and grasses and nine species of *Sedum* over three years. All nine of the *Sedum* thrived, but only four of the 18 native taxa were found to be acceptable on non-irrigated roofs. In another study, six herbaceous plant taxa grown commonly on German rooftops were tested over three years under three soil depths in Quebec, Canada (Boivin et al., 2001). Low temperature plant injury was more pronounced at the 5 cm depth than at either 10 cm or 15 cm; and *Sedum* grown at 10 cm and 15 cm substrate depth showed less injury than the non-succulent species grown at these depths.

The ability to grow in low nutrient substrates is another factor that must be met for survival on a green roof. Heavy additions of chemical fertilizers and herbicides should not be added on rooftops as nutrient leaching in the runoff could lead to environmental problems (Bucheli et al., 1998a; Bucheli et al., 1998b; Mason et al., 1999). The shallow substrate depth and low cation exchange capacity limits nutrient availability (Emilsson, 2004). Furthermore, providing nutrients from organic matter is a potential problem as organic matter (beyond the 2-5% provided by decaying plant material) will break down or blow away, thus requiring future additional applications of substrate to maintain a particular substrate depth (Beattie and Berghage, 2004; Panayiotis et al., 2003). Excess fertilizer applications can weaken the plants by elongating the stems and leaves, making them more susceptible to harsh environmental conditions (Emilsson, 2004).

Within the last century, extensive ecological literature has hypothesized, modeled, and predicted succession of natural communities. Knowledge of persistence, competition, and diversity are important to predict stability of the planted communities and preserve the aesthetic goals of a roof design. The purpose of plant competition experiments is to predict successional species composition under different ecological scenarios (Damgaard, 1998). German researchers have evaluated green roofs over the past few decades, and some green roofs over 90 years old are available where biodiversity can be observed (Brenneisen, 2004). However, the emerging green roof industry in the United States has provided limited research to project long term plant composition (colonization). Therefore, the objective of this study was to determine the effect of three substrate depths on plant diversity and relative abundance of 25 Crassulacean species growing on simulated roof platforms.

Materials and Methods

A competition and diversity analysis was conducted on simulated raised roof platforms at the Horticulture Teaching and Research Center at Michigan State University (MSU) East Lansing, Mich. The study was a split-plot completely random design with substrate depth as the main plot factor and species as a nested factor within depth. Twenty-five species were replicated three times with three substrate depths (2.5, 5.0, 7.5 cm) for a total of 225 individual plants.

Platforms and Substrate. Nine 123 cm X 123 cm raised roof platforms were constructed as described in Durhman (2005). Platforms contained a Xeroflor XF 108 green roof drainage layer, 1.5 cm thick, and Xeroflor XF 301 vegetation carrier (Wolfgang Behrens Systementwicklung, GmbH, Groß Ipener, Germany) (Figure 1). The vegetation carrier included a water retention fabric layer (0.75 cm thick) with the capacity to hold up to 800 $g{\bullet}m^{-2}$ of water.

The XF 301 vegetation carrier was filled with 2.5, 5.0, or 7.5 cm of substrate. Substrate consisted of 40% heat-expanded slate (gradation of 3 mm to 5 mm) (PermaTill®, Carolina Stalite Company, Salisbury, N.C.), 40% United States Golf Association (USGA) grade sand (Osburn Industries, Taylor, Mich.), 10% Michigan Peat (Osburn Industries, Taylor, Mich.), 5% Dolomite (Osburn Industries, Taylor, Mich.), 3.33% composted yard waste (Kalamazoo Landscape

Supplies, Kalamazoo, Mich.), and 1.67% composted turkey litter (Herbruck's, Saranac, Mich.). At time of planting, electrical conductivity (EC) and pH of the media were 3.29 mmho•cm^{-1} and 7.9, respectively. All treatments had 100 g•m^{-2} of Nutricote® type 100, 18N-6P-9K controlled release fertilizer (Agrivert, Webster, Texas) hand-applied 47 days after planting on 28 July 2003, and the following summer on 29 July 2004 at the same rate.

Plant species. Stem and leaf cuttings of 25 Crassulacean plant species (listed below) were excised from stock plants growing in the MSU Plant Science Greenhouses on 11 June 2003 and propagated the following day on the outdoor platforms as described by Durhman (2005). Cuttings were placed on 20 cm centers with 25 individual species per plot. The location of individual cuttings within each plot was randomly assigned.

Graptopetalum paraguayense subsp. *Bern.* Rose	*S. mexicanum* Britt.
Phedimus spurius Raf. 'Leningrad White'	*S. middendorffianum* L.
Rhodiola pachyclada L.	*S. moranense* Kunth
R. trollii L.	*S. pachyphyllum* Clausen
Sedum acre L.	*S. reflexum* L.
S. album L. 'Bella d'Inverno'	*S. sediforme* J.
S. clavatum C.	*S.* 'Rockery Challenger' H.
S. confusum minor form Hemsley	*S.* 'Spiral Staircase' H.
S. dasyphyllum L. 'Burnati'	*S. spurium* Bieb. 'Summer Glory'
S. dasyphyllum L. 'Lilac Mound'	*S. surculosum* var. *luteum* Cos.
S. diffusum W.	*S.* x *luteoviride* C.
S. hispanicum diploid L.	*S.* x *rubrontinctum* C.
S. kamtschaticum Fisch.	

During the establishment period, platforms were intermittently covered with a shade cloth to acclimate plants until day 31 and periodically irrigated the first year as described in Durhman (2005). No supplemental irrigation was provided during the second season. In order to properly record competition and diversity among the 25 potential green roof species, plots were kept weed free after day 86. As seen as common industry practice during the establishment period, weed management is often intensive until total coverage of desired vegetation is achieved.

Data collection. A point-frame transect method was utilized to measure species frequency (area of foliage) and diversity (Wilson, 1960). The transect was a stainless steal frame with an internal diameter of 119.4 cm x 116.8 cm with a depth of 3.8 cm. Ten strings (50 pound fish line) separated by 10 cm increments ran in both directions across the frame creating a 100 point grid. Another set of strings was located 3.8 cm below that created another 100 points of intersection parallel to the top grid. Accuracy was assured as the point frame was placed over four pegs that were permanently attached at the corners of each plot. Therefore, the point frame transect was set at the exact same location above the platform every week.

During data collection, a needle was inserted vertically through each of the 200 points where the wires crossed and all species that came in contact with the needle were recorded. For inter-specific contacts, location within the canopy layers was also documented. Individuals were counted once for every point they were present at each of the 200 points. Data collection occurred weekly beginning 28 July 2003 (week 1). In 2003, collection ended with the onset of snowfall, 21 October 2003 (week 13). Weekly data collection resumed 7 April 2004 (week 41) until a hard frost occurred on 6 October 2004 (week 67).

Statistical analysis. The Shannon (or Shannon-Weaver) index was chosen to quantify diversity among plots, which was appropriate because there was a random sample of species abundances from the larger community (Brower et al., 1998). The Shannon Index is: $H = -\sum \rho_i \log_e \rho_i$, where ρ_i is the proportion of the number of individuals that belong to the species *i*, and H is roughly proportional to the logarithm of the number of species. The resultant natural log of H, e^H, proportional to the number of species, was used in statistical analysis. Data were separated by year. First year (2003) analysis comparisons were made every three weeks. An ANOCVA table was created, and regression was done by SAS PROC GLM with time as a continuous variable and depth was a discrete variable. A type 1 multiple comparisons (least significant differences) t test was performed to compare overall means across depths.

Species evenness was calculated as the relative abundance (ρ_i) where each species is represented within a given area (Brower et al., 1998). Within each depth and period (analyzed separately for years 2003 and 2004) the relative abundance data were analyzed as a randomized complete block design with repeated measures. In the model, each of the nine plots were the block term, the treatment was species, and repeated measures analyzed as "week within species." After fitting several covariance structures, the compound symmetry model gave the best fit in the two periods. Hypothesis testing was done in the following order: first the overall interaction of species by week was tested in case of rejection of the null hypothesis. A slice of the interaction was done to determine within which week there were differences between species and for which species there was differences between weeks. Finally, all pairwise comparisons were performed within those weeks and species with significant slice test. *Sedum clavatum* was not recognized in the analysis due to its mortality early in the study.

Results and Discussion

Plot diversity. Diversity is quantified by the natural log of H, $e^{H'}$, which is proportional to the number of species. Throughout 2003 and 2004, the plant diversity of 2.5 cm depth plots was lower than the 5.0 and 7.5 cm depth plots ($P \leq 0.05$) (Figure 1). However, at times there was no difference overall between the 5.0 and 7.5 cm plots. In 2003, plot diversity increased as plants spread over time. Initially, 25 species were planted, however, many did not get recorded because they did not fall under the intersection points. Thereafter, a greater number of individuals were recognized as growth increased. A sharp decrease in species diversity occurred following winter because several of the species did not survive the winter (Figure 1). A slight increase in diversity after week 46 was due to the regeneration of several species in mid-May of the second year.

In both years, diversity was usually greatest in the deepest substrate of 7.5 cm. This supports findings from Gedge and Kadas (2004) where substrate depth influenced species richness. Deeper substrates created a richer environment by providing greater moisture retention, root protection from temperature fluctuations, and more vertical space for plant roots to grow before reaching the root barrier. In general, a more suitable environment allows plants to grow stronger and healthier, which affects their ability to survive harsh climatic conditions of drought and temperatures and naturalize an area over time. The results also support Boivin et al. (2001) where low temperature plant injury was more pronounced at the 5 cm depth than at either 10 cm or 15 cm. However, even with deeper substrates, mortality during winter could be due to death of the root systems, which are generally not as cold tolerant as the tops of plants (Wu and Cosgrove, 2000).

A regression analysis on diversity was done to project future behaviors of green roof plant performance. However, since this is considered a cultivated system, where natural occurrences such as weed emergence was not allowed, results showed consistent diversity over time. Independent regressions at the three substrate depths for 2004 are reported in Figure 2. Assuming the plots would be maintained similarly over time, projected outcomes show that 2.5 cm depth will become more diverse over time, and eventually reach a level of diversity similar to 5.0 and 7.5 cm substrate depths. Since the 2.5 cm depth did not experience full coverage over the two year time span, potential species may colonize in the bare spots, thereby increasing diversity. Emilsson (2003) complemented findings where species grown during establishment exhibited little competition from others. Since the regression slopes are small for 5.0 and 7.5 cm substrate depths, only slight increase in diversity is expected over time.

Relative abundance. In general, relative abundance for individual species, or species evenness, was not constant, nor were there consistent increasing or decreasing trends (Tables 1 and 2, Figure 3). Fluctuations can be explained by several factors. As mentioned, length of the unrooted cuttings ranged from 2 to 4 cm, but was uniform in size within species. Difference in original size could have influenced initial comparison of species. Overall, species growth and abundance could correlate to weather conditions, as seen in Durhman (2005). The amount of time between rain events was a major factor. In response to drought, some species reverted in size by forming tight clusters of leaves close to the stem. Following a rainfall event, plants recovered by expanding their leaves in order to facilitate water storage, and subsequently increased biomass, though this phenomenon was not observed for all species.

Plant life cycles, especially at the flowering stage, were another factor that influenced the variability in abundance. Some species such as *S. album* 'Bella d'Inverno', *S. sediforme,* and *S. reflexum* produced reproductive shoots that carried inflorescences. After flowering, some of the reproductive shoots died back. This rapid increase and decrease in biomass was recorded if plant tissues were alive and was evident throughout the summer (Figure 3).

Overall, in 2003, some individual species behavior was different relative to other species, meaning some environmental factors had no affect on certain species. For example, the plants growing in the 2.5 cm substrate depth demonstrated differences in terms of relative abundance (*S. album* 'Bella d'Inverno', *S. sediforme, S. spurium* 'Summer Glory'). Seven species grown in

5.0 cm substrate depth displayed differences (*S. acre, S. album, S. diffusum, S. kamtschaticum, S. sediforme, S. spurium* 'Summer Glory', *S.* X *rubrotinctum*). Relative abundance was different relative to the others for five species grown in the 7.5 cm substrate depth (*S. acre, S. album* 'Bella d'Inverno', *S. sediforme, S. spurium* 'Summer Glory', *S.* 'Spiral Staircase'). However, although some species were independent of each other, this information does not report on their performance (level of dominance) in the plots. For example, *S.* X *rubrotinctum* grown in the 5.0 cm substrate depth did not exhibit high relative abundance at any point in the 2003 growing season.

Due to fluctuations in relative abundance during 2003, specific dates were further selected to compare relative abundance within substrate depths across weeks (Table 1). *Sedum album* 'Bella d'Inverno,' *S. diffusum, S. acre, S. hispanicum* diploid, and *S. middendorffianum* increased their relative abundance over time. After the first week of data collection, *S. mexicanum, S. hispanicum, S. album* 'Bella d'Inverno,' and *S. diffusum* were highly abundant across all depths. Some species demonstrated a preference to being grown at a certain depth. For example, *S. hispanicum* and *S. sediforme* were more abundant in the 2.5 cm depth, whereas *P. spurius* 'Leningrad White' and *S. diffusum* seemed to prefer the 7.5 cm depth.

Regardless of depth, relative abundance decreased over time for several species (*G. paraguayense* subsp. *Bern., S. dasyphyllum* L. 'Lilac Mound,' *S. kamtschaticum, S. moranense, S.* 'Spiral Staircase,' *S. surculosum* var. *luteum, S.* x *luteoviride,* and *S. spurium* 'Summer Glory'). Decreased abundance results support findings from Durhman (2005) where those species did not increase biomass and coverage, and therefore did not exhibit strong spatial competitive characteristics.

Consistently high or low relative abundance is also important when looking at the whole plant community on rooftops. Where open space is abundant, slow initial growth rates exhibited by one species may allow another species to encroach on open space. *Sedum mexicanum* and *S. album* 'Bella d'Inverno, maintained high relative abundance in the first year and were able to compete spatially. Subsidiary species like *S. dasyphyllum* 'Burnati' and *S. reflexum* did not have high abundances, however, remained alive and were present throughout the first growing season.

Because overwintering had such a dramatic effect on species diversity in this study, further evaluation on relative abundance was examined for the second growing season. Of the 25 species planted, only 13 survived through the winter. This greatly altered the plant community dynamics as newly opened and previously unoccupied areas in the plots allowed for replacement species to encroach. For example, *S. mexicanum* accounted for approximately 10% of the plant communities in 2003, but since it did not overwinter, that area occupied became available for competition the following year. The fast coverage rate of *S. mexicanum* may make it a competitive green roof species in warmer climates, but not in Michigan.

Similar to the initial growing season, relative abundance again fluctuated and was not consistent during 2004 (Figure 3). Specific dates were further selected to compare relative abundance within substrate depths across weeks (Table 2). In the shallow substrate depth of 2.5 cm, only eight species survived into the second year. The dominant species in the plant community at 2.5 cm substrate depth was *S. album* 'Bella d'Inverno,' as it was able to take advantage of resource availability and low levels of competition (Table 2a). Ten species survived the 5.0 cm substrate depth, however, abundance appeared more evenly distributed among the subsidiary species by the end of the second year. Growing in 5.0 cm substrate depth, *S. acre* exhibited consistently high competition and dominance, however, *S. album* and *S. middendorffianum* values were also high. The deepest substrate depth of 7.5 cm comprised of 13 species. At the deepest depth, overall dominance shifted among *P. spurius* 'Leningrad White,' *S. acre*, *S. album* 'Bella d'Inverno,' and *S. middendorffianum*. Competitive pressure was high in the 7.5 cm depth, and *S. album* 'Bella d'Inverno' was not as successful at the deepest substrate depth relative to the shallower depths.

Individual species behavior was different in substrate depths. For example, *S. dasyphyllum* 'Burnati' and *S. dasyphyllum* 'Lilac Mound' were more abundant and able to compete successfully in the 7.5 cm depth, but did not perform well in 2.5 or 5.0 cm substrate depths. Similarly, in the second year, *S. spurium* 'Summer Glory' was most abundant in the shallow depth. In contrast, *S. kamtschaticum* trends were similar in the 5.0 and 7.5 cm depths, however, it did not grow in 2.5 cm depth. Trends for some species were similar across all depths, although abundance was greater as depth increased. This statement was true for *S. acre, S. reflexum, S. album* 'Bella d'Inverno,' and *S. middendorffianum.* This supports results from Durhman (2005 chapter 2 thesis) where *S. kamtschaticum* did not survive in the shallowest depth, and *S. acre* and *S. reflexum* exhibited a positive relationship between substrate depth and growth.

Interestingly, in 2004 no supplemental irrigation was needed for plant growth, and minimal to no plant stress was observed. East Lansing experienced consistent precipitation from March through October, thereby minimizing the time between rain events. The exception to this happened on two occasions where there was no precipitation for 11 days, occurring on 14 August until 24 August and 17 September until 27 September 2004. However, this did not appear to have an observable effect on any species relative abundance.

Conclusion

Results show that plant diversity had a direct relationship with deeper substrates. Relative abundance was highest for *P. spurius* 'Leningrad White,' *S. acre*, *S. album* 'Bella d'Inverno,' and *S. middendorffianum* compared to other species. These four species competed for resources more successfully than the other plants in the community and could be considered the dominant species of the 25 evaluated. Subsidiary species are those that may not be relatively abundant, but exhibit some level of success under simulated rooftop conditions. Subsidiary species include *S. hispanicum* diploid, *S. kamtschaticum, S. sediforme*, *S. spurium* 'Summer Glory,' *S. dasyphyllum* 'Burnati' and *S. reflexum.* Substrate depth influenced species behavior. For example, *S. kamtschaticum*, *S. dasyphyllum* 'Burnati,' and *S. dasyphyllum* 'Lilac Mound' were abundant and able to compete successfully in the 7.5 cm depth, but did not perform well in 2.5 or 5.0 cm substrate depths. Trends for some species were similar across all depths, although abundance was greater as depth increased, specifically for *S. acre, S. reflexum, S. album* 'Bella d'Inverno,' and *S. middendorffianum.* Substrate depth and plant species factors can create dynamic green roof systems that evolve over time according to plant life cycles and competitive characteristics. Complete vegetation on a green roof is recommended, and plant communities will exhibit varying degrees of dominance as populations change in response to rooftop environmental conditions and resource availability.

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Table 1. Relative abundance of 24 species (*Phedimus, Rhodiola,* and *Sedum*) cultivated at three substrate depths (2.5, 5.0, and 7.5 cm) over the 2003 growing season. Abundance reported in weeks, where week 1= 29 July 2003; week 7= 9 September 2003; week 13= 28 October 2003.

	Relative Abundance 2003								
	2.5 cm			5.0 cm			7.5 cm		
	1	7	13	1	7	13	1	7	13
G. paraguayense sbsp. *Bern.*	0.030 a	0.033 a	0.029 a	0.079 a	0.028 b	0.029 b	0.045 a	0.018 b	0.011 b
P. spurius 'Leningrad White'	0.030 a	0.042 a	0.029 a	0.045 a	0.068 a	0.029 a	0.064 a	0.064 a	0.062 a
R. pachyclada					0.012 a				
R. trollii				0.045 a	0.013 a				
S. acre	0.064 a	0.042 a	0.061 a	0.021 a	0.081 b	0.061 b	0.019 a	0.052 b	0.082 b
S. album 'Bella d'Inverno'		0.159 b	0.166 b	0.045 a	0.121 b	0.166 c	0.082 a	0.139 b	0.137 b
S. confusum minor form	0.030 a	0.033 a	0.017 a	0.076 a	0.040 b	0.017 b	0.019 a	0.007 a	0.022 a
S. dasyphyllum 'Burnatii'	0.033 a	0.022 a	0.016 a	0.045 a	0.025 a	0.016 a	0.020 a	0.026 a	0.044 a
S. dasyphyllum 'Lilac Mound'				0.024 a	0.013 a	0.000 a	0.044 a	0.016 b	0.011 b
S. diffusum		0.059 b	0.071 b	0.065 a	0.090 b	0.071 b	0.095 a	0.083 a	0.091 a
S. hispanicum diploid	0.067 a	0.097 a	0.106 a	0.045 a	0.040 a	0.106 b	0.064 a	0.076 a	0.080 a
S. kamtschaticum	0.064 a	0.020 a	0.013 a	0.100 a	0.040 b	0.013 b	0.045 a	0.033 a	0.022 a
S. mexicanum	0.097 a	0.084 a	0.100 a	0.076 a	0.078 a	0.100 a	0.089 a	0.120 a	0.107 a
S. middendorffianum	0.030 a	0.095 b	0.075 ab	0.045 a	0.081 a	0.075 a	0.064 a	0.077 a	0.063 a
S. moranense	0.100 a	0.056 ab	0.033 b	0.021 a	0.012 a	0.033 a	0.038 a	0.052 a	0.034 a
S. pachyphyllum	0.033 a	0.022 a	0.033 a	0.024 a	0.028 a	0.033 a	0.045 a	0.018 b	0.011 b
S. reflexum	0.064 a	0.056 a	0.045 a	0.045 a	0.053 a	0.045 a		0.035 b	0.058 a
S. 'Rockery Challenger'			0.033 a			0.033 a	0.019 a	0.026 a	0.017 a
S. sediforme	0.030 ab	0.020 a	0.074 b		0.055 b	0.074 b	0.020 a	0.028 a	0.038 a
S. 'Spiral Staircase'	0.097 a	0.033 b	0.029 b		0.028 b	0.029 b	0.064 a	0.026 b	0.017 b
S. spurium 'Summer Glory'	0.130 a	0.053 b	0.029 b	0.177 a	0.053 b	0.029 b	0.063 a	0.053 a	0.048 a
S. surculosum var. luteum	0.033 a						0.020 a		
S. X luteoviride				0.024 a			0.038 a	0.026 a	0.017 a
S. X rubrotinctum	0.067 a	0.075 a	0.042 a		0.040 b	0.042 b	0.045 a	0.026 a	0.022 a

Mean separation in rows for each species by LSD (P≤0.05). Lowercase letters denote comparisons over time within individual substrate depths (n=3). The standard error for 2.5, 5.0, and 7.5 cm was ± 0.028, 0.016, and 0.014, respectively. Blanks denote no surviving plants for specific species.

Table 2. Relative abundance of 13 taxa (*Phedimus, Rhodiola,* and *Sedum*) cultivated at three substrate depths (2.5, 5.0, and 7.5 cm) over the 2004 growing season. Abundance reported in weeks, where week 41= 7 April 2004; week 50= 9 June 2004; week 59= 11 August 2004; week 67= 6 October 2004.

	Relative Abundance (2.5 cm)			
	41	**50**	**59**	**67**
P. spurius 'Leningrad White'	0.045 a C	0.069 ab B	0.090 b C	0.080 ab C
R. pachyclada				
S. acre	0.196 a B	0.192 a A	0.187 a A	0.204 a AB
S. album 'Bella d'Inverno'	0.301 a A	0.251 ab A	0.247 b A	0.280 a A
S. dasyphyllum 'Burnatii'				
S. dasyphyllum 'Lilac Mound'				
S. diffusum				
S. hispanicum diploid		0.050 b B	0.041 a C	0.051 a C
S. kamtschaticum	0.021 a C			
S. middendorffianum	0.179 ab B	0.146 a A	0.192 b A	0.157 a B
S. reflexum	0.065 a C	0.114 a AB	0.075 ab C	0.088 a C
S. sediforme	0.110 a C	0.081 a B	0.052 b C	0.050 a C
S. spurium 'Summer Glory'	0.083 a C	0.097 a B	0.116 a B	0.089 a C

Mean separation in rows for each species by LSD ($P \leq 0.05$). Lowercase letters in rows denote differences in weeks (n= 3). Uppercase letters in columns denote differences among species (n=3). Standard error was ± 0.026. Blanks denote no surviving plants for specific species.

Table 2 continued.

	Relative Abundance (5.0 cm)			
	41	**50**	**59**	**67**
P. spurius 'Leningrad White'	0.086 a C	0.091 a D	0.087 a CD	0.077 a C
R. pachyclada				
S. acre	0.208 a A	0.158 b AB	0.197 a A	0.236 a A
S. album 'Bella d'Inverno'	0.200 a A	0.180 a A	0.123 b BC	0.146 b B
S. dasyphyllum 'Burnatii'	0.013 a D	0.020 a D	0.018 a F	0.007 a D
S. dasyphyllum 'Lilac Mound'				
S. diffusum				
S. hispanicum diploid	0.043 a D	0.065 ab D	0.070 ab DE	0.078 b C
S. kamtschaticum	0.046 a D	0.111 b BC	0.118 b BC	0.103 b B
S. middendorffianum	0.147 a B	0.155 a AB	0.167 a AB	0.166 a B
S. reflexum	0.061 a D	0.075 a D	0.076 a D	0.087 a C
S. sediforme	0.091 a C	0.042 b D	0.047 b E	0.044 b C
S. spurium 'Summer Glory'	0.106 a BC	0.104 a BC	0.096 a BC	0.057 b C

Mean separation in rows for each species by LSD ($P \leq 0.05$). Lowercase letters in rows denote differences in weeks (n= 3). Uppercase letters in columns denote differences among species (n=3). Standard error was ± 0.018. Blanks denote no surviving plants for specific species.

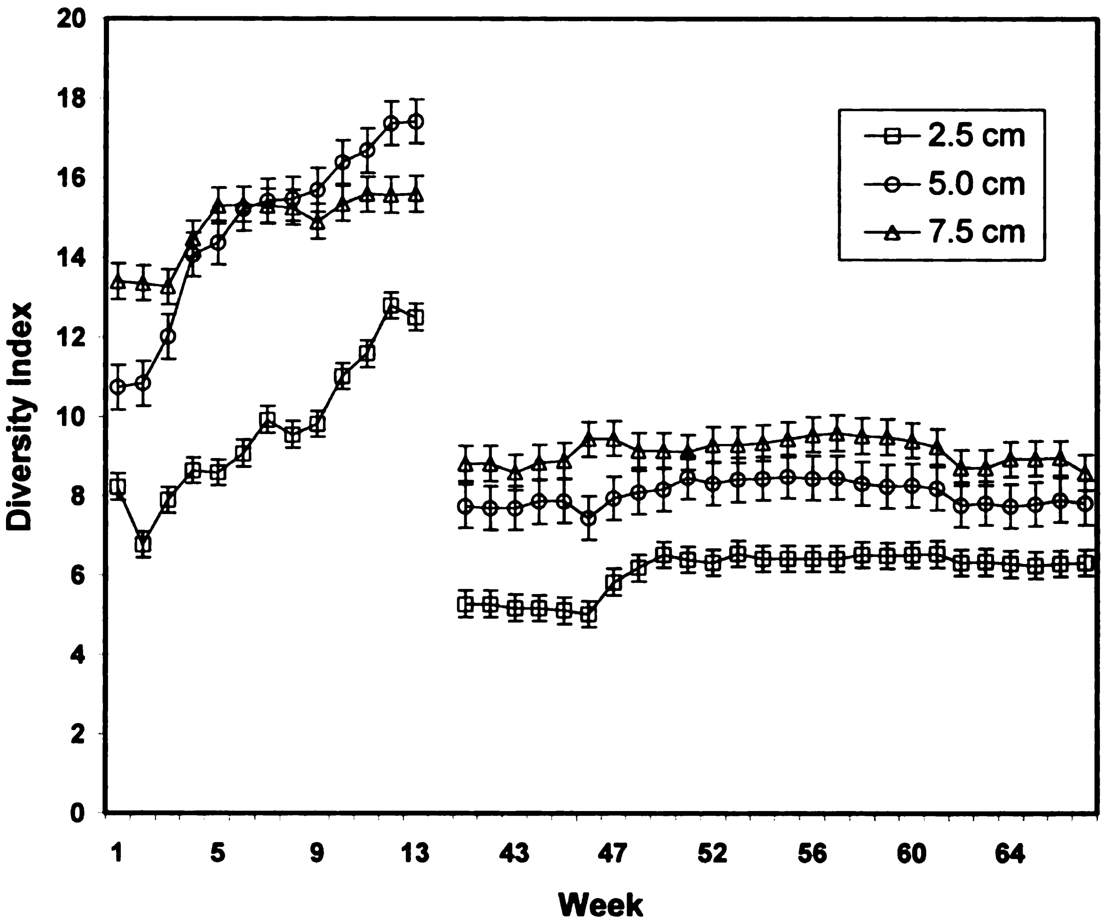
Table 2 continued.

	Relative Abundance (7.5 cm)			
	41	50	59	67
P. spurius 'Leningrad White'	0.103 a B	0.141 b A	0.130 a A	0.136 b A
R. pachyclada			0.002 a D	0.003 a C
S. acre	0.108 a B	0.095 a AB	0.146 b A	0.205 c A
S. album 'Bella d'Inverno'	0.185 a A	0.165 a A	0.100 b AB	0.086 b B
S. dasyphyllum 'Burnatii'	0.071 a B	0.046 a C	0.061 a BC	0.042 a B
S. dasyphyllum 'Lilac Mound'	0.018 a C	0.029 a C	0.050 b C	0.046 b B
S. diffusum		0.003 a D	0.002 a D	0.015 a B
S. hispanicum diploid	0.122 a B	0.125 a A	0.102 a A	0.074 a B
S. kamtschaticum	0.024 a C	0.072 b B	0.078 b B	0.071 b B
S. middendorffianum	0.142 a AB	0.144 a A	0.177 b A	0.202 b A
S. reflexum	0.095 a B	0.097 a A	0.080 a B	0.063 a B
S. sediforme	0.059 a B	0.028 a C	0.047 a C	0.042 a B
S. spurium 'Summer Glory'	0.073 a B	0.054 a BC	0.026 b C	0.014 b B

Mean separation in rows for each species by LSD ($P \leq 0.05$). Lowercase letters in rows denote differences in weeks (n= 3). Uppercase letters in columns denote differences among species (n=3). Standard error was ± 0.017. Blanks denote no surviving plants for specific species.

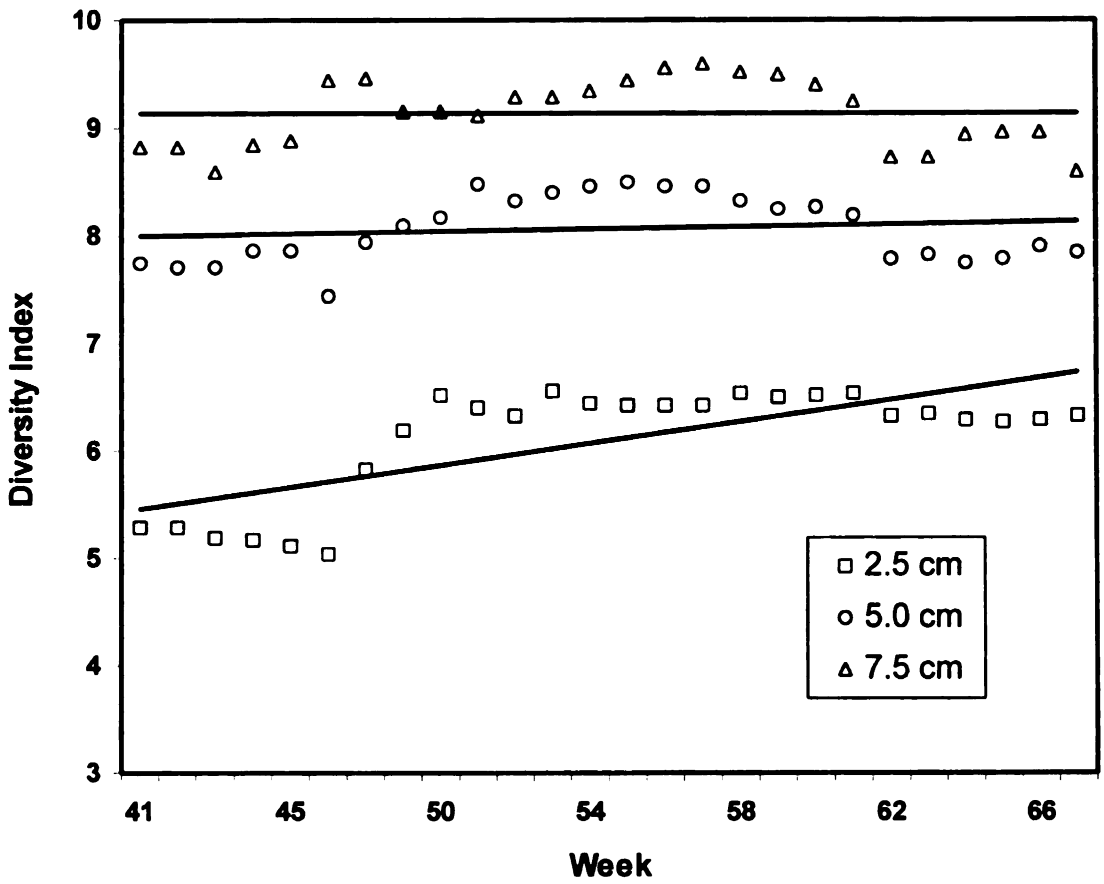
LIST OF FIGURES

Figure 1.



Diversity index (e^H) calculated using the Shannon Index over the entirety of the study. Symbols represent indices which were averaged across depths. Notice time lag in the x-axis which denotes over-wintering. Error bars represent standard error.

Figure 2.



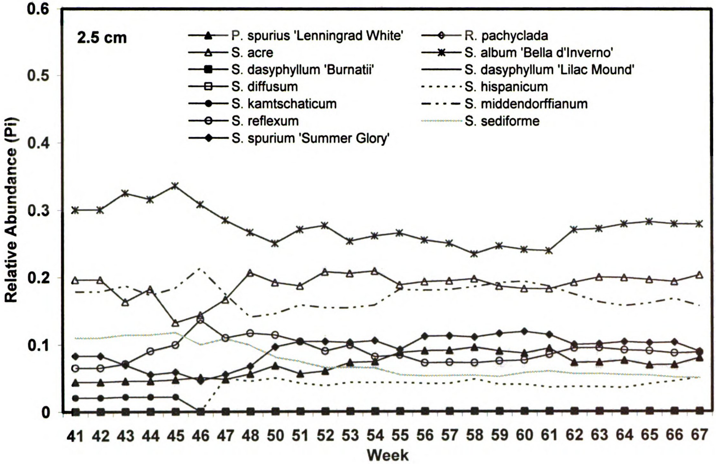
Diversity index (e^H) calculated using the Shannon Index over 2004. Symbols represent actual treatment means. The independent regression equation of three substrate depths (2.5, 5.0, 7.5 cm) was Y= β_0 +β_1*week (n=78), where

2.5 cm y = 3.4326 +0.0492*week

5.0 cm y = 7.7168 +0.0064*week

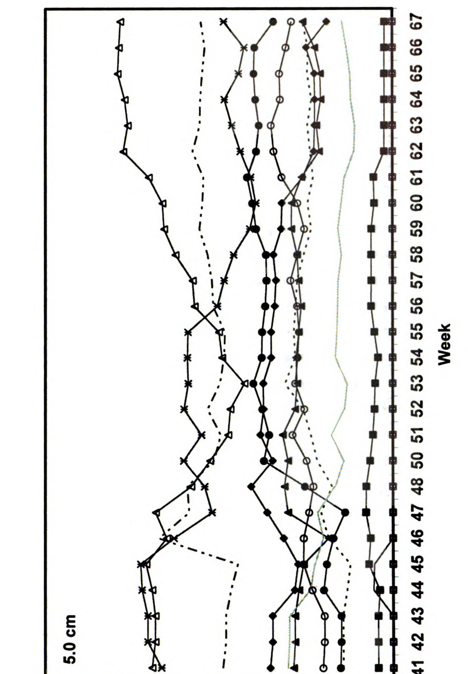
7.5 cm y = 9.0707 +0.0012*week

Figure 3a.



2.5 cm
P. spurius 'Lenningrad White'
S. acre
S. dasyphyllum 'Burnatii'
S. diffusum
S. kamtschaticum
S. reflexum
S. spurium 'Summer Glory'
R. pachyclada
S. album 'Bella d'Inverno'
S. dasyphyllum 'Lilac Mound'
S. hispanicum
S. middendorffianum
S. sediforme
Relative Abundance (Pi)
0.6
0.5
0.4
0.3
0.2
0.1
0
41 42 43 44 45 46 47 48 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67
Week

Figure 3b.



5.0 cm
Relative Abundance (Pi)
0.3
0.25
0.2
0.15
0.1
0.05
0
Week
41 42 43 44 45 46 47 48 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67

Figure 3b.

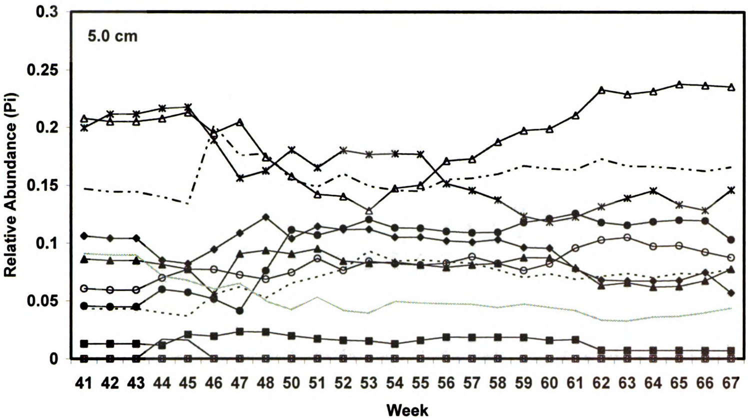
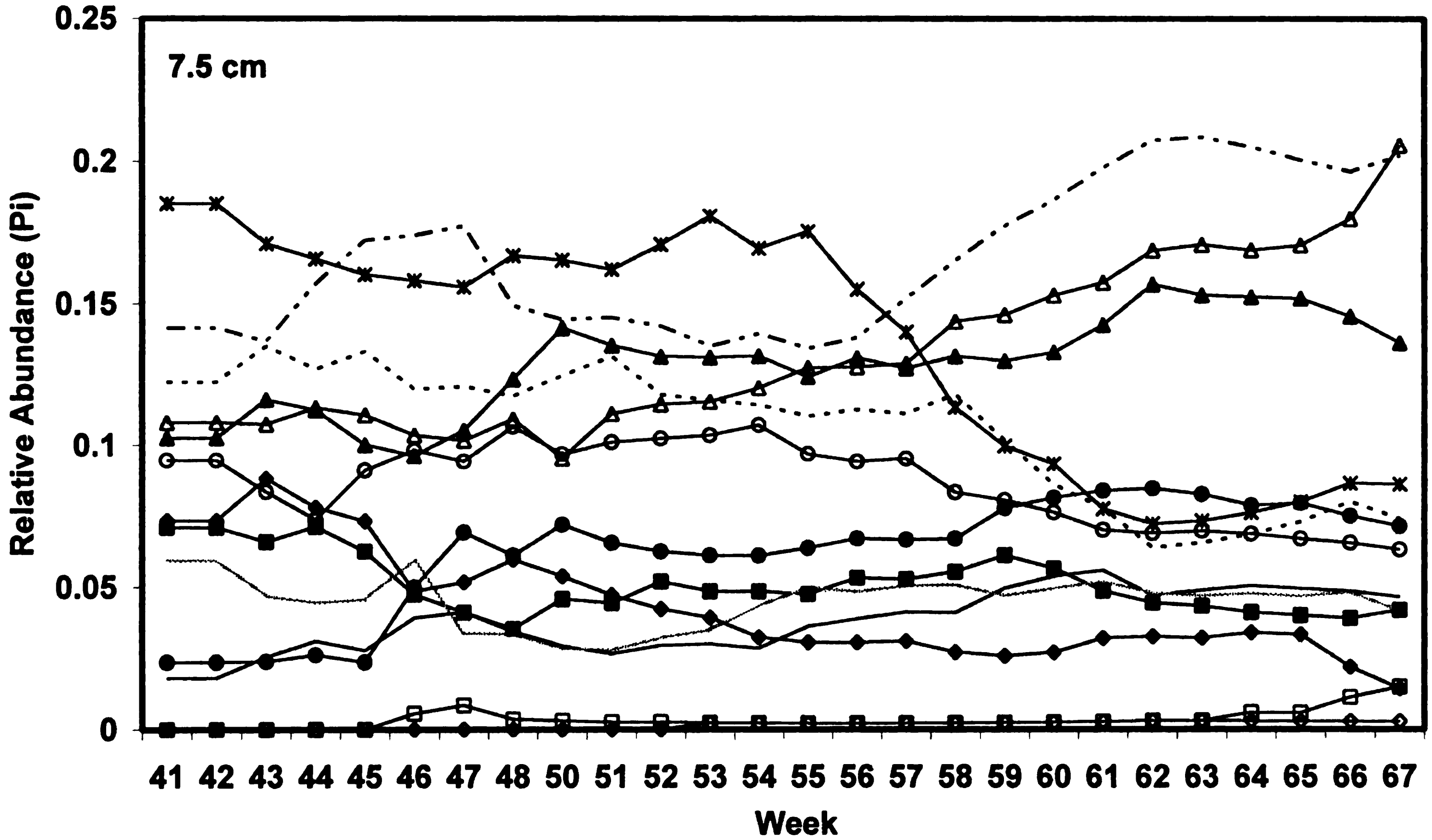

5.0 cm
Relative Abundance (Pi)
0.3
0.25
0.2
0.15
0.1
0.05
0
41 42 43 44 45 46 47 48 50 51 52 53 54 55 56 57 58 59 60 61 62 63 64 65 66 67
Week

Figure 3c.



Relative abundance of 13 taxa (*Phedimus, Rhodiola,* and *Sedum*) cultivated at three substrate depths (2.5, 5.0, and 7.5 cm) over the 2004 growing season. Symbols represent abundance means (n=3).

CHAPTER THREE

Drought tolerance of various extensive green roof plant taxa

Drought tolerance of various extensive green roof plant taxa

Additional index words. vegetative roof, living roof, chlorophyll fluorescence, drought stress, Sedum, Crassulacean acid metabolism

Abstract

Green roofs, or vegetative or living roofs, are an emerging technology in the United States. Because environmental conditions are often more extreme on rooftops, many xerophytic plants, especially *Sedum,* are ideal for extensive green roofs because they are physiologically and morphologically adapted to withstand drought. Limited studies have been performed to determine the water requirements necessary to sustain vegetation on rooftops in Michigan region. A greenhouse experiment was conducted to determine the effect of watering regimes on plant stress as measured by chlorophyll fluorescence (F_v/F_m), plant dry weight accumulation, and substrate moisture on succulent plants of *Sedum acre* L., *S. reflexum* L., *S. kamtschaticum ellacombianum* Fisch., and non-CAM plants of *Schizachyrium scoparium* Nash, and *Coreopsis lanceolata* L. Plants were grown at a substrate depth of 7.5 cm. Results indicate even after the four month period, *Sedum* spp. survived and maintained active photosynthetic metabolism, relative to *Schizachyrium* and *Coreopsis.* Furthermore, when *Sedum* was watered after 28 days of drought, chlorophyll fluorescence (F_v/F_m) values recovered to values characteristic of the 2 days between watering (DBW) treatment. In contrast, non-CAM plants required watering frequency every other day in order to survive and maintain active growth and development.

Regardless of species, the greatest increase in total biomass accumulation and fastest growth occurred under the 2 DBW regimes.

Introduction

Extreme environmental conditions often found on rooftops present challenges for sustaining plant material on green roofs. Increased wind velocities, sun exposure, extreme heat, cold, shallow substrate depths and drought are usually associated with rooftops can restrict the plant pallet to species capable of tolerating these harsh conditions. Water availability is one of the most limiting factors for a green roof (Kirschstein, 1997; Dunnett and Kingsbury, 2004). Extensive green roof systems are shallow (3 cm-10 cm) and lightweight (70 to 170 kg/m^2), and generally rely on natural precipitation to maintain viable plant life, although irrigation systems are sometimes used during establishment or when plant health begins to decline (Dunnett and Kingsbury, 2004). The presence of drought tolerant vegetation is essential for the longevity of green roofs designed for long-term sustainability.

Many xerophytic plants are ideal for extensive green roofs because they are physiologically and morphologically adapted to withstand harsh environmental conditions (Gebauer, 1988). Some exhibit Crassulacean acid metabolism (CAM), a physiological pathway that enables these plants to adapt to water-stress conditions (Gebauer, 1988; Ting, 1985; Sayed, 2001). CAM is defined as a massive diurnal fluctuation of titratable acidity, accounted for by malic acid (Ting, 1985). Typically, the diurnal curve of CO_2 exchange can be divided into four phases: (1) malic acid is carboxylated and stored in large vacuoles, (2) CO_2 fixation produces malic acid and there is an increase in stomatal conductance, (3) malic acid is decarboxylated and CO_2 is accumulated, and (4) typical photosynthesis and carbohydrate synthesis occurs. Because stomata are closed during the day, plant gas exchange occurs at night, thus reducing transpirational water loss. The nocturnal uptake and fixation of CO_2 produces oxalacetate, which quickly reduces to malate. Subsequently, malic acid accumulates and is stored in large vacuoles until the light period. During the light period, malic acid floods from the vacuole, and is decarboxylated to produce pyruvate, phosphoenolpyruvate (PEP), or other storage carbohydrates such as starch. Generally, CAM activity directly related to water availability and temperature.

CAM plants also have fewer stomata than C_3 and C_4 plants (Sayed, 2001). Some CAM plants are classified as facultative CAM (otherwise called C_3- C_4-intermediate or inducible) where the photosynthetic pathway can shift from C_3 to CAM under stressed conditions (Kluge, 1977; Lee and Kim, 1994). Facultative CAM has been demonstrated in *Sedum acre* L., *S. kamtschaticum ellacombianum* Fisch., *S. pulchellum* L., *S. reflexum* L., and *S. ruprestre* L. (Lee and Kim, 1994; Sayed, 2001). Additionally, many succulents, such as *Sedum,* have the capacity to store greater amounts of water in their fleshy leaves (Sayed, 2001).

In general, when water deficit develops slowly and affects plant developmental processes, cell volume decreases, and lowers turgor pressure

(Taiz and Zeiger, 1998). Decreased root water potential and inhibited leaf expansion lowers plant transpiration rates, to conserve water (Taiz and Zeiger, 1998). Drought stress can affect Photosystem II efficiency, decreasing the photosynthetic potential yield of the photochemical reaction (Krause and Weis, 1991). This yield can be measured as chlorophyll fluorescence, a re-emittance of light energy from the PS II reaction, known as the "Kautsky Effect" (Bolhar-Nordenkampf et al., 1989). Measurements of chlorophyll fluorescence can detect direct effects on the photosynthetic apparatus and other physiological effects that feed back to photosynthesis (Bolhar-Nordenkampf et al., 1989). The ratio of variable fluorescence to maximum fluorescence (F_v/F_m) is a relatively easy method to quantify drought stress before it becomes visually apparent (Willits and Peet, 1999).

The transpiration ratio, the reciprocal of water use efficiency, is a value that measures the effectiveness of plants in moderating water loss while allowing sufficient CO_2 uptake for photosynthesis (Taiz and Zeiger, 1998). C_3 and C_4 plants generally transpire less water per molecule of CO_2 fixed, thus exhibit a higher transpiration ratio. CAM plants have a much lower ratio, or high water use efficiency, because less water molecules are lost when CO_2 is fixed.

Several studies have looked at drought stress on various taxa grown on green roof applications and demonstrate that *Sedum* spp. commonly outperform other taxa (Monterusso et al., 2005; Gómez-Campo, 1994; Kirschstein, 1997; LasSalle,1998; Durhman et al., 2004; VanWoert et al., 2005; Dunnett and Nolan, 2004). Knowledge of water requirements for individual plant species is important in choosing green roof vegetation type and maintaining plant health. Therefore, the objective of this study was to determine the effect of watering regime on plant stress as measured by chlorophyll fluorescence, plant dry weight accumulation, evapotranspiration, and substrate moisture.

Materials and Methods

A drought tolerance study comparing three species of *Sedum* and two non-CAM plants was conducted at the Plant Science Greenhouses at Michigan State University, East Lansing, Mich. The experiment was a two-way factorial design consisting of five species, five watering regimes, and an unvegetated control treatment to aid in tracking water use. There were seven replications of each treatment for a total of 175 pots. Pots were arranged in a completely randomized design with a single non-sampled border row, consisting of vegetated and un-vegetated control pots, surrounding the study.

Plastic pots (11 cm x 11 cm x 12 cm deep) were fitted with a green roof filtration drainage layer (XF108) and vegetation carrier (XF301) (Wolfgang Behrens Systementwicklung, GmbH, Groß Ipener, Germany). Total thickness of the drainage layer and vegetation carrier was approximately 3.75 cm. This system allowed excess water from the retention fabric and planting media to drain through the nylon coils and exit the pot without losing substrate (Figure 1).

Pots were filled with media to a depth of 7.5 cm. Media consisted of 40% heat-expanded slate (gradation of 3 mm to 5 mm) (PermaTill®, Carolina Stalite Company, Salisbury, N.C.), 40% United States Golf Association (USGA) grade sand (Osburn Industries, Taylor, Mich.), 10% Michigan peat (Osburn Industries, Taylor, Mich.), 5% dolomite (Osburn Industries, Taylor, Mich.), 3.33% composted yard waste (Kalamazoo Landscape Supplies, Kalamazoo, Mich.), and 1.67% composted poultry litter (Herbruck's, Saranac, Mich.). At time of planting, electrical conductivity (EC) and pH of the media were 3.29 mmho•cm^{-1} and 7.9, respectively. All treatments had 100 g•m^{-2} of Nutricote® type 100, 20N-7P-10K controlled release fertilizer (Agrivert, Webster, TX) hand-applied at the time of planting.

The perennials in this study were selected based on their low winter mortality when grown on green roof platforms in East Lansing, Michigan (Monterusso et al., 2005). Seeds of *Sedum acre* L. (biting stonecrop), *S. reflexum* L. (crooked stonecrop), *S. kamtschaticum ellacombianum* Fisch. (kirin-sō), *Schizachyrium scoparium* Nash (little bluestem), and *Coreopsis lanceolata* L. (lanceleaf coreopsis), were sown on 14 January 2003. Seeds of *S. acre, S. reflexum,* and *S. kamtschaticum ellacombianum* were sown at rates of 1 g•m^{-2}, 0.5 g•m^{-2}, and 0.5 g•m^{-2}, respectively. The non-CAM species *Schizachyrium scoparium* , a Michigan native perennial grass, and *Coreopsis lanceolata* a Michigan native perennial forb, were planted at a rate of ten seeds/pot, and then thinned to one seedling/pot. Seeds of *S. scoparium* and *C. lanceolata* were obtained from Prairie Nursery (Westfield, Wis.), while *Sedum* seed was provided by Jelitto Staudensamen, GmbH (Schwarmstedt, Germany). Due to its extremely small size, seeds of *Sedum* were mixed in dry sand prior to application to ensure even distribution within each pot. Plants germinated, established, and grew for an 85 day period; and watered daily for the first 20 days to keep the substrate moist, then once every other day for the next 65 days. Plants were considered established when they covered 90% of the substrate surface.

Following the establishment period, watering regime factors of 2, 7, 14, 28, or 88 days between watering (DBW) were randomly assigned to each pot. All plants received a consistent amount of tap water,157 mL, with each watering, which converted to 13 mm of precipitation. Excess water was allowed to drain out of the pot.

During both the establishment and data collection periods, natural lighting in the greenhouse was supplemented with 400 watt incandescent bulbs for a 16 h photoperiod. Average light meter (model LI-250, LI-COR, Inc., Lincoln, NE.) measurements at canopy height ranged from 338.4 $\mu mol \bullet s^{-1}\ m^{-2}$ to 897.1 $\mu mol \bullet s^{-1}\ m^{-2}$. Air temperature was controlled by a thermostat set at 21±1°C.

Data Collection. Data collection began on 10 April 2003. Measurements were taken daily the first 7 days of the study, every other day from days 9 to 33, and once a week until the study was terminated on day 89. Each data collection event included measuring chlorophyll fluorescence, soil moisture, and whole pot weights to record evapotranspiration before the watering treatment.

To establish an initial mean dry weight of the biomass, a representative sub-sample of five plants per species was selected and harvested on the first day of the study. The above ground biomass was destructively harvested at the substrate interface and dried for 144 h at 60°C. Upon completion of the study, 89 days later, shoots from every treatment were destructively harvested and dried at 60°C. Biomass accumulation was calculated as the difference between the mean initial (sub-sample) and final shoot dryweights. To compare plant growth across species, percent increase in biomass was calculated by dividing biomass accumulation over initial dry weight.

A Hansatech plant efficiency analyzer (PEA) was used to measure chlorophyll fluorescence induction by the high time resolution continuous excitation principle (Hansatech Instruments, Ltd., Norfolk, England). Each plant was dark adapted for ten minutes prior to measurement and illuminated with a 50% light level. Maximum quantum efficiency of photosystem II was recorded (F_v/F_m). Single leaf blades of *S. scoparium*, *C. lanceolata*, and *S. kamtschaticum* were randomly selected and measured while attached to the plant. Leaf blades of *S. acre* and *S. reflexum* were randomly selected and excised from the plant to be dark adapted and measured. This was necessary because the PEA clips were not secure on the leaf while still attached to the whole plant. The standard error for this method was $\pm$ 0.03.

Substrate moisture was monitored throughout the study by inserting a theta probe (ML2x, Delta-T Devices, Ltd., Cambridge, United Kingdom) into the media until the points of the prongs contacted the vegetation carrier. The theta probe instrument has a range of 0.0 to 1.0 $m^3 \cdot m^{-3}$, with accuracy of $\pm$0.01 $m^3 \cdot m^{-3}$ for values from 0.05 to 0.6 $m^3 \cdot m^{-3}$. However, accuracy was likely lower for values below 0.05 $m^3 \cdot m^{-3}$ (Delta-T Devices, 1999). Soil moisture was taken to evaluate water availability for the plants and determine the amount of time it takes for treatments to reach complete dehydration.

Evapotranspiration (ET) values were derived from pot weight measurements over the first week of the study, similar to VanWoert et al. (2005). An estimate of water retention by each pot was measured by pot weight before and after watering on the first day. For the rest of the week, pot weights were taken directly before the watering event.

Statistical analysis. Chlorophyll fluorescence data were analyzed by PROC GLM, least significant differences (LSD) with a Tukey-Kramer adjustment (SAS version 8.02, SAS Institute Inc., Cary, N.C.). Evapotranspiration values derived from pot weights and soil moisture data were subjected to repeated measures using an unstructured covariance structure (PROC MIXED). Total shoot dryweight and shoot biomass percent accumulation data were analyzed by PROC MIXED, LSD with a Tukey-Kramer adjustment.

Results and Discussion

Chlorophyll fluorescence. Watering regime influenced F_v/F_m (Figures 2 and 3). The F_v/F_m values decreased for plants grown under the less frequent watering regimes. This occurred for the three species of *Sedum* at the 88 DBW regime; and at all watering regimes longer than 2 DBW for *C. lanceolata* and *S. scoparium.* The three species of *Sedum* maintained active photosynthetic capacity and survived the four month period, including those plants that were never watered during the 88 day period. In contrast, the non-CAM plants, *C. lanceolata* and *S. scoparium,* died unless they received water every other day.

The three species of *Sedum* exhibited similar F_v/F_m trends throughout the study, much different from the non-CAM species. The F_v/F_m mean over the whole study for *S. acre* under the 2 DBW was 0.758. Although all *Sedum* behaved similarly, *S. acre* exhibited slightly higher F_v/F_m values than either *S. kamtschaticum ellacombianum* or *S. reflexum.* In the most extreme drought treatment of 88 DBW, the F_v/F_m values for *S. acre* fell under 0.500 only twice during the course of the study, occurring first on day 68 (data not shown). In contrast, *S. kamtschaticum ellacombianum* and *S. reflexum* F_v/F_m values fell below 0.500 more often and earlier, by day 40 and day 50, respectively. The data suggests *S. acre* may be more drought tolerant than *S. kamtschaticum ellacombianum* and *S. reflexum.*

One interesting observation was the recovery rate for the three species of *Sedum* following watering events. Upon watering the 28 DBW regime, *Sedum* F_v/F_m values returned to those values characteristic of the 2 DBW treatments. At the end of the three month period, there was no difference ($P \leq 0.05$) in chlorophyll fluorescence between 2 DBW and 28 DBW post watering (data not shown).

In contrast, all F_v/F_m values for *C. lanceolata* and *S. scoparium* declined rapidly by day 4 for all watering regimes except 2 DBW (Figure 2). Over the 89 day study, the average F_v/F_m ratio for *C. lanceolata*, was 0.793 for the 2 DBW treatment. However, for all other watering treatments, both *C. lanceolata* and *S. scoparium* reached a permanent wilting point by day 33. These results complemented the results of LasSalle (1998) in which *S. album* outperformed

Festuca glauca Vill. and *Chrysanthemum leucanthemum* L. in response to watering regimes.

Every species is unique and will vary in biological activity in response to environmental conditions, but one study observed *S. rubrotinctum* survived under greenhouse conditions for two years without water (Teeri et al., 1986). *Sedum* species are able to tolerate drought, maintain functional photosynthetic systems, and survive relative to *C. lanceolata* and *S. scoparium* because they demonstrate facultative CAM and are efficient in water use. In contrast, *S. scoparium* and *C. lanceolata* exhibit C_4 and C_3 plant physiology in response to the natural environments they live in. Under extensive green roof conditions with a shallow depth of 7.5 cm, watering frequency greater than 7 DBW was necessary for plant growth and development for *C. lanceolata* and *S. scoparium*.

Biomass accumulation. The greatest increase in biomass generally occurred under the 2 DBW regimes. This is especially evident for the native plants where drought conditions created by 7, 14, 28 and 88 DBW permitted little biomass accumulation (Table 1). The result confirms the observation that non-CAM plants, *C. lanceolata* and *S. scoparium,* were dead within 33 days of the study if they did not receive the 2 DBW treatment.

Sedum reflexum accumulated greater biomass than the other species under the 88 DBW regime, and for most other watering regimes except the 2 DBW treatment (Table 1). *Sedum reflexum* was least affected by the 88 DBW regime. Among the three *Sedum*, S. *kamtschaticum ellacombianum* most affected by watering regime, as it has been documented to grow in less xeric conditions than *S. acre* and *S. reflexum* (Kirschstein, 1997; Stephenson, 2002). Additionally, S. *kamtschaticum ellacombianum* has more spreading shoots and wide, broad, and thin leaf structure, presenting a thicker canopy with than either *S. acre* or *S. reflexum*, whose leaves are linear and crowded against the stem (Eggli and Hartmann, 2003) which may attribute to higher water demands.

Percentage increase in shoot dry weight. Mean initial shoot dry weights taken from representative samples for *C. lanceolata*, *S. scoparium* , *S. acre*, *S. kamtschaticum ellacombianum,* and *S. reflexum* were 0.992, 0.799, 1.441, 1.781, and 0.869 g, respectively. Biomass percentage increases makes it possible to make direct comparisons between species across different watering treatments (Table 2). Overall, *S. reflexum* consistently grew faster compared to *S. acre* and *S. kamtschaticum ellacombianum*. The 2 and 7 DBW regimes resulted in four times as much growth as 88 DBW for *S. reflexum*.

A range of percent biomass increases for different species occurred under the 2 DBW treatment, where *C. lanceolata* (475%), *S. scoparium* (461%) and *S. reflexum* (334%) exhibited high percent increases, relative to *S. kamtschaticum ellacombianum* (309%) and *S. acre* (267%). With adequate watering, all plants displayed healthy and consistent growth and development. When considering planting a mixture of different plant species for a green roof, plants that require frequent watering could be planted in areas designed with zoned irrigation or in deeper substrates. However, with watering intervals of seven days or more, growth was not significant for *C. lanceolata*, *S. scoparium* or *S. kamtschaticum ellacombianum.* The phenomenon of a decrease in biomass accumulation supports findings from VanWoert et al. (2005) which could be attributed to the high demand of water needs required by larger vegetation. Potential degradation of non-structural carbohydrates within the plants could have occurred after the establishment period in response to a lack of water (Taiz and Zeiger, 1998).

Substrate moisture. Observed volumetric substrate moisture content was typical of sandy soils. Initial content after a watering event was as high as 0.34 $m^3 \cdot m^{-3}$. However by day 5, no pots had detectable soil moisture except for those that received the 2 DBW treatment (Figure 4). During the first week of data collection, substrate moisture content at 7 DBW is representative of the 14, 28, 88 DBW treatments, therefore, only the 7 DBW regime is shown.

Comparing soil moisture among treatments on the last day of the study, pots with *S. acre* and *S. reflexum* held more moisture under the 2 DBW regime than those of S. *kamtschaticum ellacombianum, S. scoparium, C. lanceolata*, and the un-vegetative control under the same regime (Figure 5). Additionally, *S. acre* held greater moisture than either of the two *Sedum* or *S. scoparium* under the 7 DBW treatment. The result may be because *S. acre* and *S. reflexum* have lower water requirements, therefore the plants did not take up as much water, which allowed moisture to be retained in the substrate. Additionally, above ground biomass for *S. acre* and *S. reflexum* was located closer to the substrate surface and may have contributed to shading, reducing evaporation from the substrate. The shading effect was reported in previous research showing intervals between irrigation could be increased after canopy closure of 'Impulse Rose' Impatients (*Impatiens wallerana* L.) grown in containers (Lohr and

Pearson-Mims, 2001). *Sedum kamtschaticum ellacombianum* had the highest biomass in the 2 DBW attributed to its numerous spreading stems and broad flat leaves, which may have contributed to higher water needs. *Schizachyrium scoparium* and *C. lanceolata* did not produce a dense canopy so there was minimal shading to reduce evaporation losses.

In a similar study comparing substrate types and vegetation effect on substrate moisture, VanWoert et al. (2005) reported that, in general, substrates with vegetation contained more water than the unvegetative treatment. However, in this study, a loose trend can be seen between vegetation type and soil moisture. By the end of the experiment, sufficient biomass had accumulated to compare the vegetation types to soil moisture. Substrate in pots of *Coreopsis lanceolata* had significantly less to soil moisture than the other species, including *S. scoparium* (Figure 3). However, pots of *S. acre* consistently retained the most moisture.

Evapotranspiration. Due to the variability in the data collection dates, evapotranspiration (ET) was analyzed daily for the first week of the study (Figure 6). ET rates were highest on the day of watering and lower on the second day, however a gradual increase over the first week occurred under the 2 DBW regime. *Coreopsis lanceolata* was most affected by watering regime as ET values were higher on the day of watering, relative to *Sedum,* and fell to the lowest value following the water treatment. This is probably due to its large leaf area, compared to the other species.

For all species, having not received water for six days resulted in fallen ET rates (between 0.1 and 0.2 mm•d^{-1}) (Figure 6). Surprisingly, over the course of the first week of drought, *S. scoparium* exhibited higher ET rates compared to *C. lanceolata*. This may be due to the differences in water use efficiencies, differences in drought tolerance, and leaf surface area. The 7 DBW results contrast VanWoert et al. (2005) where rates dropped to 0.0 mm•d^{-1} for *Sedum spp.* mixture. This difference may due to differences in substrate composition and depth as greenhouse conditions were comparable.

ET rates presented for 2 and 7 DBW are probably conservative, compared to measurements taken outdoors. In the natural environment, climatic variables are altered by solar radiation and wind where ET rates are directly related. However, observations under controlled greenhouse conditions allow for general assumptions to be made in regards to drought stress.

Conclusion

CAM species such as *Sedum acre, S. reflexum,* and *S. kamtschaticum ellacombianum* do not require as much water to maintain plant vigor and metabolic activity compared to the non-CAM species *Schizachyrium scoparium,* and *Coreopsis lanceolata*. *Sedum* plants sustained photosynthetic activity over a period of four months without watering, although biomass was reduced relative to more frequently watered treatments. One can assume that under frequent watering regimes the native plants can remain photosynthetically active and continue growth and development. However, they need irrigation more frequently than once every seven days to remain photosynthetically active over prolonged periods.

Based on greenhouse results, relative irrigation recommendations may be derived for CAM versus non-CAM species. The result from this study can be extrapolated to many other succulents, herbaceous forbs, and grasses by considering their photosynthetic processes, life-form characteristics, and growth habits for use on an extensive green roof system. Additionally, a method of measuring photosynthetic yield, such as chlorophyll fluorescence, is effective in evaluating plant stress and can be used in green roof applications to maintain plant health and vigor while minimizing excess water use.

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Table 1. Shoot dry-weight biomass accumulation (g) for each treatment over the course of the study. Values were calculated as final dry weight minus initial sub-sample dry weight. Treatment means of different species (*Sedum, Coreopsis,* and *Schizachyrium*) within each watering regime are presented.

	Days Between Watering (DBW)				
	2	7	14	28	88
S. acre	3.85 a ABC	2.11 a A	0.47 b B	0.64 b A	-0.23 b C
S. kamtschaticum	5.51 a A	1.56 b B	1.14 b A	0.30 b A	-0.36 b C
S. reflexum	2.90 a C	2.92 a A	1.22 a A	0.81 a A	1.57 a A
C. lanceolata	4.71 a AB	-0.21 b B	-0.23 b B	0.28 b A	0.43 b B
S. scoparium	3.68 a C	0.01 b B	0.19 b B	-0.08 b B	0.22 b B

Means followed by different lowercase letters (within rows) or uppercase letters (within columns) are significantly different (P≤ 0.05).

Table 2. Percent increase (%) Shoot dry-weight biomass for each treatment over the course of the study. Values were calculated by dividing biomass accumulation over initial dry weight. Treatment means of different species (*Sedum, Coreopsis,* and *Schizachyrium*) within each watering regime are presented.

	Days Between Watering (DBW)				
	2	7	14	28	88
S. acre	267 a B	147 ab B	32 b B	44 b A	16 bc B
S. kamtschaticum	309 a B	88 b B	64 b B	17 b A	-20 b B
S..reflexum	334 a A	336 a A	140 b A	93 b A	181 b A
C. lanceolata	475 a A	-21 b B	-23 b B	28 b A	13 b B
S. scoparium	461 a A	1 b B	24 b B	-10 b A	28 b B

Means followed by different lowercase letters (within rows) or uppercase letters (within columns) are significantly different (P≤ 0.05).

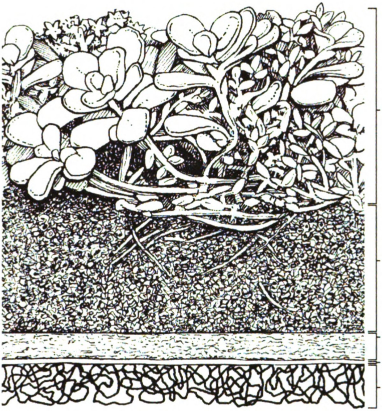
LIST OF FIGURES

Figure | Page

6. Evapotranspiration values ($mm \cdot d^{-1}$) over the first week of the study for watering regimes of 2 days between watering (DBW) and 7 DBW. Symbols represent species of *Sedum, Coreopsis,* and *Schizachyrium*. Error bars represent standard error.

124

Figure 1.



Cross section representative of an extensive green roof system used in the study. Substrate depth in the container was 7.5 cm.

Figure 2.

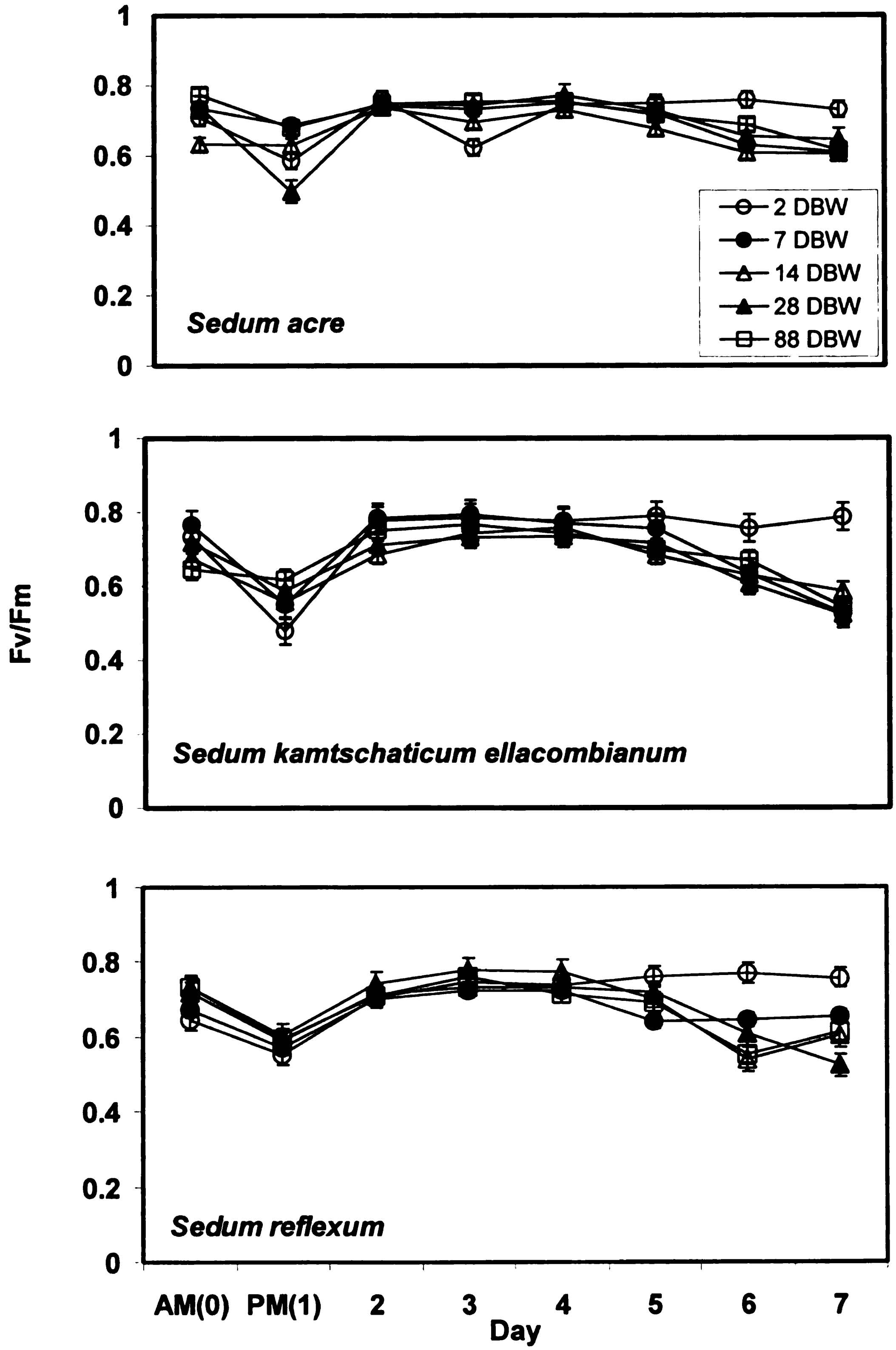
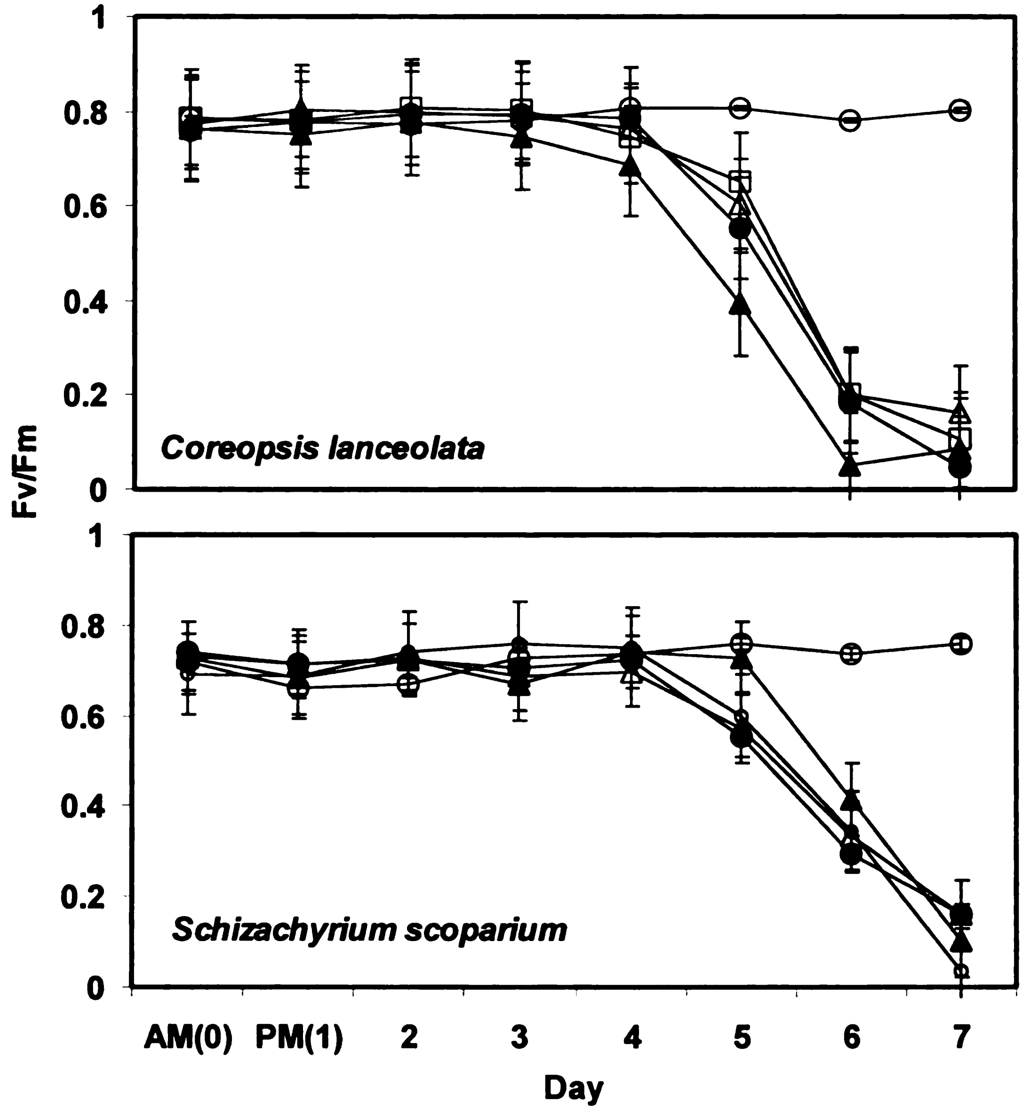
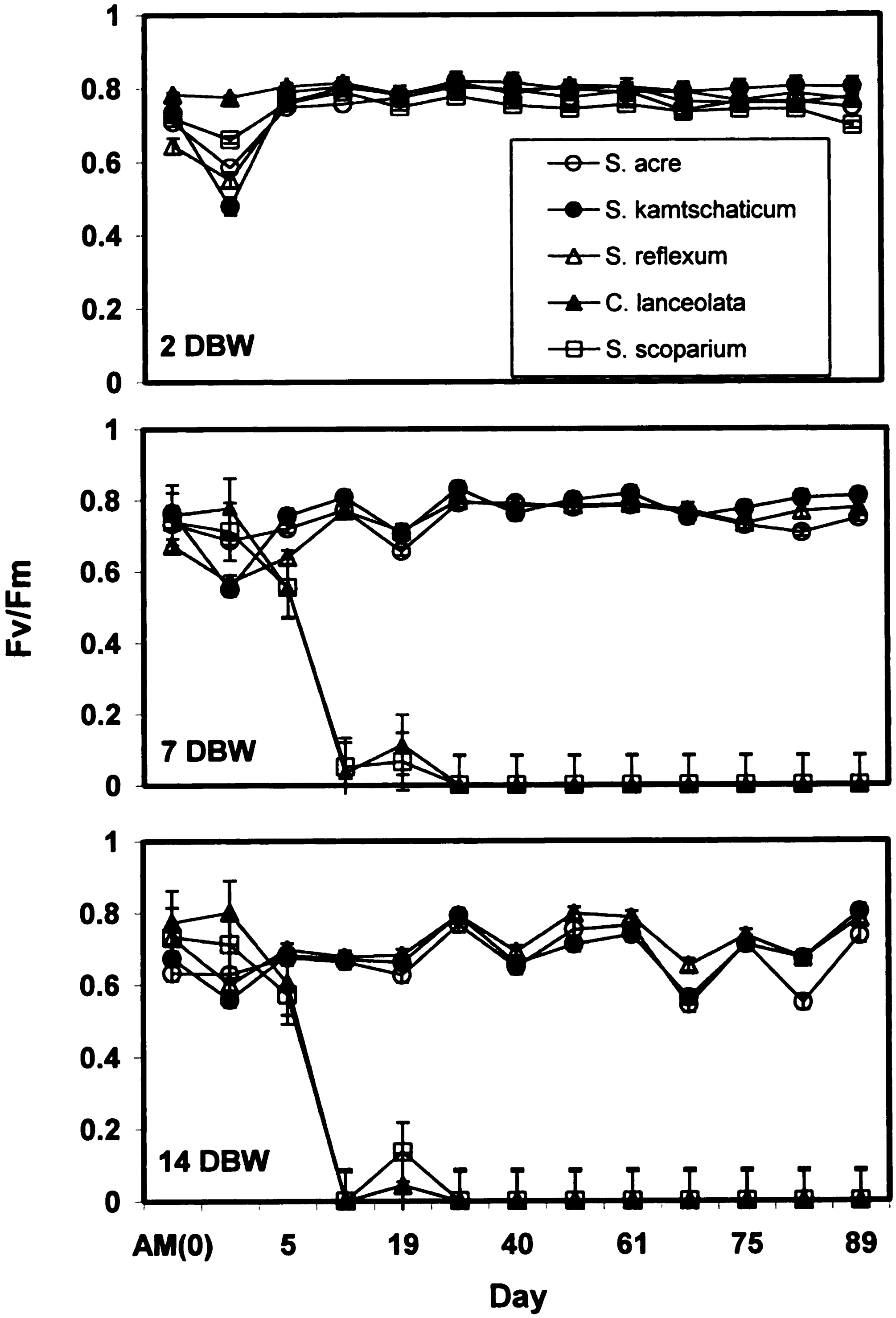

1
0.8
0.6
0.4
0.2
0
Sedum acre
2 DBW
7 DBW
14 DBW
28 DBW
88 DBW
Fv/Fm
Sedum kamtschaticum ellacombianum
Sedum reflexum
AM(0)
PM(1)
2
3
4
5
6
7
Day

Figure 2 continued.



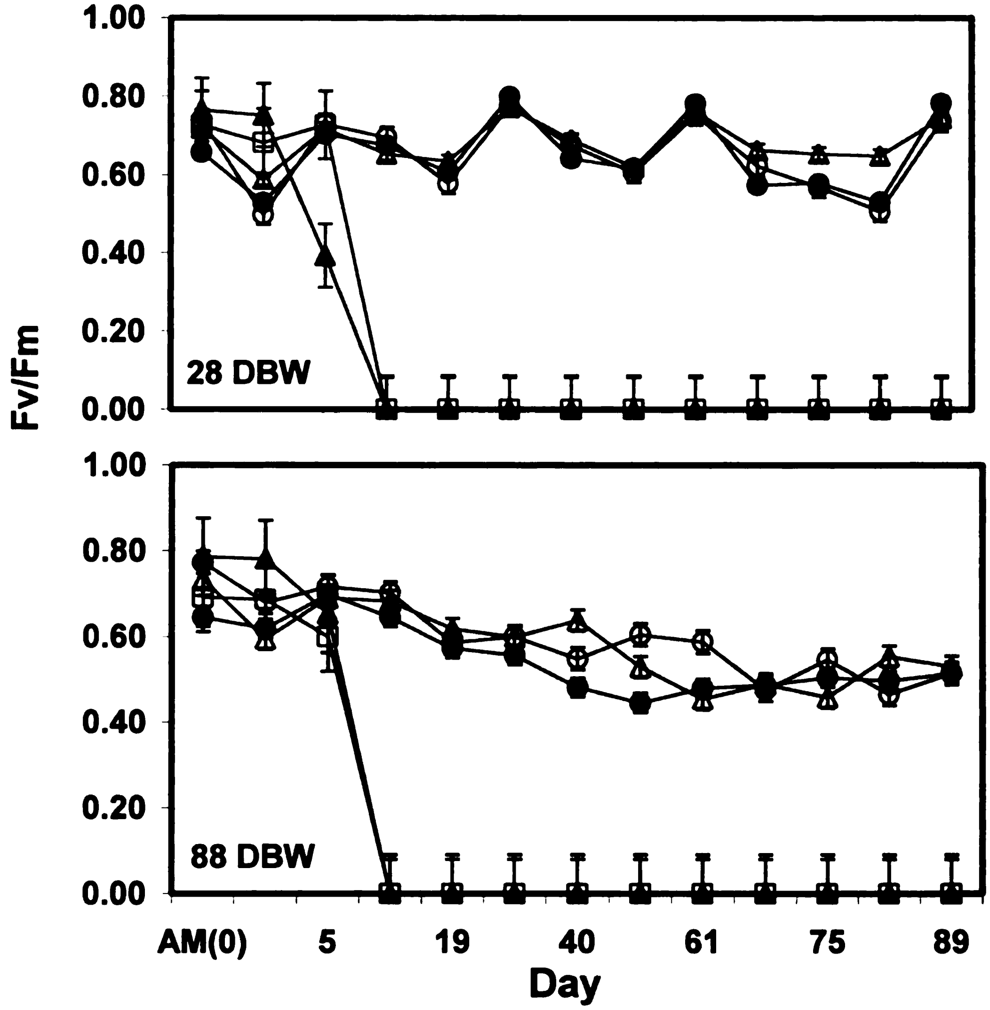
Chlorophyll fluorescence (F_v/F_m) over the first week of the study for five species. Symbols represent means for watering regimes of 2 days between watering (DBW), 7 DBW, 14 DBW, 28 DBW, and 88 DBW (n=7). Data collection on the first day was taken before and after the watering event, denoted by "AM(0)" and "PM(1)." For the duration of the experiment, measurements resumed immediately before the watering event. Error bars represent standard error.

Figure 3.



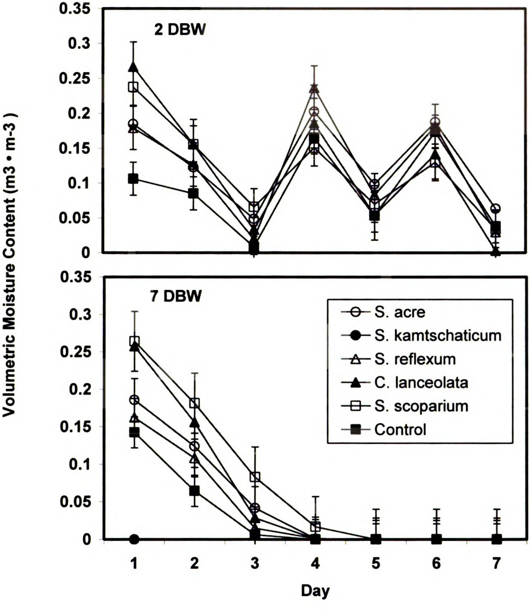
S. acre
S. kamtschaticum
S. reflexum
C. lanceolata
S. scoparium
2 DBW
7 DBW
14 DBW
Fv/Fm
0
0.2
0.4
0.6
0.8
1
AM(0)
5
19
40
61
75
89
Day

Figure 3 continued.



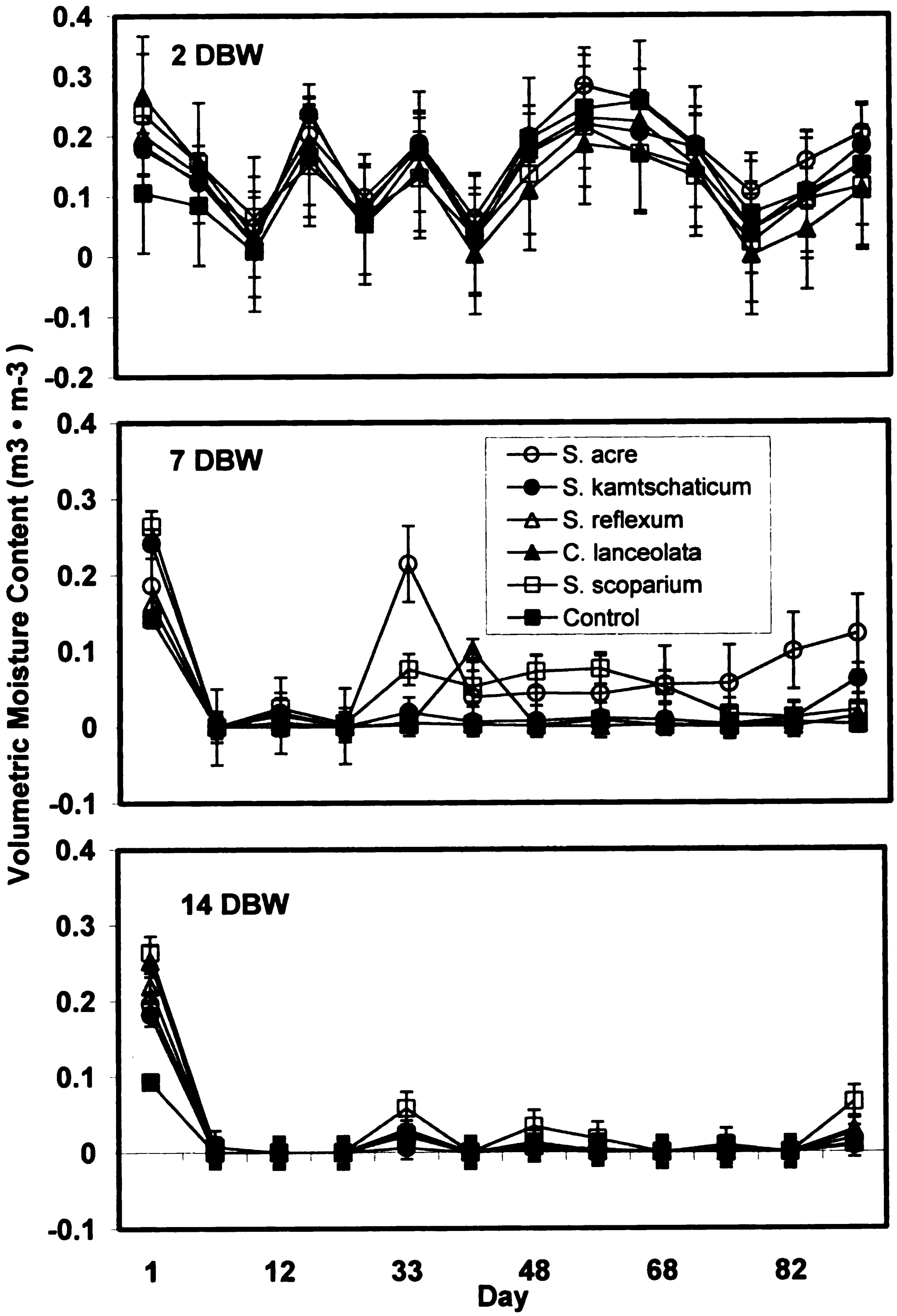
Chlorophyll fluorescence (F_v/F_m) over the 88 day study for five watering regimes of 2 days between watering (DBW), 7 DBW, 14 DBW, 28 DBW, and 88 DBW (n=7). Symbols represent means for five species of (*Sedum, Coreopsis,* and *Schizachyrium*). Data collection on the first day was taken before and after the watering event, denoted by "AM(0)" and "PM(1)." For the duration of the experiment, measurements resumed immediately before the watering event. Error bars represent standard error.

Figure 4.



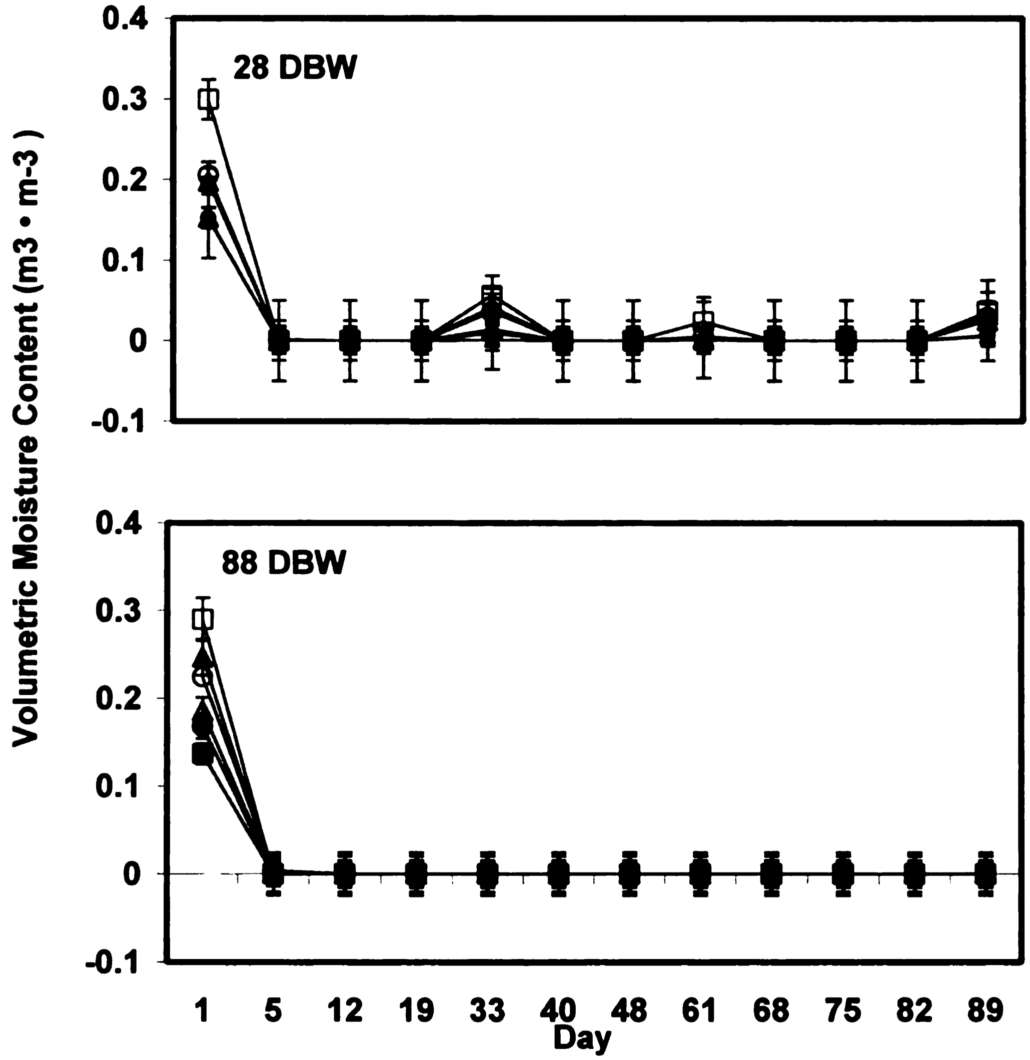
Substrate volumetric moisture content ($m^3 \cdot m^{-3}$) collected over the first week of the study for watering regimes of 2 days between watering (DBW) and 7 DBW (n=7). The graph for 7 DBW is representative of 14, 28, and 88 DBW during the first seven days of the study. Symbols represent species means (*Sedum, Coreopsis,* and *Schizachyrium)* and a non-vegetated control. Error bars represent standard error.

Figure 5.



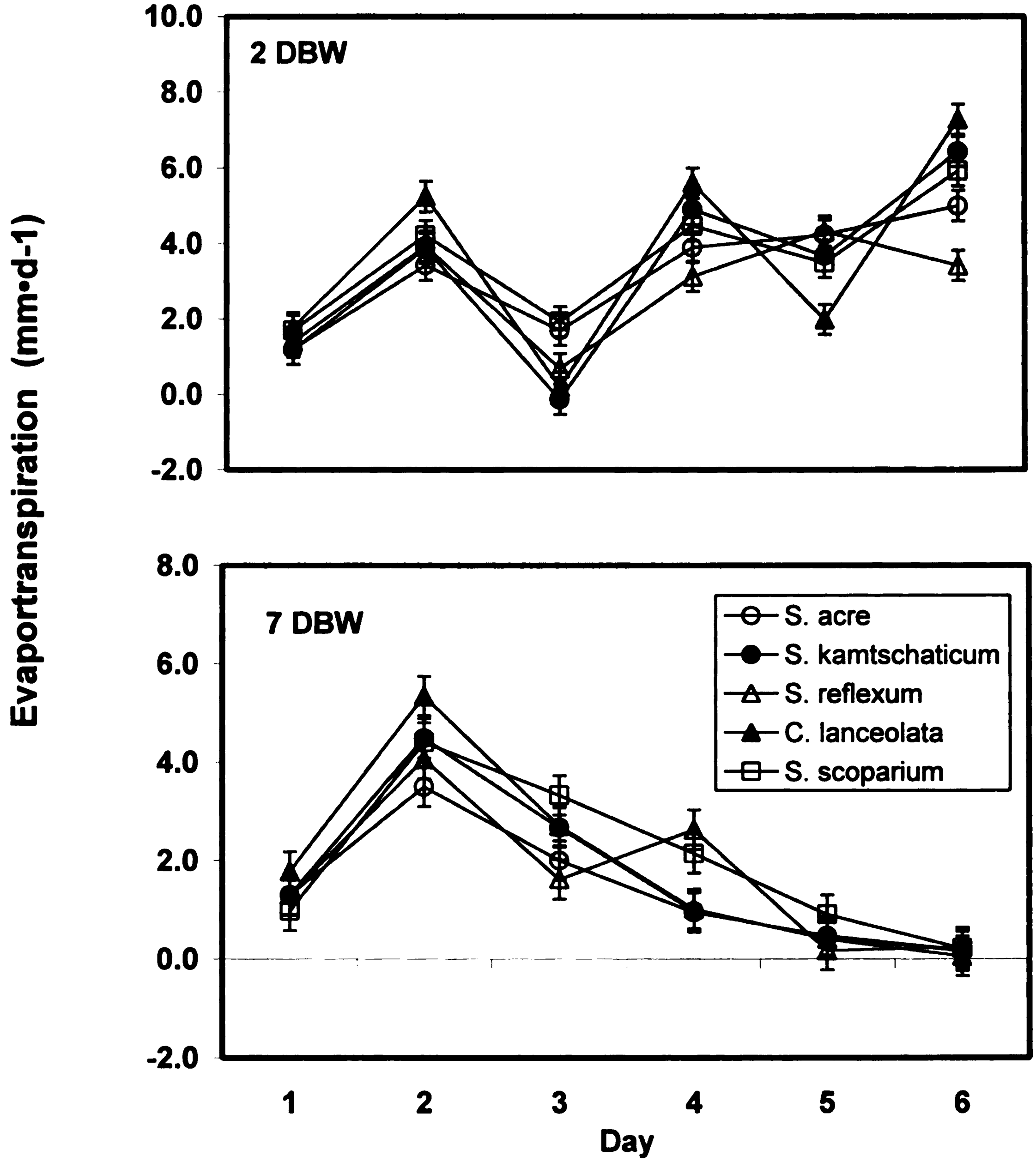
2 DBW
7 DBW
14 DBW
S. acre
S. kamtschaticum
S. reflexum
C. lanceolata
S. scoparium
Control
Volumetric Moisture Content (m3 • m-3)
0.4
0.3
0.2
0.1
0
-0.1
-0.2
1
12
33
48
68
82
Day

Figure 5 continued.



Substrate volumetric moisture content ($m^3 \cdot m^{-3}$) collected over the 88 day study for five watering regimes of 2 days between watering (DBW), 7 DBW, 14 DBW, 28 DBW, and 88 DBW (n=7). Symbols represent species means (*Sedum, Coreopsis,* and *Schizachyrium)* and a non-vegetated control. Error bars represent standard error.

Figure 6.



Evapotranspiration values (mm•d^{-1}) over the first week of the study for watering regimes of 2 days between watering (DBW) and 7 DBW. Symbols represent species of *Sedum, Coreopsis,* and *Schizachyrium.* Error bars represent standard error.

THESIS CONCLUSION

The preceding chapters represent three studies in the ongoing Green Roof Research Program in the Department of Horticulture at Michigan State University. Aside from short and long term studies detailing plant characteristics and ecological interactions for the Michigan region, additional experiments include comparing commercially available drainage systems, substrate depth influencing watering regimes, stormwater runoff monitoring, and monitoring a vegetated roof on the Plant and Soil Sciences Building.

Results from the studies reported in this thesis recommend an additional 13 species suited for growth in extensive green roof applications for Michigan. A diversity index allowed us to define dominant and subsidiary species whose presence and abundance on the roofing platforms may change in population dynamics. Dominance on platforms may have been attributed to a species ability to establish itself quickly after planting. Specifically, plants that exhibited this characteristic include *Phedimus spurius* Raf. 'Leningrad White,' *Sedum acre* L., *S. album* 'Bella d'Inverno' L., and *S. middendorffianum* L. Subsidiary species may not have established as quickly as the dominant species, though they were able to overwinter in even the shallowest of substrate (2.5 cm), included *S. hispanicum* diploid L., *S. sediforme* J., and *S. reflexum* L. Some subsidiary species did not survive in shallow media, however, were able to live in the substrate depths of 5.0 and 7.5 cm and included *S. kamtschaticum* Fisch, *S. dasyphyllum* L. 'Burnati,' *S. dasyphyllum* L. 'Lilac Mound,' and *S. spurium* Bieb.

'Summer Glory.' A higher level of diversity created by planting a combination of plant species is recommend for any green roof design to improve long term sustainability and vegetative coverage.

A drought study compared three recommended species from the platform study to two non-CAM (Michigan natives) species under different watering regimes. Results indicate that even under conditions of not receiving water for three months, *Sedum* were able to maintain active photosynthetic activity and recover after a single watering event. In contrast, the non-CAM plants needed consistent watering of a duration less than seven days.

These findings can be used by growers located in USDA Hardiness Zone 5 to supply green roof plants to the region with a certain level of confidence the recommended plants will survive and thrive under extensive green roof criteria. Furthermore, irrigation schedules could be established to maintain plant health in certain zones of the green roof based results under greenhouse conditions.

Further research will strengthen the ecological study of green roofs by comparing the initial results from this research and determine species composition on the platforms over several years. This is important as the green roof industry in North America becomes increasingly common in the future. As seen in Europe, aside from the benefits of stormwater retention, reducing the Urban Heat Island Effect, and conserving energy, the biodiversity of a green roof can be a major reason green roof technology is sought for the built environment.