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POTENTIAL AND SPECIES EVALUATIONS

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KRISTIN LOUISE GETTER

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**EXTENSIVE GREEN ROOFS: CARBON SEQUESTRATION POTENTIAL AND
SPECIES EVALUATIONS**

By

Kristin Louise Getter

A DISSERTATION

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ABSTRACT

EXTENSIVE GREEN ROOFS: CARBON SEQUESTRATION POTENTIAL AND SPECIES EVALUATIONS

By

Kristin Louise Getter

Green roofs, or vegetated roofs, are often adopted for energy savings and can thus mitigate climate change by lowering demand for heating and air conditioning use which results in less carbon dioxide emitted from power plants and furnaces. The goal of this research was to quantify the intrinsic carbon storage potential of extensive green roofs by plants and soils. Plots of four species of *Sedum* plus a substrate only treatment were established on a roof with a 6.0 cm substrate depth, replicated four times. Carbon analysis was performed by sampling above-ground biomass, below-ground biomass (roots), and substrate carbon content, harvested seven times across two growing seasons. After two growing seasons, above-ground plant material stored an average of $168 \text{ g C}\cdot\text{m}^{-2}$ and below-ground biomass stored an average of $107 \text{ g C}\cdot\text{m}^{-2}$. Substrate carbon content averaged $913 \text{ g C}\cdot\text{m}^{-2}$, sequestering $100 \text{ g C}\cdot\text{m}^{-2}$ beyond what was in the initial substrate. The entire extensive green roof system sequestered $375 \text{ g C}\cdot\text{m}^{-2}$. There was a species effect on above- and below-ground carbon, but not on substrate carbon.

Proper plant selection for green roofs is of the utmost importance, for if the plants fail, the energy savings and carbon mitigation will likely be reduced and future green roof sales may be affected. Two additional studies evaluated the effect of green roof substrate depth on plant community development over four years in a

Midwestern climate. The first study evaluated plugs of 12 *Sedum* species bi-weekly for absolute cover (AC) at 4.0 cm, 7.0 cm, and 10.0 cm substrate depths. Most species exhibited greater growth and coverage at a substrate depth of 7.0 cm and 10.0 cm relative to 4.0 cm. Species exhibiting the greatest AC at all substrate depths were *S. floriferum*, *S. sexangulare*, *S. spurium* 'John Creech', and *S. stefco*. In general, species that are less suitable at these substrate depths are *S. 'Angelina'*, *S. caudicola* 'Lidakense', *S. ewersii*, *S. ochroleucum*, and *S. reflexum* 'Blue Spruce'. The second study quantified the effect of solar radiation (full sun vs. full shade) on several U.S. native and non-native species for potential use on extensive green roofs. Plugs of six native and three non-native species and seed of six typical extensive green roof species of *Sedum* were established at three different substrate depths (8.0 cm, 10.0 cm, and 12.0 cm) both in sun and shade. AC was recorded as before. By week 174 (23 Sept 2008), most species exhibited different AC within a depth between sun and shade. However, when all species were combined, overall AC did not differ between sun and shade within a depth. This indicated that while species make-up was changing among solar radiation levels, that overall coverage was not significantly different. The most abundant species were *Allium cernuum*, *S. acre*, *S. album*, *S. kamtschaticum*, *S. spurium* and *Talinum calycinum*. Less suitable species included *Carex flacca*, *S. divergens*, *S. pulchellum*, *S. stenopetalum*, and *Talinum parviflorum*. With the exception of *T. calycinum*, native species were less abundant than non-native species. *Allium cernuum*, *S. acre*, *S. kamtschaticum*, and *S. spurium* are suitable in the shade.

This dissertation is dedicated to the memory of my grandmother, Frances Rossman, who was instrumental in my interest in higher education. Frances received her masters from Michigan State University and nearly completed her PhD as well. We miss you grandma.

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A LITERATURE REVIEW

Green Roofs as a Tool to Mitigate Urbanization

Problems with Urbanization

According to the United Nations Department of Economic and Social Affairs (UN ESA), the world's urban population is rapidly increasing. In 2005, 49% of the world population resided in urban areas worldwide (UN ESA, 2007). This number is expected to grow to 60% by 2030. As urban areas expand, constructed surfaces will increase in the form of buildings, roads, and parking lots.

In the continental United States, urban areas are covered by up to 95% in impervious surfaces (Ferguson, 1998). As a result, an average of only 25% of rainfall infiltrates into soil (Scholz-Barth, 2001) and the remaining 75% generates urban runoff that may be highly contaminated with pollutants such as oil, heavy metals, salts, pesticides, and animal wastes (Novotny and Chesters, 1981). Furthermore, high volumes of stormwater runoff can also overwhelm municipal sewer systems (US EPA, 2008b).

Since the quantity of water available for evapotranspiration is reduced due to urbanization, a great deal of incoming solar energy that would have been used to evaporate water is instead transformed into sensible heat, which in turn warms the surface (Barnes et al., 2001). In addition, since the albedo of urban surfaces is generally 10% lower than the albedo of rural surfaces (Oliver, 1973), urban areas can have higher ambient air temperatures as compared to surrounding suburbs or countryside, a phenomenon known as the Urban Heat Island Effect

(UHIE). According to the U.S. Environmental Protection Agency (US EPA) (2009), urban air temperatures can be 10 to 15 °C (18 - 27 °F) warmer than the surrounding countryside. In the summer, this translates into higher air conditioning use. For every 0.6 °C (1 °F) increase in air temperature, peak summer utility load may increase by 2% (US EPA, 2009).

In order to meet increased demands for energy due to the UHIE and population growth, more than 100 new coal fired plants are proposed in the U.S. by 2017 (US Department of Energy, 2008). Such fossil fuel use releases CO₂ as a by-product of combustion. According to the Intergovernmental Panel on Climate Change (IPCC, 2007), human activity related to the combustion of fossil fuels has increased carbon dioxide (CO₂) concentrations in the atmosphere 32% since 1750. Because CO₂ is one of the atmospheric gases that reduce the amount of outgoing terrestrial energy from escaping into space, increased levels of this gas will ultimately lead to an increase in earth's temperature. The National Academy of Sciences reports that warming of the earth's surface is already occurring as air temperatures have warmed 0.6°C over the last 100 years (National Research Council, 2001).

In 1997, the United Nations Framework Convention on Climate Change (UNFCCC) protocol was adopted in Kyoto, Japan as an international effort to reduce six greenhouse gases, especially CO₂. As of 05 February 2009, 184 countries ratified or accepted the Kyoto Protocol (UNFCCC, 2008), for an

average 5.2% reduction in 1990 greenhouse gases. While the protocol mandates each nation to meet their own reductions by 2012, it also allows other flexible mechanisms to achieve these reductions, including emissions trading and emission reduction/removal projects in other countries.

Green roofs as one tool to mitigate urbanization

Establishing green roofs, or vegetated roofs, is one way to mitigate some of the many problems caused by population growth and urbanization. They are similar to other cool roof technologies, since they have a high albedo - ranging from 0.7 to 0.85, depending on water availability (Gaffin et al., 2005). Other cool roof technologies, such as white roofs, may start with an albedo of 0.8, but reflectivity can decline up to 11% due to dust and debris accumulation. Conventional roof surfaces have much lower albedos ranging from 0.05 to 0.25 (US EPA, 2005a).

Green roofs are categorized as 'intensive' or 'extensive' systems. Intensive green roofs are designed to be similar to landscaping found at natural ground level, and as such require substrate depths greater than 15.2 cm (6 in) and have 'intense' maintenance needs. By contrast, extensive green roofs use shallower media depths (less than 15.2 cm (6 in)) and require minimal maintenance. Due to building weight restrictions and costs, shallow substrate extensive green roofs are much more common than deeper intensive roofs. Because of their shallower media depth, plant species are limited to herbs, grasses, mosses, and drought

tolerant succulents such as *Sedum*. In addition, extensive green roofs can be built upon a sloped surface.

Green roofs in many areas of the world are typically implemented because of their ability to reduce stormwater runoff. In a green roof system, much of the precipitation is captured in the media or vegetation and will eventually evaporate from the soil surface or will be released back into the atmosphere by transpiration. Green roofs reduce runoff by 50% to 100% depending on the type of green roof system (Carter and Jackson, 2007; DeNardo et al., 2005; Getter et al., 2007; Hilten et al., 2008; Jarrett and Berghage, 2008; VanWoert et al., 2005a). Water retention depends on design factors such as substrate depth, composition, roof slope, and plant species, as well as weather factors such as intensity, duration of rainfall, and antecedent substrate moisture conditions.

However, in many areas of North America the primary reason for choosing a green roof is due to the energy conservation they provide. Green roofs shade and insulate buildings, which when combined with the evapotranspiration of the substrate and plant material reduce summer air temperatures just above a green roof as well as indoor temperatures underneath a green roof (Connelly and Liu, 2005; Santamouris et al., 2007; Sailor, 2008; Takebayashi and Moriyama, 2007). Since buildings consume 39% of total energy use and 71% total electricity consumption (U.S. Green Building Council, 2007), green roof implementation on a wide scale could significantly impact the UHIE while providing economic

savings. Laberge (2003) estimated that for the Chicago city hall, energy savings alone could result in \$4,000 annually for heating and cooling combined. If all of Chicago had green roofs, the savings could be \$100,000,000 annually (Laberge, 2003).

Other benefits of green roofs include extended roof lifespan, habitat for wildlife, mitigation of noise and air pollution, and improved aesthetic value. Because growing media and plant material protect roofing membranes from solar exposure and ultraviolet radiation that can damage the traditional bituminous roof membrane, green roofs are estimated to last 45 years or longer in terms of mechanical lifespan (Kosareo and Ries, 2007). This translates into a better return on investment compared to traditional roofs (Clark et al., 2008). Since most extensive green roofs are inaccessible to the public, they can provide undisturbed habitat for microorganisms, insects, and birds (Baumann, 2006; Brenneisen, 2006). When humans view green plants and nature, it has beneficial health effects (Ulrich and Simmons, 1986) as well as improved health and worker productivity (Kaplan et al., 1988; Ulrich, 1984). Green roofs have been also found to reduce noise pollution by 10 db (Van Renterghem and Botteldooren, 2008) and air pollution (in the form of O₃, NO₂, PM₁₀, and SO₂) by 85 kg•ha⁻¹•yr⁻¹ (Yang et al., 2008).

Green roofs have also been shown to achieve public health benefits. Nitrogen oxides (NO_x) result from combustion of fossil fuels and can form ground level

ozone causing serious human respiratory problems, including premature death, as well as a reduction in crop yields, all of which have economic impacts (US EPA, 1998). Clark et al. (2008) found that green roofs yield an annual benefit of \$0.45 to \$1.70 per m² (\$0.04 to \$0.16 per square foot) in terms of nitrogen oxide (NO_x) uptake per year.

Although green roofs are often adopted for energy savings and heat island mitigation, rarely has this technology been promoted for its ability to mitigate climate change, even though they do reduce carbon emissions. By lowering electricity demand for air conditioning use, less carbon dioxide is released from power plants. Sailor (2008) integrated green roof energy balance into Energy Plus, a building energy simulation model supported by the U.S. Department of Energy. His simulations suggested 2% reductions in electricity consumption and 9 to 11% reductions in natural gas consumption. Based on his model of a generic building with a 2,000 m² green roof, these annual savings ranged from 27.2 to 30.7 GJ of electricity saved and 9.5 to 38.6 GJ of natural gas saved, depending on climate and green roof design. When considering the national averages of CO₂ produced for generating electricity and burning natural gas (US EPA, 2007; US EPA, 2008a), these figures translate to 2.3 to 2.6 kg CO₂ per square meter of green roof in electricity and 0.24 to 0.97 kg CO₂ per square meter of green roof in natural gas each year. Another 25% reduction in electricity use may additionally occur due to indirect heat island reduction achieved from

large-scale green roof implementation throughout an urban area (Akbari and Konopacki, 2005).

As an example of these potential emission savings using Sailor's (2008) model, the campus of Michigan State University in East Lansing, MI has 1.1 km² of flat roof surface. If all of these roofs were greened, they could avoid 3,640,263 kg CO₂ emitted per year in electricity and natural gas consumption combined. This is the equivalent of taking 661 vehicles off the road each year (US EPA, 2005b). These figures depend on climate, green roof design, and source of fuel for electricity and gas.

However, many components of a green roof have a CO₂ 'cost' in terms of the manufacturing process. Embodied energy is a term used to describe total energy consumed, or carbon released, of a product over its life cycle. Typical components of a green roof include a root barrier installed on top of the normal roofing membrane (which protects the roof from root penetration damage), a drainage layer above the root barrier (which allows excess water to flow away from the roof), and a growing substrate. Many life cycle analysis studies ignore these unique components of a green roof by making the assumption that the root barrier, drainage layers, and substrate will all have a carbon cost similar to the traditional roofs' gravel ballast (Alcazar and Bass, 2006; Kosareo and Ries, 2007). But, this assumption may not be valid.

One cradle-to-gate study (Hammond and Jones, 2008) analyzed many building materials from the beginning (cradle) through the entire production process up until the product leaves the factory (gate). Material consisting of low density polyethylene (LDPE) similar to a root barrier was found to average $78.1 \text{ MJ}\cdot\text{kg}^{-1}$ of embodied energy or $1.7 \text{ kg CO}_2\cdot\text{kg}^{-1}$ of embodied carbon (Hammond and Jones, 2008). Assuming 0.51 mm thickness and a density of $925 \text{ kg}\cdot\text{m}^{-3}$ (Raven Industries, Sioux Falls, SD), this translates to 0.8 kg CO₂ per square meter of green roof. Drainage layers are commonly made from polypropylene (Colbond Inc., Enka, NC) which is found to contain 5.03 kg CO₂ per kg of product (Hammond and Jones, 2008). Assuming a weight of $0.39 \text{ kg}\cdot\text{m}^{-2}$ (Xero Flor America LLC, Durham, NC), this translates into 1.9 kg CO₂ per square meter of green roof. The embodied energy for a substrate consisting of sand and expanded slate is 0.005 and $0.44 \text{ kg CO}_2\cdot\text{kg}^{-1}$, respectively (GBC, 2008; Hammond and Jones, 2008). A 6.0 cm substrate depth consisting of half sand and half expanded slate by volume with densities of $2,240$ and $1,600 \text{ kg}\cdot\text{m}^{-3}$, respectively (Expanded Shale, Clay and Slate Institute. 2008; Hammond and Jones, 2008) calculates to 0.03 and 21.1 kg CO₂ per square meter of green roof. These green roof components add up to an embodied carbon content of 24.2 kg CO₂ per square meter of green roof. But, the embodied carbon of a traditional roof's gravel ballast is estimated at $0.017 \text{ kg CO}_2\cdot\text{kg}^{-1}$ which equates to $50.0 \text{ kg CO}_2\cdot\text{m}^{-2}$ of roof, assuming a density of $1,800 \text{ kg}\cdot\text{m}^{-3}$ and a 2 cm depth (Hammond and Jones, 2008). Subtracting out the unneeded gravel ballast, total adjusted embodied carbon for this extensive green roof is then 23.6 kg CO₂ per

square meter of green roof. Based on Sailor's (2008) minimum energy savings (above) of $2.54 \text{ kg CO}_2 \cdot \text{m}^{-2}$, it would take at most 9.3 years to 'pay' for the carbon cost of the green roof materials.

In addition, green roofs may also be a tool for further reducing carbon footprints due to the presence of plants and soils. The process of photosynthesis removes carbon dioxide from the atmosphere and stores carbon in plant biomass, commonly referred to as terrestrial carbon sequestration. Carbon is transferred to the substrate via plant litter and exudates. The length of time that this carbon remains in the soil before decomposition has yet to be quantified for green roofs. But, immediately after initial green roof installation, net primary production should exceed decomposition making this man-made ecosystem a carbon sink, at least in the short-term. Once an equilibrium has been reached whereby carbon gain is offset by respiratory losses and decomposition, this ecosystem will likely no longer be sequestering new carbon, but will still be storing more carbon than the original barren roof.

Due to both emission improvements and sequestration potential, green roofs could be a new way for companies to develop carbon trading credits in a cap and trade system. Market based carbon trading is a low-cost method for many companies to manage and lower emissions. Chicago Climate Exchange (CCX) is such a pilot trading program that is voluntary in the United States. This program "seeks to demonstrate that greenhouse gas trading can reduce

emissions across different business sectors” (CCX, 2007). It is similar to the highly successful sulfur dioxide (SO₂) emissions trading program implemented in the 1990s (Chestnut and Mills, 2005). Participation in CCX trading for greenhouse gases could help companies meet their reduction targets by purchasing credits from other companies who have exceeded their reduction target, as well as provide financial incentives for those companies who exceed their reduction goals.

Importance of Plant Selection for Green Roofs

In order to capitalize on the benefits of green roofs, plant selection is critical. If the plants do not survive, albedo, stormwater retention, evaporative cooling, and carbon sequestration may all be reduced. But selecting plants for green roofs is often difficult due to the harsh urban environment and because plants are also more susceptible to extremes in temperature and drought due to their shallow substrate and elevation above ground.

The genus *Sedum* is a popular choice among extensive green roofing projects due to its tolerance for drought (Durhman et al., 2006; Wolf and Lundholm, 2008), shallow substrate adaptability (Durhman et al., 2007; Emilsson, 2008), persistence (Köhler, 2006; Monterusso et al., 2005; Rowe et al., 2006), and ability to limit transpiration (Kluge, 1977; Lee and Kim, 1994) and store water (Gravatt, 2003; Teeri et al., 1986). But even for such a well suited genus, substrate depth can influence the rate of substrate coverage and subsequent

plant growth (Durhman et al., 2007; Getter and Rowe, 2008; Rowe et al., 2006). Deeper substrates are beneficial for both increased water holding capacity (VanWoert et al, 2005a; VanWoert et al., 2005b) and as a buffer for overwintering survival as shallow substrates are more subject to fluctuations in temperature (Boivin et al., 2001). Despite the cultural limitations of shallow substrate depths, they are often desirable because buildings must be structurally able to support the added weight of the green roof.

Overall climate and roof microclimate are factors that will determine plant success as well as the design intent for the green roof project. A good example of this is the state of Florida's first pilot green roof installed in Naples, Florida in 2003. The plant species chosen for this project were selected because of their green roof success in northern latitudes. But these species failed to survive in Florida's environment. The researchers concluded that the "type of media used and the green roof profile structure are secondary to the correct choice of plants" (Livingston et al., 2004).

Many studies for plant survival on green roofs collect data for one to two years (Durhman et al., 2007; Emilsson and Rolf, 2005; Kircher, 2004; MacDonagh et al., 2006; Nagase and Dunnett, 2008). Since green roofs exhibit such a long lifespan (Kosareo and Ries, 2007), long-term plant performance beyond the first few years' growth is important. Plants that survive initially on a green roof may

not continue to exist there in the long term because of variability in climate and other factors.

In addition, research involving plant selection thus far has typically been for roofs exposed only to full sun (Monterusso et al., 2005; Durhman et al., 2007; Getter and Rowe, 2008). However, as green roof implementation continues, it is likely that many green roofs will be shaded by other structures. Incoming solar radiation (insolation) directly and indirectly impacts plant growth. Depending on the species, this impact may be severe or negligible. In Utah, it was observed that high solar radiation zones differed from low solar radiation zones in terms of species performance (Dewey et al., 2004). Another study in the Pacific Northwest looked at a sloped roof and found that in some cases the amount of solar radiation influenced plant performance (Martin and Hinckley, 2007).

Often clients desire the use of native species because of their real and perceived benefits, such as their longevity without the use of pesticides, fertilizers, or irrigation (US EPA, 2008c). But, plants could not actually be native to rooftops since roofs are man-made artificial structures. However, many plant species are adapted to these type of conditions. Because of client demand for native species, researchers in Michigan evaluated 18 native taxa on unirrigated extensive green roof platforms (Monterusso et al., 2005; Rowe et al., 2005). After three years, only four of the species survived. The majority of the plants tested were considered to be drought tolerant, but their survival in a native

environment relies on deep tap roots to obtain moisture. In a shallow extensive roof, these roots can still grow sideways, but without supplemental irrigation periods of drought resulted in death.

Research Objectives

The research presented here involves three studies on green roofs. The first two studies evaluate initial growth, survival, and persistence of species on extensive green roofs. The third study focuses on how traditional green roof plants can contribute to the terrestrial carbon sink in the artificial roof environment. The three studies are complementary and build upon previous species research in that the best suited species for green roof habitation should also be those that sequester the most carbon simply because those species are more likely to survive and persist in a roof ecosystem.

Because of the need to expand the plant palette of green roof species in local climates, the objective of the first study was to evaluate the effect of substrate depth on long-term plant survival of 12 *Sedum* species, seven of which have never been tested in a Midwestern climate. The expected outcome of this study was that some species would be more suited for roof habitation than others and that some would perform better at deeper or shallower substrate depths relative to other species. The mechanism for this prediction is that soil depth influences plant water availability and thus plant growth. Therefore, the research hypothesis

of this study was that the mean percentage of abundance of each species will differ among substrate treatments and species.

There is also a need to evaluate the effect of solar radiation intensities on plant community development, as well as evaluate the performance of native species. Therefore, the objective of the second study was to evaluate long-term growth, survival, and persistence of both native and typical green roof species as a function of media depth and irradiation levels (full sun vs. full shade). The expected outcome of this study was that some species would be more suited for roof habitation than others and that some would perform better at deeper or shallower substrate depths as well as different irradiation levels relative to other species. The mechanism for this prediction was that soil depth and irradiation levels influence plant water availability and photosynthetic rates, both of which impact plant growth. Therefore, the research hypothesis of this study was that the mean percentage of abundance of each species would differ between substrate treatments, irradiance levels, and species.

Finally, there is an increasing momentum in the U.S. to offset carbon emissions. Thus far, most studies on terrestrial carbon sequestration have focused on forests and crops, but there have been no studies of green roofs. The objective of the third study was to quantify the carbon storage potential of extensive green roofs and to evaluate the effect that species has on carbon flux. The research hypothesis was twofold. The first hypothesis was that species which exhibit

greater coverage and growth on extensive green roofs would affect the total carbon sequestered both above-ground and below-ground due to greater plant size and survival. The second hypothesis was that green roofs would have greater carbon storage than a traditional roof.

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CHAPTER ONE

Getter, K.L., and D.B. Rowe. 2009. Substrate Depth Influences *Sedum* Plant Community on a Green Roof. HortScience. Accepted.

Abstract

Since the waterproofing membrane beneath green roofs is estimated to last at least 45 years, long-term plant performance beyond initial establishment is critical. Plants that survive initially on a green roof may not exist in the long term because of variability in climate and other factors. This study evaluated the effect of green roof substrate depth on substrate moisture, plant stress as measured by chlorophyll fluorescence, and plant community development and survival of 12 *Sedum* species over four years in a Midwestern U.S. climate during four years of growth. Plugs of 12 species of *Sedum* were planted on 8 June 2005 and evaluated bi-weekly for absolute cover (AC). Most species exhibited greater growth and coverage at a substrate depth of 7.0 cm and 10.0 cm relative to 4.0 cm. For the species evaluated, substrate depths of at least 7.0 cm are highly recommended. AC of *Sedum* was significantly greater at this substrate depth than at 4.0 cm. Mean volumetric moisture content of the three substrate depths followed the same pattern as AC. When averaged over time, the 4.0 cm substrate depth held less moisture than depths of 7.0 or 10.0 cm, while the 7.0 and 10.0 cm substrate depths were statistically the same. Species exhibiting the greatest AC at all substrate depths were *S. floriferum*, *S. sexangulare*, *S. spurium* 'John Creech', and *S. stefco*. In general, species that are less suitable at these substrate depths are *S. 'Angelina'*, *S. cauticola* 'Lidakense', *S. ewersii*, *S. ochroleucum*, and *S. reflexum* 'Blue Spruce'.

Introduction

In 2007, 223,666 m² (2,407,525 ft²) of green roofs, or vegetated roofs, were installed in North America representing a 30% increase over 2006 (Green Roofs for Healthy Cities, 2008). By placing plants on rooftops, the vegetated footprint that was previously destroyed during building construction is at least partially replaced. Increased adoption of this roofing technology may be due to the many benefits they provide, such as improved stormwater management (Carter and Jackson, 2007; Getter et al., 2007; Hilten et al., 2008; Jarrett and Berghage, 2008), energy conservation (Sailor, 2008; Santamouris et al., 2007), mitigation of the urban heat island effect (Takebayashi and Moriyama, 2007), increased longevity of roofing membranes (Kosareo and Ries, 2007), a better return on investment than traditional roofs (Clark et al., 2008), reduced noise and air pollution (Van Renterghem and Botteldooren, 2008; Yang et al., 2008), increased urban biodiversity (Baumann, 2006; Brenneisen, 2006), as well as providing a more aesthetically pleasing environment to experience (Getter and Rowe, 2006; Oberndorfer et al., 2007).

In order for green roofs to be successful, as well as to meet client expectations, plant selection is critical. Species selected must survive extremes in roof microclimate. Green roofs are likely to experience drought and severe fluctuations in root zone temperatures due to shallow substrates, as well as high temperatures, and windy conditions. These conditions combined with heat

radiating from the building will likely alter hardness zones and soil moisture content, thus impacting which species are able to survive.

Successful candidate species for extensive green roofs (i.e., green roofs with substrate depths of 10.0 cm (3.93 in) or less) must exhibit characteristics such as easy propagation, rapid establishment, and high groundcover density (Dunnett and Kingsbury, 2004; Getter and Rowe, 2006; Snodgrass and Snodgrass, 2006). Low growing plants that spread and cover the substrate in a short period of time reduce potential erosion problems, inhibit weeds, and provide improved aesthetics. Although rapid coverage is important, the ability of plant species to be self-sustaining reduces the need for future replanting and maintenance. Species that are long-lived, that reseed themselves, or spread vegetatively should continue to provide ample coverage (60% or greater, as defined by FLL guidelines (FLL, 1995)) as long as environmental conditions are favorable.

The genus *Sedum* is a popular choice among extensive green roofing projects due to its tolerance for drought (Durhman et al., 2006; Wolf and Lundholm, 2008), shallow substrate adaptability (Durhman et al., 2007; Emilsson, 2008), persistence (Köhler, 2006; Monterusso et al., 2005; Rowe et al., 2006), and ability to limit transpiration (Kluge, 1977; Lee and Kim, 1994) and store water (Gravatt, 2003; Teeri et al., 1986). But even for such a well suited genus, substrate depth can influence the rate of substrate coverage and subsequent plant growth (Durhman et al., 2007; Getter and Rowe, 2008; Rowe et al., 2006).

Deeper substrates are beneficial for both increased water holding capacity (VanWoert et al, 2005a; VanWoert et al., 2005b) and as a buffer in fluctuating winter temperatures (Boivin et al., 2001). Despite the cultural limitations of shallow substrate depths, they are often desirable because of lighter roof loads.

Plant stress due to shallow substrate and other conditions on a roof can be recorded by measuring chlorophyll fluorescence. This technique is used to quantify the efficiency of the photosynthetic apparatus (Maxwell and Johnson, 2000). Photon energy absorbed by a chlorophyll molecule can be used to fuel photosynthesis, dissipated as heat, or re-emitted as fluorescence. Measurement of the latter is used to indicate how efficient the former two processes are proceeding. Fluorimeters are used to measure this value, usually reporting the ratio (F_v/F_m) of variable fluorescence (F_v) to maximum fluorescence (F_m) that typically ranges from 0.70 to 0.83, with values less than 0.60 indicating photosynthetic stress (Ritchie, 2006).

Many studies for plant survival on green roofs collect data for one to two years (Durhman et al., 2007; Emilsson and Rolf, 2005; Kircher, 2004; MacDonagh et al., 2006; Nagase and Dunnett, 2008). Since the waterproofing membrane beneath green roofs is estimated to last 45 years or longer (Kosareo and Ries, 2007), long-term plant performance beyond the first few years' growth is important. Plants that survive initially on a green roof may not exist there in the long term because of variability in climate and other factors. Therefore, the

objective of this study was to evaluate the effect of substrate depth on substrate moisture, plant stress as measured by chlorophyll fluorescence, and plant community development and survival of 12 *Sedum* species over a period of four years.

Materials and Methods

Green Roof Platforms. Three roof platforms with dimensions of 2.44 m x 2.44 m (8.0 ft x 8.0 ft) were utilized at the Michigan State University Horticulture Teaching and Research Center (East Lansing, MI). Each platform was situated at ground level and replicated a commercial extensive green roof, including insulation, protective and waterproofing membrane layers. Construction details are outlined in VanWoert et al. (2005a).

The wood-framed platforms included sides that extend 20.3 cm (8.0 in) above the platform deck. Each platform was divided into three equal sections measuring 0.77 m x 2.40 m (2.53 ft x 7.87 ft) using wood dividers. The platform sides and dividers were also covered with waterproofing membrane. Each platform was set at a 2% slope and was placed with the low end of the slope facing south to maximize sun exposure.

Drainage System and Vegetation Carrier. Each platform was constructed with a Xero Flor XF108 drainage mat (Wolfgang Behrens Systementwicklung, GmbH, Groß Ippener, Germany) installed over the waterproofing system which allows

excess water to flow off the roof. For additional water holding capacity, a 0.75 cm (0.26 in) thick moisture retention fabric (Xero Flor XF159) capable of retaining 5.92 kg·m⁻² of water was placed over the drainage layer followed by the vegetation carrier (Xero Flor XF301). Growing substrate was placed on the vegetation carrier at three different depths (4.0 cm, 7.0 cm, or 10.0 cm (1.6, 2.8, and 3.9 in)). Initially, the substrate consisted of 86% sand, 10% silt, and 4% clay and had a bulk density of 1.37 g·cm⁻³ and a water holding capacity at 0.01 MPa of 16.05%. Further details of the initial physical and chemical properties of the substrate are detailed in Getter and Rowe (2008).

Plant Species. The twelve species tested included *Sedum* 'Angelina' (crooked stonecrop), *Sedum cauticola* 'Lidakense' (stonecrop), *Sedum ewersii* (stonecrop), *Sedum floriferum* (kamtschatka stonecrop), *Sedum hispanicum* (Spanish stonecrop), *Sedum ochroleucum* (European stonecrop), *Sedum reflexum* 'Blue Spruce' (crooked stonecrop), *Sedum sarmentosum* (stringy stonecrop), *Sedum sediforme* (pale stonecrop), *Sedum sexangulare* (tasteless stonecrop), *Sedum spurium* 'John Creech' (creeping sedum), and *Sedum stefco* (stonecrop). Plants were obtained from Emory Knoll Farms (Street, MD) as plugs (120 cm³; 72/flat) that were established in a standard propagation mix of peat, perlite, and vermiculite (Super-Fine Germination Media, Farfard, Inc., Agawam, MA). Plugs were planted on 8 June, 2005 with four plants in twelve rows. Each species was planted four times randomly in each section resulting in plugs spaced 17.0 cm (6.7 in) apart from each other and platform walls. All plots were fertilized

(Nutricote controlled release fertilizer 18-6-8 type 120 (Agrivert, Webster, Tex.) at $100.0 \text{ g}\cdot\text{m}^{-2}$) and watered to field capacity by hand on the day of planting. No further irrigation was provided.

This planting arrangement resulted in a split plot design that was arranged in randomized complete blocks with two factors replicated three times. The main plot was substrate depth (4.0, 7.0, and 10.0 cm (1.6, 2.8, and 3.9 in)) and the sub-plot factor was plant species which had 12 treatments, each replicated four times within a sub-plot for a total of 48 plants per substrate depth per plot.

Data Collection and Analysis. A transect (a stainless steel point-frame) was used every two weeks during the first three growing seasons and monthly in the fourth growing season to measure community composition and change (Waite, 2000). The point-frame had internal measurements of 0.77 m x 1.2 m (2.5 ft x 3.9 ft) and had eight strings (50 pound Berkley Gorilla Super Braid Fishing Line) vertically and eight strings horizontally to create 64 measurement points. The point-frame sat directly on top of the platform sides, secured by finishing nails that allowed the frame to be positioned in the exact same spot every time. A stainless steel skewer was placed vertically at each measuring point and each species the skewer contacted was recorded, up to three canopy layers.

Substrate moisture and chlorophyll fluorescence data were collected throughout the last two growing seasons. Substrate moisture measurements were

monitored by inserting a theta probe (ML2x, Delta-T Devices, Ltd., Cambridge, United Kingdom) with 6.0 cm (2.4 in) rods into the media until they were completely buried. Measurements were collected at random times each week in triplicate in each subplot. Chlorophyll fluorescence measurements were collected at six different times (21 May 2007, 18 June 2007, 2 August 2007, 17 September 2007, 29 May 2008, and 20 August 2008) using a Hansatech plant efficiency analyzer (PEA; Hansatech Instruments, Ltd., Norfolk, England). These measurement dates were selected in order to cover a wide range of environmental conditions including active growth and drought stress during the growing season. Leaves from each plant were dark adapted for 20 minutes prior to measurement. Maximum quantum efficiency of photosystem II was recorded (F_v/F_m). Three single leaf blades of each surviving species were randomly selected in each subplot and excised from the plant to be dark adapted and measured. This was necessary because the PEA clips were not secure on the leaf of most species while still attached to the whole plant.

Data Analysis. Absolute cover (AC) was calculated for each species at each substrate depth as the total number of contacts recorded divided by the number of data collection points. Data was then analyzed as mean AC using repeated measures. Although original means are presented, all AC values were transformed prior to analysis using a log transformation to stabilize the variance and normalize the data set (Underwood, 1998). Significant differences between treatments were determined using multiple comparisons (PROC MIXED, SAS

version 8.02, SAS Institute, Cary, NC). In addition, mean substrate volumetric moisture content and mean chlorophyll fluorescence data were analyzed by PROC MIXED, least significant differences (SAS version 8.02, SAS Institute, Cary, NC)

Results and Discussion

Four points in time (weeks 15, 67, 120, and 172) were chosen for comparing growth that represent the end of each growing season (before first frost). At a substrate depth of 4.0 cm four species exhibited no significant growth between the end of the first and fourth growing seasons (*S.* 'Angelina', *S. caudicola* 'Lidakense', *S. ewersii*, and *S. ochroleucum*), while at 7.0 cm five species (*S. ewersii*, *S. ochroleucum*, *S. reflexum* 'Blue Spruce', and *S. sediforme*) fit this category (Table 1.1 rows, Figure 1.1). At the 10.0 cm substrate depth there were six such species (*S.* 'Angelina', *S. caudicola* 'Lidakense', *S. ewersii*, *S. ochroleucum*, *S. reflexum* 'Blue Spruce', and *S. sediforme*). As a result, at their respective substrate depths, all of these species have zero or near zero AC by week 172.

At each substrate depth there were also species that decreased in AC across the four growing seasons, also resulting in zero AC by week 172 (Table 1.1 rows; Figure 1.1). At substrate depths of 4.0 cm (*S. sarmentosum* and *S. sediforme*) and 10.0 cm (*S. hispanicum* and *S. sarmentosum*) there were two such species.

The 7.0 cm substrate depth had three species (*S. caudicola* 'Lidakense', *S. hispanicum*, and *S. sarmentosum*).

The remaining species at each substrate depth increased in AC across the four growing seasons (Table 1.1; Figure 1.1). All substrate depths had the same four species (*S. floriferum*, *S. sexangulare*, *S. spurium* 'John Creech', and *S. stefco*) with the 4.0 cm substrate depth having an additional two species (*S. hispanicum* and *S. reflexum* 'Blue Spruce'). For all species, the increase in AC was only significant between the first and second growing season. This perhaps indicates that by the end of the second growing season, the plant community had reached a mature or stable state.

Results for the first growing season, as previously published, demonstrated that by the end of the first growing season (week 19) at all three substrate depths *S. sarmentosum* exhibited a much higher AC than all other species (Getter and Rowe, 2008; Figure 1.1). However, subsequent growing seasons produced very different results, highlighting the importance of long term studies. For the 4.0 cm substrate depth, this species remained at near zero AC for the remaining growing seasons. At the 7.0 cm and 10.0 cm substrate depths though, this species represents more than half of the coverage by the end of the second growing season, has a slow recovery in the third growing season to represent nearly 20% of coverage, but then falls to near zero AC at the end of the fourth growing season.

It is possible that the reason for *S. sarmentosum*'s eventual failure at all three substrate depths is due to incorrect hardiness zone classification for this species. Minimum air temperatures were lower during the second winter (-22.0°C) and had a longer duration of extreme cold (33 days less than -10°C) as compared to the first winter (-19.9°C; 20 days less than -10°C) in which this species successfully recovered (Figure 1.2). East Lansing, Mich. is classified as zone 5 on the USDA plant hardiness map, a value corresponding to an average minimum temperature between -26 °C to -29 °C (-20 °F to -10 °F) (Cathey, 1990). Plants that are classified with hardiness zones less than or equal to a geographical area should in theory survive in that climate (assuming all other plant requirements are met). *Sedum sarmentosum* is categorized as a zone 5 species (Snodgrass and Snodgrass, 2006), but typically species are assigned a hardiness zone based on observation only or based on how related species have performed in the past. Hardiness zones are also meant for plants growing at ground level. While initial work with this species indicated that it was able to overwinter successfully when given enough establishment time before first frost (Getter and Rowe, 2007), this current study shows that *S. sarmentosum* is likely unsuitable for this climate. In climates with warmer winters, it is possible that this species may cover a majority of the roof, as suggested by first year data here. However, this situation poses a threat in that an unusual cold spell may completely wipe out *S. sarmentosum* resulting in a many bare spots on the roof.

Differences in growth as measured by AC across the sampled substrate depths and time may be partially explained by the habit of the species themselves. Some species, such as *S. 'Angelina'*, *S. caudicola 'Lidakense'*, *S. ochroleucom*, *S. reflexum 'Blue Spruce'*, and *S. sediforme* are more erect in nature and therefore may be underrepresented in point-frame sampling techniques (Wilson, 1960). Furthermore, some species vegetatively reproduce easier than others, allowing them to cover more area than simple growth would allow. Within this genus, Stephenson (2002) reports that increasing degrees of succulence are correlated with improved ability of a species to reproduce asexually (such as *S. stefco*, *S. sexangulare*, and to some extent *S. sarmentosum*). Some species also seem to allocate more energy to sexual reproduction (such as *S. hispanicum*) while others allocate more energy to creeping growth (such as *S. sarmentosum*, which has sterile flowers).

At all substrate depths, by the end of the fourth growing season (week 172) the same four species (*S. floriferum*, *S. sexangulare*, *S. spurium 'John Creech'*, and *S. stefco*) consistently exhibited the greatest AC (Table 1.2). However, relative abundance differed between substrate depths. For example, *S. stefco* was most abundant at the 4.0 cm substrate depth, followed by *S. floriferum*, *S. spurium 'John Creech'*, and *S. sexangulare*. By contrast, at 7.0 cm and 10.0 cm, *S. floriferum* was most abundant, followed by *S. spurium 'John Creech'*, *S. sexangulare*, and *S. stefco*.

These same four species are also the only four species that were influenced by substrate depth at the end of four growing seasons (week 172; Table 1.2).

Sedum floriferum is the only species exhibiting significant differences in AC at all three substrate depths. The remaining three species primarily see the difference between 4.0 cm and 7.0 cm, but not between 7.0 cm and 10.0 cm.

When AC is averaged over species, all depths demonstrated a statistically significant increase in AC across time (Table 1.3). AC for the 4.0 cm substrate depth increased from 0.1406 at week 15 to 1.1953 at week 172, while AC for the 10.0 cm substrate depth increased from 0.4036 to 1.3411. With the exception of week 15, the other times all showed significant substrate depth effects within sampled times, but only between 4.0 cm and 7.0 cm, but not between 7.0 cm and 10.0 cm. This indicates that for the surviving and most abundant species, substrate depths greater than 7.0 cm gains no benefit in terms of abundance as measured with a point-frame. However, at deeper substrate depths, these plants would likely be healthier, contain greater biomass, and be less susceptible to adverse environmental conditions.

Mean volumetric moisture content of the three substrate depths follows the same pattern as AC (Figure 1.3). While extremely variable, when averaged over time the 4.0 cm substrate depth held less moisture than the 7.0 or 10.0 cm depths. The 7.0 and 10.0 cm substrate depths were statistically the same. The observation that deeper extensive green roof substrates consistently had higher

moisture content than shallower substrates is consistent with similar studies (Liesecke, 1998; VanWoert et al., 2005a; VanWoert et al., 2005b). In addition, it appears that initially after a rain event the 4.0 cm substrate depth dries out faster than either the 7.0 or the 10.0 depths (Figure 1.4).

This greater water availability at the deeper substrate depths may explain why the 7.0 cm and 10.0 cm substrate depths had higher AC than the 4.0 cm depth. Another factor may be due to substrate temperature differences. Boivin et al. (2001) found that shallower extensive green roof substrates experienced much more severe temperature fluctuations than deeper substrates. During the growing season, shallower substrates will likely experience higher soil temperatures, which in turn will influence plant growth (Bouma et al. 1997; Prasad et al. 2000). This is exacerbated by the fact that lower AC of the 4.0 cm substrate depth exposes more substrate to direct sun resulting in higher substrate temperatures. In addition, some species are more suited for these temperature or water fluctuations than others. Durhman et al. (2007) found that *S. album* was the only species of 25 that exceeded 1.5 cm² of growth per day at a substrate depth of 2.5 cm (1.0 in). At a substrate depth of 5.0 cm (2.0 in) and 7.5 cm (3.0 in), this increased to 3 species and 8 species respectively.

Chlorophyll fluorescence data did not follow the same pattern as AC and substrate moisture content. Mean F_v/F_m values were not significantly different at 0.795, 0.779, and 0.781 for substrate depths of 4.0 cm, 7.0 cm, and 10 cm,

respectively. There were also very few differences between species within the same depth (data not shown). This may be due to the fact that measurements for chlorophyll fluorescence occurred during the third and fourth growing season only, whereby three (*Sedum caudicola* 'Lidakense', *Sedum ochroleucum*, and *Sedum sediforme*) of the twelve initial species had zero AC (i.e., no plants to take measurements upon). Had chlorophyll fluorescence data been taken during the first growing season, perhaps noticeable differences would have been detected between species that ultimately survived the four year study and those that did not. In addition, at individual measuring times which represent the driest portions of the growing season (18 June 2007, 2 August 2007, and 20 August 2008), mean chlorophyll fluorescence values of individual species never fell below 0.60, indicating very little, if any, stress to the photosynthetic system (Ritchie, 2006). Other research has established the same trend for many species in this genus. In a controlled greenhouse watering study, Durhman et al. (2006) found that three *Sedum* species maintained active photosynthetic capacity for at least 88 days without water. This may at least partially explain why *Sedum* species are such good candidates for extensive green roofs.

Conclusions

These results show the importance of substrate depth on plant performance, as well as long-term evaluation of species. Of the substrate depths and species evaluated in this paper, substrate depths of at least 7.0 cm are highly recommended. AC was significantly greater at this substrate depth relative to the

shallower depth of 4.0 cm. Species exhibiting the greatest AC at all substrate depths were *S. floriferum*, *S. sexangulare*, *S. spurium* 'John Creech', and *S. stefco*. In general, species that are less suitable are *S. 'Angelina'*, *S. caudicola* 'Lidakense', *S. ewersii*, *S. ochroleucum*, and *S. reflexum* 'Blue Spruce'.

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Table 1.1. Mean absolute cover $\pm$ standard deviations of 12 *Sedum* species cultivated at three substrate depths (4.0, 7.0, and 10.0 cm) at the end of four growing seasons (2005 to 2008). Cover reported in weeks, where week 15 = 23 September 2005; week 67 = 19 September 2006; week 120 = 24 September 2007; week 172 = 25 September 2008. Absolute cover was calculated for each species at each substrate depth as the total number of point-frame contacts divided by the number of data collection points.

Species	Absolute Cover (Depth=4.0 cm)			
	Week 15	Week 67	Week 120	Week 172
<i>S. 'Angelina'</i>	0.0052 $\pm$ 0.0045 a ABC	0.0182 $\pm$ 0.0045 b BC	0.0104 $\pm$ 0.0119 ab AB	0.0052 $\pm$ 0.0045 a AB
<i>S. cauticola</i> 'Lidakense'	0.0000 $\pm$ 0.0000 a A	0.0000 $\pm$ 0.0000 a A	0.0000 $\pm$ 0.0000 a A	0.0000 $\pm$ 0.0000 a A
<i>S. ewersii</i>	0.0000 $\pm$ 0.0000 a A	0.0130 $\pm$ 0.0226 a AB	0.0104 $\pm$ 0.0180 a AB	0.0182 $\pm$ 0.0316 a AB
<i>S. floriferum</i>	0.0130 $\pm$ 0.0163 a BC	0.1016 $\pm$ 0.0135 b DE	0.1979 $\pm$ 0.0726 b C	0.2891 $\pm$ 0.0639 b C
<i>S. hispanicum</i>	0.0000 $\pm$ 0.0000 a A	0.0469 $\pm$ 0.0282 b CD	0.0234 $\pm$ 0.0207 b B	0.0391 $\pm$ 0.0435 b B
<i>S. ochroleucum</i>	0.0026 $\pm$ 0.0045 ab AB	0.0078 $\pm$ 0.0078 b AB	0.0000 $\pm$ 0.0000 a A	0.0000 $\pm$ 0.0000 a A
<i>S. reflexum</i> 'Blue Spruce'	0.0000 $\pm$ 0.0000 a A	0.0208 $\pm$ 0.0180 b BC	0.0234 $\pm$ 0.0207 b B	0.0104 $\pm$ 0.0045 b AB
<i>S. sarmentosum</i>	0.0729 $\pm$ 0.0163 c D	0.0130 $\pm$ 0.0119 b AB	0.0000 $\pm$ 0.0000 a A	0.0000 $\pm$ 0.0000 a A
<i>S. sedifforme</i>	0.0052 $\pm$ 0.0045 b ABC	0.0000 $\pm$ 0.0000 a A	0.0000 $\pm$ 0.0000 a A	0.0000 $\pm$ 0.0000 a A
<i>S. sexangulare</i>	0.0104 $\pm$ 0.0119 a BC	0.1120 $\pm$ 0.0296 b DE	0.2214 $\pm$ 0.0813 b C	0.2031 $\pm$ 0.0979 b C
<i>S. spurium</i> 'John Creech'	0.0182 $\pm$ 0.0119 a CD	0.1172 $\pm$ 0.0413 b DE	0.1719 $\pm$ 0.0668 b C	0.2318 $\pm$ 0.0592 b C
<i>S. stefco</i>	0.0130 $\pm$ 0.0045 a C	0.2292 $\pm$ 0.0627 b E	0.3698 $\pm$ 0.0325 b C	0.3984 $\pm$ 0.0547 b C

Mean separation in rows and columns for each species by LSD ($P \leq 0.05$). Lowercase letters in rows denote comparisons over time within individual substrate depths and species ($n=12$). Uppercase letters in columns denote differences among species ($n=12$). Standard error was ± 0.0975 and ± 0.1757 for rows and columns respectively.

Table 1.1 continued.

Species	Absolute Cover (Depth=7.0 cm)			
	Week 15	Week 67	Week 120	Week 172
<i>S. 'Angelina'</i>	0.0078 ± 0.0078 a AB	0.0599 ± 0.0239 b DE	0.0339 ± 0.0197 b B	0.0104 ± 0.0119 a B
<i>S. caudicola</i> 'Lidakense'	0.0052 ± 0.0045 b AB	0.0000 ± 0.0000 a A	0.0000 ± 0.0000 a A	0.0000 ± 0.0000 a A
<i>S. ewersii</i>	0.0156 ± 0.0156 ab BC	0.0312 ± 0.0207 b CD	0.0286 ± 0.0369 ab B	0.0130 ± 0.0119 a B
<i>S. floriferum</i>	0.0443 ± 0.0090 a DE	0.1536 ± 0.0180 b EF	0.2760 ± 0.0502 b C	0.3880 ± 0.0296 b D
<i>S. hispanicum</i>	0.0156 ± 0.0156 b BC	0.0156 ± 0.0078 b BC	0.0000 ± 0.0000 a A	0.0000 ± 0.0000 a A
<i>S. ochroleucum</i>	0.0026 ± 0.0045 a A	0.0182 ± 0.0045 b BCD	0.0000 ± 0.0000 a A	0.0000 ± 0.0000 a A
<i>S. reflexum</i> 'Blue Spruce'	0.0026 ± 0.0045 a A	0.0391 ± 0.0135 b CD	0.0234 ± 0.0000 b B	0.0000 ± 0.0000 a A
<i>S. sarmentosum</i>	0.1641 ± 0.0156 b E	0.5286 ± 0.1329 b F	0.2031 ± 0.0812 b C	0.0443 ± 0.0325 a C
<i>S. sediforme</i>	0.0026 ± 0.0045 ab A	0.0104 ± 0.0090 b B	0.0000 ± 0.0000 a A	0.0000 ± 0.0000 a A
<i>S. sexangulare</i>	0.0208 ± 0.0045 a CD	0.1745 ± 0.0430 b EF	0.2891 ± 0.0207 b C	0.2839 ± 0.0163 b D
<i>S. spurium</i> 'John Creech'	0.0260 ± 0.0119 a CD	0.1458 ± 0.0197 b EF	0.3385 ± 0.0180 b C	0.3802 ± 0.0251 b D
<i>S. stefco</i>	0.0260 ± 0.0197 a CD	0.2161 ± 0.0722 b EF	0.2552 ± 0.0705 b C	0.2396 ± 0.0759 b D

Mean separation in rows and columns for each species by LSD ($P \leq 0.05$). Lowercase letters in rows denote comparisons over time within individual substrate depths and species ($n=12$). Uppercase letters in columns denote differences among species ($n=12$). Standard error was ± 0.0763 and ± 0.1376 for rows and columns respectively.

Table 1.1 continued.

Species	Absolute Cover (Depth=10.0 cm)		
	Week 15	Week 67	Week 120
<i>S. 'Angelina'</i>	0.0052 ± 0.0090 a AB	0.0469 ± 0.0207 b BCD	0.0078 ± 0.0135 a AB
<i>S. caudicola</i> 'Lidakense'	0.0000 ± 0.0000 a A	0.0000 ± 0.0000 a A	0.0000 ± 0.0000 a A
<i>S. ewersii</i>	0.0104 ± 0.0119 a BC	0.0339 ± 0.0119 b BC	0.0130 ± 0.0119 a B
<i>S. floriferum</i>	0.0677 ± 0.0119 a DE	0.1979 ± 0.0709 ab DE	0.4219 ± 0.0870 b C
<i>S. hispanicum</i>	0.0182 ± 0.0045 c CD	0.0052 ± 0.0045 b A	0.0339 ± 0.0401 bc B
<i>S. ochroleucum</i>	0.0026 ± 0.0045 a AB	0.0000 ± 0.0000 a A	0.0000 ± 0.0000 a A
<i>S. reflexum</i> 'Blue Spruce'	0.0026 ± 0.0045 ab AB	0.0286 ± 0.0226 c B	0.0104 ± 0.0090 b B
<i>S. sarmentosum</i>	0.1745 ± 0.0369 b E	0.6641 ± 0.1369 c E	0.1693 ± 0.1466 b C
<i>S. sedifforme</i>	0.0026 ± 0.0045 ab AB	0.0052 ± 0.0045 b A	0.0000 ± 0.0000 a A
<i>S. sexangulare</i>	0.0365 ± 0.0119 a D	0.1406 ± 0.0078 b CD	0.2292 ± 0.0759 b C
<i>S. spurium</i> 'John Creech'	0.0286 ± 0.0090 a D	0.1484 ± 0.0078 b DE	0.3333 ± 0.0576 b C
<i>S. stefco</i>	0.0547 ± 0.0135 a DE	0.1849 ± 0.1331 ab DE	0.2474 ± 0.1641 b C

Mean separation in rows and columns for each species by LSD ($P \leq 0.05$). Lowercase letters in rows denote comparisons over time within individual substrate depths and species ($n=12$). Uppercase letters in columns denote differences among species ($n=12$). Standard error was ± 0.0856 and ± 0.1543 for rows and columns respectively.

Table 1.2. Mean absolute cover $\pm$ standard deviations of 12 *Sedum* species cultivated at three substrate depths (4.0, 7.0, and 10.0 cm) reported on week 172 (25 September 2008). Absolute cover was calculated for each species at each substrate depth as the total number of point-frame contacts divided by the number of data collection points.

Species	Absolute Cover (Week 172)		
	4.0 cm	7.0 cm	10.0 cm
<i>S. 'Angelina'</i>	0.0052 $\pm$ 0.0045 a	0.0104 $\pm$ 0.0119 a	0.0104 $\pm$ 0.0119 a
<i>S. cauticola</i> 'Lidakense'	0.0000 $\pm$ 0.0000 a	0.0000 $\pm$ 0.0000 a	0.0000 $\pm$ 0.0000 a
<i>S. ewersii</i>	0.0182 $\pm$ 0.0316 a	0.0130 $\pm$ 0.0119 a	0.0078 $\pm$ 0.0135 a
<i>S. floriferum</i>	0.2891 $\pm$ 0.0639 a	0.3880 $\pm$ 0.0296 b	0.5599 $\pm$ 0.0502 c
<i>S. hispanicum</i>	0.0391 $\pm$ 0.0435 a	0.0000 $\pm$ 0.0000 a	0.0000 $\pm$ 0.0000 a
<i>S. ochroleucum</i>	0.0000 $\pm$ 0.0000 a	0.0000 $\pm$ 0.0000 a	0.0000 $\pm$ 0.0000 a
<i>S. reflexum</i> 'Blue Spruce'	0.0104 $\pm$ 0.0045 a	0.0000 $\pm$ 0.0000 a	0.0000 $\pm$ 0.0000 a
<i>S. sarmentosum</i>	0.0000 $\pm$ 0.0000 a	0.0443 $\pm$ 0.0325 a	0.0521 $\pm$ 0.0709 a
<i>S. sedifforme</i>	0.0000 $\pm$ 0.0000 a	0.0000 $\pm$ 0.0000 a	0.0000 $\pm$ 0.0000 a
<i>S. sexangulare</i>	0.2031 $\pm$ 0.0979 a	0.2839 $\pm$ 0.0163 b	0.1901 $\pm$ 0.0554 a
<i>S. spurium</i> 'John Creech'	0.2318 $\pm$ 0.0592 a	0.3802 $\pm$ 0.0251 b	0.3333 $\pm$ 0.0726 b
<i>S. stefco</i>	0.3984 $\pm$ 0.0547 b	0.2396 $\pm$ 0.0759 a	0.1875 $\pm$ 0.1447 a

Mean separation in rows for each species by LSD ($P \leq 0.05$). Lowercase letters denote comparisons within the same row ($n=12$) with standard error $\pm$ 0.0146.

Table 1.3. Mean absolute cover $\pm$ standard deviations averaged over species cultivated at three substrate depths (4.0, 7.0, and 10.0 cm) over the 2005 to 2008 growing seasons. Cover reported in weeks, where week 15 = 23 September 2005; week 67 = 19 September 2006; week 120 = 24 September 2007; week 172 = 25 September 2008. Absolute cover was calculated for each species at each substrate depth as the total number of point-frame contacts divided by the number of data collection points.

Depth	Absolute Cover			
	Week 15	Week 67	Week 120	Week 172
4.0 cm	0.1406 ± 0.0282 a A	0.6797 ± 0.2115 a A	1.0286 ± 0.1864 b A	1.1953 ± 0.1151 c A
7.0 cm	0.3333 ± 0.0119 a A	1.3932 ± 0.0722 bc B	1.4479 ± 0.0798 b B	1.3594 ± 0.0078 c B
10.0 cm	0.4036 ± 0.0508 a A	1.4557 ± 0.0607 b B	1.4661 ± 0.0369 b B	1.3411 ± 0.0430 c B

Mean separation in rows for each depth by LSD ($P \leq 0.05$). Lowercase letters denote comparisons over time within individual substrate depths ($n=12$). Uppercase letters in columns denote differences among depths ($n=12$). Standard error was ± 0.0251 and ± 0.0904 for rows and columns respectively.

Figure 1.1. Absolute cover $\pm$ standard deviations of 12 *Sedum* spp. cultivated at three substrate depths (4.0, 7.0, and 10.0 cm) over the 2005-2008 growing seasons. Symbols represent absolute cover means with standard deviations (n=3). For clarity of graphing, weeks 0 through 120 were plotted at every other data point.

Figure 1.1a.

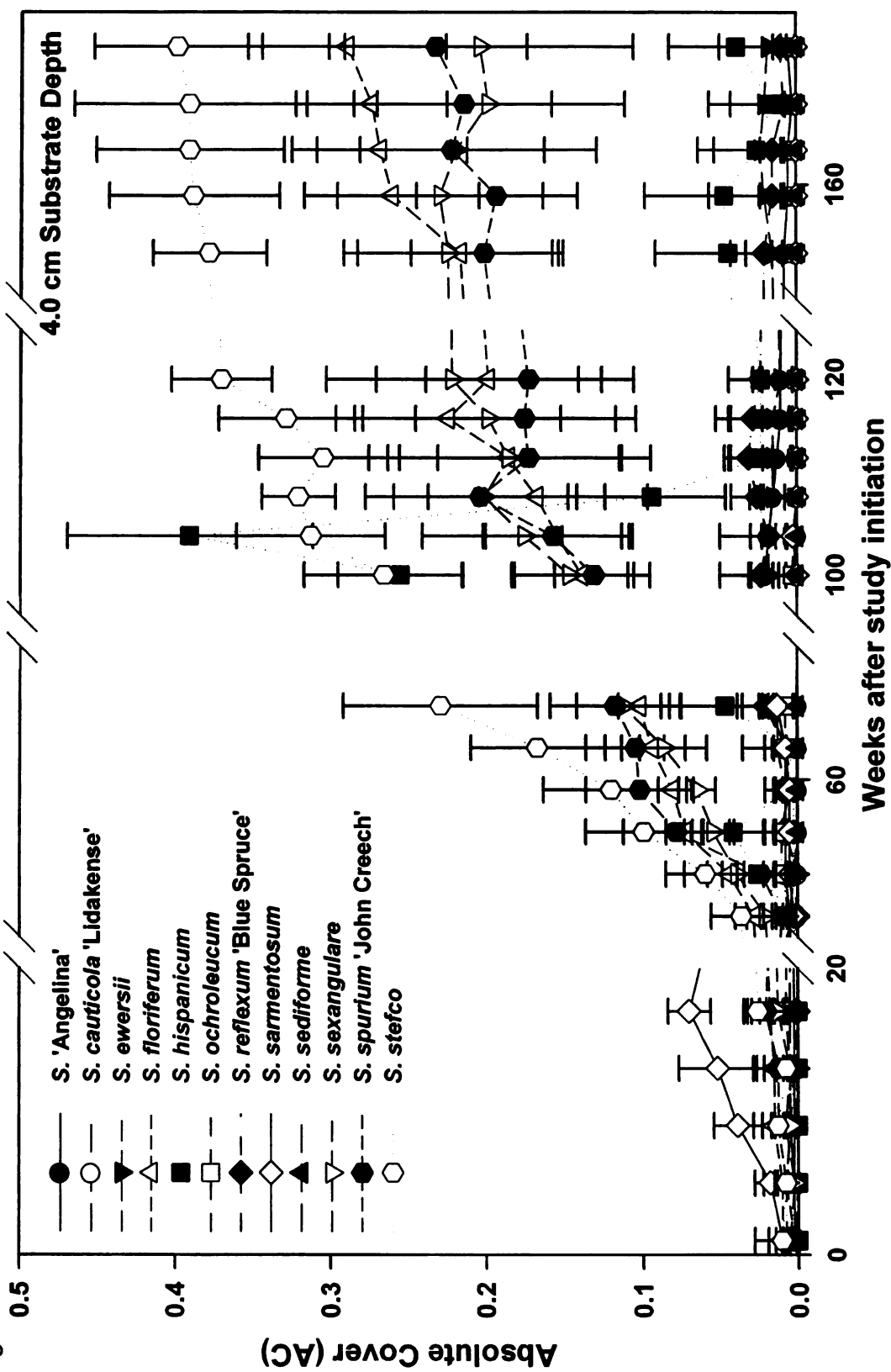


Figure 1.1b.

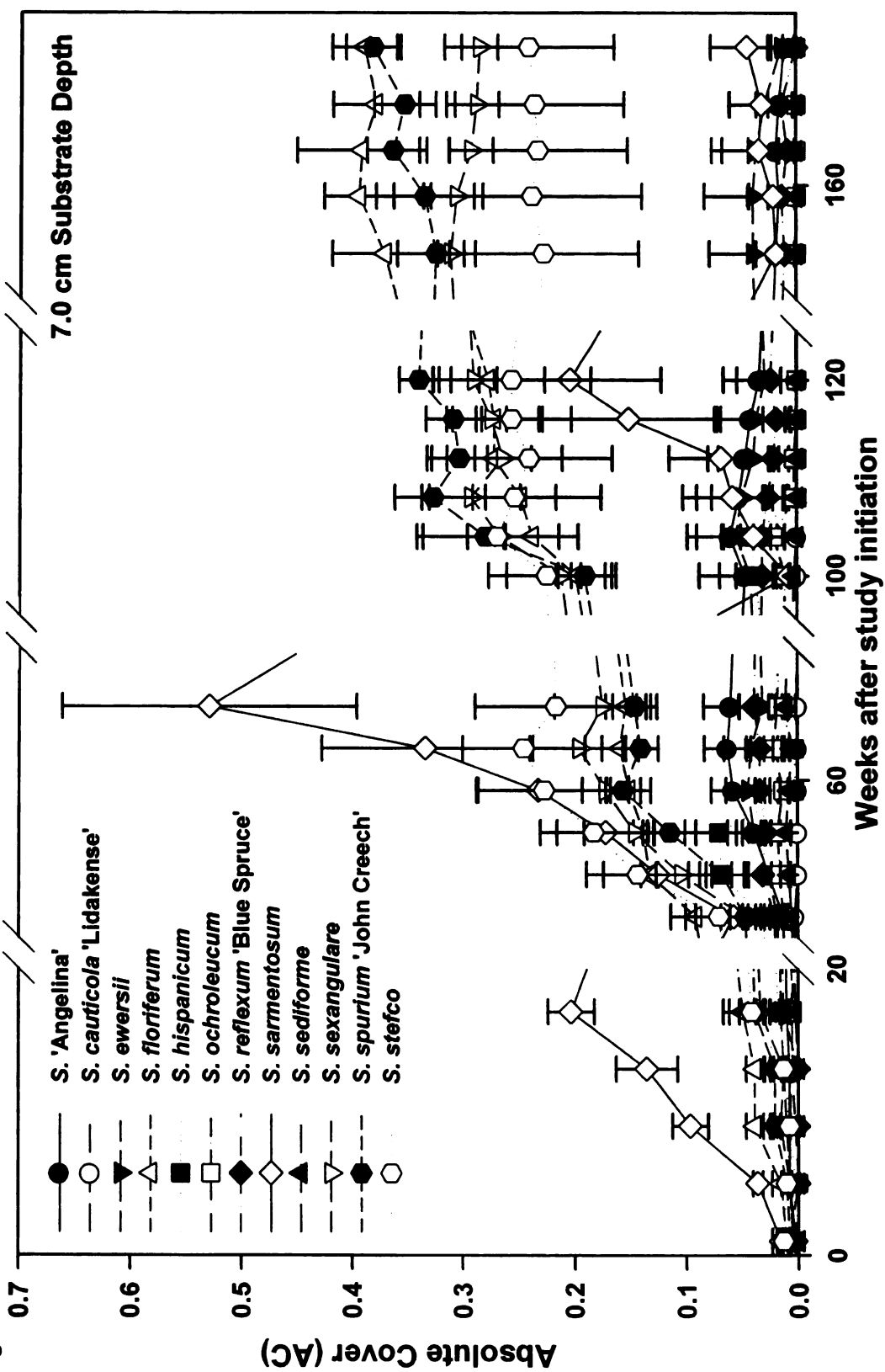
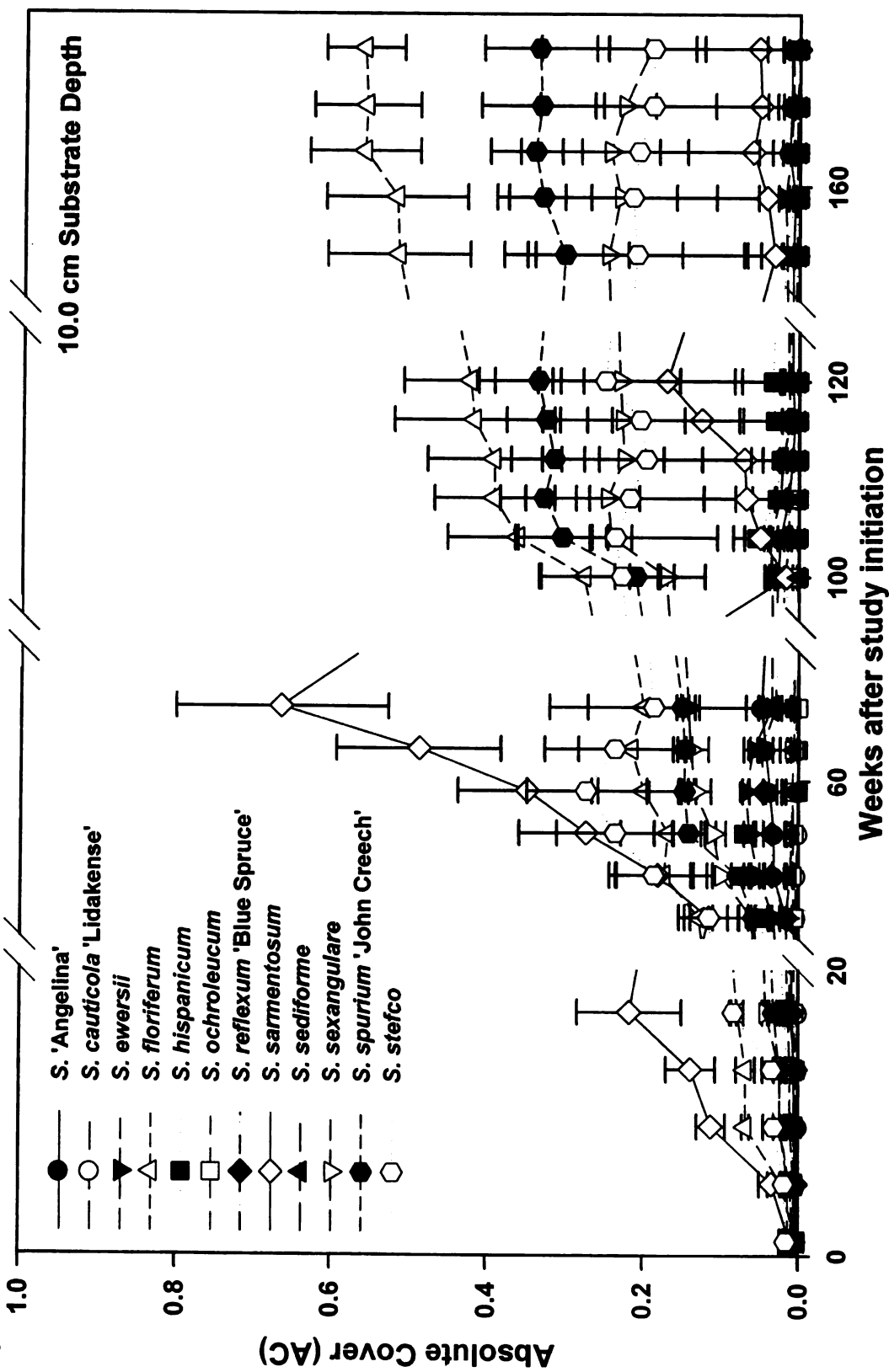


Figure 1.1c.



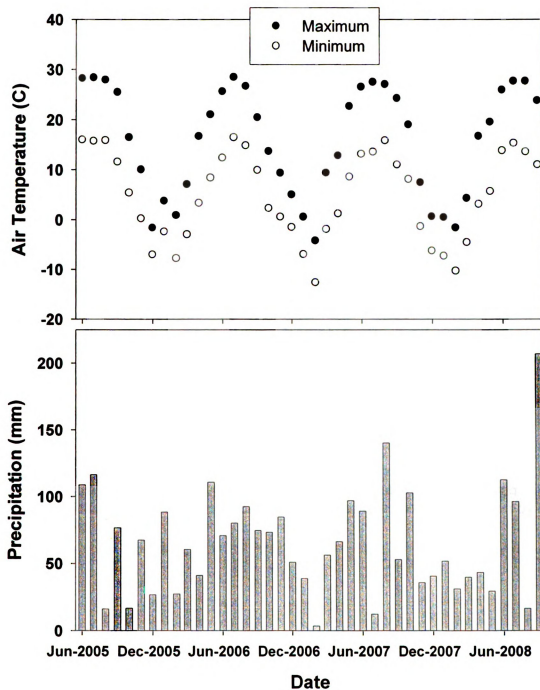


Figure 1.2. Monthly average maximum air temperatures ($^{\circ}\text{C}$), monthly average minimum air temperatures ($^{\circ}\text{C}$), and monthly total precipitation (mm) throughout the study (1 June 2005 to 30 September 2008). Data is from the Michigan Automated Weather Network's East Lansing weather station (located adjacent to the research site).

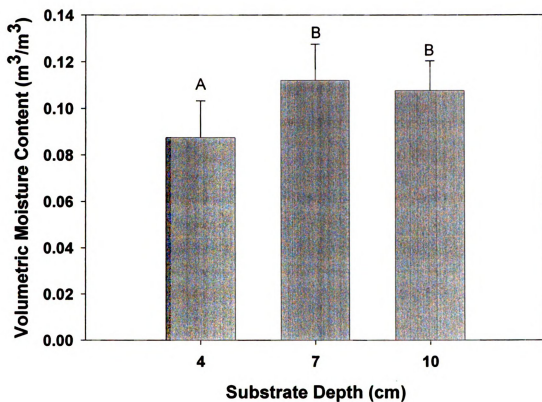


Figure 1.3. Substrate volumetric moisture content (m^3/m^3) $\pm$ standard errors for three substrate depths (4.0, 7.0, and 10.0 cm) averaged over two growing seasons (2007 and 2008). Uppercase letters represent mean separation by LSD ($P \leq 0.05$).

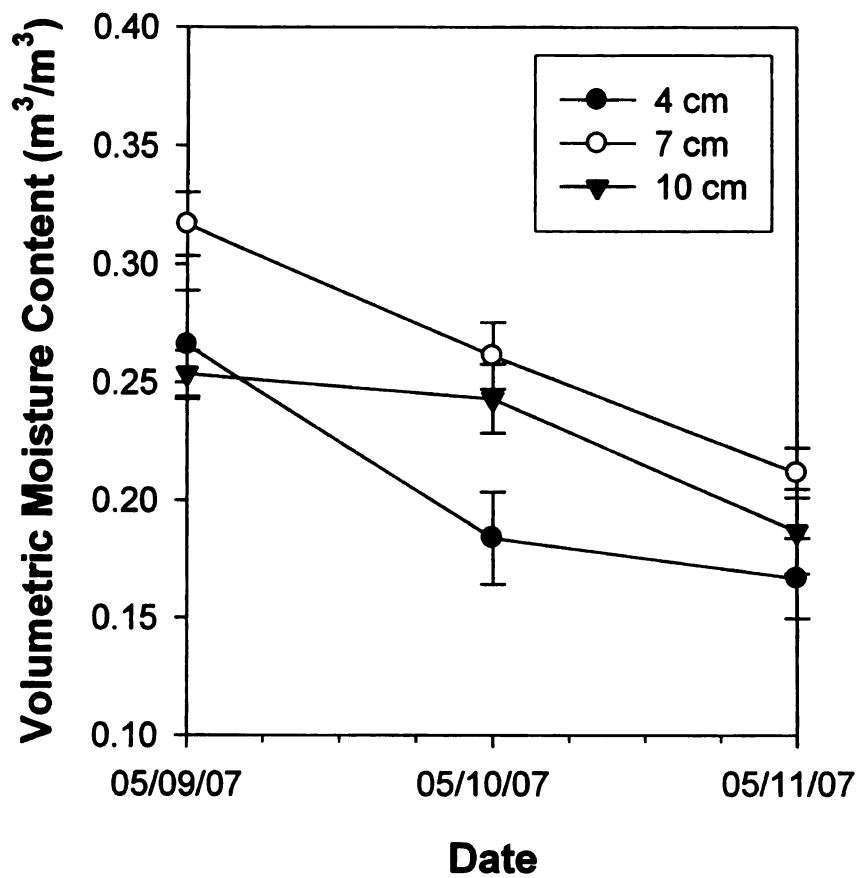


Figure 1.4. Substrate volumetric moisture content (m^3/m^3) $\pm$ standard errors for a selected three day period following a 22.1 mm rain event at three substrate depths (4.0, 7.0, and 10.0 cm).

CHAPTER TWO

Solar Radiation Intensity Influences Extensive Green Roof Plant Communities

Abstract

Two studies were conducted on a third-story rooftop to quantify the effect of solar radiation (full sun vs. full shade) on several U.S. native and non-native species for potential use on extensive green roofs. In the first study, plugs of six native and three non-native species were planted in May 2005 at two different substrate depths (8.0 cm and 12.0 cm) both in sun and shade. Absolute cover (AC) was recorded using a point-frame transect during the growing season beginning in June 2005 and every two weeks thereafter for a period of four years. By week 174 (23 Sept 2008), most species exhibited different AC within a depth between sun and shade. However, when all species were combined, overall AC did not differ between sun and shade within a depth. This indicated that while species make-up was changing among solar radiation levels, that overall coverage was not significantly different between sun and shade. For all substrate depths and solar levels, the most abundant species were *Sedum acre*, *Allium cernuum*, *Sedum album* 'Coral Carpet', and *Talinum calycinum*. Less suitable species included *Talinum parviflorum*, *Carex flacca*, *Sedum stenopetalum*, and *Sedum divergens*, which all exhibited 0 or near 0 AC regardless of depth or solar radiation levels. With the exception of *T. calycinum*, native species were less abundant than non-native species.

In the second study, six typical extensive green roof species of *Sedum* grown from seed in 10.0 cm (3.9 in) of substrate were compared in both sun and shade during May 2005. AC was evaluated as in the previous study. Solar radiation

did not affect AC, but over all species composition differed between sun and shade levels. The most prolific species in full sun were *Sedum acre* (0.57 AC) and *Sedum album* 'Coral Carpet' (0.51 AC). *Sedum kamtschaticum* (0.57 AC) and *Sedum spurium* 'Coccineum' (0.35 AC) performed the best in the shade. For both solar levels, the least abundant species at week 174 were *Sedum pulchellum* (0.0 AC) and *Sedum album* 'Coral Carpet' (0.1 AC).

Introduction

Green roofs, or vegetated roofs, are frequently installed in urban areas because of their ability to improve stormwater management (Carter and Jackson, 2007; Getter et al., 2007; Hilten et al., 2008; Jarrett and Berghage, 2008) and mitigate the urban heat island effect (Takebayashi and Moriyama, 2007). Green roofs provide many additional benefits as compared to traditional roofs including energy conservation (Santamouris et al., 2007; Sailor, 2008), increased longevity of roofing membranes (Kosareo and Ries, 2007), reduction in noise and air pollution (Van Renterghem and Botteldooren, 2008; Yang et al., 2008), increased urban biodiversity (Baumann, 2006; Brenneisen, 2006), as well as providing a more aesthetically pleasing living environment (Getter and Rowe, 2006; Oberndorfer et al., 2007). Recent research has suggested that green roofs are also a better return on investment than traditional roofs (Clark et al., 2008).

Green roofs are categorized as 'intensive' or 'extensive' systems. Intensive green roofs are designed to be similar to landscaping found at ground level, and

as such require substrate depths greater than 15.0 cm and have 'intense' maintenance needs. In contrast, extensive green roofs use shallower substrate depths (less than 15.0 cm) and usually require minimal maintenance. Due to building weight restrictions and costs, shallow substrate extensive green roofs are much more common than deeper intensive roofs. Therefore, the focus of this paper is on extensive green roofs.

Plant selection for green roofs is often difficult due to the harsh urban environment and because plants are frequently subjected to extremes in temperature and drought due to their shallow substrate and elevation above ground. In addition, research involving plant selection thus far has typically been for roofs exposed only to full sun (Monterusso et al., 2005; Durhman et al., 2007; Getter and Rowe, 2008). However, as green roof implementation continues, it is likely that many green roofs will be shaded by other structures. Incoming solar radiation (insolation) directly and indirectly impacts plant growth. Depending on species, this impact may be severe or negligible. In Utah, USA, high solar radiation zones differed from low solar radiation zones in terms of species performance (Dewey et al., 2004). Another study in the U.S. Pacific Northwest examined sloped roofs and found that in some cases the amount of solar radiation influenced plant performance (Martin and Hinckley, 2007).

Furthermore, overall climate and roof microclimate will determine plant success as well as the design intent for the green roof. A good example of this is the

state of Florida's first pilot green roof installed in Naples, Florida, USA in 2003. The plant species chosen for this project were selected because of their green roof success in northern latitudes. But these species failed to survive in Florida's environment. The researchers concluded that the "type of media used and the green roof profile structure are secondary to the correct choice of plants" (Livingston et al., 2004).

Often clients desire the use of native species because of their real and perceived benefits, such as their longevity without the use of pesticides, fertilizers, or irrigation (US EPA, 2008). But, plants could not actually be native to rooftops since roofs are man-made artificial structures. However, many plant species have evolved in extreme environments and are adapted to green roof conditions. Because of client demand for native species, researchers in Michigan, USA evaluated 18 native taxa on unirrigated extensive green roof platforms (Monterusso et al., 2005; Rowe et al., 2005). After three years, only four of the species survived. The majority of the plants tested were considered to be drought tolerant, but their survival in a native environment relies on deep tap roots to obtain moisture. In a shallow extensive roof, these roots can still grow sideways, but periods of drought resulted in death. These plants may have all survived with deeper substrates or supplemental irrigation.

One technique used to assess plant stress in harsh conditions is measurement of chlorophyll fluorescence. This technique is used to quantify the efficiency of the

photosynthetic apparatus (Maxwell and Johnson, 2000). Photon energy absorbed by a chlorophyll molecule can be used to fuel photosynthesis, dissipated as heat, or re-emitted as fluorescence. Measurement of the latter is used to indicate how efficient the former two processes are proceeding. Fluorimeters are used to measure this value, usually reporting the ratio (F_v/F_m) of variable fluorescence (F_v) to maximum fluorescence (F_m) which typically range from 0.70 to 0.83, with values less than 0.60 indicating photosynthetic stress (Ritchie, 2006).

Many studies of plant survival on green roofs are based on one to two years data (Kircher, 2004; Emilsson and Rolf, 2005; MacDonagh et al., 2006; Durhman et al., 2007; Nagase and Dunnett, 2008). Since green roofs are estimated to last 45 years or longer in terms of mechanical lifespan (Kosareo and Ries, 2007), long-term plant performance beyond the first few years of establishment is important. Plants that survive initially on a green roof may not continue to exist in the long term because of variability in climate and other factors. Therefore, the objective of this study was to evaluate the effect of substrate depth and solar radiation intensities (full sun vs. full shade) on substrate moisture, plant stress as measured by chlorophyll fluorescence, and plant community development of both U.S. native and typical non-native green roof species in a Midwestern climate over a period of four years. Native species chosen were native to the U.S. and were drought tolerant without the benefit of deep rooted systems.

Materials and Methods

Green Roof Plots. Green roof plots were established on the Communication Arts building on the campus of Michigan State University in East Lansing, Michigan, USA in May 2005. The roof of this building is constructed such that it can easily accommodate varying substrate depths and it is tiered in such a way that approximately 10% of the roof is always in complete shade (defined here as the absence of direct solar radiation). Six wooden frames were built measuring 120 cm x 234 cm with sides of 15.2 cm in depth. Each frame was divided into three subplots with internal dimensions of 115 cm x 75 cm. Three frames were situated in full shade (rarely receiving direct sunlight) and three in full sun (rarely receiving shade from natural or human structures).

The wood frames were placed directly on the roof over a root barrier membrane. Drainage material (Xero Flor XF108; XeroFlor America, Durham, North Carolina, USA) was placed inside each subplot. For additional water holding capacity, a 0.75 cm thick moisture retention fabric (Xero Flor XF159) capable of retaining up to $5.92 \text{ kg}\cdot\text{m}^{-2}$ of water was placed over the drainage layer. Above the retention fabric was the vegetation carrier (Xero Flor XF301). Growing substrate (Table 2.1) was then placed in each subplot on top of the vegetation carrier to a depth of 8.0 cm, 10.0 cm, or 12.0 cm. Substrate treatments were blocked by arranging each depth randomly in each plot, replicated three times. This resulted in an experimental model that was a randomized complete block design with three factors replicated three times.

Plant Establishment – Study 1. In order to compare native with non-native species, six species native to the U.S. (*Allium cernuum* (wild nodding onion), *Carex flacca* (heath sedge), *Sedum divergens* (cascade stonecrop), *Sedum stenopetalum* (narrow-petaled stonecrop), *Talinum calycinum* (largeflower fameflower), and *Talinum parviflorum* (sunbright)), as well as three non-native species (*Sedum acre* 'Oktoberfest' (biting stonecrop), *Sedum album* 'Coral Carpet' (white stonecrop), and *Sedum urvillei* (stonecrop)), were acquired as plugs (120 cm³; 72/flat; Emory Knoll Farms, Street, Maryland, USA) that were established in a standard propagation mix of peat, perlite, and vermiculite (Super-Fine Germination Media, Farfard, Inc., Agawam, Massachusetts, USA). On May 25, 2005, plugs were planted in both the 8.0 cm and 12.0 cm substrate depth plots with seven plants per row 15 cm apart resulting in four rows. Each plant species was randomly planted three times in each subplot, resulting in a total of 162 plants in the study. Since this arrangement results in 28 spots and there were nine species planted three times each, one spot remained empty in each sub-plot.

Plant Establishment – Study 2. Seeds (Jelitto Staudensamen, GmbH (Schwarmstedt, Germany)) of six typical extensive green roof species (*Sedum acre* (biting stonecrop), *Sedum album* (white stonecrop), *Sedum kamtschaticum* (stonecrop), *Sedum pulchellum* (bird's claw sedum), *Sedum reflexum* (crooked sedum), and *Sedum spurium* 'Coccineum' (creeping sedum)) were planted in

each 10.0 cm subplot. On May 25, 2005, seeds were sown after weighing 1.13 g of each species in a beaker and combining the seed with 28.0 grams of fine vermiculite. This mixture was then evenly distributed in the subplot. Shade cloth was placed over the seeds for three weeks to aid in germination and establishment.

For both studies, plots were irrigated three times daily for 20 minutes for the first four weeks and once daily for 20 minutes for the next six weeks. Irrigation was then terminated for the remainder of the studies. Removal of weeds took place every two weeks.

Data Collection and Analysis. For both studies, a stainless steel point-frame was used every two weeks during the first three growing seasons and monthly in the fourth growing season to measure community composition and change (Waite, 2000). The point frame had internal measurements of 115 cm x 75 cm and had 7 strings (50 pound Berkley Gorilla Super Braid Fishing Line) vertically and 10 strings horizontally to create 70 measurement points. The point frame sat 14 cm above the frame surface on top of wooden pegs which were secured into the corners of each frame. The point-frame sat directly on top of the wooden plots, secured by finishing nails that allowed the frame to be positioned in the exact same spot every time. A stainless steel skewer (measuring 38.0 cm long) was placed vertically at each measuring point in the point-frame and each species the skewer contacted was recorded, up to three canopy layers. Absolute cover was

calculated for each species at each substrate depth as the total number of contacts recorded divided by the number of data collection points (Waite, 2000).

Environmental conditions were continuously recorded on a CR10X Campbell Scientific Datalogger (Campbell Scientific Inc., Logan, Utah, USA) throughout the experiments. Two 105T-L thermocouples (Campbell Scientific Inc., Logan, Utah, USA) were placed in radiation shields and mounted on the wooden plots, one in the sun and one in the shade, and connected to the datalogger. In addition, two LI200X-L LI-COR Silicon Pyranometers (Campbell Scientific Inc., Logan, Utah, USA) quantified total incoming solar radiation at each location; one in the sun and one in the shade. A weather station with a 03001-L R.M. Young Wind Sentry Set (consisting of a 3-cup anemometer and a wind vane) (Campbell Scientific Inc., Logan, Utah, USA) and a TE525WS-L Texas Electronics 8" Rain Gage (Campbell Scientific Inc., Logan, Utah, USA) was also situated on the roof. A MSX20 solar panel (Campbell Scientific Inc., Logan, Utah, USA) was installed to power all electronic equipment.

Substrate moisture and chlorophyll fluorescence data were collected throughout the final two growing seasons. Substrate volumetric moisture was monitored by inserting a theta probe (ML2x, Delta-T Devices, Ltd., Cambridge, United Kingdom) into the substrate until the 6 cm prongs were completely buried. Measurements were collected at random times each week in triplicate in each subplot. Chlorophyll fluorescence measurements were collected at six different

times (21 May 2007, 18 June 2007, 2 August 2007, 17 September 2007, 29 May 2008, and 20 August 2008) using a Hansatech plant efficiency analyzer (PEA; Hansatech Instruments, Ltd., Norfolk, England). These measurement dates were selected in order to cover a wide range of environmental conditions including active growth and drought stress during the growing season. Each plant was dark adapted for 20 minutes prior to measurement and illuminated with a 50% light level. Maximum quantum efficiency of photosystem II was recorded (F_v/F_m). Three single leaf blades of each surviving species were randomly selected in each subplot and excised from the plant to be dark adapted and measured. This was necessary because the PEA clips were not secure on the leaf of most species while still attached to the whole plant.

Data Analysis. Absolute cover (AC) was calculated for each species at each solar radiation intensity and substrate depth as the total number of contacts recorded divided by the number of data collection points. Data was then analyzed as mean AC using repeated measures with a first-order autoregressive (AR(1)) covariance structure (Wolfinger, 1996). Significant differences between treatments were determined using multiple comparisons (PROC MIXED, SAS version 9.1.3, SAS Institute, Cary, NC). In addition, mean substrate volumetric moisture content and mean chlorophyll fluorescence data were analyzed by PROC MIXED, least significant differences (SAS version 9.1.3, SAS Institute, Cary, NC)

Results and Discussion

Throughout the study, maximum daily solar radiation and maximum daily air temperatures varied in the sun and shade. Representative data for year two (1 January 2006 – 31 December 2006) are shown in Figure 2.1. Mean maximum daily air temperature and mean maximum daily solar radiation flux during July 2006, which represents the peak of the growing season, were 33.9 C and 0.71 kW·m⁻² in the sun and 33.8 C and 0.44 kW·m⁻² in the shade. More variability was seen among maximum solar radiation than in temperature between radiation intensities, likely because temperatures above the surface of the roof were well mixed (Figure 2.1).

Study 1 – Plugs of U.S. native and non-native species

When analyzed across all growing seasons, solar exposure, substrate depth, and species treatments were all significant ($P=0.05$). There were also significant interactions between species and solar level, species and substrate depth, as well as a three-way interaction between depth, solar exposure, and species. These results confirm that the choice of species depends on solar exposure and substrate depth.

At the end of the first growing season, *C. flacca* appeared to be one of the most abundant species for both substrate depths in the shade (Figure 2.2). However, in subsequent years, it decreased in abundance during the driest portions of the summer which likely impacted overall regeneration. By the end of the four years,

this species exhibited zero or near-zero AC. In contrast, at the end of the second growing season, *S. acre* 'Oktoberfest' had established itself as the most abundant species for both substrate depths in the shade and exceeded an AC of 0.6 by the third growing season (Figure 2.2). For both substrate depths in the shade, *A. cernuum* is the next most abundant species by the end of the fourth growing season, followed by *S. album* 'Coral Carpet' and *T. calycinum*. For all depths and solar radiation levels, *T. parviflorum* (which had completely disappeared after the first growing season), *S. stenopetalum*, and *S. divergens* had the lowest AC (Figure 2.2).

In the sun, by the second growing season both substrate depths were dominated by *S. album* 'Coral Carpet', followed by *T. calycinum* and *S. acre* 'Oktoberfest' (Figure 2.2). At 12 cm, *A. cernuum* closely follows as the fourth most abundant, but this species was not nearly as abundant as it was in the shade at the same depth. This is likely due to a severe phototropic bending when grown in the shade, which may overrepresent this species in point-frame sampling techniques (Wilson, 1960), as it will fall under a sampling point more often than the erect habit exhibited in the sun. While not measured in this study, *A. cernuum* appeared to have greater biomass per given area due to its upright growth habit than the AC measure suggests.

For specific point-in-time comparisons, week 174 (23 September 2008) of the study was chosen to represent the end of the fourth growing season, where

maximum biomass should have been reached for the year for most species. At the 8 cm substrate depth, AC only varied for four species between sun and shade (*A. cernuum*, *S. acre* 'Oktoberfest', *S. album* 'Coral Carpet', and *T. calycinum*) (Table 2.2). At 12 cm, the same four species, plus *C. flacca* had differing AC between sun and shade. The remaining four species all exhibited 0 or near 0 AC for both sun and shade, indicating that they are unsuitable species for these substrate depths in this climate regardless of solar radiation intensities, at least when supplemental irrigation is not available.

When all species are combined, overall AC did not differ between solar exposures within each substrate depth (Table 2.2). This indicates that while species make-up changed among solar radiation levels, overall coverage was not significantly different between sun and shade for this time. Species most suited to the environmental conditions present will expand into open space. This emphasizes the importance of planting numerous species to ensure plant diversity in order to obtain and maintain full coverage on a roof. However, what this study does not capture is the difference in above-ground biomass between solar levels. Within a given substrate depth, the shade canopy was much taller than the sun canopy (personal observation).

As a group, the native species chosen for this study did not grow as well as non-natives. *Talinum calycinum* was the most abundant native species in the sun, while *A. cernuum* had a higher AC in the shade. Two of the native species (*S.*

stenopetalum and *S. divergens*) are native to the western U.S. (USDA, 2008) and thus may not have been suited for the hot humid summer conditions of the Midwestern U.S. (Snodgrass and Snodgrass, 2006). By contrast, *C. flacca* is native to Michigan (USDA, 2008), but its poor performance is likely because it requires a substrate depth of at least 15 cm (Snodgrass and Snodgrass, 2006). The native *Talinum* species (*T. calycinum* and *T. parviflorum*) were outside of their hardiness zone (zone 6; Snodgrass and Snodgrass, 2006) in this study (zone 5; Cathey, 1990) and as such were self-sowing annuals, which may explain why they did not perform as well as other (non-native) species. They are prolific seeders, but need bare soil in order to germinate.

Mean substrate volumetric moisture content did not differ between the two solar radiation levels at the 8.0 cm substrate depth (Table 2.3). However, at the 12.0 cm substrate depth and when averaged across depths, soil moisture was higher in the shade than in the sun. These results indicate that the full sun environment likely had greater evaporation from the soil and plant transpiration losses leading to less water held in the soil at any given measurement time. It is likely that differences in AC between shade and sun for some species were due to lower water availability in the sun compared to the shade. This confirms what others have found; that when all else is equal, shaded environments often have greater substrate moisture than sunny environments (Williams et al., 1993; Kobayashi et al., 1997).

Within the same solar radiation level, mean volumetric moisture content was statistically the same between the substrate depths. But, had a shallower substrate depth been used, it is likely that there would be a difference in moisture content. VanWoert et al. (2005) found substrate moisture differences between 2.0 cm and 6.0 cm substrate depths. Getter and Rowe (2009) found that 4.0 cm substrate depths held less moisture than 7.0 or 10.0 cm depths, but that 7.0 and 10.0 cm substrate depths were statistically the same. The latter two are very similar to the two substrate depth treatments (8 cm and 12cm) used in this study.

Chlorophyll fluorescence data exhibited mixed results. Within an individual species, mean F_v/F_m values were not significantly different between solar radiation or depth treatments (data not shown). This may be due to the fact that measurements for chlorophyll fluorescence occurred during the third and fourth growing season only, whereby three (*Sedum divergens*, *Sedum stenopetalum*, and *Talinum parviflorum*) of the nine initial species had zero AC (i.e., no plants to take measurements upon). Had chlorophyll fluorescence data been taken during the first growing season, perhaps noticeable differences would have been detected between species that ultimately survived the four year study and those that did not. Then again, chlorophyll fluorescence is only a tool to quantify plant stress and not necessarily a prediction of survival.

When averaged across all species, solar levels were significant, while substrate depth and the interaction between the two were not significant. Mean F_v/F_m

values within the same substrate depth are higher in the shade than in the sun (Figure 2.3). This indicates that perhaps the shaded environment induced less photosynthetic stress than the sun, although neither of the average F_v/F_m values was considered stressful (Ritchie, 2006). It is possible that the number of observations (N) was insufficient for individual species to find a difference in F_v/F_m values, whereas combined data provided more degrees of freedom.

Study 2 – Seed of typical non-native green roof species

When analyzed across all growing seasons, solar exposure and species were both significant ($P=0.05$). There were also significant interactions between solar level and species, highlighting the importance of species choice for any given solar exposure.

In the shade, *S. pulchellum* was initially the most abundant species during the majority of the first growing season and into the beginning of the second (Figure 2.4). But as the community developed, *S. acre* clearly becomes more abundant by the end of the second growing season and the first half of the third. However, the fourth growing season produced very different results, highlighting the importance of long term studies. During the entire fourth growing season, *S. pulchellum* was the least abundant species and virtually absent. By the end of that season, *S. kamtschaticum* was most abundant, followed by *S. spurium* 'Coccineum', *S. acre*, and *S. album*. While *S. reflexum* was not highly abundant at this time, it was still a respectable accent plant with an AC of 0.2.

By contrast, in the sun, *S. acre* was the most abundant species across all four growing seasons (Figure 2.4), although by the end of the fourth season *S. album* was nearly as abundant. The next most abundant species are *S. kamtschaticum* and *S. spurium* 'Coccineum'. *Sedum pulchellum* begins the study as the second most abundant species in the sun, but then fails to reappear after the second growing season. *Sedum reflexum* is also virtually non-existent at this solar load, making it an unsuitable choice as well.

The initial prominence of *S. pulchellum* in the first two growing seasons, followed by its disappearance is likely due to its growth strategy. This species is a spring ephemeral, whereby its seed germinates in very early spring or late winter, flowers, and sets seed before other species crowd it out in mid June. In the second growing season, this species reached a maximum AC of 0.77 and 0.29 in the shade and sun, respectively, before dieing off for the summer (Figure 2.4). In year three, *S. pulchellum* only reached a maximum AC of 0.14 and 0.07 in the shade and sun, respectively. This is probably due to fewer gaps in the canopy for seed germination to occur because evergreen species like *S. acre* and *S. album* had closed much of the canopy by that time.

For specific point-in-time comparisons, week 174 (23 September 2008) of the study was chosen to represent the end of the fourth growing season, where maximum biomass should have been reached for the year for most species.

Within a given species, most exhibited similar AC between sun and shade (Table 2.4). The exception was *S. acre* and *S. album*, both of which were more abundant in the sun than in the shade. This agrees with the general observation that these two species tend to dominate shallow green roofs. They seem to be better adapted to withstand full sun and limited substrate moisture. For all species combined, there was no difference between total AC in the sun and shade (Table 2.4). This indicates that while species make-up is changing amongst solar radiation levels, that overall coverage is not significantly different between sun and shade for this time period.

Mean substrate volumetric moisture content for the two solar radiation levels at this 10 cm substrate depth was 0.138 and 0.122 for shade and sun respectively (data not shown). Over the entire growing season, it is evident that at almost every measurement time, shade moisture content was equal to or greater than sun moisture content (Figure 2.5).

Chlorophyll fluorescence differed between solar radiation levels. Mean F_v/F_m values for two species (*S. album* and *S. spurium* 'Coccineum'), as well as when averaged across all species, had higher values in the shade than in the sun (Figure 2.6). Mean chlorophyll fluorescence values of individual species never fell below 0.70, indicating very little, if any, stress to the photosynthetic system (Ritchie, 2006). Other research has established the same trend for many species in this genus. In a controlled greenhouse watering study, Durhman et al.

(2006) found that three *Sedum* (*S. acre*, *S. kamtschaticum*, and *S. reflexum*) species maintained active photosynthetic capacity for at least 88 days without water. In addition, F_v/F_m values for these species did not fall below 0.5 until at least 40 days without water. This may at least partially explain why *Sedum* species are such good candidates for extensive green roofs.

Conclusions

Results show the importance of long-term plant evaluations at different substrate depths and solar radiation intensities. For shaded locations, *S. acre* and *S. kamtschaticum* are both excellent choices for all of the depths tested. Other suitable species are *S. spurium*, *S. album* 'Coral Carpet', and *A. cernuum*. Where native species are desired, *T. calycinum* is also a good choice. For sunny locations, *S. album* 'Coral Carpet' and *S. album* are the best choices of the species tested. Other good choices for the sun are *S. acre* and the U.S. native species *T. calycinum*. Species to avoid in Midwestern (or similar) climates include *T. parviflorum*, *S. stenopetalum*, *S. divergens*, and possibly *S. pulchellum*. The latter would work well as a flowering spring species, but may disappear after several years. Plants that would make good accent species, but will likely never dominate or fill in gaps include *S. reflexum*, *S. urvillei*, and *C. flacca*.

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Table 2.1. Initial Physical and Chemical Properties of Substrate.

Component	Unit	Method
Total Sand	86 %	Gee and Bauder, 1986
Very Coarse Sand (1-2 mm)	2.62 %	Gee and Bauder, 1986
Coarse Sand (0.5-1 mm)	20.08 %	Gee and Bauder, 1986
Medium Sand (0.25-0.5 mm)	41.68 %	Gee and Bauder, 1986
Fine Sand (0.10-0.25 mm)	19.92 %	Gee and Bauder, 1986
Very Fine Sand (0.05-0.10 mm)	1.7 %	Gee and Bauder, 1986
Silt	10 %	Bouyoucos, 1962
Clay	4 %	Bouyoucos, 1962
Soil Textural Class	Loamy Sand	Bouyoucos, 1962
 Bulk Density	 1.37 g·cm ⁻³	 Ferguson et al., 1960
Capillary Pore Space	22.05 %	Ferguson et al., 1960
Non-Capillary Pore Space	10.30 %	Ferguson et al., 1960
Water Holding Capacity at 0.01 MPa	16.05 %	Ferguson et al., 1960
Infiltration Rate	13.472 in/hr	Ferguson et al., 1960
 pH	 7.9	 NCR-13, 1998
Conductivity (EC)	1.38 mmho·cm ⁻¹	NCR-13, 1998
 Nitrate	 47 ppm	 NCR-13, 1998
Phosphorus	3.6 ppm	NCR-13, 1998
Potassium	23 ppm	NCR-13, 1998
Calcium	388 ppm	NCR-13, 1998
Magnesium	38 ppm	NCR-13, 1998
Sodium	77 ppm	NCR-13, 1998
Sulfur	73 ppm	NCR-13, 1998
Boron	.7 ppm	NCR-13, 1998
Iron	8.2 ppm	NCR-13, 1998
Manganese	2.6 ppm	NCR-13, 1998
Zinc	6.4 ppm	NCR-13, 1998
Copper	1.0 ppm	NCR-13, 1998

Analysis per A&L Great Lakes Laboratories, Inc., Ft. Wayne, Indiana

Table 2.2. Mean absolute cover +/- standard errors of nine species at two solar radiation intensities (sun versus shade) cultivated at two substrate depths (8.0 cm and 12.0 cm) reported on week 174 (23 September 2008). Six species are native to the U.S. (denoted with (N) after the species name). Absolute cover was calculated for each species as the total number of point-frame contacts divided by the number of data collection points.

Species	Absolute Cover (Week 174)			
	Depth=8.0 cm		Depth=12.0 cm	
	Sun	Shade	Sun	Shade
<i>Allium cernuum</i> (N)	0.057 ± 0.008 a A	0.448 ± 0.099 b B	0.195 ± 0.062 a B	0.462 ± 0.064 b D
<i>Carex flacca</i> (N)	0.000 ± 0.000 a A	0.000 ± 0.000 a A	0.000 ± 0.000 a A	0.076 ± 0.055 b B
<i>Sedum acre</i> 'Oktoberfest'	0.233 ± 0.081 a B	0.681 ± 0.099 b C	0.305 ± 0.026 a C	0.614 ± 0.086 b E
<i>Sedum album</i> 'Coral Carpet'	0.719 ± 0.047 b C	0.167 ± 0.095 a B	0.557 ± 0.029 b E	0.195 ± 0.067 a C
<i>Sedum divergens</i> (N)	0.005 ± 0.005 a A	0.000 ± 0.000 a A	0.005 ± 0.005 a A	0.000 ± 0.000 a A
<i>Sedum stenopetalum</i> (N)	0.005 ± 0.005 a A	0.005 ± 0.005 a A	0.005 ± 0.005 a A	0.000 ± 0.000 a A
<i>Sedum urvillei</i>	0.052 ± 0.017 a A	0.019 ± 0.013 a A	0.129 ± 0.008 a B	0.048 ± 0.029 a B
<i>Talinum calycinum</i> (N)	0.429 ± 0.079 b B	0.224 ± 0.045 a B	0.405 ± 0.050 b D	0.076 ± 0.026 a B
<i>Talinum parviflorum</i> (N)	0.000 ± 0.000 a A	0.000 ± 0.000 a A	0.000 ± 0.000 a A	0.000 ± 0.000 a A
All Species Combined	1.500 ± 0.0587 a	1.543 ± 0.066 a	1.600 ± 0.022 a	1.471 ± 0.179 a

Mean separation in rows for each species by LSD ($P \leq 0.05$). Lowercase letters denote comparisons within the same row ($n=9$). Upper case letters denote comparisons within the same column ($n=9$).

Table 2.3. Mean substrate volumetric moisture content +/- standard errors of two substrate depths (8.0 cm and 12.0 cm) at two solar radiation intensities (sun versus shade) averaged over the 2007 and 2008 growing seasons.

Substrate Depth	Volumetric Moisture Content (m ³ /m ³)		
	Sun	Shade	Combined
8 cm	0.131 ± 0.011 a A	0.150 ± 0.011 a A	0.140 ± 0.008 A
12 cm	0.109 ± 0.009 a A	0.133 ± 0.009 b A	0.121 ± 0.006 A
Combined	0.120 ± 0.007 a	0.141 ± 0.007 b	

Mean separation in rows for each species by LSD ($P \leq 0.05$). Lowercase letters denote comparisons within the same row (n=3). Upper case letters denote comparisons within the same column (n=3).

Table 2.4. Mean absolute cover +/- standard errors of 6 *Sedum* species at two solar radiation intensities (sun versus shade) cultivated at a substrate depth of 10.0 cm reported on week 174 (23 September 2008). Absolute cover was calculated for each species as the total number of point-frame contacts divided by the number of data collection points.

Species	Absolute Cover (Week 174)	
	Sun	Shade
<i>Sedum acre</i> 'Oktoberfest'	0.576 ± 0.243 b C	0.109 ± 0.055 a AB
<i>Sedum album</i>	0.509 ± 0.252 b C	0.095 ± 0.055 a A
<i>Sedum kamschaticum</i>	0.286 ± 0.254 a B	0.571 ± 0.254 a C
<i>Sedum pulchellum</i>	0.000 ± 0.000 a A	0.000 ± 0.000 a A
<i>Sedum reflexum</i>	0.033 ± 0.022 a A	0.200 ± 0.159 a AB
<i>Sedum spurium</i> 'Coccineum'	0.267 ± 0.194 a B	0.348 ± 0.085 a BC
All Species Combined	1.671 ± 0.054 a	1.324 ± 0.080 a

Mean separation in rows for each species by LSD ($P \leq 0.05$). Lowercase letters denote comparisons within the same row ($n=3$). Upper case letters denote comparisons within the same column ($n=3$).

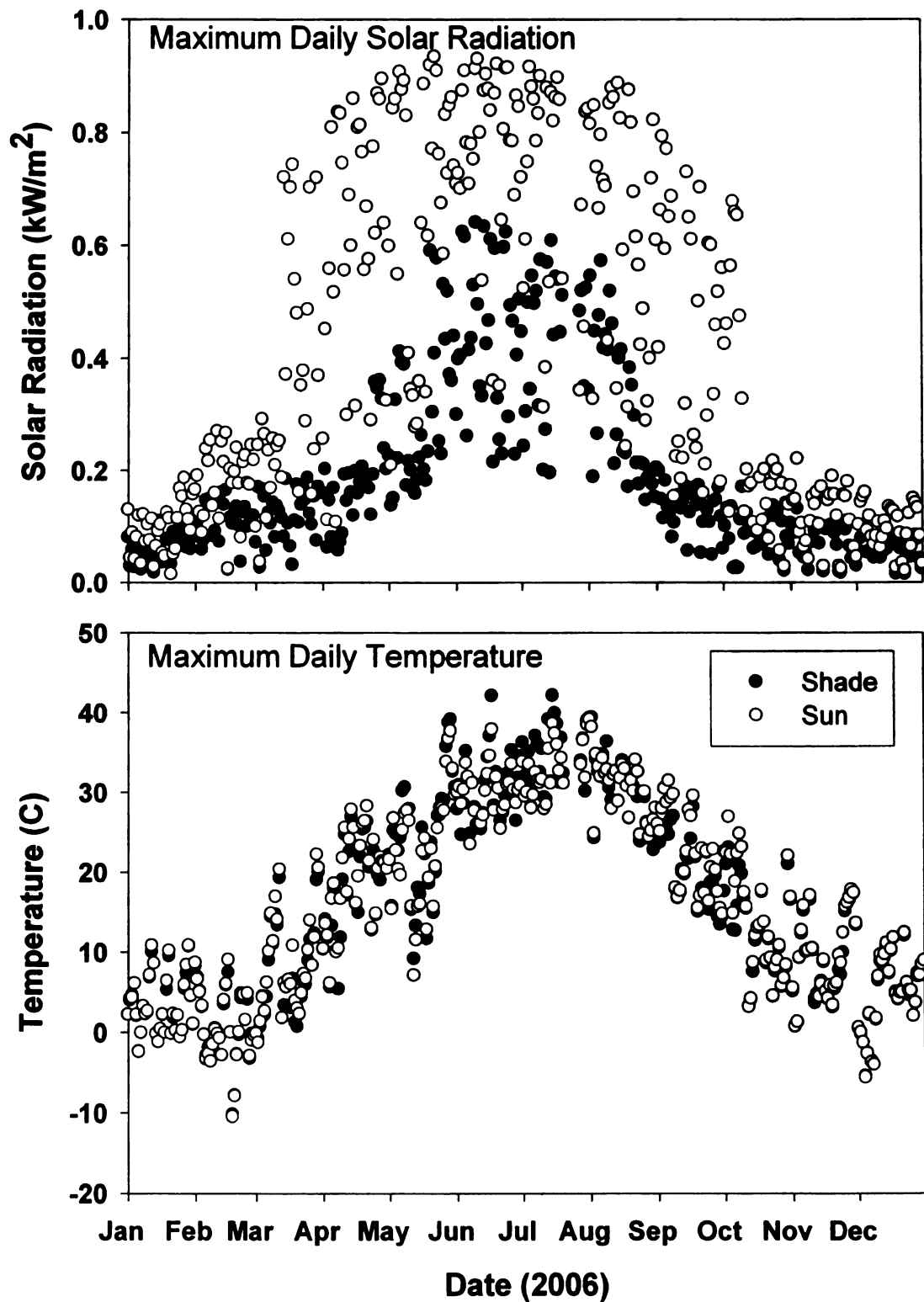


Figure 2.1. Representative data for maximum daily solar radiation intensities (kW/m²) and maximum daily air temperatures (C) during the second year (1 January 2006 to 31 December 2006).

Figure 2.2. Absolute cover of 9 species cultivated at two substrate depths (8.0 cm and 12.0 cm) at two solar radiation intensities (sun versus shade) during the four growing seasons (2005-2007). Six species are native to the U.S. (denoted with (N) after species name). Symbols represent absolute cover means with standard errors (n=9). For clarity of graphing, weeks 0 through 120 were plotted at every other data point

Figure 2.2a.

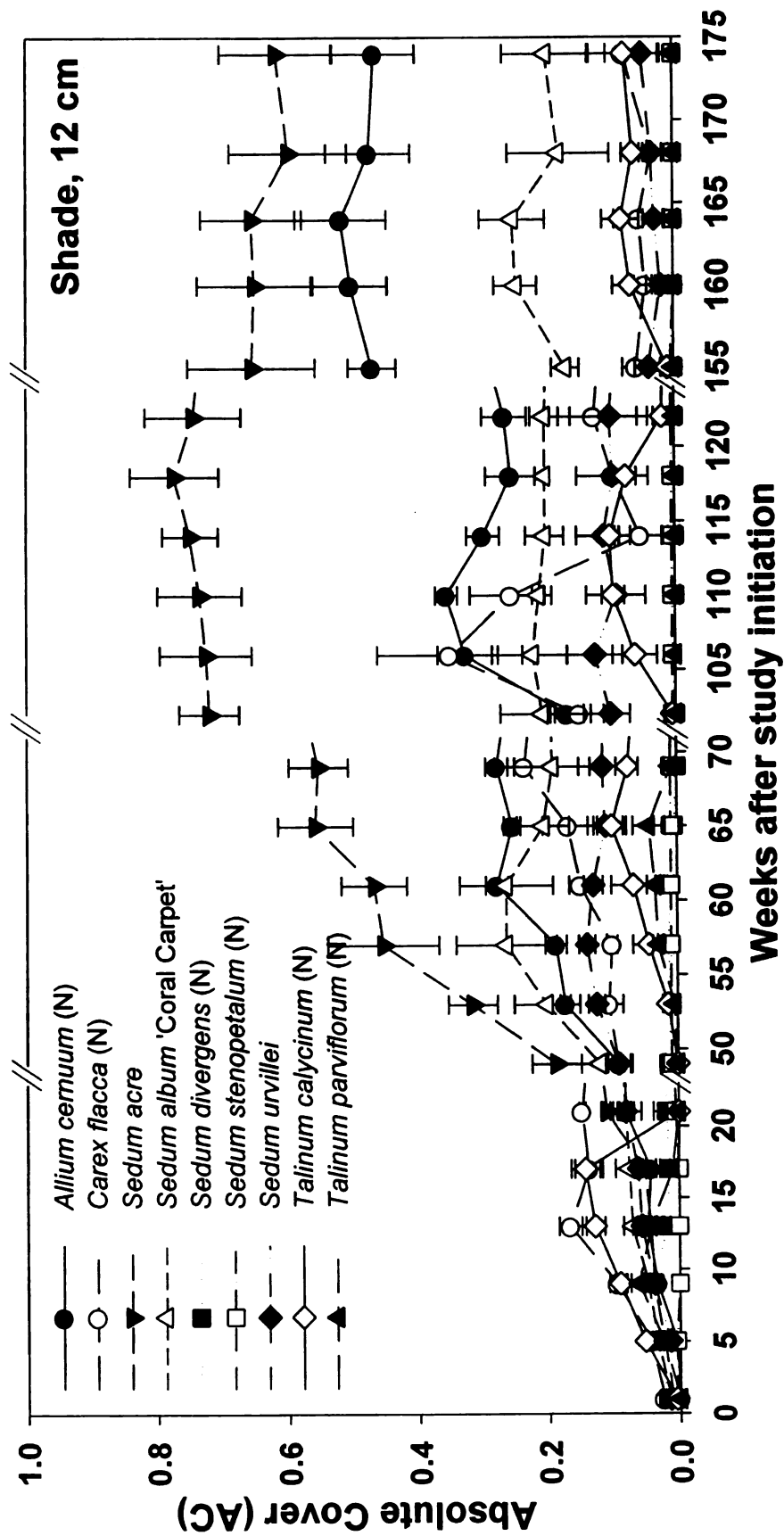


Figure 2.2b.

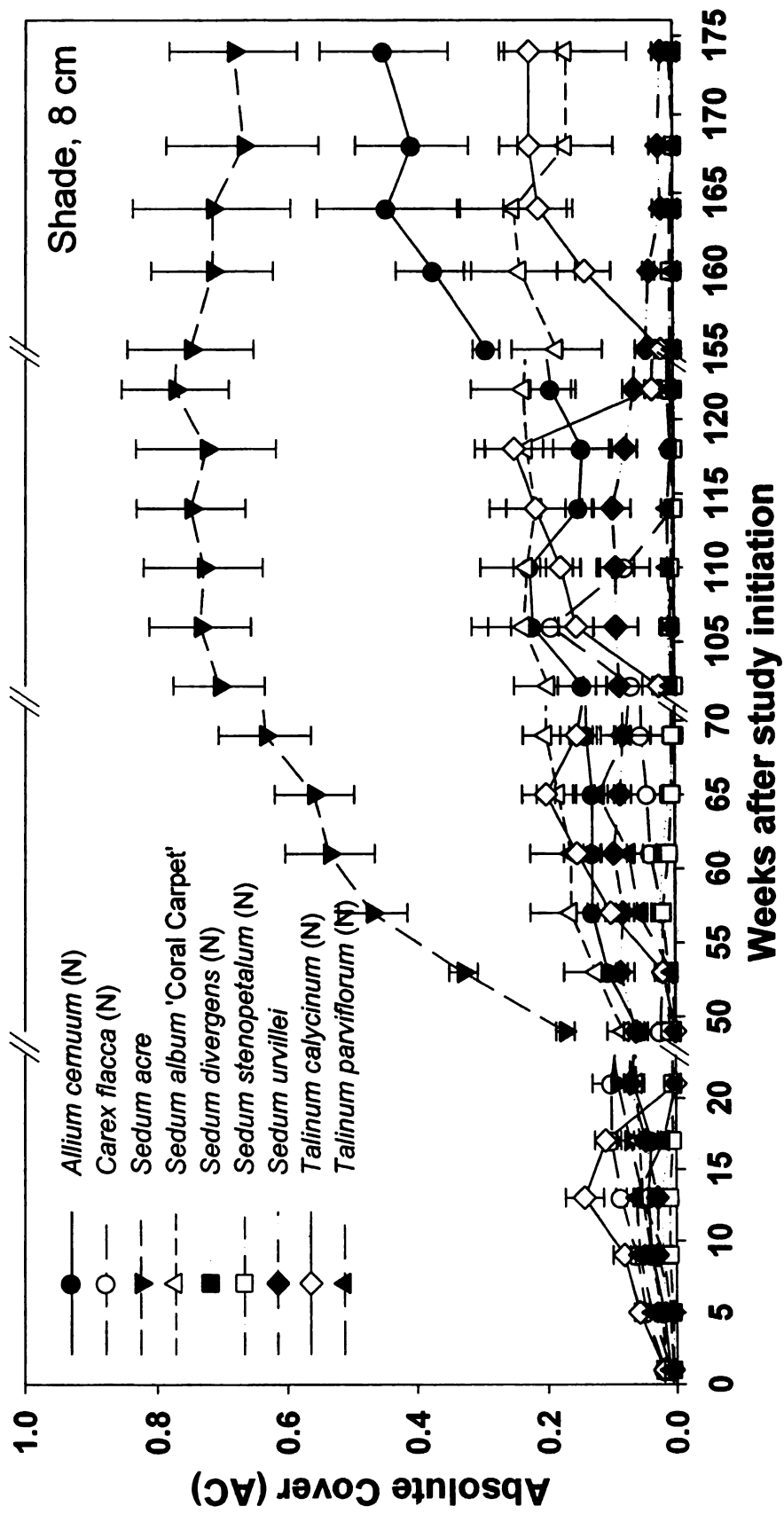


Figure 2.2c.

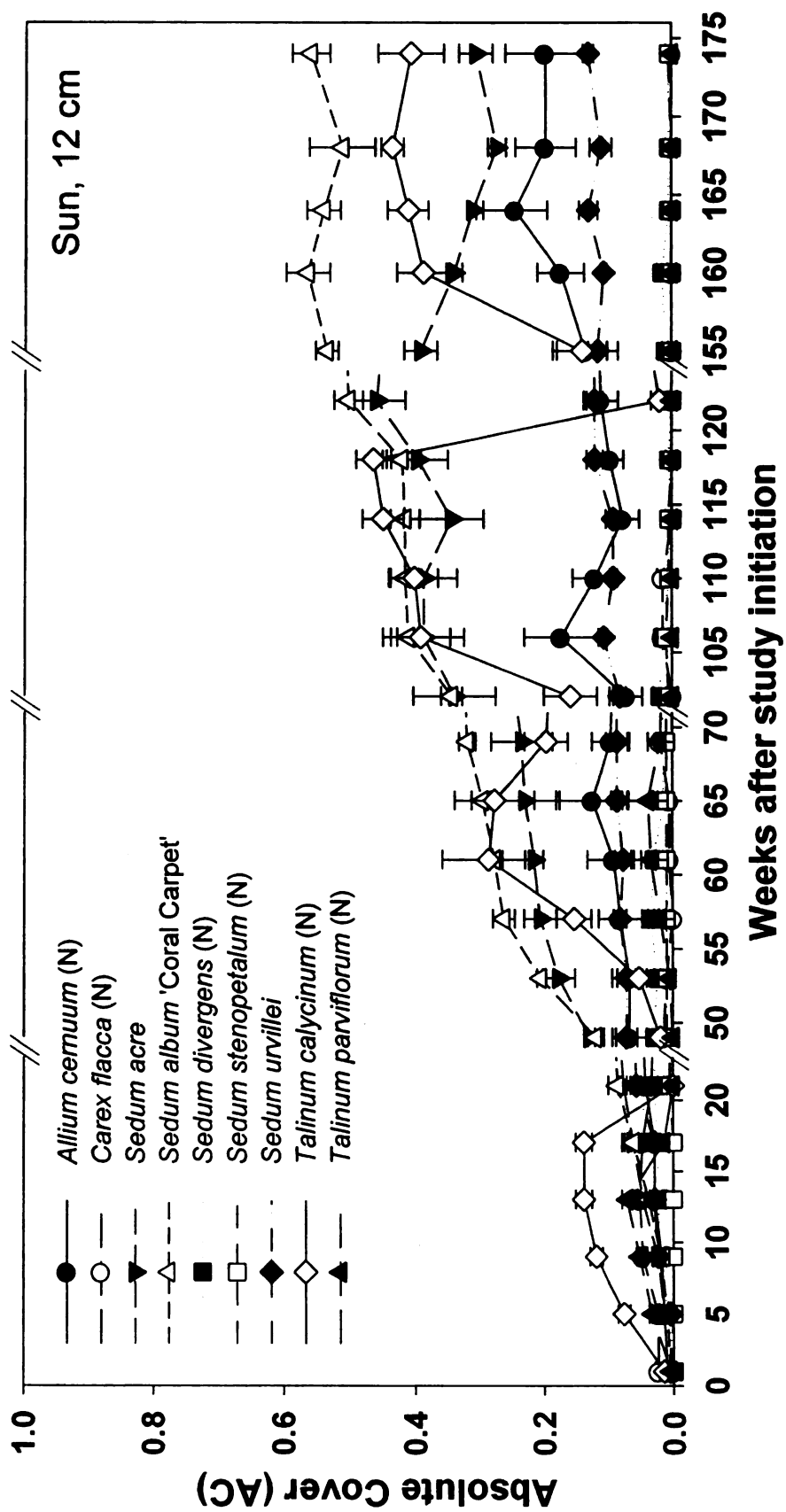
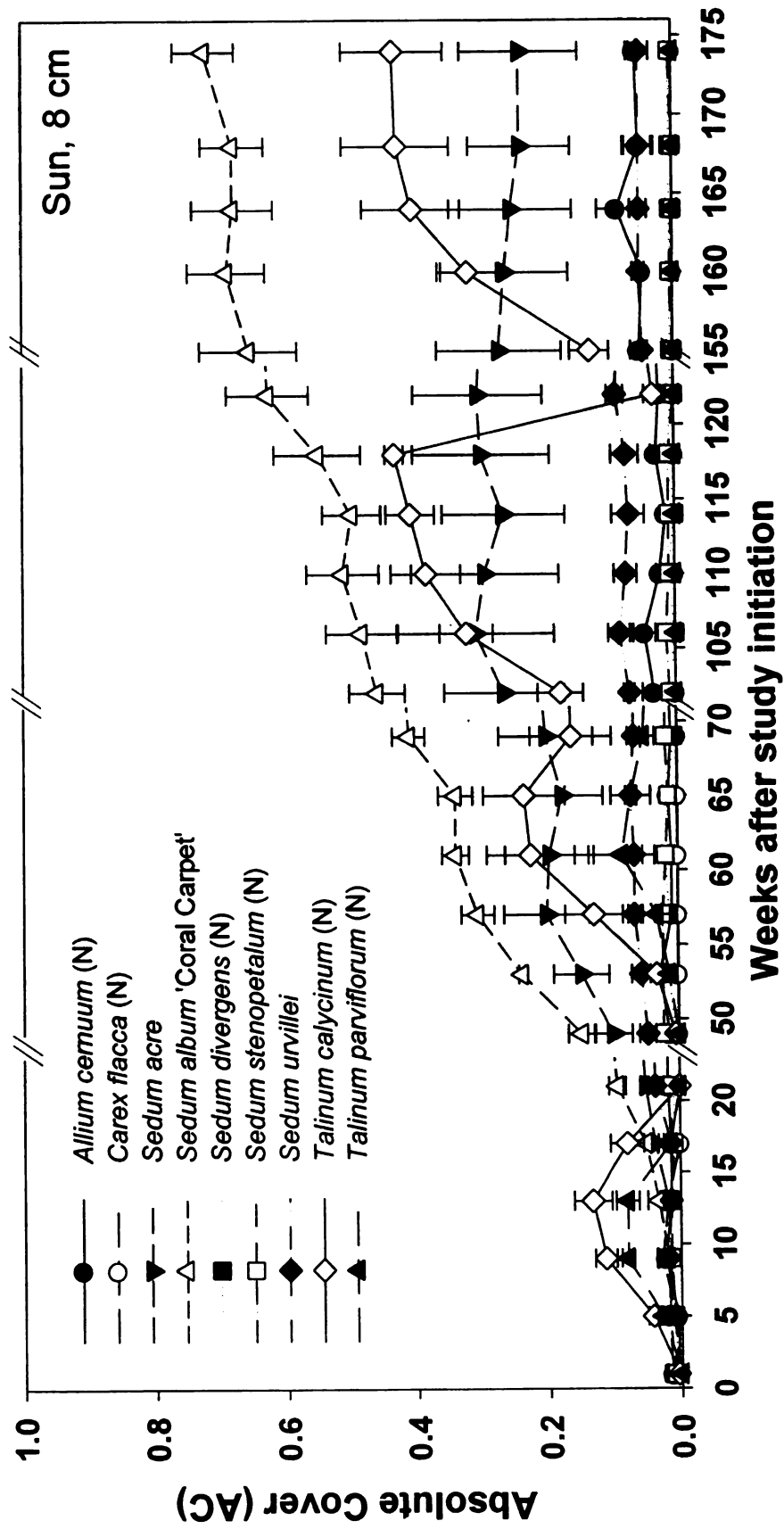


Figure 2.2d.



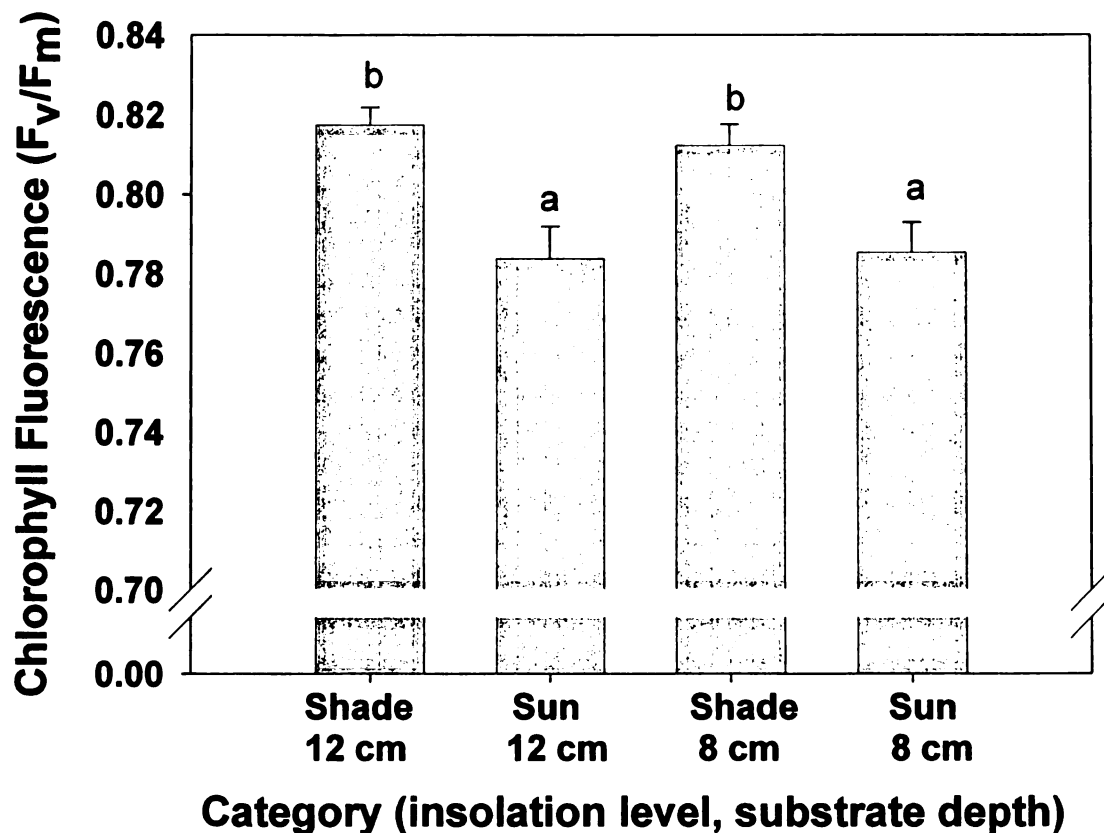


Figure 2.3. Mean chlorophyll fluorescence with standard errors of 9 species averaged over two substrate depths (8.0 cm and 12.0 cm) at two solar radiation intensities (sun versus shade) over the last two growing seasons (2007 - 2008). Lower case letters denote mean separation by LSD ($P \leq 0.05$).

Figure 2.4. Absolute cover of 6 *Sedum* species cultivated at a 10.0 cm substrate depth at two solar radiation intensities (sun versus shade) over four growing seasons (2005 - 2008). Symbols represent absolute cover means with standard errors (n=3). For clarity of graphing, weeks 0 through 120 were plotted at every other data point.

Figure 2.4a.

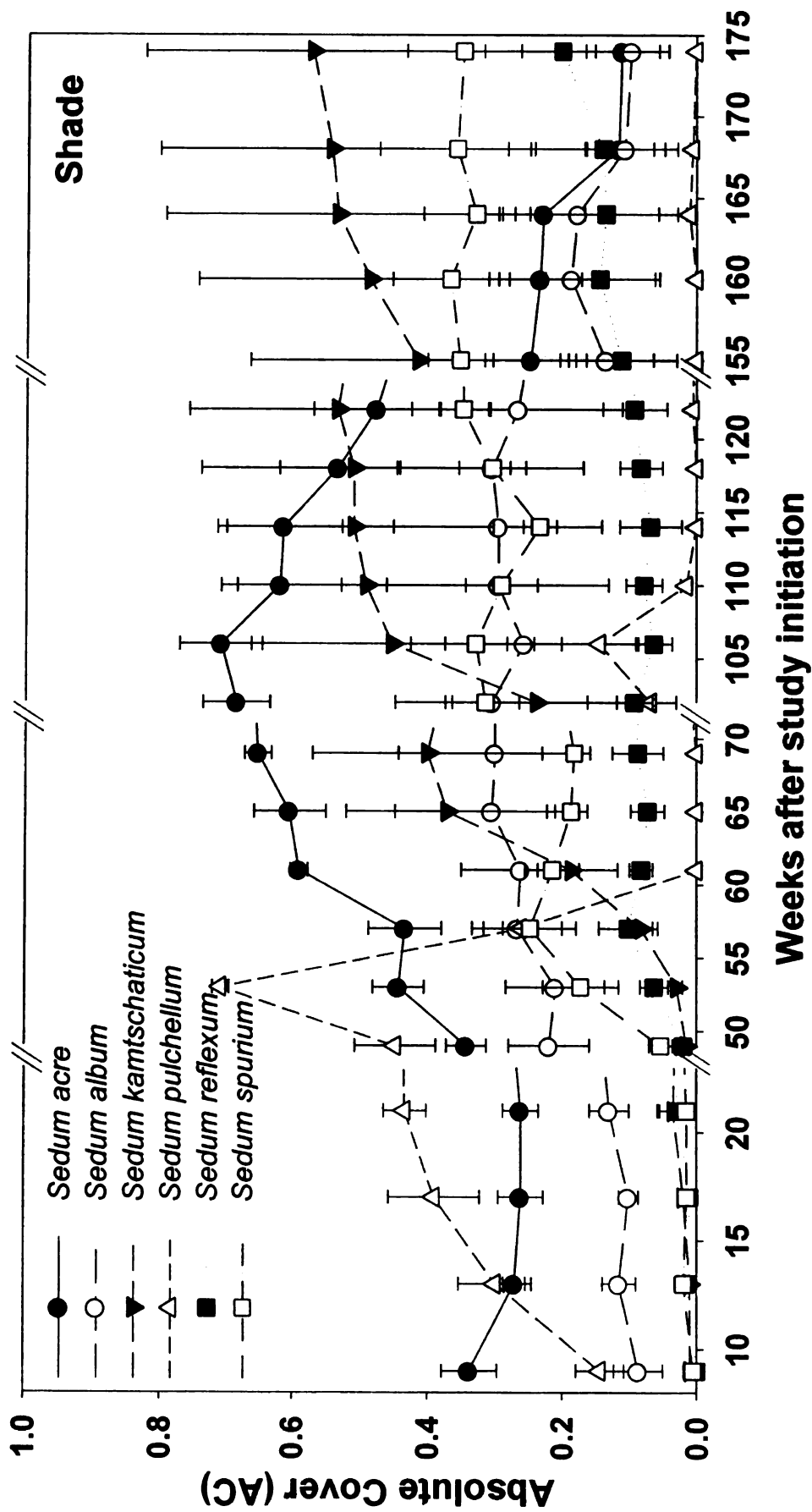
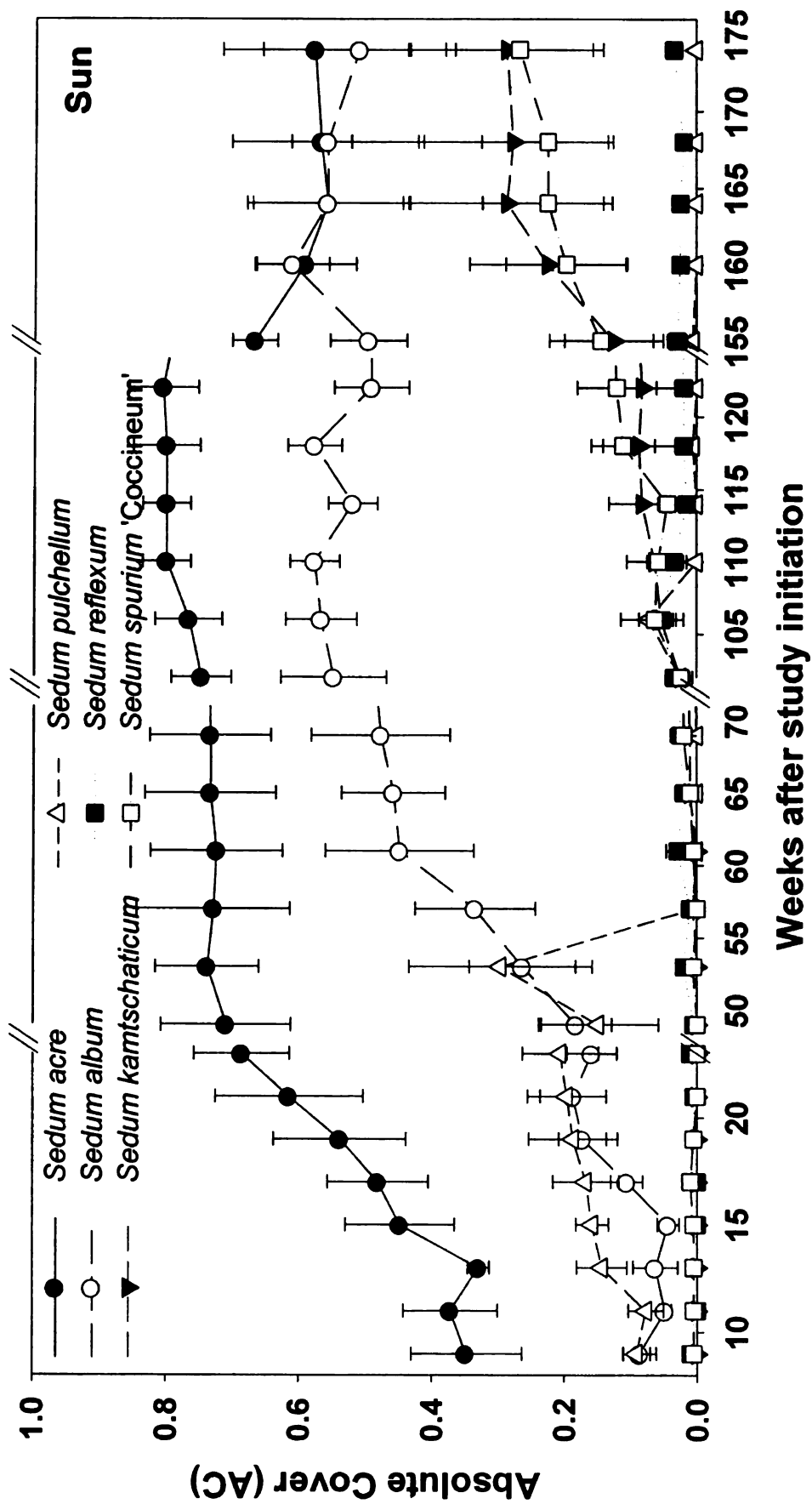


Figure 2.4b.



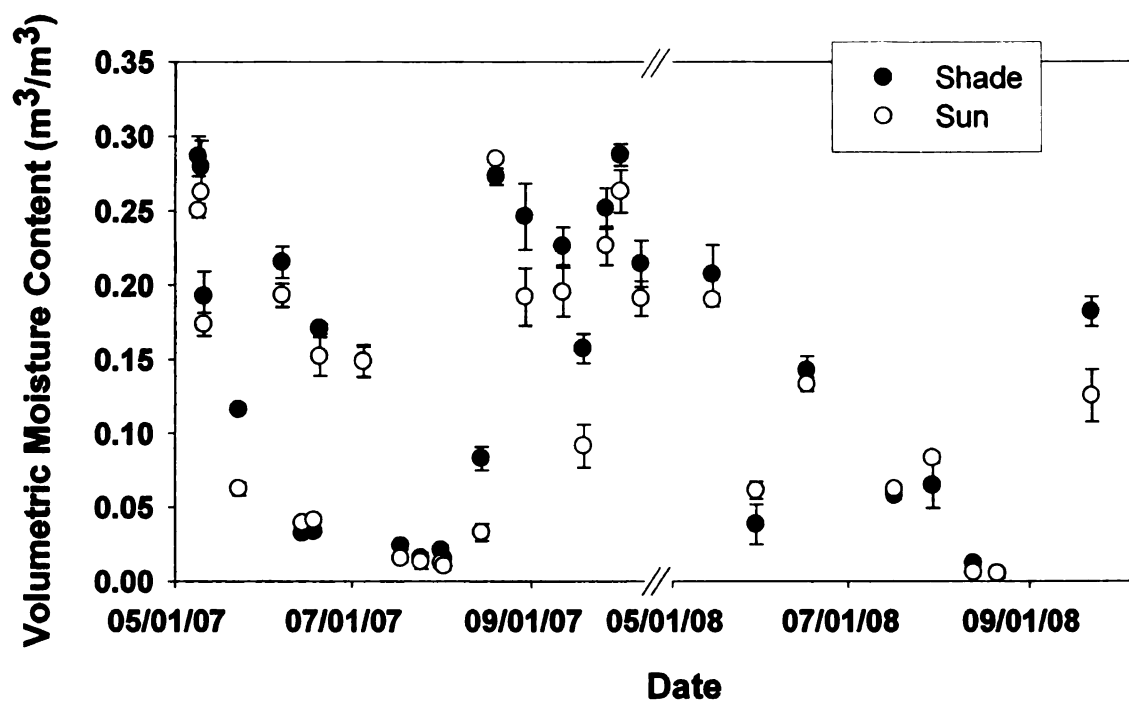


Figure 2.5. Mean substrate volumetric moisture content with standard errors at two solar radiation intensities (sun versus shade) over the 2007 and 2008 growing seasons.

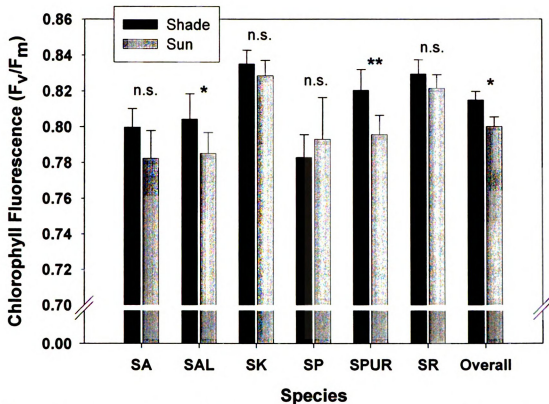


Figure 2.6. Mean chlorophyll fluorescence with standard errors of 6 *Sedum* species cultivated at 10.0 cm substrate depth at two solar radiation intensities (sun versus shade) over the last two growing seasons (2007 - 2008) where SA=*Sedum acre*; SAL=*S. album*; SK=*S. kamtschaticum*; SP=*S. pulchellum*; SPUR=*S. spurium* 'Coccineum'; SR=*S. reflexum*; OVERALL=all species combined. *=Significant at $P=0.1$; **=Significant at $P=0.05$; n.s.=not significant.

CHAPTER THREE

Carbon Sequestration Potential of Extensive Green Roofs

Abstract

The objective of this study was to quantify the carbon storage potential of extensive green roofs and to evaluate the effect of species selection on carbon flux. Two studies were conducted. The first was performed on eight roofs in Michigan and four in Maryland, ranging from one year to six years in age. All twelve *Sedum* based extensive green roofs ranged from 2.5 cm to 12.7 cm in substrate depth. Above-ground plant material was harvested in the fall of 2006. On average, these roofs stored $162 \text{ g C}\cdot\text{m}^{-2}$ in above-ground biomass. These figures are based on the end of the growing season (after flowering) and therefore should be the maximal biomass of most *Sedum* species. The second study was conducted on the roof of the Plant and Soil Sciences Building on the campus of Michigan State University in East Lansing, MI. Twenty plots were established on 21 April 2007 with a substrate depth of 6.0 cm. In addition to a substrate only control treatment, the other plots were sown with a single species of *Sedum* (*S. acre*, *S. album*, *S. kamtschaticum*, or *S. spurium*). Species and substrate depth represent typical extensive green roofs in the United States. Carbon analysis was performed by sampling above-ground biomass, below-ground biomass (roots), and substrate carbon content. Plant material and substrate were harvested seven times across two growing seasons. Results at the end of the second year show that above-ground plant material storage varied by species, with an average of $168 \text{ g C}\cdot\text{m}^{-2}$ across species, ranging from 64 to $239 \text{ g C}\cdot\text{m}^{-2}$. Below-ground biomass averaged $107 \text{ g C}\cdot\text{m}^{-2}$, but ranged from $37 \text{ g C}\cdot\text{m}^{-2}$ (*S. acre*) to $185 \text{ g C}\cdot\text{m}^{-2}$ (*S. kamtschaticum*). Substrate carbon content

averaged $913 \text{ g C}\cdot\text{m}^{-2}$, with no species effect, sequestering $100 \text{ g C}\cdot\text{m}^{-2}$ beyond what was in the initial substrate. The entire extensive green roof system sequestered $375 \text{ g C}\cdot\text{m}^{-2}$.

Introduction

Establishing green roofs, or vegetated roofs, can improve stormwater management (Carter and Jackson, 2007; Getter et al., 2007; Hilten et al., 2008; Jarrett and Berghage, 2008), conserve energy (Santamouris et al., 2007; Sailor, 2008), mitigate urban heat island effects (Takebayashi and Moriyama, 2007), increase longevity of roofing membranes (Kosareo and Ries, 2007), improve return on investment compared to traditional roofs (Clark et al., 2008), reduce noise and air pollution (Van Renterghem and Botteldooren, 2008; Yang et al., 2008), increase urban biodiversity (Baumann, 2006; Brenneisen, 2006), and provide a more aesthetically pleasing environment (Getter and Rowe, 2006; Oberndorfer et al., 2007). Green roofs are either 'intensive' or 'extensive'. Intensive green roofs may include shrubs and trees and appear similar to landscaping found at natural ground level. As such, they require substrate depths greater than 15 cm and have 'intense' maintenance needs. By contrast, extensive green roofs consist of herbaceous perennials or annuals, use shallower media depths (less than 15 cm), and require minimal maintenance. Due to building weight restrictions and costs, shallow substrate extensive green

roofs are more common than deeper intensive roofs and will be the focus of this study.

Although green roofs are often adopted for energy savings and heat island mitigation, rarely has this technology been promoted for its ability to mitigate climate change. By lowering demand for heating and air conditioning use, less carbon dioxide is released from power plants and furnaces. Sailor (2008) integrated green roof energy balance into Energy Plus, a building energy simulation model supported by the U.S. Department of Energy. His simulations found 2% reduction in electricity consumption and 9 to 11% in natural gas consumption. Based on his model of a generic building with a 2000 m² green roof, these annual savings ranged from 27.2 to 30.7 GJ of electricity saved and 9.5 to 38.6 GJ of natural gas saved, depending on climate and green roof design. When considering the national averages of CO₂ produced for generating electricity and burning natural gas (U.S. EPA, 2007; U.S. EPA, 2008), these figures translate to 637 to 719 g C per square meter of green roof in electricity and 65 to 266 g C per square meter of green roof in natural gas each year. Another 25% reduction in electricity use may additionally occur due to indirect heat island reduction achieved from large-scale green roof implementation throughout an urban area (Akbari and Konopacki, 2005).

Green roofs may also sequester carbon in plants and soils. Photosynthesis removes carbon dioxide from the atmosphere and stores carbon in plant

biomass, a process commonly referred to as terrestrial carbon sequestration.

Carbon is transferred to the substrate via plant litter and exudates. The length of time that this carbon remains in the soil before decomposition has yet to be quantified for green roofs. But, immediately after initial green roof installation, if net primary production exceeds decomposition, this man-made ecosystem will be a net carbon sink, at least in the short-term.

However, this ecosystem will not likely sequester large amounts of carbon due to the types of species used and shallow substrate. Many species used on extensive green roofs exhibit some form of Crassulacean acid metabolism (CAM; Getter and Rowe, 2006). CAM photosynthesis operates by opening stomata during the night to uptake CO₂ and storing it in the form of an organic acid in the cells vacuoles. During the following daylight period, stomata remain closed while stored organic acid is decarboxylated back into CO₂ as the source for the normal photosynthetic carbon reduction cycle (Cushman, 2001). When operating in CAM mode, rates for daily carbon assimilation are 1/2 to 1/3 that of non-CAM species (Hopkins and Huner, 2004).

The goal of this research was to evaluate the intrinsic carbon storage potential of extensive green roofs and the effect of species selection on carbon accumulation. Two studies were conducted in the United States to meet these objectives.

Materials and Methods

Study 1. Above-ground biomass was determined on eight *Sedum* based extensive green roofs in Michigan and four in Maryland (Table 3.1). Roofs ranged from one year to six years in age and from 2.5 cm to 12.7 cm in substrate depth. Above-ground biomass was sampled in quadruplicate on each roof with a 13.0 cm ring during the Fall of 2006 (see Table 3.1 for specific dates). Any above-ground biomass that was within the ring was clipped at substrate level, placed in paper bags, and dried in an oven at 70 °C for one week. Samples were then weighed and ground through a 60-mesh stainless steel screen using a Wiley mill. The material was stored in glass vials in a desiccator prior to carbon analysis to prevent moisture uptake. Total carbon concentration was determined by using a Carlo Erba NA1500 Series 2 N/C/S analyzer (CE Instruments, Milan, Italy). Carbon accumulation was determined by multiplying dry matter weight by total C concentration. Regression analysis was performed with location of the roof (Michigan or Maryland) as a categorical independent variable and age of roof (in months) and substrate depth of the roof (in cm) as independent variables against grams of carbon per square meter of green roof as the dependent variable (PROC REG, SAS version 9.1, SAS Institute, Cary, NC).

Study 2. The second study was performed on the roof of the Plant and Soil Sciences Building on the campus of Michigan State University in East Lansing, MI. An existing extensive green roof was expanded on 21 April 2007 to include a study area measuring 2.84 m x 4.6 m with 20 plots, each measuring 0.71 m x

0.92 m. The study area was covered with a Xero Flor XF108 drainage layer (Xero Flor America LLC, Durham, NC) installed over the waterproofing system. Above the drainage layer, substrate (Table 3.2) was installed to a uniform depth of 6.0 cm, which represents the physical limitations of this building and many other roofs in the U.S..

Each plot was covered with one of four species of *Sedum* typically used on U.S. green roofs; *Sedum acre* L. (biting stonecrop), *Sedum album* L. (white stonecrop), *Sedum kamtschaticum* var *ellacombianum* Fisch. (stonecrop), and *Sedum spurium* Bieb. 'Summer Glory' (creeping sedum), or a fifth 'substrate only' treatment. Planted plots were sown with 0.65 g of seeds of the treatment species (Jelitto Staudensamen, GmbH, Schwarmstedt, Germany) mixed with 20.0 g of fine vermiculite (Therm-O-Rock, Inc., New Eagle, PA) and distributed evenly. The 'substrate only' treatment had 20.0 g of fine vermiculite distributed evenly across it. This arrangement resulted in a randomized complete block design, with four replicates and five treatments. To improve seed germination, the entire study area was covered with shade cloth until 27 June 2007. In addition, the roof was irrigated for the first three months, three times daily for 20 minutes, with 2.8 mm applied at each irrigation cycle. Weeding occurred on a monthly basis, when needed.

Carbon analysis was performed by sampling above-ground biomass, below-ground biomass (roots), and substrate carbon content over two growing seasons.

Sampling occurred every second month (30 June 2007, 23 August 2007, 17 October 2007, 15 April 2008, 12 June 2008, 15 August 2008, 13 October 2008) in order to capture the full variability of the green roof ecosystem, especially since different species exhibit varying growth rates and timing of peak biomass. To keep track of which portions of a plot had been sampled, a transect was used to split each plot into 12 equal portions. The portion that was sampled was randomized and recorded so that no portion was sampled twice.

At each collection time, above-ground biomass was sampled and analyzed as in Study 1. Below-ground substrate carbon content and below-ground biomass were also determined at each sampling time. All substrate and below-ground biomass were removed from the 13.0 cm ring into a plastic bag. The entire bag was weighed and the substrate was passed through a 4.0 mm sieve. Gravel that was retained on the sieve was saved and weighed. Roots were removed from the retained and sieved matter with forceps. Roots were then cleaned with a phosphate-free dilute detergent followed by a $0.01 \text{ mol}\cdot\text{L}^{-1}$ NaEDTA solution for 5 minutes, each cleaning followed by a rinse with deionized water. The cleaned roots were placed in paper bags and dried for 2 days at 65°C . Dried biomass was ground and analyzed for carbon as previously described. Remaining sieved substrate was mixed and a portion (25.0 g) was removed and oven dried at 105°C in a small paper bag. Dried substrate and bag weight were subtracted from original weight to determine moisture content. All substrate material was ground

with a roller mill until it was a completely pulverized powder and then analyzed for carbon as above.

Mean percent carbon and grams of carbon per square meter were analyzed using an ANOVA model with species as a fixed effect. Significant differences between treatments were determined using multiple comparisons by LSD (PROC MIXED, SAS version 9.1, SAS Institute, Cary, NC).

Results and Discussion

Study 1 – Aboveground harvest of 12 green roofs. Average above-ground carbon stored at the time of sampling for the twelve roofs was $162.3 \text{ g C}\cdot\text{m}^{-2}$ (Table 3.3). These figures are based on the end of the growing season (after flowering) and therefore should be the maximal biomass of most *Sedum* species. However, there was a high degree of variability. Carbon sequestered ranged from 73.2 to $276.5 \text{ g C}\cdot\text{m}^{-2}$, influenced by such factors as age of the green roof and substrate depth.

Regression analysis (Figure 3.1) showed that there was a weak association ($r^2=0.32$) between age of the green roof and grams of carbon sequestered, indicating that older roofs tend to store more above-ground carbon than younger roofs. However, substrate depth may be a confounding factor, because substrate depth has been shown to influence plant growth on a green roof (Durhman et al., 2007; Getter and Rowe, 2008). This appears to be the case in

Table 3.3 where three roofs have a mean substrate depth of 2.5 cm. These roofs increase in carbon with respect to age. The 15, 39, and 48 month aged roofs contain 96.8, 143.5, and 196.3 g C•m⁻², respectively.

There was no significant location (MI or MD) effect, suggesting that other variables besides substrate depth and roof age may be impacting carbon storage. For example, management techniques would likely impact how much carbon can be sequestered in above-ground material at any given time. Fertilizer applications or the use of supplemental irrigation may increase plant biomass since nitrogen and water are often the limiting component to primary production in many ecosystems (Vitousek and Howarth, 1991). Design choices may also influence carbon storage. For example, substrate composition has been shown to impact plant growth on an extensive green roof (Hunt et al., 2006; Rowe et al., 2006), which in turn impacts total above-ground carbon. Species selection may also impact above-ground carbon stores, as species vary in their net primary production and allocation to biomass (Naeem et al, 1996).

Study 2 – Plant and Substrate Harvested Seven Times over Two Growing Seasons. Monthly average maximum air temperatures (°C), monthly average minimum air temperatures (°C), and monthly total precipitation (mm) (not including initial irrigation), are shown in Figure 3.2. East Lansing, MI is in the midwestern U.S. and is characterized as a temperate climate with four well-defined seasons. Thirty-year average mean low temperatures in January and

high temperatures in July are -10.2°C and 27.5°C, respectively. The average number of days per year with precipitation greater than 2.54 mm is 70.3, which are generally well distributed throughout the year (Michigan State Climatologist's Office, 2008).

Harvest date, species, and the interaction affected total C for above- and below-ground plant biomass, but not for substrate (Table 3.4). Across all species, mean carbon on an area basis in above-ground biomass was comparable to the previous study, averaging 168 g C·m⁻² at the end of the second year (Table 3.5). *Sedum album* held the greatest amount of carbon, followed by *S. kamtschaticum*, *S. spurium*, and *S. acre*. Carbon contained in root biomass averaged 107 g C·m⁻² at the end of the second growing season (Table 3.5). Root biomass values for *S. kamtschaticum* were highest, while values for *S. acre* were lowest. The relatively low allocation to roots may help explain why *S. acre* seems to be the least heat and drought tolerant species among those tested.

At the end of the second growing season, substrate carbon content averaged 913 g C·m⁻² (Table 3.5). Unlike the plant material, there were no significant differences among species treatments for substrate carbon content. At establishment, substrate consisted of 810 g C·m⁻² (Table 3.2). As such, there was 100 g C·m⁻² sequestered in the soils after two growing seasons.

Percent carbon averaged 42.1% C, 41.4% C, and 4.6% C for above-ground biomass, root biomass, and substrate, respectively (Table 3.5). The percentage of carbon stored in plant tissues is slightly lower than the expected 45-50% C in most other vascular plants (Ovington, 1957; Pettersen, 1984; Schlesinger, 1997), but is similar to other succulent species (Lindsay and French, 2004). Substrate values correspond well to other ecosystems (Jones et al., 2005; Harte et al., 2006). Averaged across species, above-ground and root carbon ($\text{g}\cdot\text{m}^{-2}$) increased the first year as plants established themselves and then remained steady throughout the second growing season (Figure 3.3). Substrate carbon also remained steady over the two growing seasons.

For individual species, first year above ground carbon for *S. acre* was similar to the other species, but by the end of the second season *S. acre* held the lowest amount of carbon (Figure 3.4). This may be because the second growing season did not have supplemental irrigation and *S. acre* is known to die back in hot growing conditions (Snodgrass and Snodgrass, 2006). The other three species also declined through the hottest portion of the second growing season without this irrigation (July and August 2008), but then rebounded by October 2008. Two species above-ground carbon decreases slightly between the end of the first and the beginning of the second growing season (Figure 3.4). This likely occurred because these species are either semi-evergreen (*S. spurium*) or deciduous (*S. kamtschaticum*) and full spring leaf-out had not yet occurred on the first sampling of 2008. In contrast, above-ground carbon values for *S. acre* and

S. album, both evergreen species, are very similar before and after the winter dormant season.

Over time, *S. kamtschaticum* contains the greatest carbon in root biomass (Figure 3.4). This is likely due to the woody nature of this species' roots (personal observation). However, all species generally increased in root carbon across both growing seasons. *Sedum acre* allocated the least amount of carbon to roots. For substrate carbon over time, all species treatments remained steady throughout the study.

Application. This entire extensive green roof system sequestered $375 \text{ g C}\cdot\text{m}^{-2}$, ($168 \text{ g C}\cdot\text{m}^{-2}$ in above-ground plant biomass, $107 \text{ g C}\cdot\text{m}^{-2}$ in below-ground plant biomass, and $100 \text{ g C}\cdot\text{m}^{-2}$ in substrate carbon) beyond what was stored originally in the initial substrate (Table 3.2; Table 3.5). However, many components of a green roof have a carbon 'cost' in terms of the manufacturing process.

Embodied energy is a term used to describe total energy consumed, or carbon released, by a product over its life cycle. Typical components of a green roof include a root barrier installed on top of the normal roofing membrane (which protects the roof from root penetration damage), a drainage layer above the root barrier (which allows excess water to flow away from the roof), and a growing substrate. Many life cycle analysis studies ignore these unique components of a green roof by making the assumption that the root barrier, drainage layers, substrate, and plant material will all have a carbon cost similar to the traditional

roofs' gravel ballast (Alcazar and Bass, 2006; Kosareo and Ries, 2007). But, this assumption may not be valid.

Hammond and Jones (2008) analyzed building materials through the entire production process. Material consisting of low density polyethylene (LDPE) similar to a root barrier was found to average $78.1 \text{ MJ}\cdot\text{kg}^{-1}$ of embodied energy or $1.7 \text{ kg CO}_2\cdot\text{kg}^{-1}$ of embodied carbon. Assuming 0.51 mm thickness and density of $925 \text{ kg}\cdot\text{m}^{-3}$ (Raven Industries, Sioux Falls, SD), this translates to 219 g C per square meter of green roof. Drainage layers are commonly made from polypropylene (Colbond Inc., Enka, NC) which contains 5.0 kg CO_2 per kg of product (Hammond and Jones, 2008). Assuming a weight of $0.39 \text{ kg}\cdot\text{m}^{-2}$ (Xero Flor America LLC, Durham, NC), this translates into 535 g C per square meter of green roof. The embodied energy for a substrate consisting of sand and expanded slate is 0.005 and $0.44 \text{ kg CO}_2\cdot\text{kg}^{-1}$, respectively (GBC, 2008; Hammond and Jones, 2008). A 6.0 cm substrate depth consisting of half sand and half expanded slate by volume with densities of $2,240$ and $1,600 \text{ kg}\cdot\text{m}^{-3}$, respectively (Expanded Shale, Clay and Slate Institute. 2008; Hammond and Jones, 2008) translates to 92 and 5769 g C per square meter of green roof. These green roof components add up to an embodied carbon content of 6615 g C per square meter of green roof.

But, a traditional roof may also have a gravel ballast, which is no longer needed on a green roof. Assuming a density of $1800 \text{ kg}\cdot\text{m}^{-3}$ and a 2 cm depth, a gravel

ballast has an embodied energy content of $0.017 \text{ kg CO}_2 \cdot \text{kg}^{-1}$ or 167 g C per square meter of roof (Hammond and Jones, 2008). Subtracting out the unneeded ballast, total adjusted embodied carbon for the extensive green roof components above and beyond a traditional roof is then $6,448 \text{ g C}$ per square meter of green roof.

While the embodied energy in the initial green roof system is greater than what is stored in the substrate and plant biomass at any given time, the emissions avoided due to energy savings will 'pay' for those costs in time. Sailor (2008) integrated green roof energy balance into Energy Plus, a building energy simulation model supported by the U.S. Department of Energy. His simulations found 2% reduction in electricity consumption and 9 to 11% in natural gas consumption. Based on his model of a generic building with a $2,000 \text{ m}^2$ green roof, the minimum annual savings were 27.2 GJ of electricity and 9.5 GJ of natural gas saved. When considering the green house potential of generating electricity and burning natural gas (U.S. EPA, 2007; U.S. EPA, 2008), these figures translate to 702 g C per square meter of green roof in electricity and natural gas savings combined per year. Since the embodied cost is $6,448 \text{ g C} \cdot \text{m}^{-2}$ (from above), it will take nine years to 'pay' for the carbon cost of the green roof materials. After this time, the emissions avoided would simply add on to the sequestration potential of the roof. The carbon sequestered by growing biomass ($375 \text{ g C} \cdot \text{m}^{-2}$ in this study) will shorten the carbon payback period in this scenario by two years.

As typically unused spaces, roofs provide a unique opportunity to sequester carbon. For example, in the Detroit Metropolitan area, land area of rooftops is estimated to be 6,335 and 8,399 hectares of commercial and industrial land use, respectively (Clark et al., 2005). If all of these roofs were covered with vegetation in a design similar to this study and thus were able to sequester 375 g C·m⁻² of green roof, 55,252 metric tons of carbon could be sequestered in the plants and substrates alone (not including avoided emissions). This is similar to taking over 10,000 mid-sized SUV or trucks off the road for a year (U.S. EPA, 2005). While these figures depend on climate and green roof design, they nonetheless represent a significant, if minimal, potential for sequestering carbon in urban environments.

Conclusions

One time sampling from twelve roofs ranging from one year to six years in age and from 2.5 cm to 12.7 cm in substrate depth found above ground biomass to store 162.3 g C·m⁻². This corresponds well with two-year multiple sampling results that averaged 168 g C·m⁻² at the end of two growing seasons. In the latter study, carbon storage varied by species (*Sedum album* held the greatest amount of carbon, followed by *S. kamtschaticum*, *S. spurium*, and *S. acre*). Carbon contained in root biomass averaged 107 g C·m⁻² and at the end of the second growing season, with a species effect (*S. kamtschaticum* were highest, while *S. acre* was lowest). Substrate carbon content averaged 913 g C·m⁻², with

no species effect, sequestering $100 \text{ g C}\cdot\text{m}^{-2}$ beyond what was in the initial substrate. The entire extensive green roof system sequestered $375 \text{ g C}\cdot\text{m}^{-2}$.

These conclusions are applicable to the midwestern United States and other geographical areas with similar climates. In addition, management techniques (such as fertilizer applications or the use of supplemental irrigation) and design choices (like substrate composition, substrate depth, or species selection) may influence these results as well. Future work needs to be performed to quantify carbon fluxes in the green roof system.

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Table 3.1. Location and description of sampled green roofs. Each location was sampled in four random places on sampling date.

Roof	Date originally planted	Sample Date	Location	Comments
CA2.5	May 2005	9/6/2006	Michigan State University (MSU) Communication Arts Building, East Lansing, MI	Research plots placed directly on roof. Primary species included: <i>S. album</i> , <i>S. middendorffianum</i> , <i>S. sexangulare</i> , <i>S. spurium</i> .
CA3.2	May 2005	9/6/2006	MSU Communication Arts Building, East Lansing, MI	Research plots placed directly on roof. Primary species included: <i>S. album</i> , <i>S. kamtschaticum</i> , <i>S. middendorffianum</i> , <i>S. sexangulare</i> .
FORD	Fall 2002	9/1/2006	Ford Motor Company, Rouge Plant, Dearborn, MI	4,047 m ² extensive green roof. Primary species included: <i>S. acre</i> , <i>S. album</i> , <i>S. kamtschaticum</i> , <i>S. middendorffianum</i> .
HTRC2.5	June 2003	9/5/2006	MSU Horticulture Teaching and Research Center (HTRC), East Lansing, MI	Roof platform. Primary species included: <i>Sedum acre</i> , <i>Sedum album</i> , <i>Sedum middendorffianum</i> , <i>Sedum spurium</i> .
HTRC5	June 2003	9/5/2006	MSU HTRC, East Lansing, MI	Roof platform. Primary species included: <i>S. acre</i> , <i>S. album</i> , <i>Sedum kamtschaticum</i> , <i>S. middendorffianum</i> , <i>Sedum reflexum</i> , <i>S. spurium</i> .
HTRC6	May 2002	9/5/2006	MSU HTRC, East Lansing, MI	Roof platform. Primary species included: <i>S. acre</i> , <i>S. album</i> , <i>S. spurium</i> .
HTRC7.5	June 2003	9/5/2006	MSU HTRC, East Lansing, MI	Roof platform. Primary species included: <i>S. album</i> , <i>Sedum kamtschaticum</i> , <i>S. middendorffianum</i> , <i>Sedum reflexum</i> , <i>S. spurium</i> .
MDG	Sept 2005	9/7/2006	MDG Corporation, Columbia, MD	752 m ² extensive green roof. Primary species included: <i>S. album</i> , <i>S. kamtschaticum</i> , <i>S. middendorffianum</i> , <i>S. spurium</i> , <i>S. boehmeri</i> , <i>Talinum</i> spp.
MF	Spring 2002	9/7/2006	Metfab, Jessup, MD	232 m ² extensive green roof. Primary species included: <i>Delosperma</i> spp., <i>S. hispanicum</i> , <i>S. kamtschaticum</i> , <i>S. middendorffianum</i> , <i>S. sexangulare</i> , <i>S. spurium</i> .
PSSB	May 2004	9/1/2006	MSU Plant and Soil Sciences Building, East Lansing, MI	325 m ² extensive green roof. Primary species included: <i>S. acre</i> , <i>S. album</i> , <i>S. kamtschaticum</i> , <i>S. reflexum</i> , <i>S. spurium</i> .
RC	Fall 2002	9/7/2006	Renaissance Center at South River Colony, Edgewater, MD	1,300 m ² extensive green roof. Primary species included: <i>Allium spp.</i> , <i>S. album</i> , <i>S. reflexum</i> , <i>S. sarmentosum</i> , <i>S. sexangulare</i> , <i>S. spurium</i> .
SEV	May 2006	9/7/2006	Severn Savings Bank Headquarters, Annapolis, MD	1,161 m ² extensive green roof. Primary species included: <i>S. album</i> , <i>S. kamtschaticum</i> , <i>S. spurium</i> .

Table 3.2. Initial Physical and Chemical Properties of Substrate.

Component	Unit	Method
Total Sand	0.79 g·g ⁻¹	Gee and Bauder, 1986
Very Coarse Sand (1-2 mm)	0.13 g·g ⁻¹	Gee and Bauder, 1986
Coarse Sand (0.5-1 mm)	0.25 g·g ⁻¹	Gee and Bauder, 1986
Medium Sand (0.25-0.5 mm)	0.29 g·g ⁻¹	Gee and Bauder, 1986
Fine Sand (0.10-0.25 mm)	0.11 g·g ⁻¹	Gee and Bauder, 1986
Very Fine Sand (0.05-0.10 mm)	0.01 g·g ⁻¹	Gee and Bauder, 1986
Silt	0.15 g·g ⁻¹	Bouyoucos, 1962
Clay	0.06 g·g ⁻¹	Bouyoucos, 1962
 Bulk Density ¹	 1.17 g·cm ⁻³	 Ferguson et al., 1960
Capillary Pore Space	0.34 cm ³ ·cm ⁻³	Ferguson et al., 1960
Non-Capillary Pore Space	0.09 cm ³ ·cm ⁻³	Ferguson et al., 1960
Water Holding Capacity at 0.01 MPa	0.29 cm ³ ·cm ⁻³	Ferguson et al., 1960
 pH	 8.2	 NCR-13, 1998
Conductivity (EC)	10.36 mmho·cm ⁻¹	NCR-13, 1998
Organic Matter by LOI @ 360 C ²	5.6 g·kg ⁻¹	NCR-13, 1998
Organic Carbon ³	810 g·m ⁻²	Jolivet et al., 1998
 Nitrate	 2.0 µg·g ⁻¹	 NCR-13, 1998
Phosphorus	53.9 µg·g ⁻¹	NCR-13, 1998
Potassium	2174.0 µg·g ⁻¹	NCR-13, 1998
Calcium	208.0 µg·g ⁻¹	NCR-13, 1998
Magnesium	57.0 µg·g ⁻¹	NCR-13, 1998
Sodium	439.0 µg·g ⁻¹	NCR-13, 1998
Sulfur	434.0 µg·g ⁻¹	NCR-13, 1998
Boron	1.5 µg·g ⁻¹	NCR-13, 1998
Iron	74.0 µg·g ⁻¹	NCR-13, 1998
Manganese	25.4 µg·g ⁻¹	NCR-13, 1998
Zinc	24.5 µg·g ⁻¹	NCR-13, 1998
Copper	3.0 µg·g ⁻¹	NCR-13, 1998

Analysis per A&L Great Lakes Laboratories, Inc., Ft. Wayne, Indiana

¹Including gravel. ²Gravel free. ³Calculated from organic matter LOI per Jolivet et al., 1998.

Table 3.3. Mean carbon ($\text{g}\cdot\text{m}^{-2}$) $\pm$ standard errors for above-ground biomass on twelve extensive green roofs.

Roof*	Mean Substrate Depth (cm)	Age at Sampling (months)	Plant Aboveground Carbon ($\text{g}\cdot\text{m}^{-2}$)
CA2.5	2.5	15	96.8 $\pm$ 27.9
CA3.2	3.2	15	126.8 $\pm$ 19.0
FORD	2.5	48	196.3 $\pm$ 64.8
HTRC2.5	2.5	39	143.5 $\pm$ 16.0
HTRC5	5.0	39	158.7 $\pm$ 32.4
HTRC6	6.0	52	224.2 $\pm$ 52.6
HTRC7.5	7.5	39	201.7 $\pm$ 11.1
MDG	7.0	12	73.2 $\pm$ 16.0
MF	7.1	53	188.9 $\pm$ 33.5
PSSB	4.0	28	148.8 $\pm$ 26.7
RC	6.4	48	276.5 $\pm$ 28.0
SEV	10.8	4	111.8 $\pm$ 30.1
*See table 1 for descriptions.			162.3 $\pm$ 11.7

Table 3.4. ANOVA table for mean carbon ($\text{g}\cdot\text{m}^{-2}$) over two growing seasons (April 2007 to October 2008) for four species and a substrate only treatment replicated four times. Grams of carbon per square meter of green roof is the dependent variable. Date harvested^a and species^b are independent variables.

Source of Variation	Aboveground			Roots			Substrate		
	DF	F	P>F	DF	F	P>F	DF	F	P>F
Block	3	3.57	0.0176	3	2.21	0.1414	3	1.26	0.2640
Date Harvested ^a	6	22.1	<0.0001	6	43.16	<0.0001	6	1.87	0.0951
Species ^b	3	5.91	0.0011	3	82.92	<0.0001	4	1.9	0.1174
DateHarvested x Species	18	2.73	0.0011	18	5.83	<0.0001	24	0.56	0.9440

^a Dates harvested were 30 June 2007, 23 August 2007, 17 October 2007, 15 April 2008, 12 June 2008, 15 August 2008, and 13 October 2008.

^b Species included *Sedum acre*, *Sedum album*, *Sedum kamtschaticum*, *Sedum spurium* and a 'substrate only' treatment.

Table 3.5. Mean $\pm$ standard errors of total carbon and carbon concentrations of *Sedum* based green roofs at end of second growing season (13 October 2008) in East Lansing, MI.

Species	Above Ground		Roots		Substrate		Total	
	C•m ⁻² (g)	C (%)	C•m ⁻² (g)	C (%)	C•m ⁻² (g)	C (%)	C•m ⁻² (g)	C (%)
<i>S. acre</i>	64 $\pm$ 6.5 A	43.6 $\pm$ 0.2 A	37 $\pm$ 3.4 A	37.2 $\pm$ 1.5 A	852 $\pm$ 72.0 A	4.3 $\pm$ 0.4 A	953 $\pm$ 75.0 A	4.3 $\pm$ 0.4 A
<i>S. album</i>	239 $\pm$ 53.6 B	42.7 $\pm$ 0.2 A	78 $\pm$ 11.3 AB	40.9 $\pm$ 0.7 AB	932 $\pm$ 77.0 A	4.7 $\pm$ 0.4 A	1,249 $\pm$ 75.8 A	4.7 $\pm$ 0.4 A
<i>S. kamtschaticum</i>	202 $\pm$ 40.5 B	40.5 $\pm$ 0.1 A	185 $\pm$ 12.0 C	43.8 $\pm$ 0.2 B	887 $\pm$ 98.1 A	4.5 $\pm$ 0.3 A	1,275 $\pm$ 183.7 A	4.5 $\pm$ 0.3 A
<i>S. spurium</i>	166 $\pm$ 29.1 AB	41.5 $\pm$ 0.3 A	126 $\pm$ 8.5 B	43.8 $\pm$ 0.2 B	981 $\pm$ 125.1 A	4.9 $\pm$ 0.5 A	1,272 $\pm$ 118.8 A	4.9 $\pm$ 0.5 A
Substrate Only					834 $\pm$ 50.6 A	4.2 $\pm$ 0.3 A		
Mean	168 $\pm$ 23.5	42.1 $\pm$ 0.2	107 $\pm$ 14.9	41.4 $\pm$ 0.6	913 $\pm$ 34.6*	4.6 $\pm$ 0.2	1,187 $\pm$ 58.8	4.6 $\pm$ 0.2

Mean separation in columns by LSD ($P \leq 0.05$). Uppercase letters in columns denote differences among species ($n=16$).

*Not including Substrate Only treatment. At establishment, substrate consisted of 810 g C•m⁻² (Table 2).

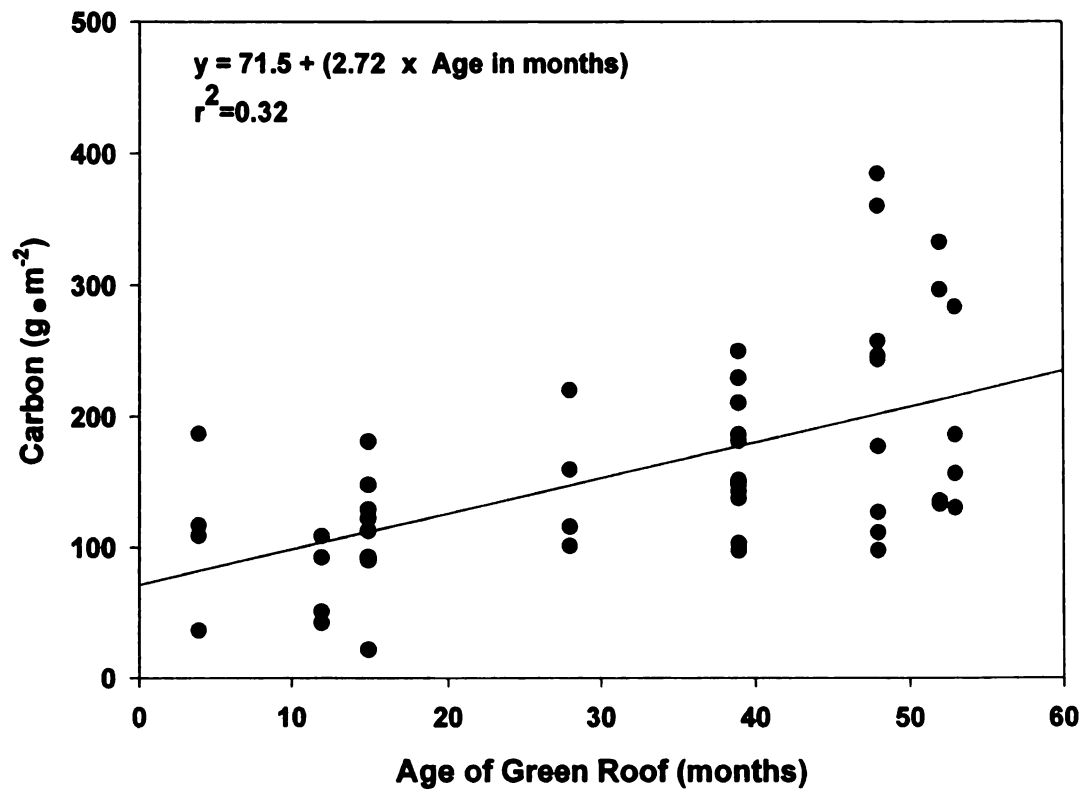


Figure 3.1. Simple linear regression of above-ground biomass on twelve extensive green roofs, each sampled four times.

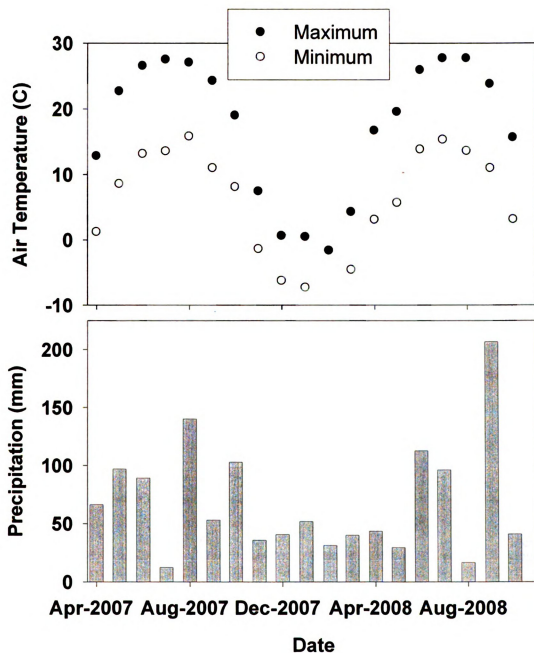


Figure 3.2. Monthly average maximum air temperatures ($^{\circ}\text{C}$), monthly average minimum air temperatures ($^{\circ}\text{C}$), and monthly total precipitation (mm) throughout the study (1 April 2007 to 31 October 2008). Data is from the nearby Michigan Automated Weather Network's East Lansing, MI weather station.

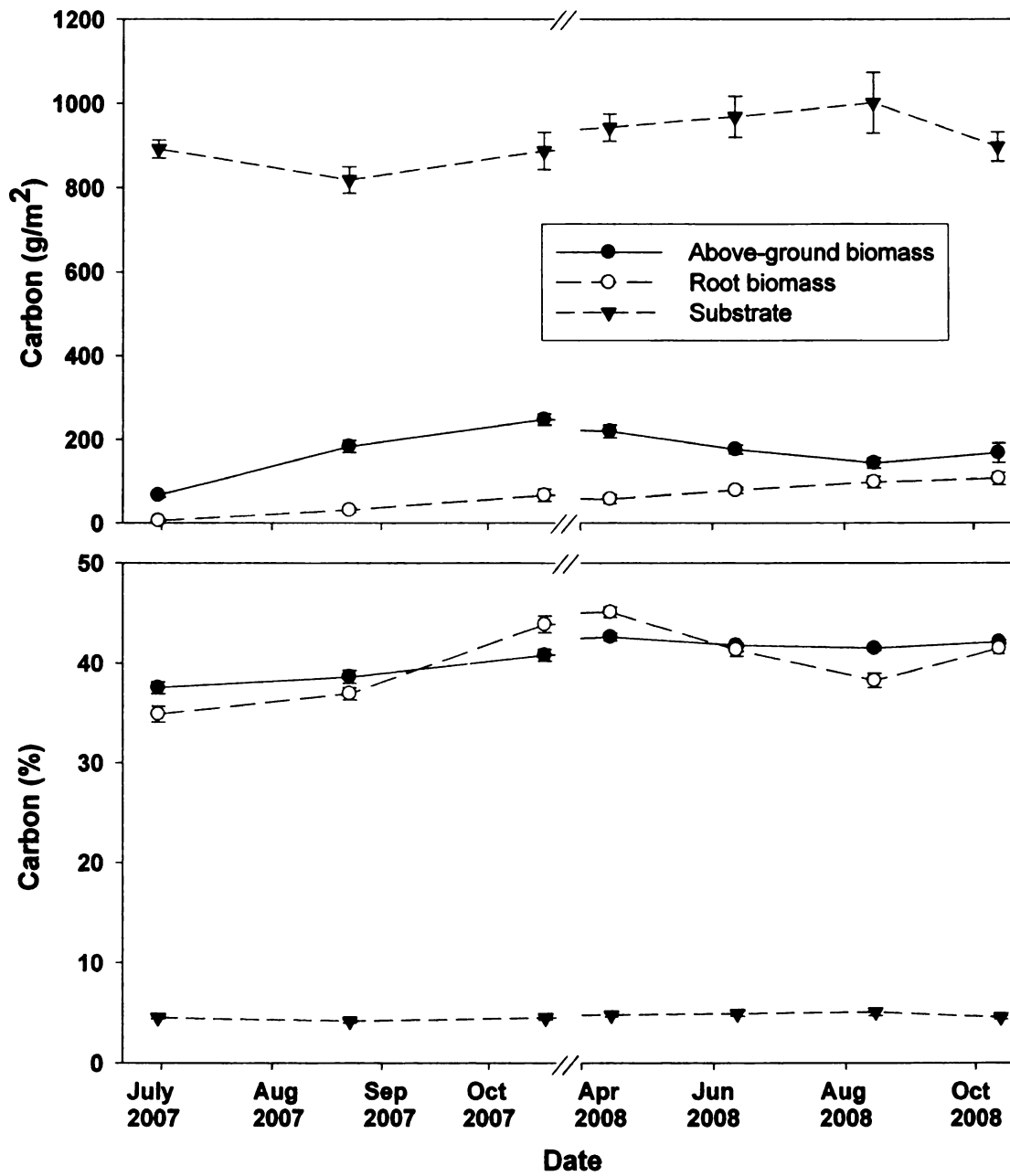


Figure 3.3. Carbon content $\pm$ standard errors for above-ground biomass, root biomass, and substrate across two growing seasons (April 2007 to October 2008).

Figure 3.4. Carbon content $\pm$ standard errors for above-ground biomass, root biomass, and substrate across two growing seasons for four species and substrate only treatment (April 2007 to October 2008).

Figure 3.4a.

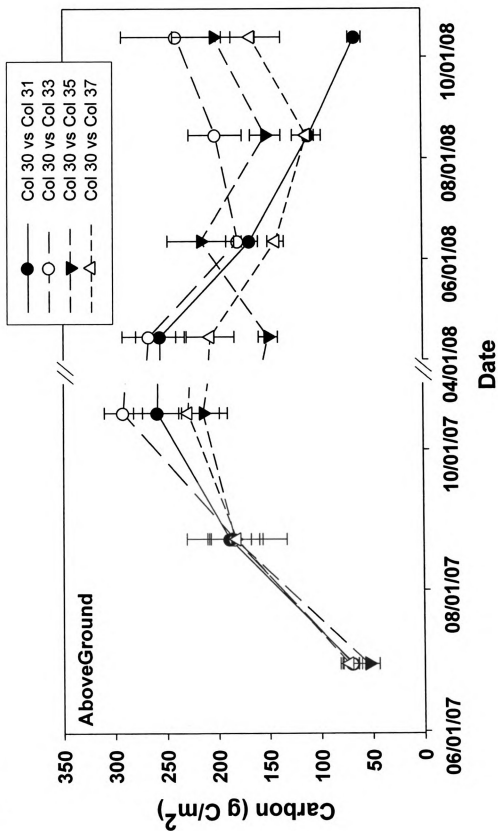


Figure 3.4b.

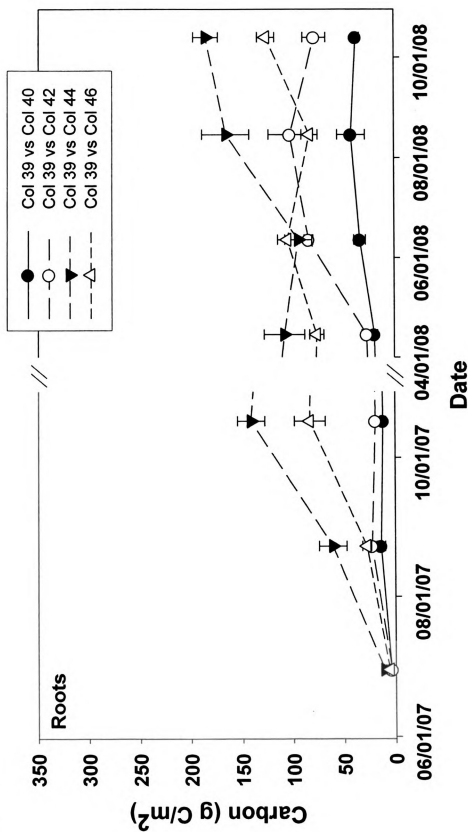
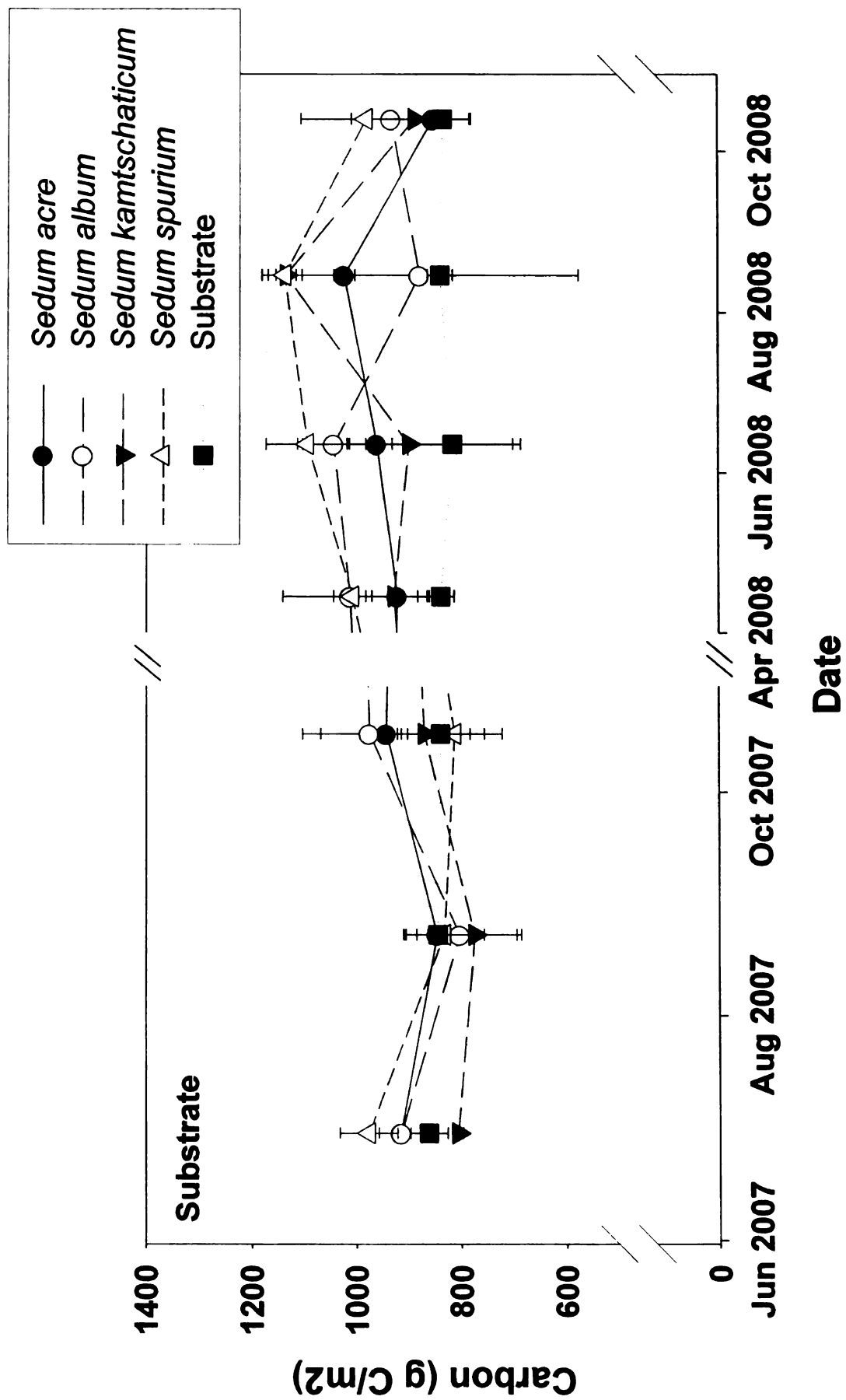


Figure 3.4c.



DISSERTATION CONCLUSION

The results presented in this thesis add to the data disseminated from the Green Roof Research Program at Michigan State University. These chapters demonstrated the importance of selecting proper species for green roofs, as well as the impact that species have on carbon sequestration. If the plants fail, either because of the specific geographical climate or because of extremes in microclimate conditions on the rooftop, carbon sequestered will be reduced.

Results from the *Sedum* plant community development study show the importance of substrate depth on plant performance, as well as long-term evaluation of species. Of the substrate depths and species evaluated, substrate depths of at least 7.0 cm are highly recommended. Species exhibiting the greatest coverage at all substrate depths were *S. floriferum*, *S. sexangulare*, *S. spurium* 'John Creech', and *S. stefco*. In general, species that are less suitable are *S. 'Angelina'*, *S. caudicola* 'Lidakense', *S. ewersii*, and *S. ochroleucum*.

The solar radiation and substrate depth study demonstrated the impact of insolation on roof-top plant growth. Species make-up differed between sun and shade. For shaded locations, *Allium cernuum*, *Sedum acre*, *S. album*, *S. kamtschaticum*, and *S. spurium* are excellent choices for all of the depths tested. Where native species are desired, *T. calycinum* is also a good choice. For sunny locations, *Sedum acre*, *S. album*, and *T. calycinum* are suitable choices. Species to avoid in Midwestern (or similar) climates include *T. parviflorum*, *S.*

stenopetalum, and *S. divergens*. Plants that would make good accent species, but will likely never dominate or fill in gaps include *C. flacca*, *S. reflexum*, and *S. urvillei*.

Results from the carbon study showed how extensive green roofs are able to sequester carbon. While the average $375 \text{ g C}\cdot\text{m}^{-2}$ is not much compared to an old-growth forest in terms of carbon storage, it still is more than a traditional barren roof. The substrate stores the majority of the carbon, which is similar to other ecosystems. However, there was a species effect on both above-ground and below-ground plant material carbon results.

These conclusions are applicable to the midwestern United States and other geographical areas with similar climates. Of course, plant growth and carbon sequestration on any roof depends on climatic factors, such as rainfall distribution and ambient air temperatures. In addition, management techniques (such as fertilizer applications or the use of supplemental irrigation) and design choices (like substrate composition, substrate depth, or species selection) may influence these results as well.

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