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THE EFFECTS OF SOIL DEPTH, COMPETITION AND FACILITATION ON PLANT GROWTH, SOIL TEMPERATURE AND WATER LOSS ON AN EXTENSIVE GREEN ROOF

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A Thesis Submitted to Saint Mary's University, Halifax, Nova Scotia,
in Partial Fulfillment of the Requirements for the
Degree of Master of Science in Applied Science

July 25, 2013, Halifax, Nova Scotia

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Date: July 25, 2013

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Abstract

This thesis analyzed various approaches in order to improve plant survival and increase species diversity on an extensive green roof. Three different techniques were used: heterogeneous soil depth, interspecies facilitation and the use of moss to enhance vascular plant survival. This study found that multiple soil depths could create niches allowing species with different growth forms and water requirements to coexist. Three potential facilitators of a vascular plant were tested: moss, lichen and bunch grass. Of these, the moss had a net positive effect on growth of the target plant (suggesting facilitation), the lichen had no net effect and the bunch-grass had a net negative effect (suggesting interspecific competition). Interestingly, even though the moss assisted the growth of neighbouring species in one experiment this was not evident in the second experiment. This indicates that more research is necessary and that moss may only be able to facilitate some plant species.

Date: July 25, 2013

Acknowledgments

I would like to thank my supervisor, Dr. Jeremy Lundholm, for his support and guidance throughout this thesis. I would also like to thank the Lundholm lab (Caitlin Porter, Stephanie Tran and Stephanie Appleby-Jones) and our summer interns for all of their ideas, assistance and support. Additionally, I would like to offer a special thank you to my husband, Adam Heim, and my family for their assistance in field collection, editing and computer programming. Finally, I would like to thank my grandparents, William and Ruth Fischer, for their constant support. My grandfather's love of the natural world is one of the reasons why I became interested in this field.

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CHAPTER 1

INTRODUCTION: THE ROLE GREEN ROOFS PLAY IN THE URBAN ENVIRONMENT AND THE EFFECT VEGATATION HAS ON TEMPERATURE AND STORM WATER RUNNOFF

Introduction

The global population has now reached 7 billion people (US Census Bureau, 2013), leading to an increase in the number and size of cities. This population boom has had a negative impact on the environment and the lives of urban inhabitants. City centers have been associated with a number a negative side effects, including air pollution, the heat island effect, storm water runoff, sound pollution and decreased green space (DeNardo *et al.*, 2005; Oberndorfer *et al.*, 2007; Thuring *et al.*, 2010). Green roofs have been presented as a possible remedy for these problems.

A green roof is composed of several different layers, including a waterproof membrane, substrate and a vegetation layer. It can also have a root barrier layer and a drainage layer (Molineux *et al.*, 2009; Castleton *et al.*, 2010). There are two types of green roofs: intensive and extensive. Intensive green roofs are generally classified as roofs with a substrate layer greater than 20cm. This type of roof can provide greater plant diversity and building insulation then an extensive green roof. However, intensive roofs require more maintenance and are heavier. An extensive green roof contains a substrate layer less than 20cm and is usually between 15cm and 6cm. Although they are unable to provide the same level of benefits as seen in intensive green roofs, they require less maintenance and can be constructed on a much wider range of structures (Carter and Butler, 2008; Olly *et al.*, 2011). Due to their lower maintenance and weight restrictions, extensive green roofs tend to be widely used. This has led to current research focusing on enhancing the benefits provided by these shallow green roofs (Castleton *et al.*, 2010).

The creation of green roofs has been linked to a number of benefits, including decreased storm water runoff, reduced temperatures and reduced air pollution. Due to this, several government incentives have been put in place to encourage their construction (Oberndorfer *et al.*, 2007). For example, the building codes in many of Germany's urban centers require architects to include a green roof in their design. In North America, incentives such as the LEED (Leadership in Energy and Environmental Design) program have encouraged the use of green roofs in sustainable building practices. Many municipalities require LEED certification in order to gain public funding for new construction (Carter and Keeler, 2008).

Two of the main reasons why green roofs are constructed include the reduction of storm water runoff and mitigation of the urban heat island affect. Storm water runoff is a significant problem in areas with low surface permeability such as cities. In these settings, rainwater is unable to permeate down into the water table. Instead, it flows over the surface of the city's concrete and into the nearest body of water, carrying with it a number of pollutants including oil, heavy metals, pesticides and fine particulates (Mentens *et al.*, 2006; Oberndorfer *et al.*, 2007; Carter and Butler, 2008; Stovin, 2010). Green roofs can help mitigate these effects by storing water in the substrate (thus delaying runoff) and by releasing water back to the atmosphere through transportation and evaporation (Oberndorfer *et al.*, 2007). Overall, green roofs, along with ground-level urban green space, could reduce the amount of runoff a city produces.

Urban areas are also associated with a phenomenon called the heat island effect, which is when the air in a city is consistently warmer than the surrounding green space (Carter and Butler, 2008). This increase in temperatures can be attributed to a number of factors, including thermal conductivity, the heat capacity of materials, urban canyons, surface albedo and anthropogenic heat (Bowler *et al.*, 2009). Urban green spaces, including green roofs, are able to reduce urban temperatures through shading, evapotranspiration, insulation and by increasing thermal mass (Oberndorfer *et al.*, 2007). Since high temperatures can lead to increased mortality rates, reducing the temperatures in highly populated urban centers could be beneficial to the whole population (Bowler *et al.*, 2009). Green roofs can also insulate buildings from urban temperatures, reducing the amount of energy needed to cool the underlying building (Castleton *et al.*, 2010). This would ultimately lead to a reduction in the resources used to cool the building such as coal, petroleum or natural gas.

Vegetation

The environment on extensive green roofs is harsh and the vegetation that is established here is exposed to drought, extreme temperatures, high wind and direct sunlight (Oberndorfer *et al.,* 2007). Due to this, the plants that should be used on extensive green roofs are ones found naturally occurring in similar conditions, such as dry grasslands, rock outcrops or coastal barrens (Oberndorfer *et al.,* 2007; Wolf and Lundholm, 2008). These plants tend to have specific characteristics to help them survive, such as a low, compact or matted growth form and evergreen, succulent or tough and twiggy foliage (Oberndorfer *et al.,* 2007).

Due to their ability to survive drought and subsist in shallow substrates, *Sedum* species make up the majority of vegetation used on extensive green roofs (Dunnett and Kingsbury, 2004; Wolf and Lundholm, 2008; MacIvor and Lundholm, 2011). Many *Sedum* are evergreen succulents that can perform CAM (crassulacean acid metabolism) photosynthesis, which is a photosynthetic system that enables greater drought tolerance (Dunnett and Kingsbury, 2004; Thuring *et al.,* 2010). *Sedum* tolerance to drought allows some of these species to survive one month with no water and some species can actively photosynthesize for four months without water. In one extreme case, *S. rubrotinctum* survived two years without water (Dunnett and Kingsbury, 2004; Rowe *et al.,* 2012). However, not all green roof environments are appropriate for *Sedum* growth. At substrate depths >10cm, surrounding vegetation can create shade and unfavorable conditions for *Sedum*s (Dunnett and Kingsbury, 2004; Oberndorfer *et al.,* 2007). *Sedum* can also have difficulties in hot and humid conditions, and root freezing in shallow substrate has been observed in cold climates (Dunnett and Kingsbury, 2004; Dvorak and Volder, 2010; Rowe *et al.,* 2012).

Species of graminoids (grass-like plants characterized by long, linear leaves) and forbs are also used on extensive green roofs, though they require deeper substrate and are not as drought tolerant as *Sedum*. Certain graminoid species have been shown to be some of the most effective types of vegetation for reducing storm water runoff and roof temperatures (MacIvor and Lundholm, 2011; Nagase and Dunnett, 2012). Depending on the species, graminoids can thrive on extensive green roofs with a substrate between 6cm and 20cm (Dunnett and Kingsbury, 2004). Species of forbs are not as drought tolerant as graminoids and most do not perform well at a depth below 10cm. That said, they do offer a wide range of flowers and cover that could be desirable to consumers (Dvorak and Volder, 2010).

There is currently a demand for the use of native species on green roofs (MacIvor and Lundholm, 2011; Butler and Orians, 2012). However, most *Sedum* species currently used on extensive green roofs are not native to North America. This indicates that there is a need for native species that can survive on a green roof with a very shallow substrate layer. Mosses and lichens are both possible solutions. Both groups can be found naturally growing on bare tile or slate rooftops and species exist in both groups that have low nutrient and water requirements (Dunnett and Kingsbury, 2004). The use of lichens for extensive green roofs has not been widely studied. However, the characteristics shared by many lichen species, such as their ability to survive frequent cycles of desiccation and rehydration, low nutrients and fluctuating temperatures (Seymour *et al.*, 2005), make them a possible candidate for establishment on extensive green roofs. Previous research examining the role of mosses on extensive green roofs has shown that moss roofs are capable of providing thermal and storm water benefits similar to those of the traditional green roof (Anderson et al., 2010).

A mixture of the aforementioned species may decrease the possible negative effects associated with monocultures, such as disease and predation. Plant diversity would also increase the range of visual display possibilities for the architect and the consumer, enhancing the aesthetic value of the roof. A diverse green roof may also increase the variety of fauna present. For example, a roof with flora that flower throughout the growing season would have more pollen available than a roof that only has a short flowering period (Cook-Patton and Bauerle, 2012).

Research has demonstrated that different plant species have different needs and requirements in terms of nutrients, space, light and water. A mixture of species with complimentary needs may improve the overall function of an extensive green roof (Cook-Patton and Bauerle, 2012; Nagase and Dunnett, 2010; Lundholm *et al.*, 2010). In terms of increased cover, Nagase and Dunnett (2010) found that, during a moderate watering regime (once every 2 weeks), several species had greater biomass when planted in a mixture compared to their biomass in a monoculture. Another study by Butler and Orians (2011) found that the growth of neighbouring species in dry conditions was enhanced when planted with sedum when compared to their growth when planted in a monoculture. In addition to this, species diversity may also increase the benefits of a green roof. For example, Lundholm *et. al.* (2010) found that modules planted solely with *D. spicata* were less effective at reducing storm water runoff than those modules containing *D. spicata* and other species. Other studies have shown that in natural systems such as in algal, prairie grass or seaweed communities increased nitrogen uptake was observed in mixtures when compared to monocultures (Cook-Patton and Bauerle, 2012). However, species diversity does not always increase the function of the roof. The addition of less effective species (in terms of roof cooling, a storm water runoff reduction or other factors) decreases the overall function of the community. This means that the different species chosen for use on an extensive green roof need to be chosen based on the overall function desired (Cook-Patton and Bauerle, 2012).

Thesis Objective

This study examined three different avenues to increase species diversity on an extensive green roof. Each experiment involved collecting data on soil temperature and water loss to determine how these attributes would be affected by the designed system. In summer, soil temperature is directly related to heat flux into the roof and thus represents an index of the ability of a green roof to cool the building and reduce energy consumption (lower soil temperatures are associated with greater thermal benefits). Water is lost from green roof soils and vegetation via runoff, evaporation from the soil/growing medium and transpiration from plant leaf surfaces. Previous work has indicated that high water loss rates are correlated with greater storm water retention; vegetation that depletes soil water allows for more water to be retained the next time it rains (Lundholm *et al.* 2010). However, drier soil also represents a more challenging condition for plant survival. Measurements on plant growth were recorded for each experiment to determine whether plant growth and survival was enhanced by the treatments.

Chapter 2 examines the role soil depth heterogeneity could play on an extensive green roof. The idea behind this chapter was that varying soil depths would lead to the provision of separate niches. These niches would allow two species with different resource requirements to grow together with less interspecific competition. It would also lead to greater diversity without increasing the weight load of the roof. For example, a roof with a 10cm deep substrate could weigh the same as a roof with a substrate mix of 5cm and 15cm depths, but the mixed substrate could lead to a more equal distribution of above-ground plant cover between species with contrasting habitat preferences.

Chapter 3 looks at the use of interspecies facilitation on the green roof. This study was based on a paper by Butler and Orians (2011) which found that species of *Sedum* could facilitate the growth of neighbouring herbaceous plants, likely by allowing more water to be retained in the soil. For this study, species native to Nova Scotia with a similar growth form to the mat-forming *Sedum* (a moss, lichens and a bunch-grass) were evaluated for their ability to facilitate the growth of a forb species.

The final experiment (Chapter 4) looks at the role three different species of mosses native to Nova Scotia could play on an extensive green roof. The potential for moss to act as a facilitator was demonstrated in Chapter 3 and this study further examines the role that moss can play in the green roof environment. In addition to mixing moss with graminoids, forbs or *Sedum*, moss-only modules were established. The purpose of this was to determine how these species affect soil temperature and water loss. Since moss can survive on very shallow substrates, they could be an alternative to *Sedum* on extremely shallow green roofs.

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CHAPTER 2

THE EFFECTS OF SOIL DEPTH HETEROGENEITY ON DROUGHT TOLERANCE AND INTERSPECIES COEXISTENCE

Abstract

The use of multiple plant species on a green roof could reduce the negative effects observed in monocultures, such as disease and predation. It would also enhance the aesthetic value of the roof. The incorporation of soil depth heterogeneity into green roof designs is one method that could be used to encourage the growth of multiple species and reduce interspecific competition. In order to determine the effect soil depth can have on plant survival in the face of drought and water uptake, a greenhouse study was performed on seven species consisting of two graminoids, two forbs, two *Sedum* and one lichen. From this data, two species with contrasting responses to soil depth and watering, *F. rubra* and *S. acre,* were chosen and planted in a rooftop soil depth heterogeneity experiment. Data was collected on plant growth, soil temperature and water loss. The percent cover of *F. rubra* increased with depth while percent cover of *S. acre* (except at 15cm) was consistent across depths except in the heterogeneous soil treatment, where it was lower. Evenness of cover between the two species was maximized in the heterogeneous vs. homogeneous soil treatment, suggesting that coexistence would be more likely under conditions of heterogeneous soil depth. Overall, soil depth heterogeneity could reduce competition between these two species by creating two separate niches, one favorable to *S. acre* (due to reduced shade) and one favorable to *F. rubra* (due to deeper soil depth).

Keywords: Extensive green roof, soil depth heterogeneity, drought tolerance, interspecies competition, water loss, soil temperature

Introduction

Denser and more numerous urban centers have resulted in a loss of green space and increased impervious surfaces. This is associated with a number of negative side effects, including air pollution, increased temperatures, storm water runoff, sound pollution and decreased biodiversity (DeNardo *et al.,* 2005; Oberndorfer *et al.,* 2007; Thuring *et al.,* 2010). Urban centers are projected to increase from 3.3 billion in 2008 to 5 billion by 2030, indicating that steps should be taken to mitigate the effects of urbanization (Yang *et al.*, 2008). In developed countries, rooftops account for 40-50% of impervious surfaces. This suggests that green roofs, which can alleviate the effects of urbanization, are one possible solution to the problem (Mentens *et al.,* 2006).

There are two types of green roofs: intensive green roofs (> 20cm of substrate) and extensive green roofs (< 20cm of substrate). Intensive green roofs can support a wide range of vegetation, including trees and shrubs, but they require more maintenance and have higher weight restrictions than extensive green roofs (Carter and Butler, 2008; Olly *et al*., 2011). Because of this, extensive green roofs are a more popular choice, as in Germany, where 80% of the green roofs are extensive (Carter and Butler, 2008). As a result, current research has focused on optimizing extensive green roofs to the needs of the consumer and the environment.

Many consider the mitigation of storm water runoff to be the main benefit of green roofs (VanWoert *et al*., 2005). Urban areas can produce five times as much runoff as a forested plot of the same size (Carter and Butler, 2008). This increased runoff can lead to reduced ground water recharge and increased sewage overflow, forcing sewage treatment plants to release waste directly into neighbouring bodies of water (Oberndorfer *et al.,* 2007). Additionally, runoff from urban areas can carry a number of pollutants, including oil, heavy metals, pesticides and fine particulates (Mentens *et al*., 2006; Oberndorfer *et al.,* 2007; Carter and Butler, 2008; Stovin, 2010). In 2003, the United States Environmental Protection Agency reported that storm water runoff was the largest source of contaminates for estuaries and the third largest for lakes (VanWoert *et al.*, 2005). The issues associated with runoff can be lessened by constructing green roofs, which have been shown to annually retain 45-70% of rainwater, depending on the climate and roof construction (Stovin, 2010). An intensive roof can reduce runoff by 65-85% and an extensive roof can reduce runoff by 27-81% (Berndtsson, 2010), though these figures can be influenced by the intensity of the rain event. Carter and Rasmussen (2006) found that, in a rain event of 25.4mm, the green roof studied could retain 88% of rainwater. However, that figure decreased as the amount of water increased. In a 25.4-76.2mm rain event, 54% of the storm water was retained and in a rain event of >76.2mm, 48% was retained.

Vegetation

In addition to soil depth, the type of vegetation used on a green roof can also affect the desired benefits. A plant's height, canopy size and plant density can affect storm water capture and heat flux (Nagase and Dunnett, 2010; MacIvor and Lundholm, 2011). Previous research has been conducted on *Sedum*, graminoids and forbs comparing their different contributions to the green roof. However, more research is necessary to expand the number of tested species and understand how species diversity affects the benefits provided by the green roof.

Sedum species are the main type of vegetation used on extensive green roofs (MacIvor and Lundholm, 2011). Many species of *Sedum* are evergreen succulents that can perform CAM (crassulacean acid metabolism) photosynthesis or switch between C3 and CAM (Dunnett and Kingsbury 2004; Thuring *et al.*, 2010). CAM plants absorb CO2 at night through their stomata and fix it during the day. This allows their stomata to stay closed during the day, reducing water loss. Those species that alternate between C3 and CAM photosynthesis do so to maintain production during unfavorable conditions such as drought or salt stress (Nagase and Dunnett, 2010; Thuring *et al.*, 2010). In addition to CAM photosynthesis, many *Sedum* are shallow rooting, allowing them to grow in soil depths of as low as 2-3cm (Dunnett and Kingsbury 2004;

Wolf and Lundholm, 2008). In terms of competition, many *Sedum* species are able to out-compete other species at depths below 10cm. At increased depths, the surrounding vegetation creates shade which is unfavorable to *Sedum* (Dunnett and Kingsbury 2004; Oberndorfer *et al.*, 2007). On a green roof, *Sedum* can reduce water loss and cool the soil (Butler and Orians, 2011). However, due to their structure they are not as capable of reducing storm water runoff when compared to thirstier species such as graminoids (grass-like plants, characterized by long, linear leaves) (Wolf and Lundholm, 2008; Lundholm *et al.*, 2010).

Graminoids are one of the more common plant types used on extensive green roofs. Many graminoids use the C4 photosynthetic pathway, which increases their drought tolerance in comparison to C3 plants and allows them to have higher growth and transpiration rates than both C3 and CAM species (Nagase and Dunnett, 2010). Certain graminoids, such as *Carex* species, have been shown to be among the most effective types of vegetation for reducing storm water runoff (MacIvor and Lundholm, 2011; Nagase and Dunnett, 2012). However, most graminoids do not do well in extremely shallow soil (<6cm). Depending on the species, graminoids can thrive on extensive green roofs with between 6 and 20cm of substrate. In addition to their drought tolerance, they can be easy to propagate on a roof, as some species can be directly seeded onto the substrate (Dunnett and Kingsbury 2004).

Other kinds of herbaceous plants, such as forbs, can also be used on extensive green roofs, but the majority of them use the C3 photosynthetic pathway. This means that they are less drought tolerant than CAM and C4 species. Most forb species do not perform well at a depth below 10cm. However, at 15cm or more, some species can survive without irrigation (Dvorak and Volder, 2010).

Due to the potential negative effects associated with monocultures, such as disease and predation, the use of plant diversity on a green roof could be beneficial to the overall system. Plant diversity can also contribute to the aesthetic value of the roof through the use of different cover types and seasonal flowering. Few studies have examined species combinations on green roofs, but those that have reported the benefits of mixtures when compared to monocultures (Lundholm *et al.,* 2010). However, not all species originally planted can coexist for long periods of time; a three-year experimental study showed that species diversity declined over the course of the experiment (Lundholm *et al.,* 2010). Due to this, there is a need to explore mechanisms to prolong coexistence of species in green roof environments. The combination of drought tolerant plant species and plants that use more water could result in greater benefits in terms of roof cooling and storm water runoff (MacIvor and Lundholm, 2011) as long as both groups can coexist on the roof. One method to encourage plant diversity and avoid competition could be to increase potential niche space in the form of varying soil depths on a green roof. The use of varied soil depths has been used in the past and it has been associated with increased invertebrate diversity (Brenneisen, 2006). However, more research is needed to see how plant species will react to heterogeneous soil on a green roof.

The use of varied soil depths could lead to a decrease in competition between two plant species. Example: at a 5cm soil depth, species of *Sedum* have been known to outperform species of grass and, at deeper soil depths (>10cm), species of grass have been shown to outperform species of *Sedum* (Dunnett and Kingsbury, 2004). A green roof with a mixed soil depth could create niches favorable to both grass and *Sedum,* encouraging coexistence between the two species. An added benefit to this mixture would be maintaining the benefits of a green roof throughout different environmental conditions. During times of drought the *Sedum* would be able to cool the roof and reduce storm water runoff and, during the favorable conditions, the graminoids would be able to uptake more water than the *Sedum*. This varied depth could also lead to increased diversity without increasing the weight requirements of the roof. For example, a roof with a uniform 15cm substrate would be heavier than a roof with a mix of 5cm and 15cm of substrate.

The Objectives of this study included:

1. Determine how soil depth affects the drought tolerance and water uptake of different plant species.
2. Determine whether soil heterogeneity promotes coexistence between a drought tolerant and less drought tolerant species, relative to more homogeneous soil conditions.

Methods

This experiment consisted of two parts: a greenhouse trial to determine which plants would be best suited for the final green roof study and a green roof experiment looking at the effect that soil depth heterogeneity can have on the interaction between two different species.

Greenhouse trial: The greenhouse at Saint Mary's University in Halifax, Nova Scotia, Canada (44°39'N, 63°35'W (Macivor, 2010) was used for the trial. The greenhouse was kept between 25/18°C (d/n), with the following photoperiod: 16/8h (d/n) (light intensity: 250umol / m^2 * s plus natural light). Plants were collected from Saint Mary's University as plugs harvested from previously established green roof experiments. The lichen used in this experiment was harvested in January from the costal barren site Chebucto Head (~ 25km SE of Halifax, Nova Scotia (Macivor, 2010)). The plants were placed in the greenhouse between October and November 2011 where they were watered and weeded twice a week until the start of the trial. During the month of January, the plants were transplanted into the experimental pots which had a width of 10.16cm, a length of 24cm and a volume of 1642ml (MT49 Treepots (Stuewe & Sons Inc., Oregon, USA)). Before planting, the roots were washed, patted dry and weighed (except for the lichen which was weighed and then placed on surface of the soil in the pot) (Wolf and Lundholm, 2008). The plants were evenly distributed between the different treatments based on weight (Appendix 1). The trial began three weeks after the final transplant, on February 21, 2012. The trial ended on April 10, 2012. For each pot, wooden chopsticks were inserted at 16.5cm, 9cm or 6.5cm from the surface of the pot. This was done to create pots with the same surface area but different soil depths. A nursery-grade weed control fabric (Quest Home & Garden, Mississauga, Ontario, Canada) was fitted into the container above the chopsticks and a 10cm² root barrier/water retention fleece was inserted on top of the fabric (EnkaRetain and Drain 3111®, Colbond Inc., North Carolina, United States). Each container was then filled to the rim with a commercial green roof growing medium (Sopraflor X), purchased in 2011 (Soprema Inc., Drummondville, Quebec, Canada) (Figures 1 and 2). This Sopraflor X consisted of crushed brick, blond peat, perlite, sand and vegetable compost with a total porosity between 60-70% and a bulk density between 1150-1250kg/m³. A soil test conducted by Nova Scotia Agriculture provided a detailed description of the elements present in the substrate (Appendix 2). The resulting soil depths were 15cm, 7.5cm and 5cm respectively. The 5cm soil depth was chosen because species of graminoids and forbs have been shown to perform poorly at this depth on a green roof (Dunnett and Kingsbury, 2004). The 15cm soil depth was chosen because graminoids and forbs have been shown to perform well at this depth on a green roof (Dunnett and Kingsbury, 2004). Finally, the 7.5cm soil depth was chosen so that a comparison could be made between the results found in this greenhouse experiment and previous experiments involving these species (Wolf and Lundholm, 2008; MacIvor and Lundholm 2011).

Vegetation

Six plant species and one lichen were selected for this trial: *Sedum acre*, *Sedum spurium*, *Solidago bicolor*, *Carex argyranthra*, *Sibbaldiopsis tridentata*, *Festuca rubra* and *Cladonia terranova* (lichen) (Table 1). All species except *C. terranova* were chosen in part due to their performance in previous studies at Saint Mary's University (Wolf and Lundholm, 2008; MacIvor and Lundholm, 2011). C. *terranova* was chosen due to its matted growth form and ability to survive drought (Brodo *et al.*, 2001).

S. acre can be found growing on cliff edges, damp walls, rocky outcrops and in dry areas. In North America, this species can be found growing from Nova Scotia to British Columbia and south to Virginia. *S. spurium* naturally grows on rocky roadsides from Newfoundland to Ontario and south to Pennsylvania. *S. bicolor* prefers dry soil on old fields, barrens and along roadsides. This species can be found growing from Nova Scotia to Ontario and south to Georgia (Roland *et al.*, 1998). *S. tridentata* grows on exposed rocky or sandy headlands, mountain tops and along shorelines (Hinds, 2000). *F. rubra* can be found in pastures, exposed areas, sand and gravel, along beaches and the upper zones of salt marshes. *F. rubra's* range in the North American continent is from Greenland to Alaska and south to North Carolina. *C. argyranthra* prefers sandy thickets, dry woods and clearings. It can be found from Nova Scotia to Manitoba and south to South Carolina (Roland *et al.*, 1998). Finally, *C. terranova* can commonly be found in boggy heaths (Brodo *et al.*, 2001).

With the exception of *C. terranova*, there were 10 replicate plantings of each species at each different soil depth (15cm, 7.5cm and 5cm), totaling 30 plantings per species, with one individual per species per replicate. The lichen was only planted in the 5cm depth treatment for a total of 10 replicates. With the exception of the lichen, each individual plant was rinsed, patted dry and weighed before planting. This was done in order to have measurements for the initial weights. The lichen was then weighed and placed on five of the 5cm pots, covering approximately 100% of the soil surface. Once planted, the pots were split into two groups, wet and dry, totaling 125 planted pots in each group. Each soil depth had four substrate-only controls for a total of 12 controls. These controls were spilt between the two groups: six to the wet group and six to the dry.

Once the trial began, the wet group was watered once per week and the dry group was watered once at the beginning of the trial. Before watering, each pot was weeded and weighed. After all the pots had been weighed, each pot received 500ml of water. Once all of the plants had been watered, they were weighed again (Wolf and Lundholm, 2008). After weighing, all plants were marked on a health scale between 0-2 as follows: 0 (dead leaves, brown stems), 1 (mostly dead leaves, green stem) and 2 (green leaves, green stem) (Butler and Orians, 2011). At the end of the trial, the above and below ground biomass was harvested, dried and weighed.

Greenhouse Statistical Method

Initial weight for each species was compared using a 1-way ANCOVA. Water capture, determined as the difference in weight before and after watering, was analyzed using depth and species in a 2-way ANOVA and a Tukey Post Hoc test. The difference in weight before and after watering was associated with the amount of water used by that plant for evaporation and transpiration (Wolf and Lundholm, 2008). Final dry biomass was compared, with initial fresh weights included as covariates to control for variation in initial plant size, in a 2-way ANCOVA.

Soil Depth Heterogeneity Experiment: The study site was located on the roof of the five-story Atrium building at Saint Mary's University in Halifax, Nova Scotia, Canada (44°39'N, 63°35'W (Macivor, 2010)). The plots were constructed on the east side of the building on an unsheltered section of the roof (Figure 3). During the study period, the weather station on the lower green roof testing facility (~50m from study site) recorded the minimum monthly temperature as 6.7 - 20.7°C and the monthly maximum as 12- 30°C (Figure 5). The monthly precipitation recorded from the green roof weather station averaged between 1.7 and 11.59mm (Figure 6). This experiment used four different soil depths: 15cm, 10cm, 5cm and a mix of 5/15cm. According to previous research, the sedum should outperform the graminoid at 5cm and the graminoid should outperform the sedum at 15cm (in terms of growth) (Dunnett and Kingsbury, 2004). Therefore, the mixed 5/15cm soil depth should decrease the competition between these two species. The amount of soil used in the 10cm treatment was equal to that used in the 5/15cm treatment. This was done to determine whether heterogeneity of the soil influenced the performance of these species. 24 wooden planter boxes with a width and length of 61 cm were constructed. They were 15cm high with no base. A nursery-grade weed control fabric (Quest Home & Garden, Mississauga, Ontario, Canada) was placed under the boxes to prevent damage to the roof. In order to create four different soil depth treatments, 5cm thick concrete slabs (length and width of 60.96cm) were placed in the wooden boxes to manipulate soil depth. Two concrete slabs were used for the 5cm soil depth, one for the 10cm depth and no concrete slabs were used for the 15cm soil depth. The 5/15cm soil depth treatment involved four concrete slabs, each with an length and width of 30.48cm and a thickness of 5cm, placed two high diagonally across from each other in a wooden box. A root barrier/water retention fleece was placed in all boxes above the concrete slabs (EnkaRetain and Drain 3111®, Colbond Inc., North Carolina, United States). The boxes were then filled to the rim with Sopraflor X substrate purchased in 2012 (Soprema Inc., Drummondville, Quebec, Canada). This Sopraflor X consisted of crushed brick, blond peat, perlite, sand and vegetable compost with a total porosity between 50-60% and a bulk density between 1100-1200kg/m^3. A soil test conducted by Nova Scotia Agriculture provided a detailed description of the elements present in the substrate at the time of planting (Appendix 2). Due to resource availability, the substrate used in this study was from a different year than that used in the greenhouse study. However, both substrates are the same brand and from the same company.

Plant species used included *S. acre* and *F. rubra,* which were chosen due to their different drought tolerance and water usage, as determined in the greenhouse trial. They which were harvested in May 2012 from previous experiments at Saint Mary's (both species) and the Dartmouth Commons (*S. acre* only) in Dartmouth, Nova Scotia, Canada (Table 1). Once harvested, plants were transplanted directly into the planter boxes until ~25-45% cover was achieved in each quarter of the box. After planting this experiment was watered twice over a two week period to encourage establishment. Each planter box was divided into four squares, each containing plants from one of the two species (two squares per species per planter box, duplicates of the same species were planted diagonally to each other) (Figure 4). Data was collected every two weeks between June 15 and October 11, 2012. The measurements gathered from this system included health and percent cover. The health of the plants was based on a scale of 0-2 as follows: 0 (dead leaves, brown stems), 1 (mostly dead leaves, green stem) and 2 (green leaves, green stem) (Butler and Orians, 2011). The percent cover was determined using photographs analyzed in ImageJ (Image Processing and Analysis in Java, http://rsbweb.nih.gov/ij/).

Temperature and Volumetric Water Content (VWC)

Soil temperatures (in °C) were recorded using a Taylor 9878 Slim-Line Pocket Thermometer Probe (Commercial Solutions Inc., Edmonton, Alberta, Canada) once a month throughout the growing season. The temperatures were taken at approximately 2cm below the soil surface in the center of one *F. rubra* and one *S. acre* square in each planter box (Figure 3). These readings were all taken no more than 2 hours from solar noon on the day of measurement, during hot periods in order to characterize maximum soil temperatures. The VWC (%) was recorded one day after a rain event and again one day later if no new showers were observed. The difference in VWC between these days was calculated to determine water loss. Measurements were taken once at the end of August and once in early September. The VWC was measured by using the ProCheck and a GS3 soil moisture sensor inserted approximately 2cm below the soil surface in the center of one *F. rubra* and one *S. acre* square in each planter box (Decagon Devices Inc., Pullman, Washington, United States). This probe estimates volumetric soil moisture content to a depth of 5cm from the surface.

Statistical Method

In order to compare relative growth rate (RGR), percent cover, temperature and the VWC across the soil depth treatments, a 1-way ANOVA and a Tukey Post Hoc test were used. These analysis all referenced soil depth as the independent variable. The RGR was calculated by using percent cover in the following formula (Harper, 1977):

$$[\mathrm{Ln}(T2) - \mathrm{Ln}(T1)]/\#\ \text{of days}$$

Results

Greenhouse Trial:

Health Score

For the dry group at 5cm *S. bicolor* was the first species to decline in health score rating, followed by *C. argyranthra*, *S. tridentata* and *F. rubra*. The last to decline were the *Sedum* species, for which the health score decreased on day 36. *S. bicolor*, *S. tridentata* and *C. argyranthra* scored 0 on day 36 and *F. rubra* scored 0 by day 43. After the initial drop, both *Sedum* species remained at 1 for the remainder of the study (Figure 7). For the 5cm wet study, the only species affected were *F. rubra*, *S. tridentata* and *S. bicolor*. No species in the wet group averaged less than 1 for the duration of the study (Figure 8 and Table 2).

For the dry group at 7.5cm, four species, *S. bicolor*, *F. rubra*, *S. tridentata* and *C. argyranthra*, declined on March 6. *S. spurium* declined 1 week before *S. acre* on day 29. After decline, the *Sedum* species did not rank lower than 1 for the rest of the trial. *S. bicolor* scored 0 by day 36, followed by *S. tridentata* and *C. argyranthra* on day 43 and *F. rubra* on day 50 (Figure 9). For the wet group, there was a small dip in the performance of *S. tridentata* on day 22, but it had recovered by the following week (Figure 10 and Table 2).

For the dry group at 15cm, only *S. tridentata* showed an early decline, with a health score of 1 on day 8. After this point it had a short recovery followed by a final decline on day 23. All other species began their decline between day 36 and 43. By day 50, all species except for *S. tridentata*, *S. spurium* and *S. acre* scored 0. The *Sedum* species had lower health scores at the end of the 15cm dry treatment when compared with the shallower depths in the dry treatment (Figure 11). For the wet block at 15cm, there was a slight decline in *S. tridentata* throughout the study and a small decline for *C. argyranthra* on day 36. However, no species passed below the 1 mark (Figure 12 and Table 2).

Water capture

C. argyranthra at 15cm (0.49g ± 0.02) was the best performer in terms of average water capture and it was the only treatment significantly different from the control. The only groups that were not significantly lower than the best performer were *C. argyranthra at* 7.5cm (0.43g ± 0.008), *C. argyranthra at* 5cm (0.43g ± 0.009), *F. rubra* at 7.5cm (0.42g ± 0.013) *and S. spurium at* 7.5 (0.42g ± 0.011). *Cladonia* (0.31g ± 0.013) had a significantly lower average water capture than *C. argyranthra* and *F. rubra* at all depths as well as *S. spurium* at 7.5cm (listed above). Although it was not a significant difference, the lichen had a lower average water capture than the 5cm control (0.35g ± 0.019) (Figure 13 and Table 2).

Dry Weight

The average dry shoot weight for both *C. argyranthra* and *F. rubra* increased with depth, with the greatest weights recorded in the wet treatment. *S. acre* and *S. tridentata* did not show an increase in shoot weight in terms of depth, however heavier shoots were recorded in the wet treatment compared to the dry treatment. The *S. spurium* and *S. bicolor* treatments only showed an increase in shoot weight with depth for the dry group. The heaviest shoot weight for these species was in the dry 15cm treatment (Table 2).

The average dry root weights for *C. argyranthra, F. rubra and S. spurium* increased with depth, with the greatest weights recorded in the wet treatment. For *S. acre*, the wet treatment did not show an increase in root weight corresponding with depth. However, in the *S. acre* dry treatment, root weight decreased as depth increased. *S. bicolor* did not demonstrate a relationship between moisture, depth and root weight, but the heaviest roots for this treatment were recorded in the wet 15cm treatment. For *S. tridentata*, the wet treatment had heavier roots than the dry treatment and weight increased as depth increased. However, the dry treatment for *S. tridentata* did not show a relationship between depth and root weight.

Carex argyranthra

The average dry shoot weight for the wet 15cm treatment (1.77g ± 0.127) had the greatest weight and was significantly heavier than all of the dry treatments. The dry 5cm treatment (0.458g ± 0.062) had the lowest shoot weight and had a significantly lower shoot weight than all other treatments except for the dry 7.5cm treatment (0.61g ± 0.094)(Figure 14). In terms of root weight, the wet 15cm treatment (38.6g ± 7.34) was significantly greater than all other treatments. The dry 5cm treatment (0.85g ± 0.231) had the lowest dry root weight but it was only significantly different from the wet 7.5cm treatment (18g ± 5.23) and the wet 15cm treatment (listed above) (Figure 14 and 15).

Festuca rubra

The wet 15cm treatment (1.27g ± 0.199) had the greatest shoot weight, but it was only significantly heavier than the wet 5cm (0.69g ± 0.118) and dry 5cm (0.44g ± 0.068) treatments (Figure 16). The greatest dry root weight was recorded for the wet 15cm treatment (19.7g ± 2.92), which had a significantly greater weight than all other treatments. The second highest root weight was recorded for the wet 7.5cm treatment (10.4g ± 2.29), which was itself significantly greater than the remaining treatments. There was no significant difference between any of the dry treatments and the wet 5cm treatment (1.72g ± 0.446) (Figures 16 and 17).

Solidago bicolor

There was no significant difference between all treatments in terms of dry shoot weight. However, the lowest shoot weight was observed in the treatments for wet 5cm (0.33g ± 0.062) and wet 7.5cm (0.18g ± 0.058) (Figure 18). The greatest root weight was recorded for the wet 15cm treatment (3.11g ± 0.542), which had a significantly greater weight than all other treatments. There was no significant difference in dry root weight between any of the other treatments (Figures 18 and 19).

Sibbaldiopsis tridentata

No significant difference was observed in dry shoot weight for all treatments of *S. tridentata.* The greatest shoot weight was measured in the treatments for dry 7.5cm (0.3g ± 0.127) and wet 15cm (0.28g ± 0.215). The lowest shoot weight was recorded for the treatments for dry 5cm (0.05g ± 0.018) and dry 15cm (0.02g ± 0.004) (Figure 20). No significant differences were observed in dry root weight for all treatments of *S. tridentata*. The greatest root weight was recorded for the wet 15cm treatment (0.61g ± 0.47) and the lowest root weight was recorded for the dry 5cm treatment (0.03g ± 0.003) (Figures 20 and 21).

Sedum acre

The heaviest dry shoot weight was in the wet 7.5cm treatment (8.12g ± 0.669), which was significantly greater than all dry treatments. The lowest shoot weight was recorded for the dry 15cm treatment (1.88g ± 0.373). No significant difference in shoot weight was observed between any of the dry treatments and the wet 5cm treatment (3.52g ± 0.661) (Figure 18). The greatest root weight was recorded in the wet 7.5cm treatment (4.74g ± 0.852), which was significantly greater than all of the dry treatments. The lowest root weight was recorded for the dry 15cm treatment (0.4g ± 0.131). However, it was only significantly lower than the wet 7.5cm treatment (listed above) (Figures 22 and 23).

Sedum spurium

The heaviest shoot weight was recorded in the dry 15cm treatment (2.85g ± 0.659), which was significantly greater than both the dry 5cm treatment (0.6g ± 0.126) and the dry 7.5cm treatment (0.80g ± 0.143). The lowest shoot weight was recorded for the dry 5cm treatment (listed above), which was significantly lower than the treatments for dry 15cm (listed above), wet 5cm (1.73g ± 0.251) and wet 7.5cm (2.11g ± 0.133) (Figure 24). The greatest root weight was observed in the wet 15cm treatment (7.1g ± 1.67). However, it was only significantly greater than the dry 5cm treatment (2.25g ± 0.48), which was the lightest for this group (Figures 24 and 25).

Soil Depth Heterogeneity Experiment:

Health Score

The health score for *S. acre* decreased at all depths during mid-late July (a period of little to no rain (Figure 6)) but recovered by August and remained at a score of 2 for the rest of the growing season (Figure 26). The health score for *F. rubra* decreased during mid-late July to a greater extent than *S. acre* at all depths except for the 15cm treatment. All treatments except for *F. rubra* at 5cm recovered after this decrease (Figures 26 and 27).

Percent cover over growing season

At the end of the 2012 growing season, *S. acre* had the greatest percent cover at 15cm (0.477 ± 0.015), followed by 5cm (0.454 ± 0.025), 10cm (0.426 ± 0.03) and 5/15cm (0.375 ± 0.017). There was a slight significant difference in percent cover between the 5/15cm treatment and the 15cm and 5cm treatments (Figure 28). *F. rubra* had the greatest percent cover at a soil depth of 15cm (0.372 ± 0.008) followed by 5/15cm (0.284 ± 0.005), 10cm (0.198 ± 0.031) and 5cm (0.028 ± 0.016). At the end of the growing season, the percent cover for *F. rubra* was significantly different between the various treatments. The lowest significant differences were observed between two groupings: 5/15cm and 10cm, and 5/15cm and 15cm (Figure 29). The ratio of *F. rubra* and *S. acre* was significantly different between the lowest ratio at 5cm (0.066 ± 0.039) and all other treatments. The 10cm (0.492 ± 0.086) treatment also had a significantly different ratio from the other treatments. The two highest ratios, 15cm (0.782 ± 0.025) and 5/15cm (0.766 ± 0.035), were not significantly different from each other (Figure 30 and Table 3). For the two treatments with an average soil depth of 10cm (the 10cm and 5/15cm treatments), the cover ratio between the two species was closer to 1.0 in the heterogeneous treatment (5/15cm) and more dominated by *S. acre* in the homogeneous treatments (10cm).

RGR

For *S. acre,* there was a significant difference in RGR between the treatments for 5cm (0.006 ± 0.0006) and 15cm (0.007 ± 0.0003), with a higher RGR seen at 15cm (Figure 31). The RGR for *F. rubra* was significantly different between the 5cm treatment (-0.018 ± 0.0055) and all other treatments. At this depth, a negative RGR was observed. The RGR for this species was greatest at 15cm (0.012 ± 0.0012), followed by 5/15cm (0.009 ± 0.0019) and 10cm (0.007 ± 0.0022) (Figure 32 and Table 3).

Soil Temperature and VWC

The highest soil temperature (°C), taken on July 1, 2012, was recorded for *F. rubra* in the 5cm treatment (33.97° ± 0.87), which was significantly higher than all other treatments except *S. acre* at 5cm (32.37° ± 0.47) and 5/15cm (31.67° ± 0.51). The lowest temperature was recorded for *S. acre* at 15cm (28.93° ± 0.86) (Figure 33). When the temperature taken for each planter box was averaged, the 5cm planter boxes (33.17° ± 0.646) had the greatest soil temperature and they were significantly greater than the 10cm treatment (30.38° ± 0.463) and the 15cm treatment (29.26° ± 0.653) (Figure 34). The difference in VWC (%) between September 11, 2012 and September 12, 2012 was used to determine water loss. 61mm of rain was recorded on September 10, 2012, with no rainfall recorded on September 11 or September 12, 2012. In terms of water loss, no significant difference between the two species was observed for all treatments. However, the greatest difference was observed for *F. rubra* at 10cm (6.23 ± 1.09) and the lowest was observed for *S. acre* at 5cm (1.32 ± 1.27) (Figure 34). For all treatments of *F. rubra*, the greatest difference in VWC was at 10cm and the lowest difference observed was at 5/15cm (2.07 ± 1.19). For all treatments of *S. acre*, the highest difference was recorded at 10cm (3.27 ± 1.71) and the lowest at 5cm (listed above) (Figure 35 and Table 4).

Discussion

Greenhouse Trial: Overall, the performance of the selected species was consistant with the results of previous research conducted on this topic (MacIvor and Lundholm, 2011; Wolf and Lundholm, 2008). For the dry group, the *Sedum* species at all soil depths were the most drought tolerant, which can be attributed to their succulent nature and ability to perform CAM photosynthesis (Thuring *et al.,* 2010; Dunnett and Kingsbury, 2004). All other species at all depths (except *S. bicolor* at 15cm) demonstrated complete desiccation by the end of the study. Out of the non-sedums, *F. rubra* was the most drought tolerant at both the 5cm and 7.5cm soil depths and *S. bicolor* was the most drought tolerant at the 15cm soil depth. The deeper soil depth resulted in extended survival, most likely due to a greater water holding capacity. The poor performance of *S. tridentata* throughout the study period was most likely due to the size of the original plantings. This could have put *S. tridentata* at a distinct disadvantage for the drought study by decreasing its ability to uptake water.

C. argyranthra was the best performer in terms of water capture and it was the only species significantly different from the control. MacIvor and Lundholm (2011) also recorded *C. argyranthra* as the best performer in terms of water capture and the only species to capture more water than substrate-only controls. The positive performance of this species is most likely due to its tall structure and high above-ground biomass which has been positively associated with water uptake (Nagase and Dunnett, 2010).

For *C. argyranthra, F. rubra and S. spurium*, deeper depth was associated with heavier shoots and roots, with the heaviest observed in the wet treatments. This is most likely due to increased nutrient availability and water retention with greater volumes of soil. *S. bicolor, S. tridentata and S. acre* did not follow this trend. It is possible that adding more water to these species didn't make a difference because they were not limited by lack of water, indicating a high drought tolerance. The poor performance of the forbs may be attributed to the size of the plants at the beginning of the trial. It is possible that the shoots did not have enough time or nutrients to grow. Since the greatest root weight for the forbs was recorded in the wet 15cm treatment, it is also possible that these species focus on root growth during favorable conditions. *S. acre* had greater root and shoot weight in the wet treatments, but the depth did not seem to make a difference. This is most likely due to *S. acre's* structure. It has a shallow rooting system which reduces the influence of substrate depth (Olly *et al*., 2011).

Due to the results from this study, as well as previous research on these species, *S. acre* and *F. rubra* were chosen for the soil depth heterogeneity experiment. *S. acre* was chosen due to its drought tolerance in shallow substrate, as well as its potential to facilitate neighbouring species through reduced water loss and soil cooling (Wolf and Lundholm, 2008; Butler and Orians, 2011). *F. rubra* was chosen due to its drought tolerance (as shown in the greenhouse trial) and its ability to create shade. Since shade is unfavorable to *S. acre,* this quality could reduce competition between the two species (Dunnett and Kingsbury, 2004; Oberndorfer *et al.*, 2007).

Soil Depth Heterogeneity Experiment: The most important comparisons here are between the 10cm and 5/15cm depth treatments, as both of these have the same mean soil depth (and same total weight and soil volume) allowing for an evaluation of the effects of soil depth heterogeneity, while the average is held constant. The two other homogeneous soil depth treatments (5cm and 15cm) are included for comparison, but do not have corresponding heterogeneous depth treatments.

Both temperature and water loss indicate that cooler temperatures and greater water storage are associated with deeper depths. Interestingly, even though *S. acre* was planted at 5cm for both the 5cm and 5/15cm treatments, a lower temperature was observed for the 5/15cm treatment, in which *F. rubra* was planted at the 15cm depth. This could be due to cooler temperatures under *F. rubra* at the deeper soil depth impacting the temperature of the areas planted with *S. acre*. Another possibility is that the greater canopy coverage observed by *F. rubra* in this soil depth compared to the 5cm soil depth provided more shade to the adjacent sections of the box, therefore cooling the whole planter box. The greater water storage in the 15cm depth patches may also have allowed for more evapotranspiration, leading to greater cooling for the whole planter box. When the temperatures taken in each species' patch were combined and averaged, the temperature in the 10cm soil depth was similar to the recordings gathered for *F. rubra*. The temperature in the 5/15cm soil depth treatment had a soil temperature closer to *S. acre*. Overall, the temperatures were not significantly different between homogeneous and heterogeneous treatments with average depth of 10cm, suggesting that there is no penalty in terms of thermal performance when using variable soil depths.

The greatest water loss was recorded for *F. rubra* in all treatments, indicating that *F. rubra* was absorbing/transpiring more water than S. *acre* during this timeframe. When comparing these results to the greenhouse trial, the only similarity is that *F. rubra*, at every depth, used more water than *S. acre*. Interestingly, the depth that led to the greatest water usage for both species was the 10cm soil depth. One reason why it was greater than the 15cm and 5/15cm soil depth could be due to the time the measurement was taken. The VWC was recorded the day after a rain event, not immediately when a rain event ended. Since greater biomass was recorded for *F. rubra* in the 15cm and 5/15cm soil depth, water uptake would have been greater at these soil depths, leading to a bias when the VWC was taken. The greater water uptake at the 10cm soil depth compared to the 5cm soil depth could be due to two factors. First, *F. rubra* had a slightly lower health score at this depth than at the 15cm and 5/15cm depths, indicating a need for more water. Previous studies have associated exposure to drought with greater water uptake (Wolf and Lundholm, 2008). Secondly, the greater biomass of *F. rubra* at this depth compared to the 5cm depth would have allowed for greater water uptake.

F. rubra was unable to recover after the late July drought at the 5cm soil depth. This indicates that there were not enough resources available for this species at this depth, indicating that continued studies of the 5/15cm depth should show little invasion of *F. rubra* into the 5cm depth patches. For both species, the greatest percent cover was observed for the 15cm treatment. For *F. rubra,* percent cover decreased as depth decreased, most likely due to resource availability. Excluding the 15cm depth, *S. acre's* percent cover increased as *F. rubra's* decreased, which could be due to decreased shading and competition from the other species. The two most even ratios in cover were recorded in the 15cm and 5/15cm treatments, with the homogeneous 10cm depth treatment showing greater dominance by *S. acre*. This suggests that spatial heterogeneity of the soil could allow for a more even distribution of canopy cover between these two species. For both *F. rubra* and *S. acre*, the RGR was greatest at a depth of 15cm and lowest at 5cm, which could be due to increased resource availability with increased depth.

In this study, concrete slabs were used to manipulate soil depth. However, due to weight restrictions this method is not feasible for many green roof systems. Other methods to manipulate soil depth could include wooden planks, pumice or other lightweight materials. Creating varied soil depths through mounding is also a possibility. However, this method may lead to a decrease in soil heterogeneity over time.

Since this study only covered one growing season, the presence of competition (measured by the dominance by one species in terms of percent cover) has not yet been observed. The decrease in the performance of *F. rubra* at 5cm was most likely due to a lack of water, not competition (since *S. acre* growth was mainly obserbved around the edges of *F. rubra*). Overall, more growing seasons are necessary to determine long-term coexistence. However, if coexistence can be achieved it could lead to increased diversity without increasing the weight of the extensive green roof.

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Tables

Table 1. A description of the vegetation used in the study. The indigenous species are native to Nova Scotia and the introduced species originate from Europe. In the collected column, CH = Chebucto Head, SMU = previous modules used at Saint Mary's University and DM = Dartmouth Commons.

Species	**Species Code**	**Growth Form**	**Origin**	**Collected**
Cladonia terranova	*Cla.*	Lichen	Indigenous	CH
Carex argyranthra	*Car. a*	Graminoid	Indigenous	SMU
Festuca rubra	*Fes. r*	Graminoid	Indigenous	SMU
Sedum acre	*Sed. a*	Succulent	Introduced	SMU/DM
Sedum spurium	*Sed. s*	Succulent	Introduced	SMU
Solidago bicolor	*Sol. b*	Forb	Indigenous	SMU
Sibbaldiopsis tridentata	*Sib. t*	Forb	Indigenous	SMU

Table 2. Measurements collected during the greenhouse trial for each species in each treatment as measured by the mean ± SE (standard error). The final health rating was measured on a scale of 0-2 as follows: 0 (dead leaves, brown stems), 1 (mostly dead leaves, green stem) and 2 (green leaves, green stem) (Butler and Orians, 2011).

Treatment	Initial Weight	Root (g)	Shoot (g)	Water Capture (g)	Final Health Rating	Days Until Rating= 0
C. argyranthra						
Wet 5cm	8.57±0.866	8.77±1.94	1.05±0.076	0.43±0.009	2	N/A
Wet 7.5cm	8.5±0.897	18±5.23	1.45±0.183	0.43±0.008	2	N/A
Wet 15cm	7.98±1	38.6±7.34	1.77±0.127	0.49±0.02	2	N/A
Dry 5cm	3.64±0.92	0.85±0.231	0.458±0.062	N/A	0	36
Dry 7.5cm	7.3±1.15	1.9±0.405	0.61±0.094	N/A	0	43
Dry 15cm	8.33±1.61	4.48±0.606	0.94±0.052	N/A	0	50
F. rubra						
Wet 5cm	3.65±0.836	1.72±0.446	0.69±0.118	0.4±0.017	1.8	N/A
Wet 7.5cm	2.32±0.146	10.4±2.29	0.91±0.072	0.42±0.013	2	N/A
Wet 15cm	2.81±0.689	19.7±2.92	1.27±0.199	0.4±0.018	2	N/A
Dry 5cm	3.04±0.623	0.58±0.193	0.44±0.068	N/A	0	43
Dry 7.5cm	4.42±0.742	1.22±0.321	0.78±0.093	N/A	0	50
Dry 15cm	7.82±1.05	3.15±0.49	1.09±0.166	N/A	0	50
S. acre						
Wet 5cm	9.64±1.95	2.29±0.558	3.52±0.661	0.36±0.014	2	N/A
Wet 7.5cm	10.3±1.68	4.74±0.852	8.12±0.669	0.36±0.021	2	N/A
Wet 15cm	9.83±.791	2.86±0.755	4.95±0.251	0.34±0.009	2	N/A
Dry 5cm	9.76±1.4	1.51±0.637	1.94±0.188	N/A	1	N/A
Dry 7.5cm	8.59±1.1	0.75±0.223	2.09±0.241	N/A	1	N/A
Dry 15cm	8.75±.845	0.4±0.131	1.88±0.373	N/A	0.2	N/A
S. spurium						
Wet 5cm	4.94±0.297	4.61±0.408	1.73±0.251	0.37±0.007	2	N/A
Wet 7.5cm	4.17±0.455	5.08±1.14	2.11±0.133	0.42±0.011	2	N/A
Wet 15cm	3.28±0.522	7.1±1.67	1.81±0.239	0.38±0.023	2	N/A
Dry 5cm	4.37±0.651	2.25±0.48	0.6±0.126	N/A	1	N/A
Dry 7.5cm	4.8±1.09	5.56±0.671	0.80±0.143	N/A	1	N/A
Dry 15cm	4.22±1.62	5.85±0.975	2.85±0.659	N/A	0.4	N/A
S. bicolor						
Wet 5cm	1.7±0.725	0.46±0.12	0.33±0.062	0.36±0.003	1.6	N/A
Wet 7.5cm	0.976±0.297	0.38±0.142	0.18±0.058	0.38±0.017	2	N/A
Wet 15cm	1.09±0.267	3.11±0.542	0.53±0.116	0.38±0.019	2	N/A
Dry 5cm	2.51±0.652	0.57±0.271	0.49±0.09	N/A	0	36
Dry 7.5cm	3.27±1.17	0.62±0.276	0.5±0.138	N/A	0	36
Dry 15cm	2.81±0.449	0.53±0.09	0.53±0.085	N/A	0.4	N/A
S. tridentata						
Wet 5cm	0.73±0.165	0.13±0.084	0.22±0.048	0.38±0.015	2	N/A
Wet 7.5cm	0.9±0.232	0.22±0.08	0.16±0.041	0.38±0.038	2	N/A
Wet 15cm	1±0.331	0.61±0.47	0.28±0.215	0.34±0.009	1.8	N/A
Dry 5cm	0.41±0.063	0.03±0.003	0.05±0.018	N/A	0	36
Dry 7.5cm	1.62±0.794	0.18±0.105	0.3±0.127	N/A	0	43
Dry 15cm	0.21±0.082	0.05±0.04	0.02±0.004	N/A	0	50
C. terranova						
Wet 5cm	15.2±1.85	N/A	5.22±0.761	0.31 ±0.013	2	N/A
Dry 5cm	12.8±1.4	N/A	4.88±0.642	N/A	2	N/A
Control						
5cm	N/A	N/A	N/A	0.35±0.019	N/A	N/A
7.5cm	N/A	N/A	N/A	0.34±0.002	N/A	N/A
15cm	N/A	N/A	N/A	0.36±0.034	N/A	N/A

Table 3. Growth measurements collected for the soil depth heterogeneity experiment for each species in each treatment. The final health rating was measured on a scale of 0-2 as follows: 0 (dead leaves, brown stems), 1 (mostly dead leaves, green stem) and 2 (green leaves, green stem) (Butler and Orians, 2011). All other data is displayed as the mean ± SE. Ratio was determined by dividing *F. rubra* by *S. acre*.

Depth	**Final Cover**		**RGR**		**Ratio**	**Final Health Rating**	
	F. rubra	***S. acre***	***F. rubra***	***S. acre***		***F. rubra***	***S. acre***
5cm	0.028±0.016	0.454±0.025	-0.018±0055	0.007±0.0006	0.066±0.039	1.25	2
10cm	0.198±0.031	0.426±0.03	0.007±0.0022	0.007±0.0006	0.492±0.086	1.92	2
15cm	0.372±0.008	0.477±0.015	0.012±0.0012	0.008±0.0004	0.782±0.025	2	2
5/15cm	0.284±0.005	0.375±0.017	0.01±0.0019	0.007±0.0003	0.766±0.035	2	2

Table 4. Temperature (°C) and water loss (%) measurements collected for the soil depth heterogeneity experiment for each species in each treatment. The temperature was taken on July 1, 2012. The water loss was determined by the difference in VWC between September 11 and September 12, 2012. Data is displayed as the mean ± SE.

Depth	**Temperature (°C) per plant**		**Treatment Temperature (°C)**	**Water Loss (%)**	
	F. rubra	***S. acre***		***F. rubra***	***S. acre***
5cm	33.97±0.87	32.37±0.47	33.17±0.646	4.38±0.51	1.32±1.27
10cm	30.63±0.62	30.12±0.48	30.38±0.463	6.23±1.09	3.27±1.71
15cm	29.58±0.53	28.93±0.86	29.26±0.653	4.22±1.23	1.9±1.75
5/15cm	30.33±1.19	31.67±0.51	31±0.826	2.07±1.19	1.91±0.85

Figures

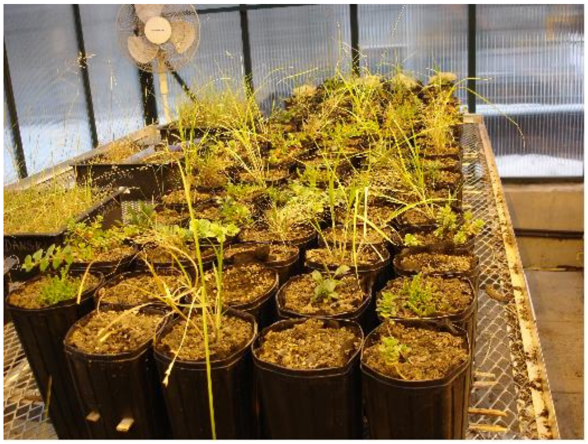

Figure 1. Treepots after planting and placement in the greenhouse.

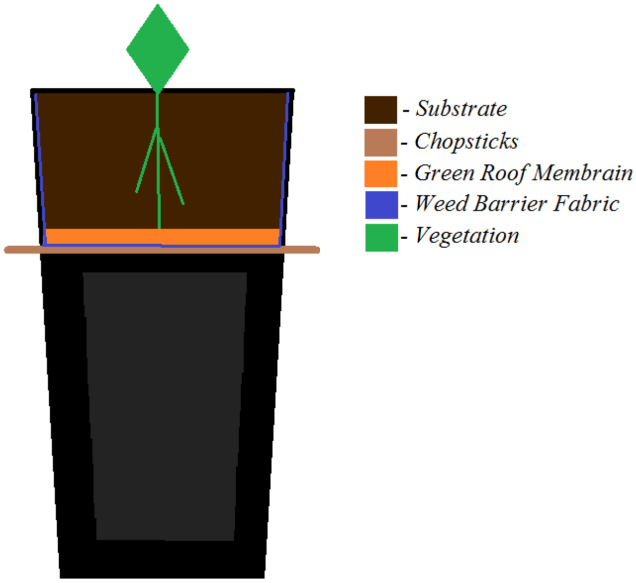

Figure 2. Composition of Treepots used in the greenhouse trial.

Figure 3. Construction and placement of the soil depth heterogeneity experiment. The image on the left depicts the planter boxes before substrate and vegetation was added. The image on the right depicts the planter boxes after planting.

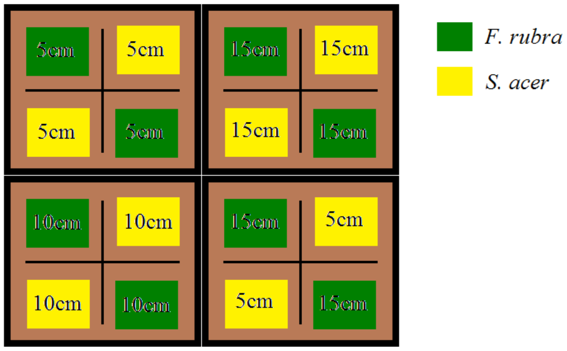

Figure 4. The position of vegetation and distribution of soil depth in the different planter boxes for the soil depth heterogeneity experiment. The homogeneous treatments include 5cm, 10cm and 15cm soil depth. The only heterogeneous treatment is the 5/15cm soil depth.

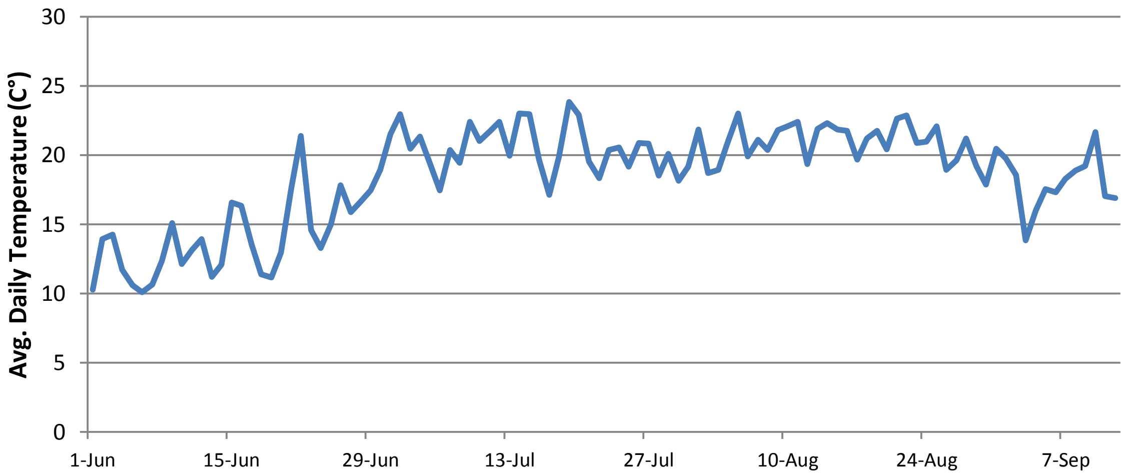

Figure 5. Average daily temperature (°C) throughout the growing season as measured by the green roof testing facility at Saint Mary's University.

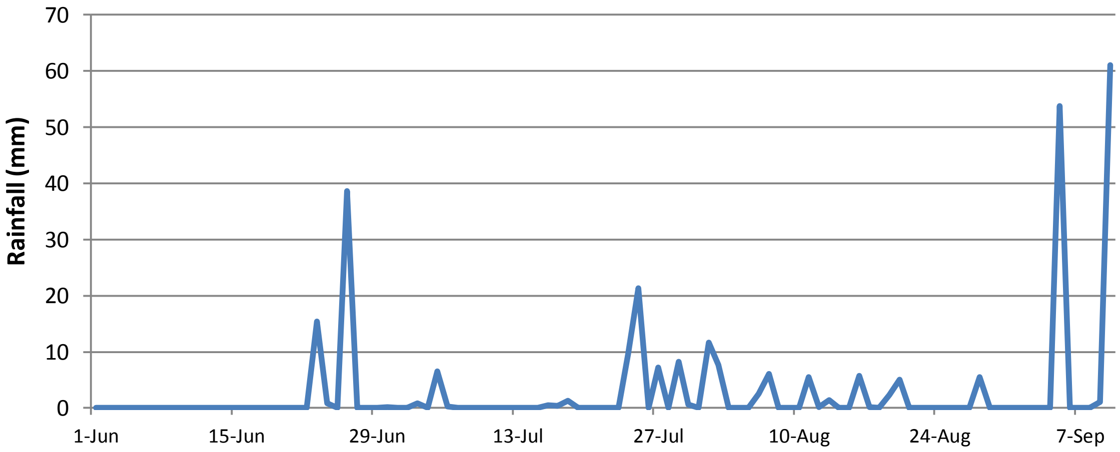

Figure 6. Daily rainfall (mm) throughout the growing season as measured by the green roof testing facility at Saint Mary's University.

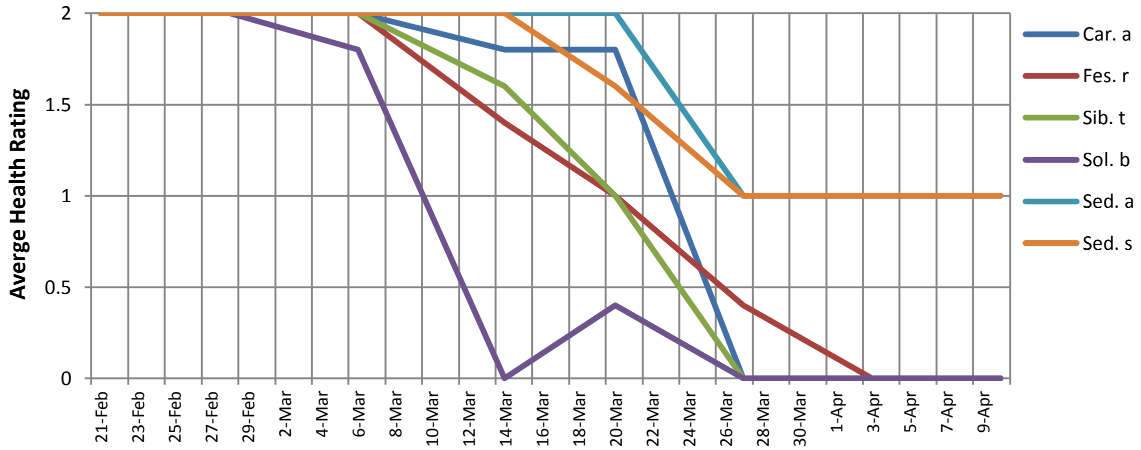

Figure 7. Average health rating throughout the greenhouse trial for all species in the dry 5cm group. The average health rating was measured on a scale of 0-2 as follows: 0 (dead leaves, brown stems), 1 (mostly dead leaves, green stem) and 2 (green leaves, green stem) (Butler and Orians, 2011).

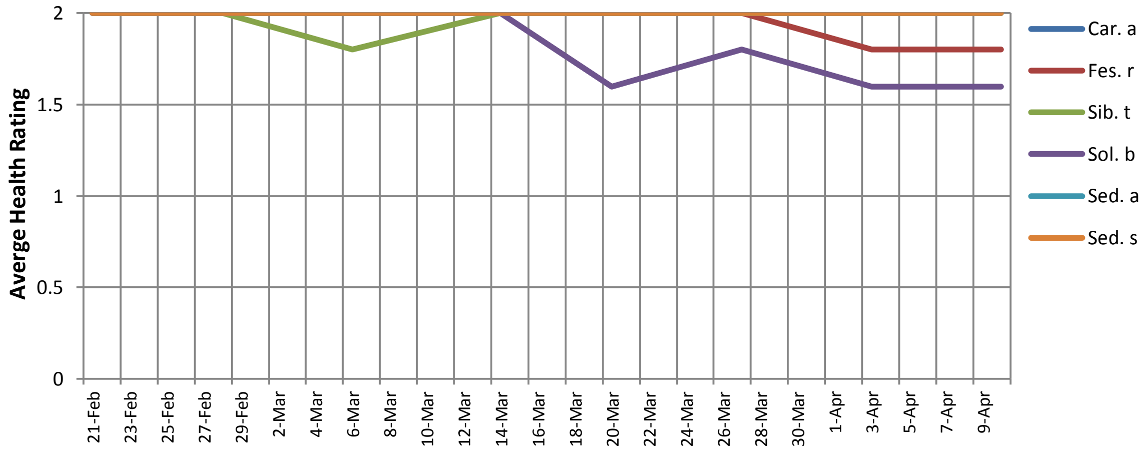

Figure 8. Average health rating throughout the greenhouse trial for all species in the wet 5cm group. The average health rating was measured on a scale of 0-2 as follows: 0 (dead leaves, brown stems), 1 (mostly dead leaves, green stem) and 2 (green leaves, green stem) (Butler and Orians, 2011).

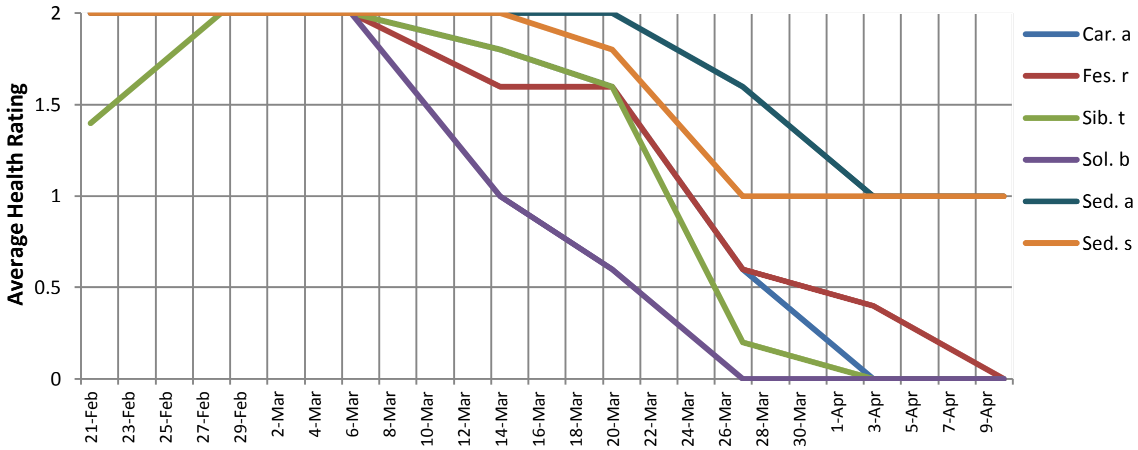

Figure 9. Average health rating throughout the greenhouse trial for all species in the dry 7.5cm group. The average health rating was measured on a scale of 0-2 as follows: 0 (dead leaves, brown stems), 1 (mostly dead leaves, green stem) and 2 (green leaves, green stem) (Butler and Orians, 2011).

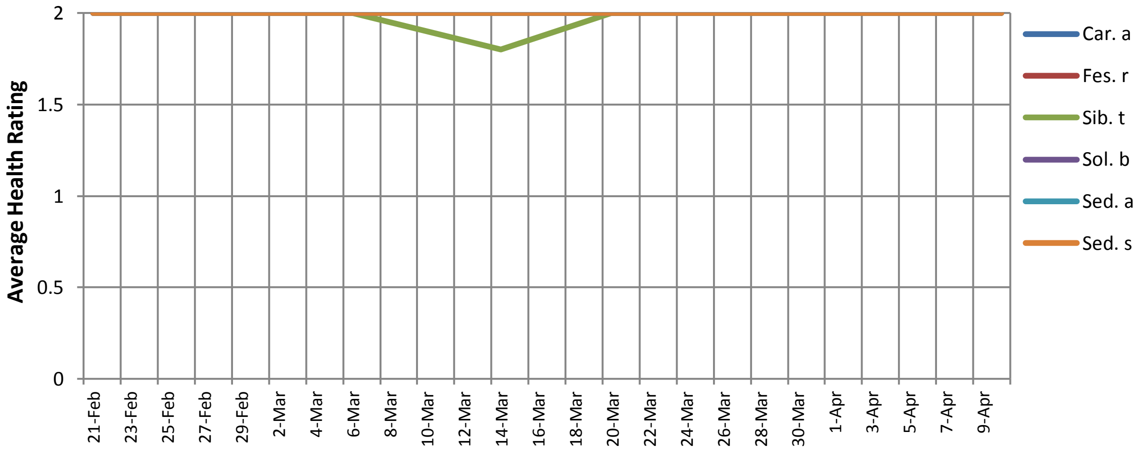

Figure 10. Average health rating throughout the greenhouse trial for all species in the wet 7.5cm group. The average health rating was measured on a scale of 0-2 as follows: 0 (dead leaves, brown stems), 1 (mostly dead leaves, green stem) and 2 (green leaves, green stem) (Butler and Orians, 2011).

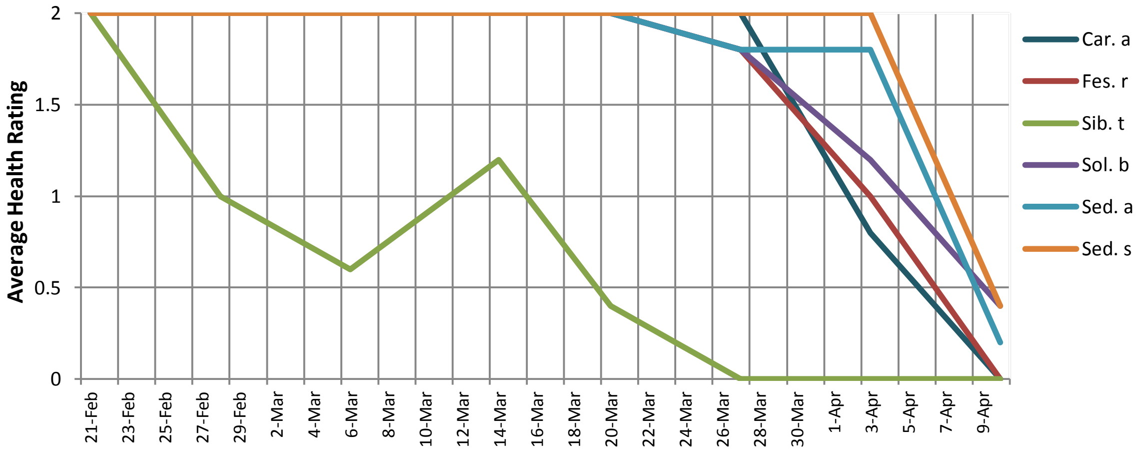

Figure 11. Average health rating throughout the greenhouse trial for all species in the dry 15cm group. The average health rating was measured on a scale of 0-2 as follows: 0 (dead leaves, brown stems), 1 (mostly dead leaves, green stem) and 2 (green leaves, green stem) (Butler and Orians, 2011).

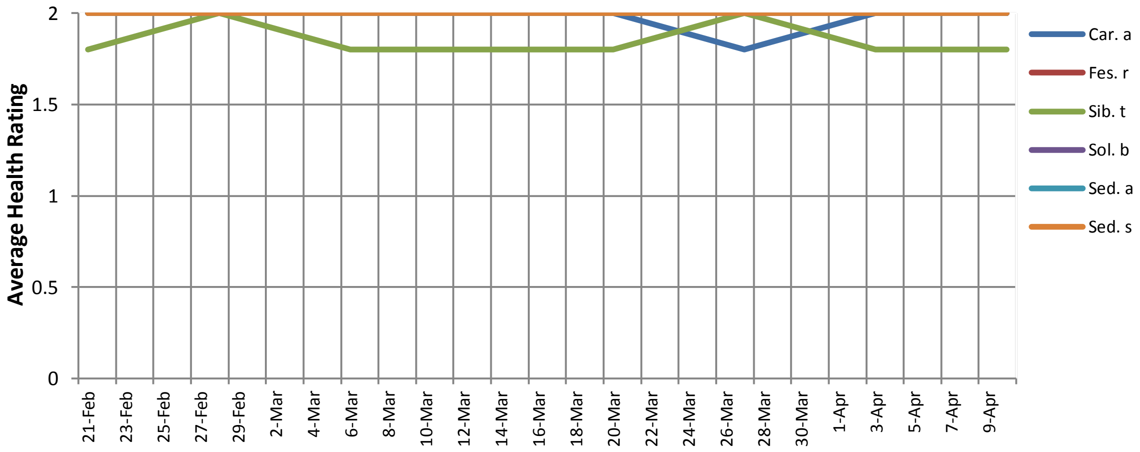

Figure 12. Average health rating throughout the greenhouse trial for all species in the wet 15cm group. The average health rating was measured on a scale of 0-2 as follows: 0 (dead leaves, brown stems), 1 (mostly dead leaves, green stem) and 2 (green leaves, green stem) (Butler and Orians, 2011).

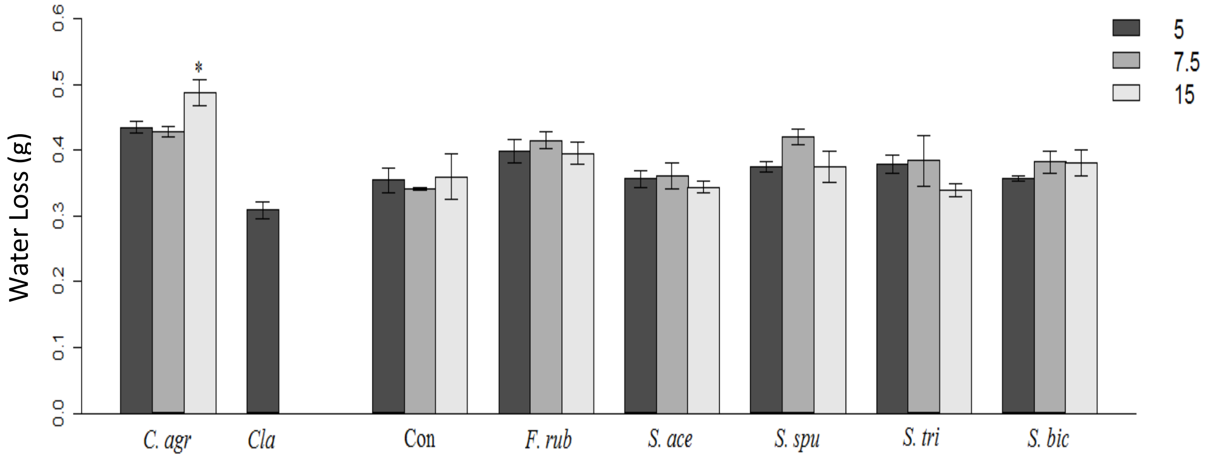

Figure 13. Water loss, determined by the difference in weight before and after watering for the wet treatments throughout the trial. The difference in weight was associated with the amount of water used by that plant for evaporation and transpiration (Wolf and Lundholm, 2008). The * indicates that the group was significantly different from the control.

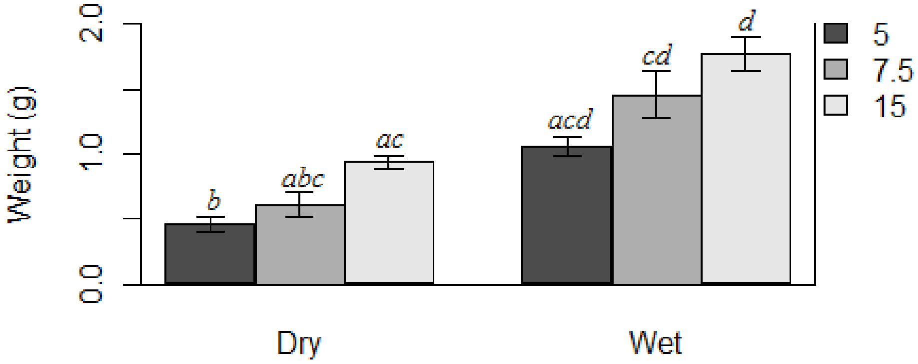

Figure 14. Average dry shoot weights for each treatment of *C. argyranthra.* The bars that share the same letter are not significantly different.

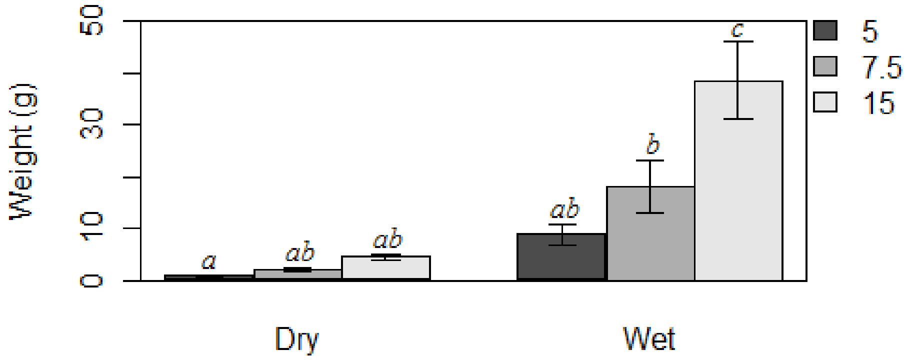

Figure 15. Average dry root weights for each treatment of *C. argyranthra.* The bars that share the same letter are not significantly different.

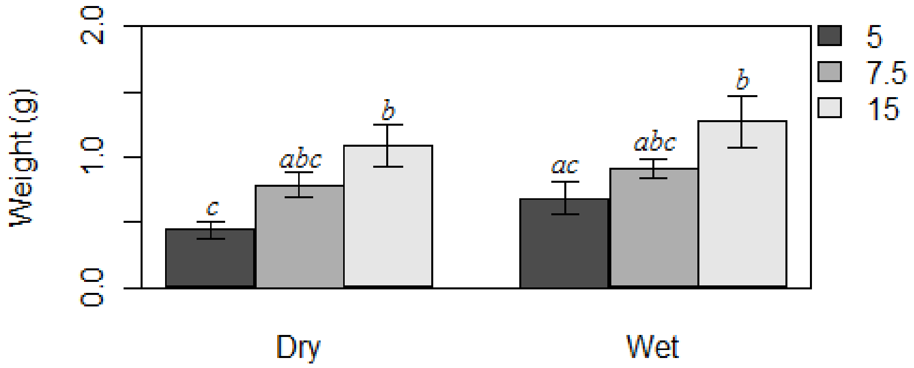

Figure 16. Average dry shoot weights for each treatment of *F. rubra*. The bars that share the same letter are not significantly different.

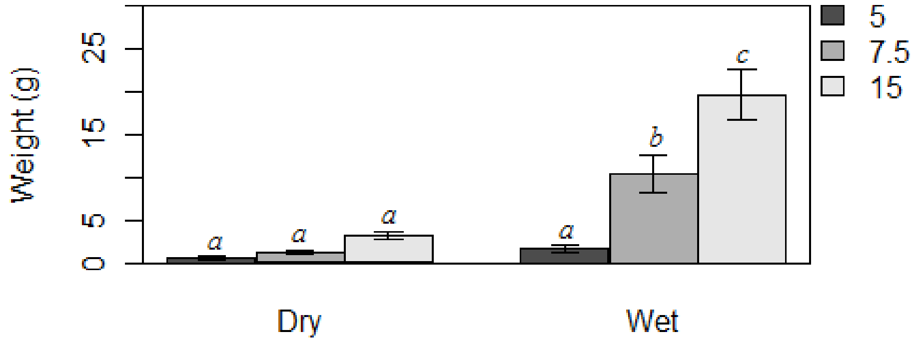

Figure 17. Average dry root weights for each treatment of *F. rubra*. The bars that share the same letter are not significantly different.

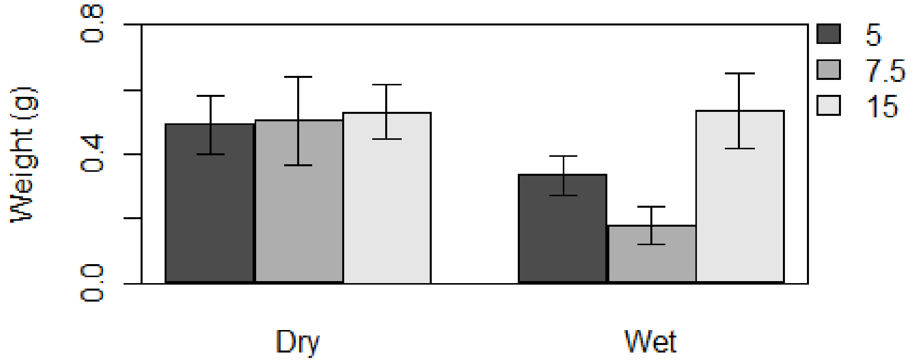

Figure 18. Average dry shoot weights for each treatment of *S. bicolor*. The bars that share the same letter are not significantly different.

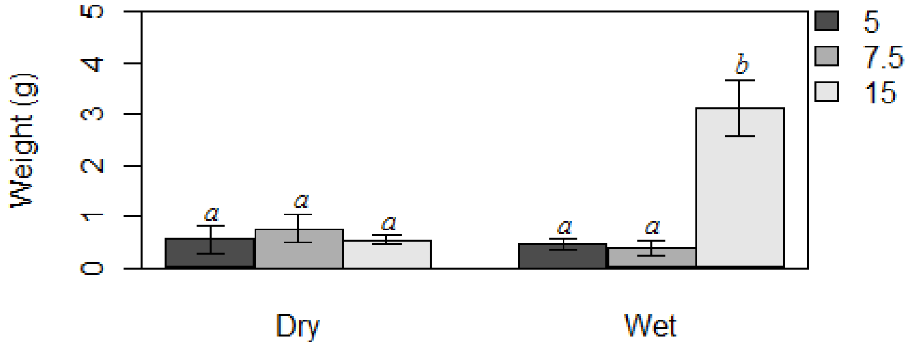

Figure 19. Average dry root weights for each treatment of *S. bicolor*. The bars that share the same letter are not significantly different.

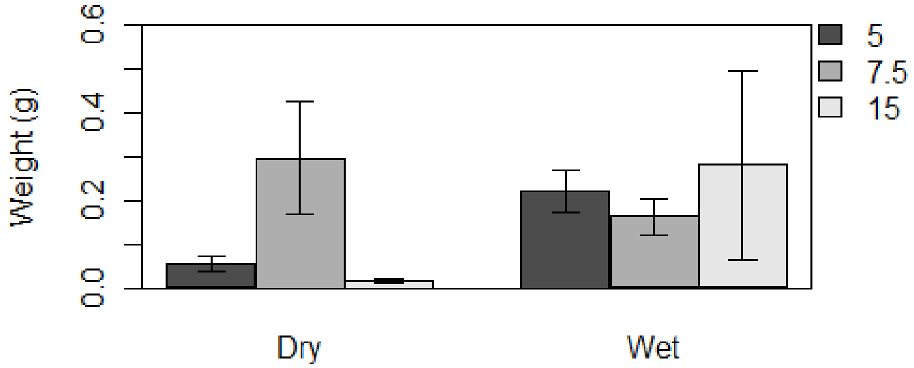

Figure 20. Average dry shoot weights for each treatment of *S. tridentata*. The bars that share the same letter are not significantly different.

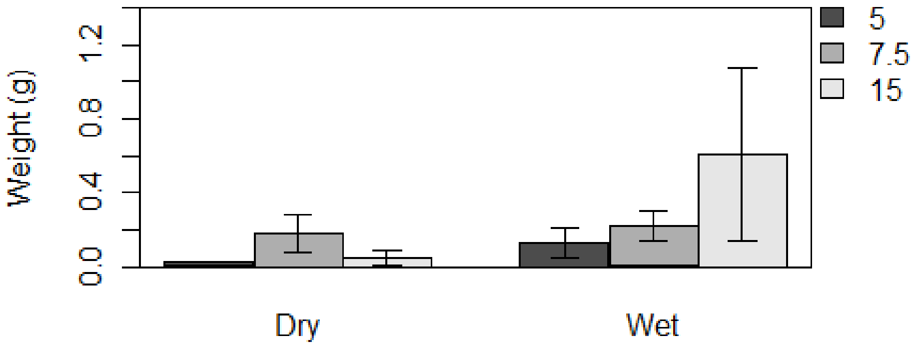

Figure 21. Average dry root weights for each treatment of *S. tridentata*. The bars that share the same letter are not significantly different.

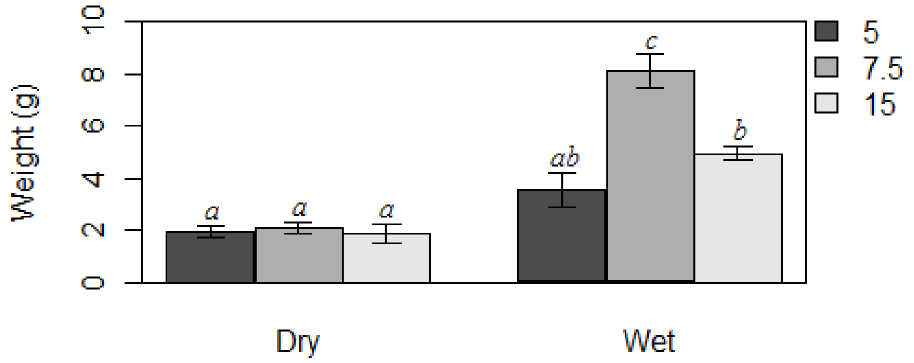

Figure 22. Average dry shoot weights for each treatment of *S. acre*. The bars that share the same letter are not significantly different.

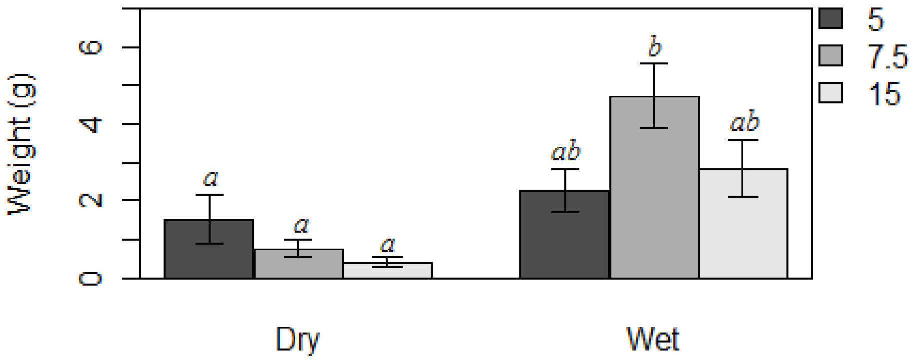

Figure 23. Average dry root weights for each treatment of *S. acre*. The bars that share the same letter are not significantly different.

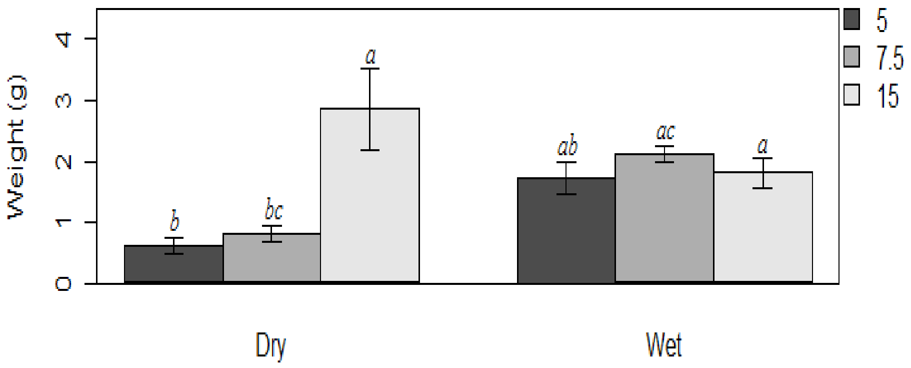

Figure 24. Average dry shoot weights for each treatment of *S. spurium.* The bars that share the same letter are not significantly different.

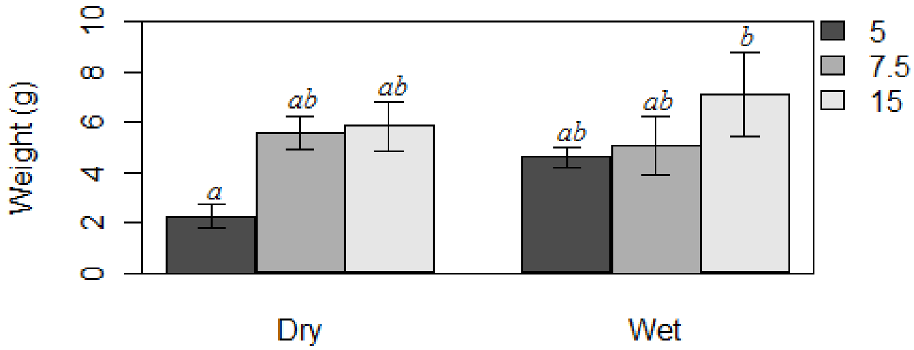

Figure 25. Average dry root weights for each treatment of *S. spurium.* The bars that share the same letter are not significantly different.

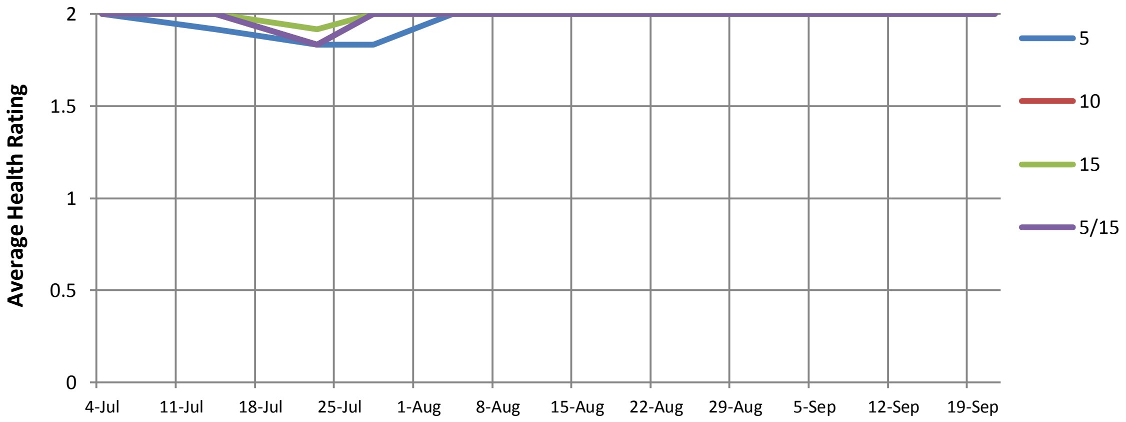

Figure 26. Health ratings for *S. acre* from the soil depth heterogeneity experiment for all treatments for the 2012 growing season. The average health rating was measured on a scale of 0-2 as follows: 0 (dead leaves, brown stems), 1 (mostly dead leaves, green stem) and 2 (green leaves, green stem) (Butler and Orians, 2011).

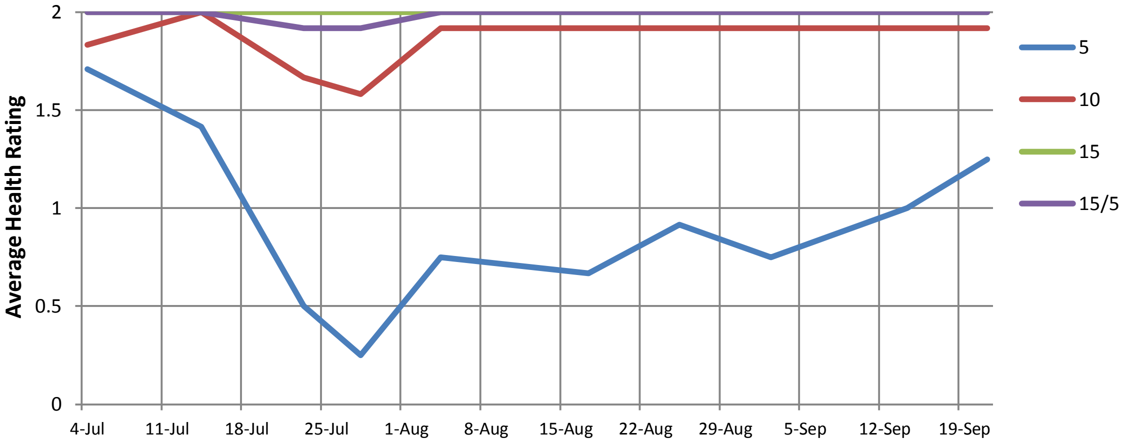

Figure 27. Health ratings for *F. rubra* from the soil depth heterogeneity experiment for all treatments for the 2012 growing season. The average health rating was measured on a scale of 0-2 as follows: 0 (dead leaves, brown stems), 1 (mostly dead leaves, green stem) and 2 (green leaves, green stem) (Butler and Orians, 2011).

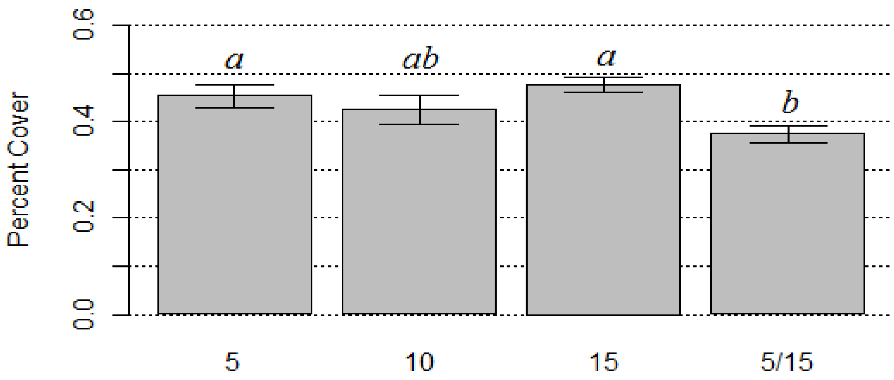

Figure 28. Final average percent cover (converted to decimal) for *S. acre* in the soil depth heterogeneity experiment. The bars that share a letter are not significantly different.

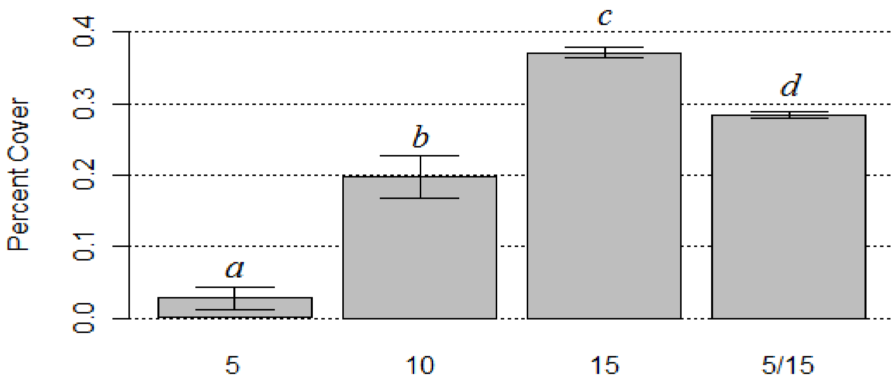

Figure 29. Final average percent cover (converted to decimal) for *F. rubra* in the soil depth heterogeneity experiment. The bars that share a letter are not significantly different.

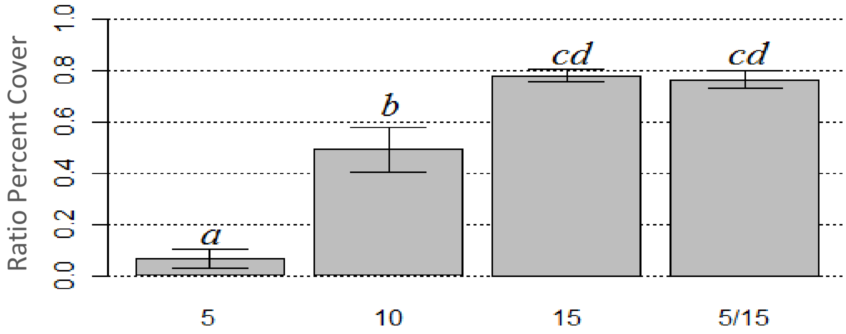

Figure 30. Average ratio of percent cover (converted to decimal) between *S. acre* and *F. rubra* for the soil depth heterogeneity experiment. The ratio was determined by dividing *F. rubra* by *S. acre*. The bars that share a letter are not significantly different.

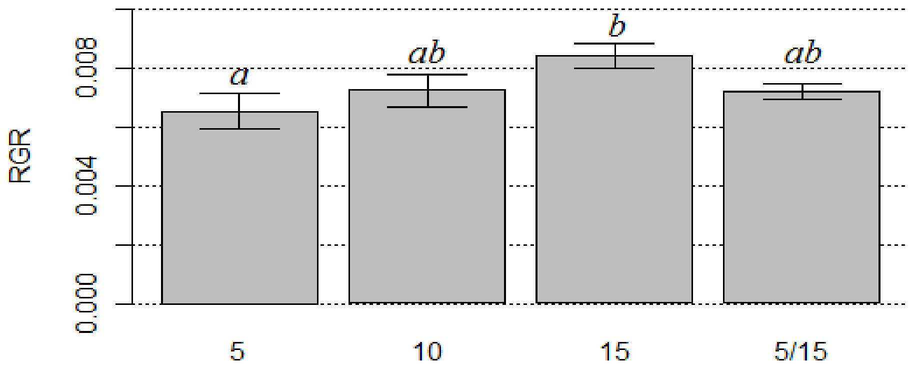

Figure 31. Average RGR for *S. acre* in the soil depth heterogeneity experiment during the 2012 growing season. The bars that share a letter are not significantly different.

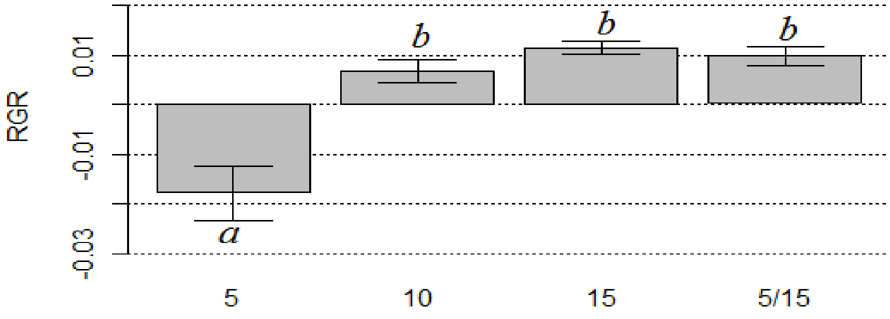

Figure 32. Average RGR for *F. rubra* in the soil depth heterogeneity experiment during the 2012 growing season. The bars that share a letter are not significantly different.

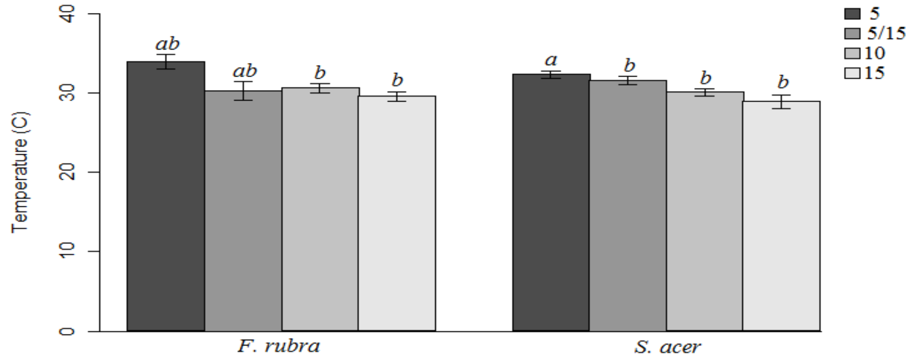

Figure 33. Average temperature (°C) for *F. rubra* and *S. acre* on July 1, 2012 for each treatment in the soil depth heterogeneity experiment. The bars that share a letter are not significantly different.

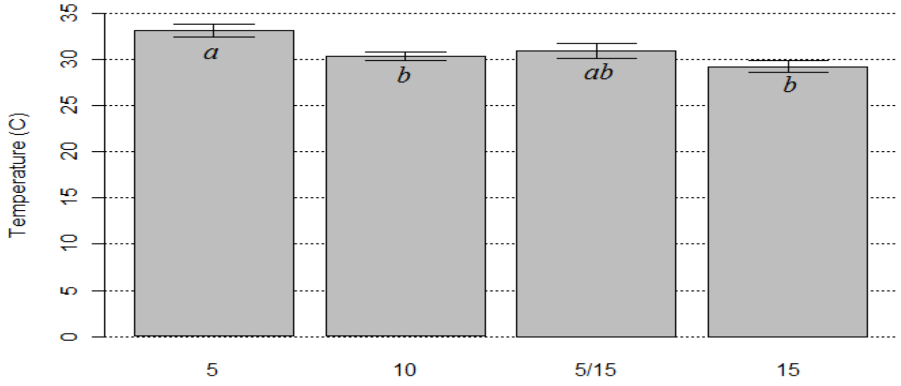

Figure 34. Average temperature (°C), for the soil depth heterogeneity experiment, for each depth treatment recorded on July 1, 2012. The bars that share a letter are not significantly different.

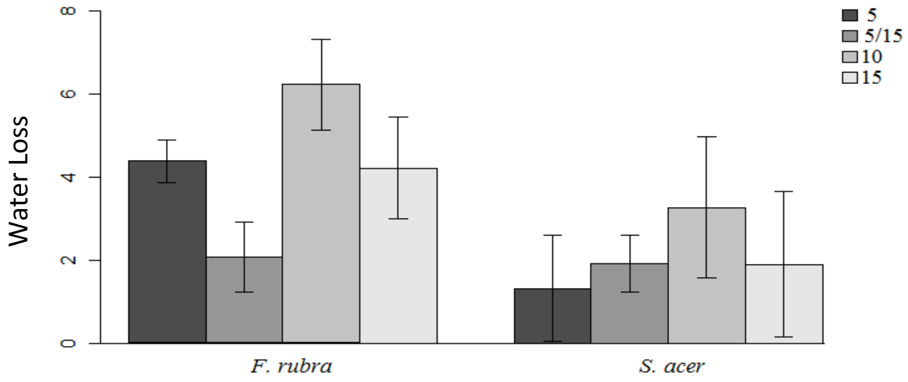

Figure 35. Water loss determined by the average difference in VWC (%), between September 11 and September 12, 2012, for each species in each treatment for the soil depth heterogeneity experiment. 61mm of rainfall was recorded on September 10, 2012, with no rainfall recorded for September 11 or September 12, 2012. No treatment was significantly different from any other treatment.

CHAPTER 3

THE ROLE MAT-FORMING SPECIES CAN PLAY IN INTERSPECIES FACILITATION ON THE EXTENSIVE GREEN ROOF

Abstract

Interspecific facilitation could be used to increase the number of plant species that can survive on an extensive green roof. Previous research has demonstrated that mat-forming, drought tolerant *Sedum* are able to facilitate the growth of neighbouring species. Three drought tolerant, mat-forming species native to Nova Scotia tested here include a bunch-grass, a moss and a lichen. These species were grown surrounding *S. bicolor* target plants to determine if a facilitative effect was present. Overall, the moss treatment showed the greatest growth of the target plant when compared to the control, suggesting that a facilitative effect was operating. The lichen had a neutral effect on the growth of *S. bicolor*, however this treatment had the coolest soil temperature and the greatest volumetric water content, indicating that it could act as a facilitator for *S. bicolor* as well as other species. The bunch-grass acted as a competitor with *S. bicolor* and should not be used as a facilitator. Overall, mosses (and possibly lichens) could be used to facilitate the growth of neighbouring vascular plant species on an extensive green roof.

Keywords: Interspecies facilitation, mosses, lichen, bunch-grass, extensive green roofs

Introduction

Over the past 10 years, the use of green roofs for environmental and ornamental purposes has become more prominent in North America. This trend can be attributed to the green roof's ability to mitigate the effects of urbanization, which include higher temperatures, air pollution and storm water runoff. Because the modern green roof industry is young, having originated in Germany at the turn of the 20th century (DeNardo *et al.,* 2005; Oberndorfer *et al.,* 2007; Thuring *et al.,* 2010), there are still unanswered questions about the role of vegetation on a green roof. This is particularly true in North America, which has only recently begun the development of green architecture (Oberndorfer *et al.,* 2007).

A green roof is composed of several different layers, including a waterproof membrane, substrate and a vegetation layer (Molineux *et al.,* 2009; Castleton *et al.,* 2010). The way a green roof is constructed affects the potential benefits that the roof has to offer (Simmons *et al.,* 2008; Olly *et al.,* 2011). This is particularly true for the depth of the substrate and the type of vegetation. For example, a roof with a deeper substrate and a shallow slope can hold more moisture and nutrients then a roof with a shallow substrate and steep slope (Getter *et al.,* 2007; Olly *et al.,* 2011). Due to weight restrictions, many consumers are interested in extensive green roofs, which have a substrate layer of less than 20cm (Carter and Butler, 2008; Castleton *et al.,* 2010; Olly *et al.,* 2011). Unfortunately, the type of vegetation that can survive at this depth is limited and the majority of extensive green roofs are planted solely with species of *Sedum* (MacIvor and Lundholm, 2011).

The lack of diversity on green roofs can also be attributed to harsh rooftop conditions, such as drought, extreme temperatures, high winds and direct sunlight (Oberndorfer *et al.,* 2007). The species that can subsist in this type of environment tend to have particular characteristics that have evolved to allow photosynthesis (Nagase and Dunnett, 2010). There are 3 photosynthetic pathways: C3, C4 and CAM (crassulacean acid metabolism). The majority of terrestrial vegetation uses the C3 photosynthetic pathway. However, generally due to arid conditions, some plants have adapted to use C4 or CAM photosynthesis (Nagase and Dunnett, 2010).

In order to photosynthesize, plants need access to both sunlight and water. They have evolved to maximize photosynthesis in their native environment. In arid conditions, these characteristics include a low, compact or matted growth form with evergreen, succulent or tough and twiggy foliage (Oberndorfer *et al.*, 2007). The shape of a leaf can also affect a plants interaction with water. Flat, waxy and/or dense leaves can cause water to adhere to the plant surface and hairy leaves are able to catch more water than needle-like leaves (Nagase and Dunnett, 2010). The size of a leaf influences leaf conductivity. Smaller leaves result in high internal negative pressure, increasing a plants ability to extract water, which in turn lengthens the duration of photosynthesis by allowing the plant to keep its stomata open longer. These adaptions can be beneficial during drought, but there is a price: leaves with greater defenses against drought are more costly and take longer to make the same photosynthate "profit" as cheaper leaves (Orians and Solbrig, 1977).

Due to the negative effects associated with monocultures, such as disease and predation, the use of plant diversity on a green roof could be beneficial to the overall system. It would also increase the design options available to the consumer through different vegetation profiles (MacIvor and Lundholm, 2011). One method that could increase species diversity is interspecific facilitation. In nature, facilitative interactions exist and have been associated with increased survival and plant growth. Facilitation can be defined as a net positive association between plant species such that components of individual fitness are higher when a neighbouring plant is present and lower when the neighbour is absent (Callaway and Walker, 1997). One of the first papers on facilitation was by Turner *et al.* (1966), describing the life of *Carnegiea gigantea* seedlings, which rely on shade from neighbouring nurse plants to survive in the arid environment. Positive associations between moss and liverwort species have also been recorded. During drought, improved performance is observed when they are grown together, possibly due to increased humidity. In the arctic, mosses with different water capture methods can be found growing together and, during a short drought, greater biomass is observed in the mixtures when compared with the monocultures (Rixen and Mulder, 2005). Plants that facilitate each other can also act as competitors. In general, plants will facilitate each other during unfavorable conditions and compete with each other during favorable conditions (Callaway and Walker, 1997). In the case of the *C. gigantea* seedlings, once they become established they will compete for resources with their former nurse plant (Butler and Orians, 2011). Intermixed moss species may facilitate each other during drought, but during favorable conditions they compete for light (Rixen and Mulder, 2005). In some ways, competition can also facilitate plant growth in arid conditions. Since plants influenced by competition tend to be smaller, they are more resilient to drought (Armas *et al.*, 2004; Butler and Orians, 2011).

There are current efforts, through incentives and policies, to conserve native species and many organizations support the use of native species on green roofs (Butler and Orians, 2011; MacIvor and Lundholm, 2011). The type of native plants used should be taken from local areas that exhibit similar conditions to the roof, such as dry grasslands, rock outcrops or coastal barrens (Lundholm, 2006; Oberndorfer *et al.,* 2007). Some research has shown that certain native species can even perform equal to or better than commonly used non-native plants (Lundholm *et al.,* 2010). For those consumers who wish to use native species on the green roof, interspecies facilitation is one method that may support native growth. In Nova Scotia, the coastal barrens are a natural area that reflects the conditions of an extensive green roof and native species found here could survive in the harsh rooftop conditions.

Forbs tend to be less drought tolerant than graminoids and succulents, therefore surrounding them with drought tolerant vegetation could lead to interspecies facilitation. This was demonstrated by Butler and Orians (2011), who surrounded the forb species *Agastache rupestris* and *Asclepias verticillata* with species of *Sedum*. They found that during favorable conditions competition was present. However, during times of drought, the *Sedum* facilitated the growth of *A. rupestris* and *A. verticilla*. This facilitative effect could be due to decreased soil temperature and greater water retention (Wolf and Lundholm, 2008; Butler and Orians, 2011). It is possible that other species sharing the matted growth form of *Sedum* could act as facilitators to species of forbs. For example, both greenhouse (Wolf and Lundholm, 2008) and rooftop experiments (Lundholm *et al.*, 2010; MacIvor and Lundholm, 2011) have shown that *Danthonia spicata*, a bunch-grass with a matted growth form native to Nova Scotia, demonstrates low water usage and it can retain more water in the soil than a substrate-only control. This stored water could facilitate the survival of less drought tolerant species. Lichens and mosses may play a similar role. Mosses, in particular, are known to facilitate the growth of vascular plants in harsh ecosystems (Sand-Jensen and Hammer, 2012) and their water-holding capacity is much higher than that of vascular plants (Anderson *et al.*, 2010).

Mosses are known to naturally colonize bare tile or slate roofs (Dunnett and Kingsbury, 2004). Their success on extensive green roofs could be attributed to the low nutrient and water needs shared by many species. They can last an extended time in drought conditions without damage and are capable of rehydration within 20 minutes. Many species are also able to start photosynthesis immediately after rehydration (Anderson *et al.*, 2010; Sand-Jensen and Hammer, 2012).

Lichens are lightweight and can be found growing naturally on bare tile or slate rooftops (Dunnett and Kingsbury, 2004). This could make them a candidate for roofs with low weight capabilities. One group of lichen with possible applications on green roofs is *Cladonia*, many species of which grow on friable soils such as sand or clay. These lichens produce bundles of hyphae which stabilize the soil and add both organic matter and fixed nitrogen. The light color of the lichen can reflect heat, keeping the soil cool and moist (Brodo *et al.*, 2001). However, these species would not be able to tolerate rooftops in areas with high air pollution, decreasing their consumer availability. The use of lichens for extensive green roofs has not been widely studied. However, the characteristics shared by many lichen species make them a possible candidate for establishment on extensive green roofs. They can be found from the arctic to deserts and can survive frequent cycles of desiccation and rehydration, low nutrients and fluctuating temperatures. They can survive and grow on the bare surface of rocks and in poor soils such as heathlands, peat lands, sand dunes and toxic spoil heaps (Seymour *et al.*, 2005).

The Objectives of this study included:

1. Determine if bunch-grasses, lichens or mosses can facilitate the growth of the target forb species.
2. Determine what attributes of the facilitators affects the growth of the target species.
3. Determine whether species mixtures can perform hydrological and thermal functions better than a monoculture.

Methods

The study site was located on the roof of the five-story Atrium building at Saint Mary's University in Halifax, Nova Scotia, Canada (44°39'N, 63°35'W (MacIvor, 2010)). The experiment was separated into two blocks. Block 1 was located on the west side of the Atrium roof and block 2 on the east side. Block 1 was surrounded by three buildings up to two stories higher than the roof. It was also exposed to an air vent which released exhaust near the modules. Block 2 was unsheltered (Figure 1). The Atrium roof contained three additional experiments during the study period (June-September 2012), with vegetation consisting of forbs, graminoids, *Sedum* and mosses. During the study period, the weather station on the lower green roof testing facility (~50m away from study site) recorded the minimum monthly temperature as 6.7 - 20.7°C and the monthly maximum as 12- 30°C (Figure 2). The monthly precipitation recorded from the green roof weather station averaged between 1.7 and 11.59mm (Figure 3).

Facilitation Study

This experiment was conducted in 60 green roof modules. Each module had a length and width of 36cm, a free-draining base (Polyflat®, Stuewe & Sons Inc., Oregon, United States) over which a root barrier/water retention fleece (length and width 36cm) was placed (EnkaRetain and Drain 3111®, Colbond Inc., North Carolina, United States). These modules contained 7.5cm of Sopraflor X substrate purchased in 2011 (Soprema Inc., Drummondville, Quebec, Canada). Sopraflor X consisted of crushed brick, blond peat, perlite, sand and vegetable compost with a total porosity between 60-70% and a bulk density between 1150-1250kg/m³. A soil test conducted by Nova Scotia Agriculture provided a detailed description of the elements present in the substrate at the time of planting (Appendix 2).

There were a total of six different planting regimes with 10 modules for all treatments except for the easter grass treatment, which only had 5 replicates. The control for this study consisted of a single *Solidago bicolor* plant surrounded by substrate alone. The neighbour treatments included a conspecific neighbour (*S. bicolor* surrounded by 8 *S. bicolor, ~6cm apart)* and four heterospecific neighbours (*S. bicolor* surrounded by *Cladonia*, *Polytrichum commune*, *Danthonia spicata or* easter grass). Each of the heterospecific neighbour treatments created a closed ring around the target *S. bicolor.* The ring was approximately 6cm - 8cm in height and 8cm wide (~3cm from the stem of the target plant), covering 60-70% of the substrate in each module (Figure 4). Before planting, this target plant was washed, patted dry and weighed. A variety of weights were included in each treatment. A 1-way ANOVA was performed which determined that there was not a significant difference between the initial weights for all treatments (Appendix 3). This species was chosen due to its poor performance during drought (Chapter 2) and a prediction that it could be facilitated by other species. For the conspecific neighbours, 1 plant was placed in each corner and between each corner plant. The *P. commune* and *D. spicata* neighbours were planted densely in the substrate around the target *S. bicolor*. The easter grass and *Cladonia* treatments were placed on the soil surface surrounding the target *S. bicolor* so that no gaps were observed in the neighbouring ring. The species of *Cladonia* used included *C. terranova* and *C. boryi*, both of which share a similar growth form. The easter grass treatment contained a fake plant composed of a metallic crinkle made from the plastic polyethylene terephthalate (Celebrate It, Bent Branch Drive, Irving, TX, USA) enclosed in plastic mesh bags and held down with three small stakes (Butler and Orians, 2009). The purpose of the fake plant was to determine the effect that shading the soil could have on *S. bicolor* without the presence of competition and water uptake by plant roots. *Cladonia*, *P. commune* and *D. spicata* were chosen due to their matted growth form which may be able to cool the soil and prevent evaporative loss of moisture from the soil surface. The species used were all indigenous to Nova Scotia and were collected in May 2013 from the coastal barrens at Chebucto Head in Nova Scotia (~25km southeast of Halifax (MacIvor, 2010)), areas owned by Saint Mary's University or from previous green roof modules used at the university (Table 1). After collection the plants were transplanted into their respective modules.

Modules were planted on May 15, 2012 and the initial data was recorded on June 11, 2012. The modules were watered once a week during this timeframe to encourage establishment. Before planting, each target *S. bicolor* was weighed and a variety of weights were included in each treatment. A 1-way ANOVA was performed which determined that there was not a significant difference between the initial weights for all treatments.

Lichen Trial

In order to understand how *Cladonia* could affect the substrate on a green roof, a separate trial was set up to determine the effects that *Cladonia* could have on soil temperature and water loss. 10 green roof modules were placed on the Atrium roof facing block 2. Each module had a length and width of 36cm with a freely-draining base (Polyflat®, Stuewe & Sons Inc., Oregon, United States). They contained a root barrier/water retention fleece (length and width 36cm) over the base (EnkaRetain and Drain 3111®, Colbond Inc., North Carolina, United States) with 6cm depth of Sopraflor X substrate, purchased in 2011 (Soprema Inc., Drummondville, QC, Canada) over the root barrier/water retention layer. This experiment consisted of two substrate-only controls and eight modules covered 100% in *Cladonia* lichen approximately 6cm thick. The lichen was collected from a coastal barrens site (Chebucto Head) in May 2012 and placed on the surface of the substrate (Figure 5 Table 2). Lichen species used were a mix of *Cladonia* (*C. terranova and C. boryi*) both of which have similar colors and heights.

Substrate Temperature and Volumetric Water Content (VWC)

The temperature (in °C) was recorded using a Taylor 9878 Slim-Line Pocket Thermometer Probe (Commercial Solutions Inc., Edmonton, Alberta, Canada) once a month throughout the growing season. The temperature was recorded from the center of each module adjacent to the target species approximately 2cm below the substrate surface when exposed to full sun, no more than two hours before or after solar noon. Only one measurement was recorded for each module on the day they were tested. The VWC (%) was recorded one day after a rain event and again one to four days later if no new showers were observed. Water loss was determined by the VWC on day one minus the VWC on day two or four. Measurements were taken once at the end of August and again in early September. The VWC was measured by using the ProCheck and a GS3 soil moisture sensor inserted into the center of each module adjacent to the target species (Decagon Devices Inc., Pullman, Washington, United States).

Plant Growth

Plant growth was determined by measuring plant height, width of the biggest leaf, length of the biggest leaf and by counting the number of leaves for the target *S. bicolor*. This information was gathered weekly, though only the final growth measurements (taken on September 11, 2012) were used in the statistical analysis. Percent cover was determined by photographs taken once every two weeks and measured with ImageJ (Image Processing and Analysis in Java, http://rsbweb.nih.gov/ij/). For each photograph, the area of the target *S. bicolor* was measured and divided by the area of the entire module to give the percent cover. Total capitulescence (flower head) count was recorded for each target *S. bicolor* until no new capitulescence was observed (October 3, 2012). The survival of the target species was based off of a health score on a scale of 0-2 as follows: 0 (dead leaves, brown stems), 1 (mostly dead leaves, green stem) and 2 (green leaves, green stem) (Butler and Orians, 2011).

Statistical Method

Separate 1-way ANOVAs were used to compare height, leaf length, leaf width, number of leaves, number of capitulescence, water loss and substrate temperature between the different treatments. For these tests the treatment and block were the independent variables. A 2-way ANOVA was used to analyze the relative growth rate (RGR) for which the treatment and block were the independent variables. A 2-way ANOVA was also used to analyze the relative interaction index (RII) and the percent cover, for which the treatment, block and initial cover were the independent variables. All residuals were analyzed for homogeneity with Levene's test. The RII was determined by the following formula:

$$[\% \text{ Cover} - \text{Average } \% \text{ Cover of Control}] / [\% \text{ Cover} + \text{Average } \% \text{ Cover of Control}]$$

Here, the controls represent the treatment with a single individual of *S. bicolor*, surrounded by bare soil. Values > 1 indicate a net facilitative effect (higher coverage of the target plant with neighbours included); values < -1 indicate net competitive effects and a value of 0 indicates that the interaction was neutral (Armas *et al.*, 2004). The relative growth rate (RGR) was determined using the percent cover in the following formula (Harper, 1977):

$$[\mathrm{Ln}(T2) - \mathrm{Ln}(T1)] / \# \text{ of days}$$

For the *Cladonia* trial, the temperature and water loss were compared using a Welch 2 sample t-test.

Results

Block Effect

A block effect was observed during the experiment and the affected data included the final percent cover, capitulescence and temperature. For these measurements, there was a significant difference in the final percent cover, capitulescence and temperature for the moss between blocks 1 and 2 (Figures 6, 7 and 8). There was also a significant difference in the temperature of the graminoid treatment between blocks 1 and 2. Block effects were included in the ANOVA models for further analysis, so reported results that follow represent significant effects once block effects are controlled for.

Survival

Except for one treatment of conspecifics, all modules had a 100% survival rate with a health score of 2 throughout the growing season. A *Solidago*-specific rust (*Coleosporium, Puccinia or Uromyces (Moorman, 2013))* was first noted on August 14 and significant leaf death due to the rust was observed after Sept 11, 2012 (Figure 9). Due to this, all analysis except for capitulescence count, which was taken until October 3, concluded on September 11, 2012. The treatments most affected by the rust included the control, *Cladonia* and *P. commune* treatments. The modules affected the least included the *D. spicata* and easter grass treatments (Figure 10).

RII

For the first growing season, all but one of the neighbour types had a negative effect on *S. bicolor*. The *P. commune* treatment (0.07 ± 0.04) was the only treatment that demonstrated a net positive RII and it's RII was significantly greater than all treatments except for the easter grass treatment (-0.08 ± 0.06). The conspecific treatment (-0.54 ± 0.07) had a significantly lower RII than all other treatments except for the *D. spicata* treatment (-0.47 ± 0.05) (Figure 11 and Table 2).

Percent Cover

Compared to the final percent cover (converted to decimal) of the control (0.27 ± 0.02), *Cladonia* (0.19 ± 0.02), *D. spicata* (0.1 ± 0.01) and the conspecific (0.09 ± 0.02) treatments had significantly lower final cover. The greatest percent cover was observed in the *P. commune* treatment (0.32 ± 0.02) (Figure 12). The RGR for the conspecific treatment (0.01 ± 0.006) was the only treatment with a significantly lower RGR. The highest RGR was observed in the easter grass treatment (0.02 ± 0.002) (Figure 13 and Table 2).

S. bicolor Leaves, Height and Capitulescence

For leaf length, the conspecific (7.2cm ± 1.14) and *D. spicata* (7.8cm ± 0.54) treatments had significantly smaller leaf lengths than the control (10.8cm ± 0.54). Only the *P. commune* treatment (12.8cm ± 1.02) had significantly longer leaves than the control (listed above) (Figures 14 and 15). For leaf width, the easter grass treatment (4.35cm ± 0.44) had significantly wider leaves than the control (3.16cm ± 0.21). The treatments for *D. spicata* (1.99cm ± 0.17) and conspecific (2.16cm ± 0.29) had significantly thinner leaves than the control (listed above) (Figures 16 and 17). Compared to the control (84.2 ± 9.05), the treatments for *D. spicata* (56 ± 4.33) and conspecific (38.2 ± 7.12) had significantly fewer leaves (Figure 18 and 19). For plant height, the *P. commune* treatment (19.4cm ± 3.62) had the tallest *S. bicolor* and it was the only treatment significantly greater than the control (14.7cm ± 2.84). The shortest *S. bicolor* was recorded in the conspecific treatment (6.58cm ± 2.32) (Figures 20 and 21). Compared to the control (68.7 ± 32.1), only the *P. commune* (209 ± 75.1) and *D. spicata* (88.4 ± 3 4.6) treatments had significantly greater capitulescence production (Figures 22 and 23).

Temperature and Water Loss

On July 1, 2012 (the hottest day at which soil temperatures (in °C) were recorded) the *Cladonia* (31° ± 0.57) and *P. commune* (33.1° ± 0.97) treatments had significantly lower soil temperatures than the control (36.5°± 0.72). For this day the hottest temperature was recorded in the conspecific treatment (36.8° ± 0.56) (Figure 24). On August 20, 5.1mm of rainfall was recorded, on August 21, 0.1mm of rainfall was recorded and no rainfall was recorded on the 22, 23 or 24 of August. The difference in VWC (%) between August 21(after rainfall) and August 24 was calculated. Compared to the control (3.98 ± 0.47), which had the lowest water loss, there was a significant difference in water loss for the treatments *D. spicata* (6.97 ± 1.16) and conspecific (6.7 ± 0.86) (Figure 25).

Lichen

On July 1, 2012 the soil temperature (°C) of the control (35.90° ± 1.70) was hotter than the *Cladonia* treatment (30.64° ±0.60). However, it was not statistically significant (Figure 26). Between the 21 and 22 of August no rainfall was recorded. The difference in VWC (%) between these two dates was calculated. A greater water loss was recorded for the control (3.35% ± 0.65) compared to the *Cladonia* (1.825% ± 1.13), but it was not statistically significant (Figure 27 Table 4).

Discussion

The block effect that was observed for the final percent cover, capitulescence count and soil temperature indicate that the sheltered conditions in block 1 resulted in higher soil temperature. This temperature increase may have impacted the final percent cover and capitulescence count in the moss modules.

Survival

Since all target plants, except one in a single replicate of the conspecific treatment, survived the growing season, more time is needed to understand how survival in *S. bicolor* might be influenced by these neighbouring species. Differences in growth rate, cover and plant size, however, were evident over a single growing season. The rust that formed at the end of the growing season most likely thrived due to an increase in rainfall during this time period.

Polytrichum commune

The measurements recorded for *P. commune* suggest a net positive or facilitative interaction. This treatment was the only one that recorded a net positive RII, meaning that there was improved performance over the treatment in which an individual *S. bicolor* was grown with no neighbours. The physical growth of *S. bicolor* in this treatment hints at a facilitative effect. The target plants in this group recorded the longest leaves, tallest height and the greatest number of leaves and capitulescences (flower heads). This indicates that this group was able to both establish itself and successfully reproduce, which is beneficial in the green roof context. Interestingly, even though this group performed well in many of the tests and had the greatest final percent cover, it was only third for RGR. Since the RGR was calculated by the percent cover, which did not take height into account, this could have affected the outcome for this species. *P. commune* was the second most effective treatment at reducing soil temperature during hot weather. High soil temperatures can cause fatality to plants (Butler and Orians, 2011). Several studies in different ecosystems also show that mosses can increase moisture availability for vascular plants growing nearby (Casanova-Katny and Cavieres, 2012; Sand-Jensen and Hammer, 2012) but, when the soil was sampled after drying, the *P. commune* neighbour treatment was not significantly different from the no-neighbour control. It is possible that the facilitative effect may come from increased moisture availability, but it is not clear whether this would result in greater moisture levels in the soil for long periods of time. It is difficult to determine what attributes of *P. commune* contributed to this facilitative effect. Compared to the other treatments, it did not have the coolest soil temperatures or the lowest water loss. This suggests that another factor was in play.

Cladonia

For the majority of the growth tests, the *Cladonia* treatment had slightly smaller overall growth than the control. However, it ranked first in terms of RGR. This may be because capitulescence did not form for this treatment until late August and it was the last treatment to flower. Due to this, the *S. bicolor* in this treatment probably put more of its energy into leaf growth than reproduction. The *Cladonia* treatment had the lowest soil temperature and second lowest water loss. This is most likely due to shading and the low water requirements of the lichen. Since the *Cladonia* treatment did not perform notably better than the control in terms of soil temperature and water loss, these factors may not influence facilitation for *S. bicolor*. Overall, the *Cladonia* treatment had a negative RII value and some response variables showed a negative effect on the target plants (Figures 8 and 9) indicating that there may be some negative effects of this species on the target species.

Danthonia spicata

The results from this study suggest that *D. spicata* acts as a competitor to *S. bicolor*. Except for plant height and capitulescence count, this treatment was ranked last in all values for target plant growth. The *D. spicata* treatments had the greatest number of flower stems at the beginning of the growing season, which indicates that the target plants in this treatment used the available resources to focus on reproduction. The smaller leaves and percent cover for this treatment also support this. Although intermediate in terms of soil temperature, this treatment lost the greatest amount of water between August 21 and 24 which indicates that this treatment had the greatest demand for water.

Conspecifics

The conspecific treatment was ranked last for all tests. It was also the only treatment that had a target plant that did not survive the growing season. Due to this, the interaction between the conspecifics and the target *S. bicolor* was most likely competitive. Since these modules were filled with nine of the same plants, they likely shared the same demands in terms of water and nutrients. This was demonstrated through the VWC data, which recorded the conspecifics as the second highest for water loss. This was most likely due to the increased demand for water in these modules. This suggests that the performance of individual plants may be enhanced by planting mixtures instead of monocultures, although *S. bicolor* is the only species for which intraspecific competition has been quantified on a green roof. This treatment also had the hottest average soil temperature which could also have affected the growth of the target plant.

Easter Grass

The purpose of the easter grass was to understand how soil shading could affect *S. bicolor* without the influence of below-ground competition. However, the results from the temperature probe show the easter grass treatment as the second hottest and it was only in the middle of the table for water loss. Since this treatment ranked second for RII and was the only treatment not significantly different from the best performer (*P. commune*), temperature and water loss were probably not the main factors influencing *S. bicolor* growth. The easter grass may have provided protection to the above ground biomass of *S. bicolor,* sheltering it from the air vent in block 1 and the wind in block 2. The width of the leaves and lack of flowering in this treatment indicate energy storage for future growing seasons. It is likely that future growing seasons will show a facilitative effect for this treatment.

Lichen Trial

The lichen trial indicates that *Cladonia* lichen could be a good candidate for facilitating neighbouring species. Compared to the substrate-only control, the *Cladonia* modules were cooler. Since the performance of *S. bicolor*, planted as plugs, was moderate in the *Cladonia* treatment despite cool soil temperatures, it is possible that benefits of facilitation by lichens may depend on the life stage of the plant; seeds planted in the modules and then covered in the lichen mats may benefit the most from *Cladonia.* Vascular plant species growing out of these lichen mats is a natural occurrence on the coastal barrens of Nova Scotia and, during the trial, seedlings of trees and grasses were observed growing out of these modules, so facilitation might occur at seedling stages. However, industrial use of lichens on a green roof is not currently feasible, as the main method for establishment is harvesting it from local ecosystems. In addition to this, lichen species, such as *Cladonia*, are sensitive to air pollution and would perform poorly in many dense urban centers (Brodo *et al.*, 2001).

In this experiment, *P. commune* was the best facilitator for *S. bicolor*. However, more research is necessary to determine the specific influences that *P. commune* had on *S. bicolor* growth. In many aspects, the *Cladonia* treatment demonstrated roughly equivalent performance to the control. This indicates that the growth of *S. bicolor* was not hampered by *Cladonia*. Although not facilitative, these species can coexist together, thereby enhancing the biodiversity and aesthetic value of the roof. The combination would also lead to cooler roof temperatures since the *Cladonia* treatment recorded lower soil temperatures than the control, conspecific and *D. spicata* treatments. Overall, more research is necessary to match the needs of the consumer (storm water reduction, reduced roof temperatures, reduced air pollution and/or aesthetics) to the suitable available vegetation.

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Tables

Table 1. A description of the vegetation used in the study. All species were indigenous to Nova Scotia, Canada. In the collected column, CH = Chebucto Head, SMU = Saint Mary's University and DM = Dartmouth Commons.

Species	**Species Code**	**Growth Form**	**Collected**
Cladonia	*Cla.*	Lichen	CH
Danthonia spicata	*Dan. s*	Bunch-grass	CH
Polytrichum commune	*Pol. c*	Moss	SMU
Solidago bicolor	*Sol. b*	Forb	SMU
Easter Grass	E	Fake Plant	

Table 2. Performance of the target *S. bicolor* for each treatment ranked from Highest (1st) to lowest (6th). The first three refer to the performance of *S. bicolor* target plants. The temperature (°C) was taken on July 1, 2012 and the water loss was determined by the difference in VWC (%) between August 21 and 24, 2012. The data is displayed as the mean ± SE. 5.1mm of rainfall was recorded on August 20, 0.1mm was recorded on August 21 and no rainfall was recorded on August 22, 23 or 24.

	Rank	**Final Cover (0 - 1.0)**	**RGR**	**RII**	**Temp (°C)**	**Water Loss**
Highest	1st	*P. commune* (0.32±0.02)	*Cladonia* (0.02±0.001)	*P. commune* (0.07±0.04)	*S. bicolor* (36.8±0.56)	*D. spicata* (6.97±1.16)
	2nd	Control (0.27±0.02)	Control (0.02±0.002)	Easter Grass (-0.08±0.06)	Easter Grass (36.6±1.33)	*S. bicolor* (6.7±0.86)
	3rd	Easter Grass (0.23±0.03)	*P. commune* (0.02±0.002)	*Cladonia* (-0.19±0.04)	Control (36.5±0.72)	*P. commune* (6.03±1.6)
	4th	*Cladonia* (0.19±0.02)	Easter Grass (0.02±0.002)	*D. spicata* (-0.47±0.05)	*D. spicata* (35.2±1)	Easter Grass (5.7±1.16)
	5th	*D. spicata* (0.1±0.01)	*D. spicata* (0.01±0.002)	*S. bicolor* (-0.54±0.07)	*P. commune* (33.1±0.97)	*Cladonia* (4.08±1.03)
Lowest	6th	*S. bicolor* (0.09±0.02)	*S. bicolor* (0.01±0.006)	Control (NA)	*Cladonia* (31±0.57)	Control (3.98±0.47)

Table 3. Final recorded growth for the target *S. bicolor* by the end of the growing season (September 11, 2012). The final capitulescence count was recorded on October 3, 2012. The highest count or measurement is ranked 1st and the lowest is ranked 6th. The data is displayed as the mean ± SE.

	Rank	Leaf Width	Leaf Length	Leaf Count	Plant height	Capitulescence
Highest	1st	Easter Grass (4.35±0.44)	*P. commune* (12.8±1.02)	*P. commune* (85.6±7.12)	*P. commune* (19.4±3.62)	*P. commune* (209±75.1)
	2nd	Control (3.16±0.21)	Easter Grass (10.9±0.8)	Control (84.2±9.05)	Control (14.7±2.84)	*D. spicata* (88.4±34.6)
	3rd	*P. commune* (3.02±0.22)	Control (10.8±0.54)	*Cladonia.* (79.8±4.99)	*D. spicata* (14.4±3.03)	Control (68.7±32.1)
	4th	*Cladonia* (2.75±0.18)	*Cladonia.* (10.4±0.81)	Easter Grass (76±7.68)	*Cladonia.* (12±1.62)	*Cladonia* (52.6±22.6)
Lowest	5th	*S. bicolor* (2.16±0.29)	*D. spicata* (7.8±0.54)	*D. spicata* (56±4.33)	Easter Grass (7.83±0.82)	Easter Grass (22±22)
	6th	*D. spicata* (1.99±0.17)	*S. bicolor* (7.2±1.14)	*S. bicolor* (38.2±7.12)	*S. bicolor* (6.58±2.32)	*S. bicolor* (21.3±14.3)

Table 4. Average temperature for the lichen trial taken on July 1, 2012 and the water loss determined by the difference in VWC (%) between August 21 and 22, 2012. 5.1mm of rainfall was recorded on August 20, 0.1mm was recorded on August 21 and no rainfall was recorded on August 22 (measurements were taken after the rain event on August 21).

Measurement	**Control**	***Cladonia***
Temperature (°C)	35.9 ± 1.70	30.64 ± 0.60
Water Loss (%)	3.35 ± 0.65	1.825 ± 1.13

Figures

Figure 1. Block design and placement for the facilitation study. Block 1 is on the top left, block 2 is on the top right and the *Cladonia* trial is shown on the bottom left.

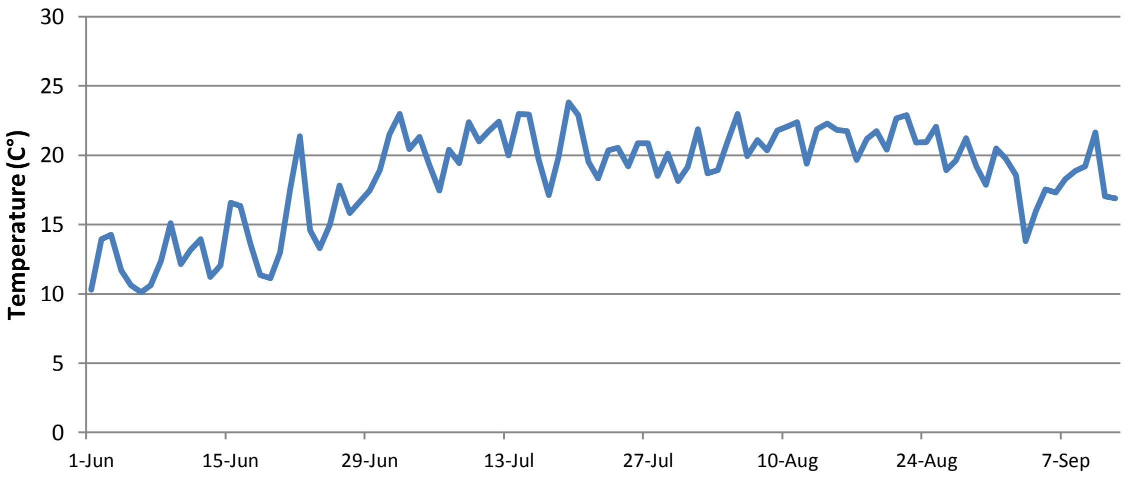

Figure 2. Average daily temperature (°C) throughout the growing season as measured by the green roof testing facility at Saint Mary's University.

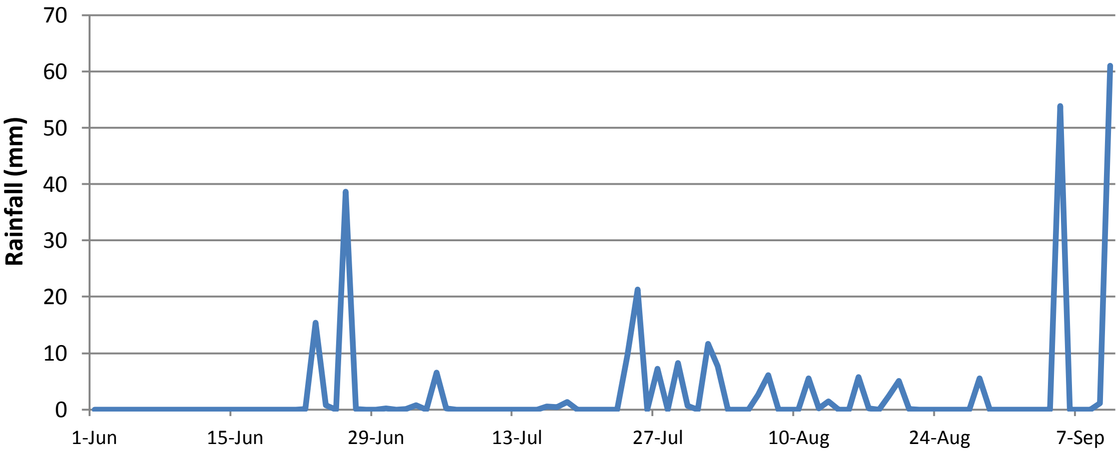

Figure 3. Daily rainfall (mm) throughout the growing season as measured by the green roof testing facility at Saint Mary's University.

Figure 4. The six different treatments used in this study. From top left: *S. bicolor* control, conspecific treatment and the easter grass treatment. From the bottom left: *Cladonia* treatment, *P. commune* treatment and the *D. spicata* treatment.

Figure 5. *Cladonia* module used in the lichen trial.

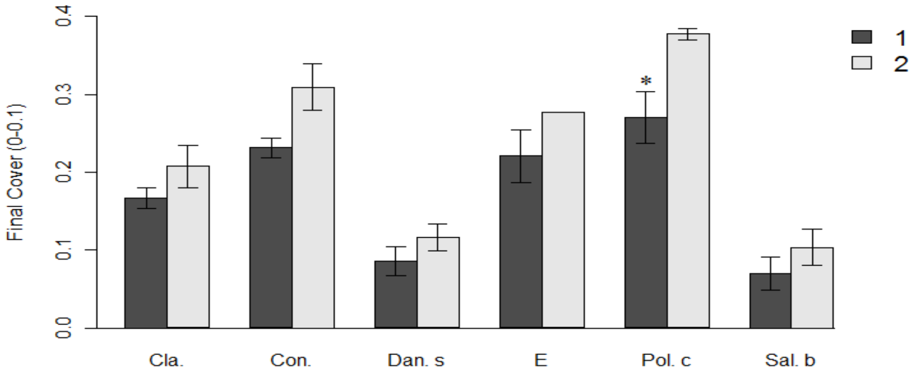

Figure 6. Block effect for the final cover of the target *S. bicolor* (0-1.0) in the facilitation experiment. (*) indicates that block 1 is significantly different from block 2.

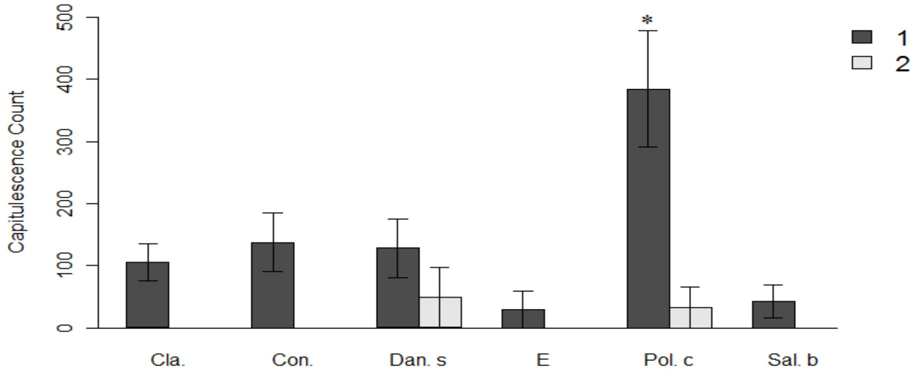

Figure 7. Block effect for the final capitulescence for the target *S. bicolor* in the facilitation experiment. (*) indicates that block 1 is significantly different from block 2.

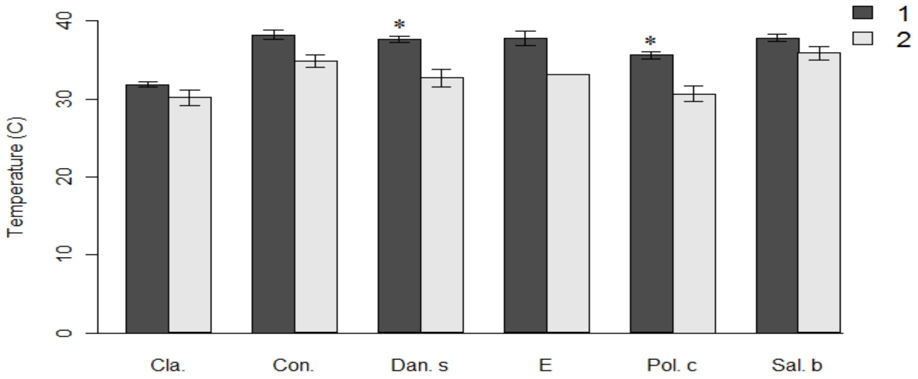

Figure 8. Block effect for the temperature (°C) on July 1, 2012 in the facilitation experiment. (*) indicates that block 1 is significantly different from block 2.

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Figure 9. A *Solidago* specific rust (*Coleosporium*, *Puccinia* or *Uromyces* (Moorman, 2013)) which was first observed on August 11, 2012. The treatments most effected by the rust were the control, *Cladonia* and *P. commune* treatments. However, by September 11, 2012 nearly all modules were infected.

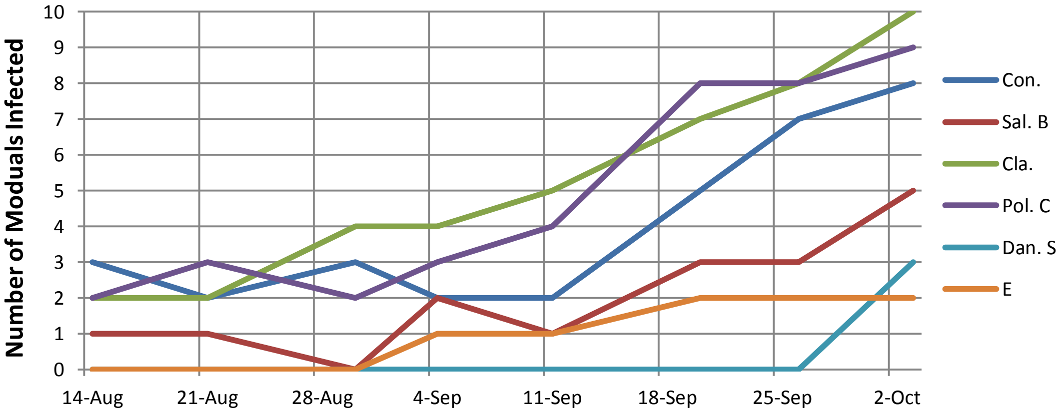

Figure 10. Timeline depicting the rate of rust infection on the modules. There were a total of 10 modules for every treatment except the easter grass (E) treatment which had a total of four modules.

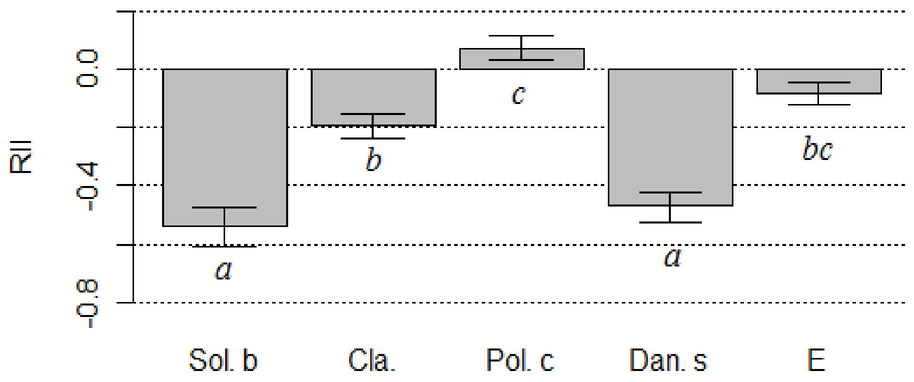

Figure 11. RII of the neighbour treatments as compared to the *S. bicolor* control. All treatments had a neutral effect on *S. bicolor*. RII was calculated using the percent cover of the target *S. bicolor* with the following formula: [% Cover – Average % Cover of Control] / [% Cover + Average % Cover of Control]. Values between 1 and 0 indicate a net facilitative effect, values between -1and 0 indicate net competitive effects and a value of 0 indicates that the interaction was neutral (Armas *et al*., 2004). The bars that share a letter are not significantly different.

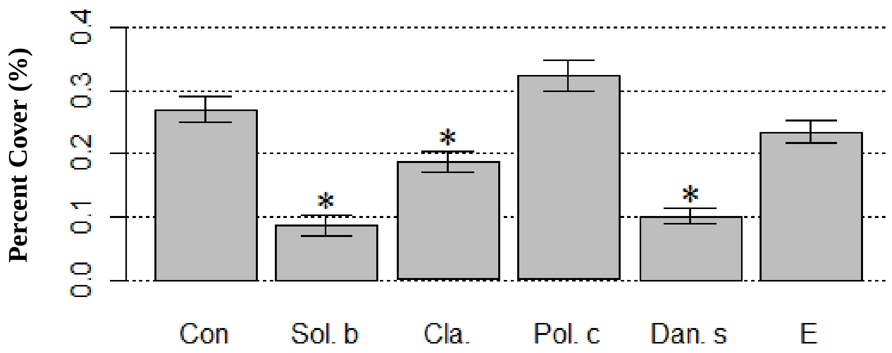

Figure 12. Final percent cover of the target *S. bicolor* (%) by the end of the growing season (September 11, 2012). (*) indicates that the treatment had significantly different final cover from the control.

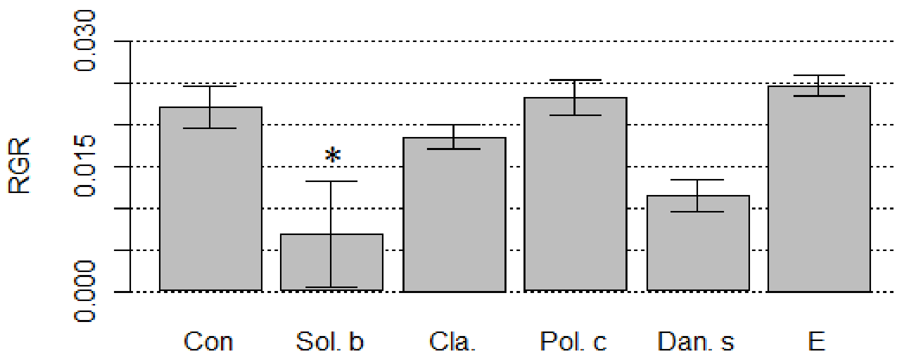

Figure 13. RGR for the target *S. bicolor* for all treatments during the 2012 growing season. (*) indicates that the treatment had a significantly different RGR from the control.

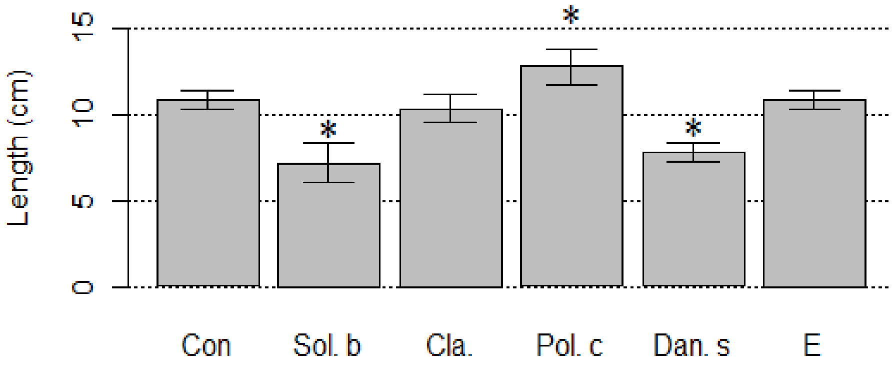

Figure 14. Final leaf length for the target *S. bicolor* by the end of the 2012 growing season. (*) indicates that the treatment had a significantly different leaf length from the control. Measurements were taken from the largest leaf.

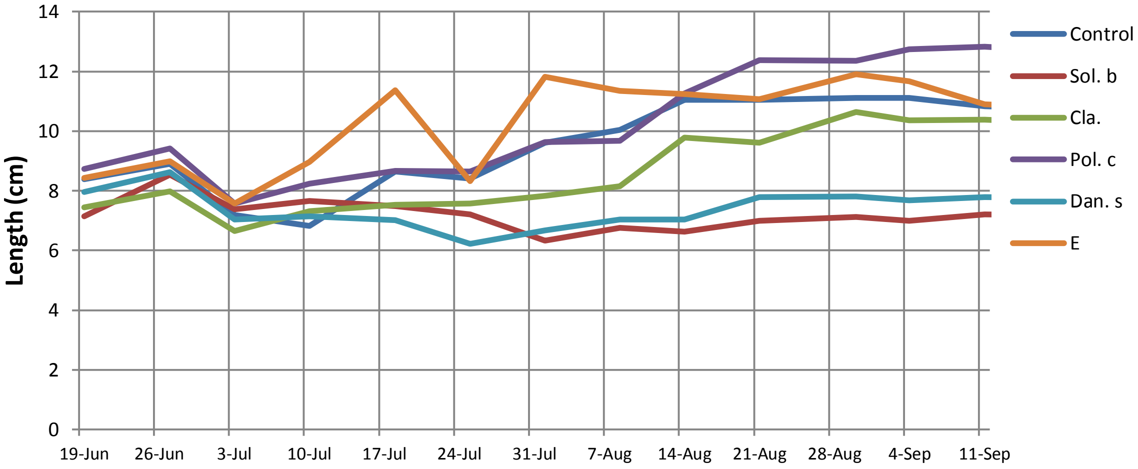

Figure 15. Average leaf length of the target *S. bicolor* for the largest leaf throughout the 2012 growing season.

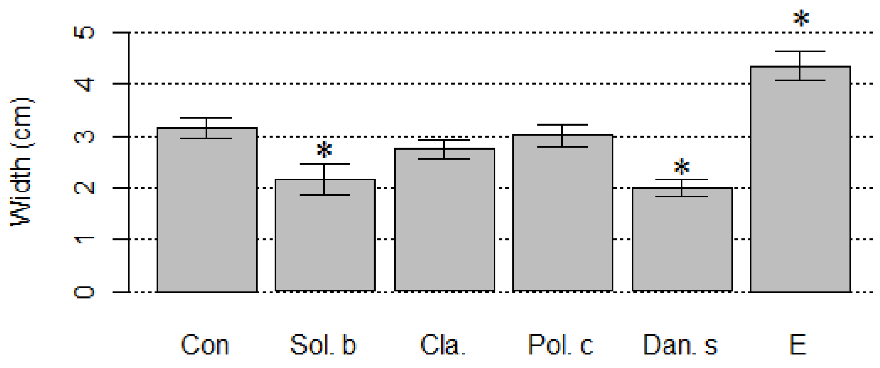

Figure 16. Final leaf width for the target *S. bicolor* by the end of 2012 growing season. (*) indicates that the treatment had a significantly different leaf width from the control. Measurements were taken from the largest leaf.

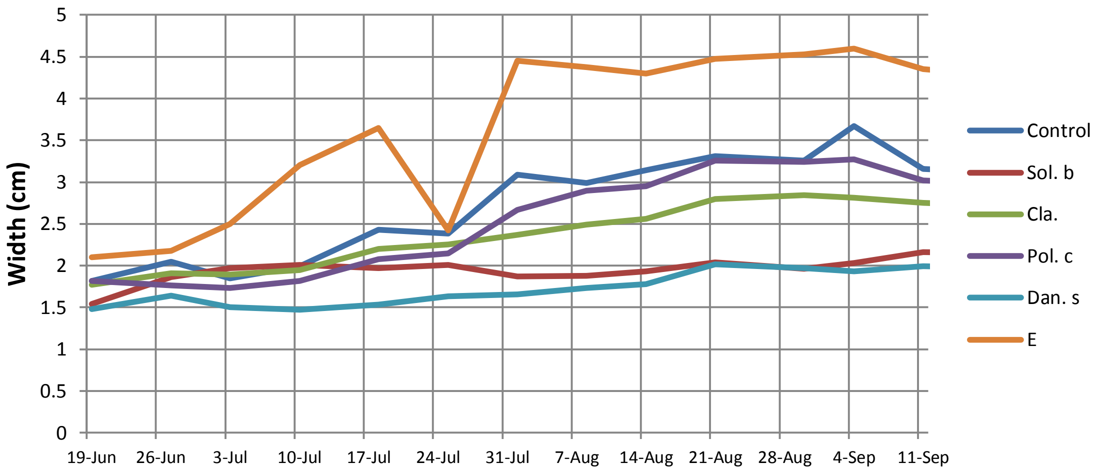

Figure 17. Average leaf width of the target *S. bicolor* for the largest leaf during the 2012 growing season.

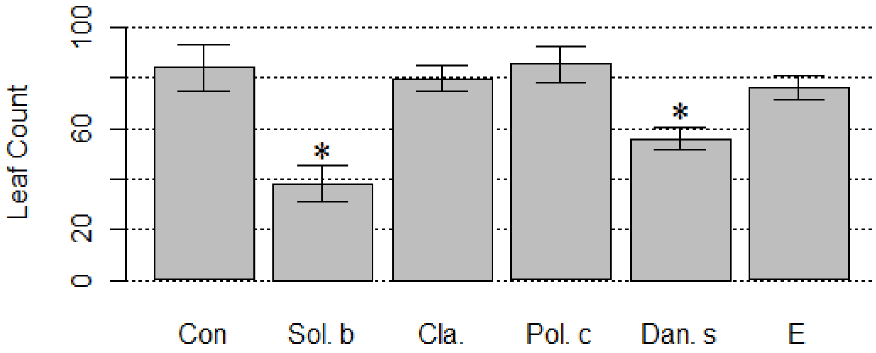

Figure 18. Final leaf count for the target *S. bicolor* by the end of 2012 growing season. (*) indicates that the treatment had a significantly different final leaf count from the control.

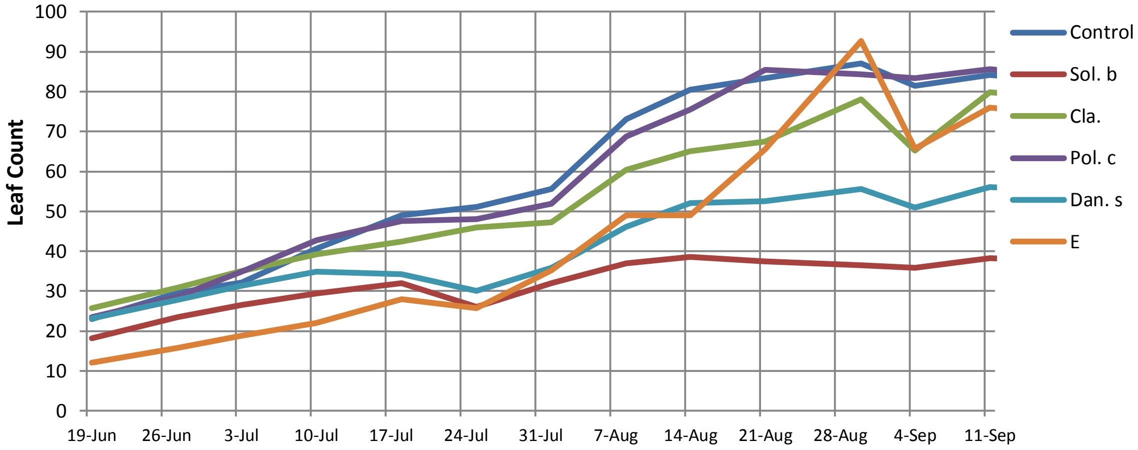

Figure 19. Average leaf count of the target *S. bicolor* for the 2012 growing season.

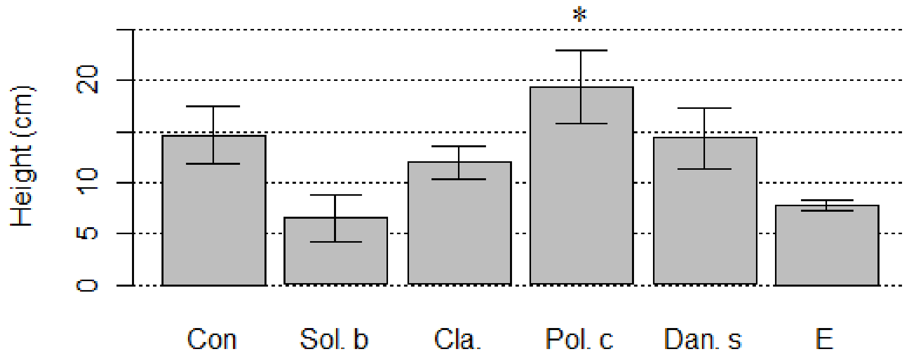

Figure 20. Average height of the target *S. bicolor* in each treatment. (*) indicates that the treatment had a significantly different height from the control.

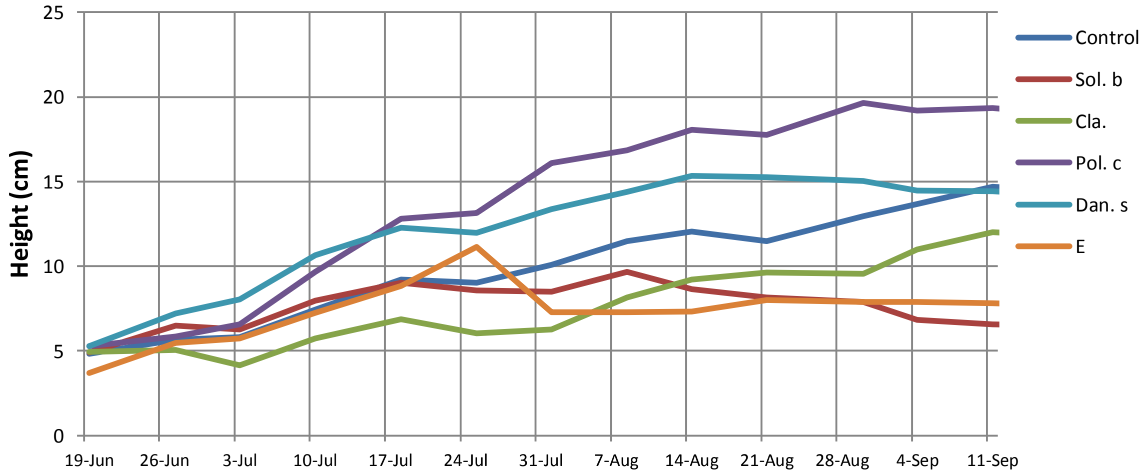

Figure 21. Average height for the target *S. bicolor* throughout the 2012 growing season.

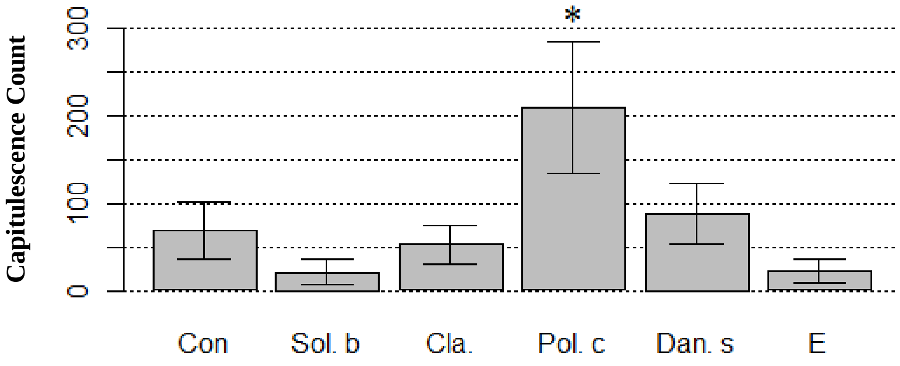

Figure 22. Total capitulescence count for the target *S. bicolor* by the end of the 2012 growing season. (*) indicates that the treatment had a significantly different final capitulescence count from the control.

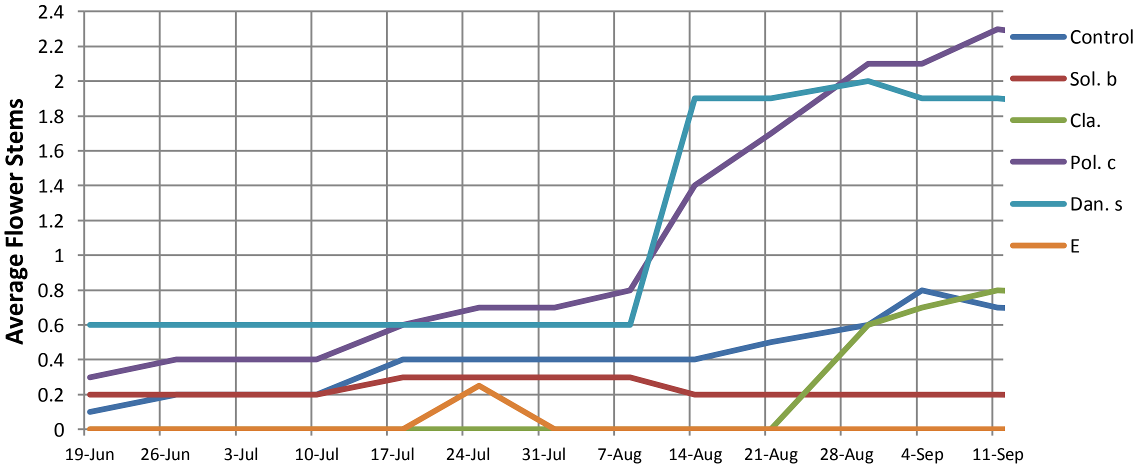

Figure 23. Average number of flower stems of the target *S. bicolor* for the 2012 growing season.

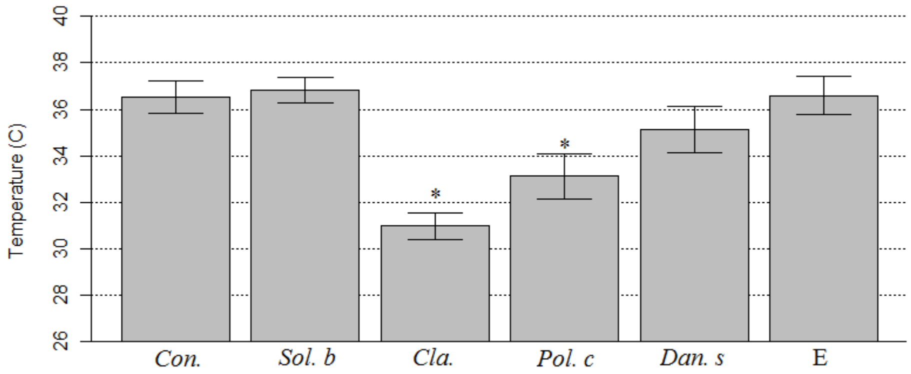

Figure 24. Average temperature (°C) per treatment on July 1, 2012. (*) indicates that the treatment had a significantly different temperature from the control.

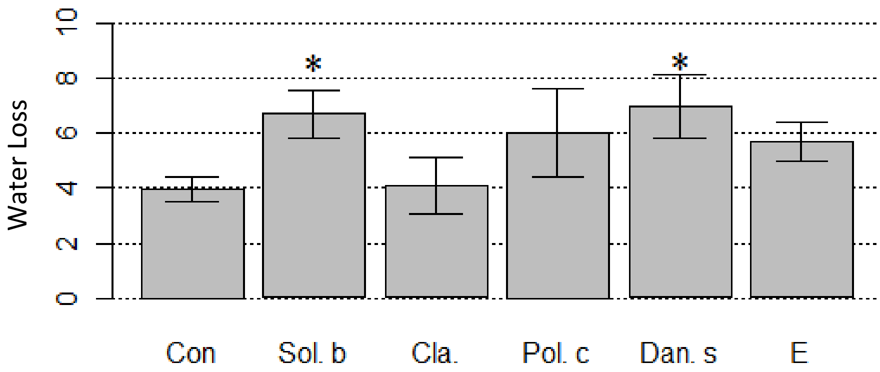

Figure 25. Water loss determined by the difference in soil VWC (%) per treatment for August 21 and 24, 2012. 5.1mm of rainfall was recorded on August 20, 0.1mm was recorded on August 21 and no rainfall was recorded on the 22, 23 or 24 of August. Measurements were recorded after the rain event on August 21, 2012. (*) indicates that the treatment had a significantly different water loss from the control.

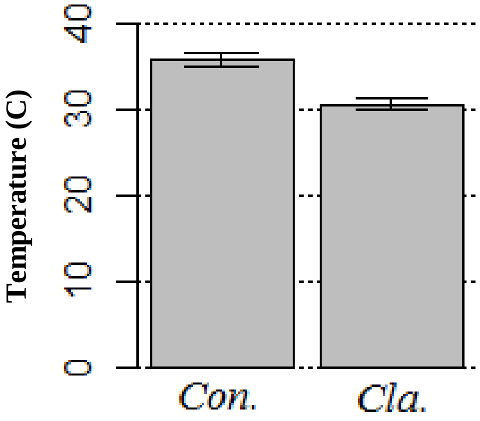

Figure 26. Average soil temperature (°C) on July 1, 2012 for the lichen trial.

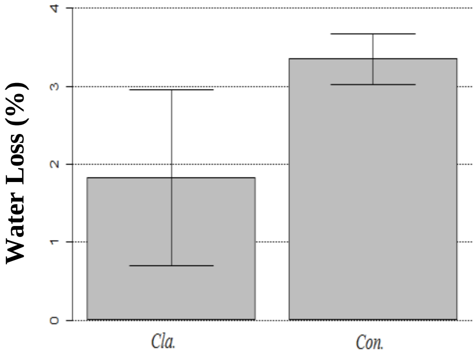

Figure 27. Water loss determined by the difference in soil VWC (%) for the lichen trial taken on August 21 and August 22, 2012. 5.1mm of rainfall was recorded on August 20, 0.1mm was recorded on August 21 and no rainfall was recorded on August 22. Measurements were recorded after the rain event on August 21, 2012.

CHAPTER 4

THE IMPACT OF MOSSES ON THE GROWTH OF NEIGHBOURING VASCULAR PLANTS, SOIL TEMPERATURE AND WATER LOSS ON AN EXTENSIVE GREEN ROOF

Abstract

Green roofs have been associated with many benefits including a reduction in urban temperatures and reduced storm water runoff. Currently most types of vegetation used on shallow extensive green roofs are species of *Sedum,* which are able to survive in the harsh green roof environment. Mosses may be an alternative to *Sedum,* and their use could increase the diversity of the roof and offer more design options to the consumer. This study examined the effect that three different moss species had on soil temperature, water loss and the growth of neighbouring species. The presence of mosses in this experiment impacted the neighbour species differently, indicating that mosses are best used in specific species combinations. In terms of temperature and water loss, the use of mosses reduced soil temperature when compared to bare substrate. However, water loss varied depending on the moss and neighbour species.

Key Words: Moss, plant growth, soil temperature, water loss, extensive green roof

Introduction

Green roofs have been linked to many benefits, including decreased urban temperatures, less air pollution and reduced storm water runoff. They can also contribute to increases in roof lifespan, green space and biodiversity (Oberndorfer *et al.*, 2007). A green roof is composed of several different layers, including a waterproof membrane, a substrate layer and a vegetation layer (Molineux *et al.*, 2009; Castleton *et al.*, 2010). Since many older buildings are unable to support the weight of a green roof with a deep substrate (>20cm), many architects are interested in extensive green roofs (<20cm), which have low weight and maintenance requirements. Although green roofs have been associated with many benefits, the primary reasons for their construction are to reduce storm water runoff and decrease urban temperatures (MacIvor, 2010).

Storm water runoff is a significant problem in cities. It can carry a number of urban pollutants, such as oil, heavy metals, pesticides and fine particulates into local bodies of water (Mentens *et al.*, 2006; Oberndorfer *et al.*, 2007; Carter and Butler, 2008; Stovin, 2010). During significant rain events, runoff can also lead to sewage overflow, forcing sewage treatment plants to release waste directly into lakes and rivers (Oberndorfer *et al.*, 2007). Current methods to reduce storm water runoff include storage reservoirs, ponds, constructed wetlands and sand filters. However, these structures can be difficult to build in a dense urban setting (Oberndorfer *et al.*, 2007). Since green roofs are built on pre-existing structures, they could be especially useful in those areas lacking space. Green roofs are able to store water, delay runoff and release water back into the atmosphere through transportation and evaporation (Oberndorfer *et al.*, 2007). Estimates in Washington D.C. demonstrated that if 20% of the buildings had a green roof, it would result in 958 million liters of stored rainwater per year (Getter *et al.*, 2007). A modeling study performed on Vancouver, Canada found that converting all of the roofs in the area into green roofs would return the area's watershed to natural conditions (in terms of flood risk, habitat and water quality) within the next 50 years (VanWoert *et al.*, 2005).

Increased metropolitan development has also resulted in increased urban temperatures, an occurrence known as the heat island effect. In these environments, the air in urban areas is constantly warmer than that of the surrounding green space (Carter and Butler, 2008). These increased temperatures can be attributed to a number of factors, including thermal conductivity, the heat capacity of materials, urban canyons, surface albedo and anthropogenic heat (Bowler *et al.*, 2009). Green roofs reduce urban temperature through shading, evapotranspiration and insulation (Oberndorfer *et al.*, 2007). Thermal research comparing summer temperatures of a traditional roof to a green roof found an average difference of 53°C between the two (Castleton *et al.*, 2010). Decreasing a building's temperature can also lower the amount of energy used for cooling, thereby reducing costs and CO_2 emissions. An experiment conducted by Liu and Minor (2005) found that a green roof could reduce the energy cost of a building in Toronto by 12%.

The type of vegetation used on a green roof can affect the benefits provided by the roof. For example, some graminoid species, such as *Carex,* have been shown to be more effective at reducing temperatures and storm water runoff than succulent species such as *Sedum* (MacIvor and Lundholm, 2011). However, many roofs are unable to support the weight of the substrate (>6cm) necessary to grow species other than *Sedum* (Dunnett and Kingsbury, 2004). Currently, species of *Sedum*, which can survive at a substrate depth of only 2cm, are the most common type of vegetation used on extensive green roofs. There are current efforts, through incentives and policies, to use indigenous species on green roofs (Butler and Orians, 2011; MacIvor and Lundholm, 2011). Since many *Sedum* species currently used by the industry are not native to North America, moss which can survive in very shallow substrates could be used as an alternative (Dunnett and Kingsbury, 2004).

Previous studies have indicated that moss roofs are capable of providing thermal and storm water benefits similar to those of a traditional green roof. The success of mosses on extensive green roofs can be attributed to the low nutrient and water needs shared by many moss species. They can last an extended time through drought without damage and are capable of rehydration within 20 minutes (Anderson *et al.,* 2010). In addition to this, many species are able to start photosynthesis immediately after rehydration. The physical structure of mat-forming mosses allows them to extend the duration of photosynthesis during drought and reduce the rate of dehydration (Sand-Jensen and Hammer, 2012). Unlike species such as *Sedum,* which close their stomata to reduce water loss, mosses rely on capillary force to retain water, which leads to greater water loss through evaporation. Since evaporation is one method to reduce storm water runoff, this quality could potentially result in a greater reduction in storm water runoff than observed with *Sedum*. Finally, since mosses only have shallow rhizoids, moss roofs could be lightweight, easy to install and require little maintenance.

The use of moss on green roofs might increase the biodiversity of shallow, extensive green roofs through intermixed *Sedum* and moss combinations. This would expand the design options and diversity of the roof. Moss-only roofs would allow consumers who desire to solely use native species to construct a green roof on a very shallow substrate. More research is necessary to determine how mosses can affect substrate temperature, storm water capture and the growth of neighbouring species.

The Objectives of this study included:

1. Determine how different moss species affect soil temperature and water loss
2. Determine the effect mosses can have on the growth of neighbouring species.

Methods

The study site was located on the roof of the five-story Atrium building at Saint Mary's University in Halifax, Nova Scotia, Canada (44°39'N, 63°35'W (MacIvor, 2010)). The experiment was separated into four randomized blocks: blocks 1 and 2 were located on the unsheltered east side of the roof and blocks 3 and 4 were located on the west side of the roof (sheltered by one connecting building two stories higher than the roof) (Figure 1). During the study period, the weather station on the lower green roof testing facility (~50m from study site) recorded the minimum monthly temperature as 6.7 - 20.7°C and the monthly maximum as 12-30°C (Figure 2). The monthly precipitation recorded from the green roof weather station averaged between 1.7 and 11.59mm (Figure 3).

Vegetation

This experiment involved 88 green roof modules, each with a length and width of 36cm (Polyflat®, Stuewe & Sons Inc., Oregon, United States) and containing a root barrier/water retention fleece (length and width 36cm) at their base (EnkaRetain and Drain 3111®, Colbond Inc., North Carolina, United States). They were filled with a mixture (250ml amendment:7.7L soil media, v/v) of approximately 10L of green roof growing media (Sopraflor X®, Soprema Inc., Drummondville, Quebec, Canada) and a microbial soil amendment (Mykomix Pro Transplant®, Biosyneterra Solutions Inc., L'Assomption, Quebec, Canada). Sopraflor X consisted of crushed brick, blond peat, perlite, sand and vegetable compost with a total porosity between 60-70% and a bulk density between 1150-1250kg/m³.

The vegetation used in this study was propagated through plant cuttings or by germinating field-collected seeds in a greenhouse at Saint Mary's University. Seedlings were maintained in the greenhouse for nine months before being transplanted into green roof modules in June 2011. The study consisted of 11 treatments: three treatments of individual moss species (*Polytrichum commune, Polytrichum piliferum, Atrichum undulatum),* one treatment planted with a mix of all three moss species, three treatments of forbs (*Solidago bicolor, Campanula rotundifolia, Anaphalis margaritacea*), graminoids (*Deschampsia flexuosa, Festuca rubra, Panicum lanugiosum*) or succulents (*Sedum acre, Sedum spurium and Sedum telephium*) planted without mosses, three treatments of forbs, graminoids or succulents planted with mosses and one substrate-only control. Each treatment consisted of eight replicate modules with a total of 18 seedlings or plugs per module (single life form group: six plants per species, moss plus life form group: three plants per species) (Figure 4). Here, a moss "plug" consisted of a clump comparable in size to a vascular plant plug (approximately 5cm in diameter).

Future descriptions for these treatments will be as follows. The treatments containing one species: *P. commune, P. piliferum and A. undulatum*. The treatments containing only the life form group: moss, forb, graminoid and *Sedum*. The treatments planted with both mosses and the life form group: forb/moss, graminoid/moss and *Sedum*/moss.

The mosses used in this study were chosen due to their ability to survive drought, their growth form and their availability. *P. commune*'s physiology enhances its resistance to drought (Potter *et. al.*, 1995). This species has an underground rhizome system and an internal water system, both of which protect it from drought and aid *P. commune* in recovery after extended dry periods. This species can exist in isolated shoots and they prefer open bare ground (Callaghan *et. al.*, 1978). *P. piliferum* also has an underground rhizome system which may allow shoots to regrow after damage. Increased shoot density in this species is associated with increased survival. This species prefers disturbed open areas (Hobbs and Pritchard, 1987). *A. undulatum* has leaves designed to reduce evaporation which in turn may increase its drought tolerance (Lowell, 1998). *A. undulatum* is naturally found in moist forest conditions (Crum, 1983).

The majority of vascular species used in this study were chosen due to their positive performance in previous studies conducted at Saint Mary's University (Lundholm *et al.,* 2010; Wolf and Lundholm, 2008). Three additional species that had not been previously tested were *P.*

lanugiosum, A. margartacea and *S. telephium*. These species had growth forms similar to previously tested green roof candidates. For locations, *S. bicolor* is typically found in dry soil in old fields, barrens or roadsides. *C. rotundifolia* can naturally be found growing near the sea, in meadows, on damp cliffs and along inland streams. *A. margaritacea* can be seen growing on dry hillsides, clearings and along the borders of woods. *D. flexuosa* is commonly found on sandy plains and sea cliffs. *P. lanugiosum* is typically found on sandy soils in open areas. *F. rubra* naturally occurs in pastures, exposed areas, in sand/gravel, along beaches and in the upper zones of salt marshes. *S. spurium* originates from Eurasia and this species can be found growing on rocky gravely roadsides. *S. acre* also originates from Eurasia and this species grows in dry areas in dense patches on cliff edges, damp walls and rocky outcrops. *S. telephium* was introduced from Europe and this species can be found growing in rich shady soil (Roland *et al*., 1998).

Plant Growth

Data collection began on July 6, 2012 and ended on October 4, 2012. Cover was determined using a three dimensional pin frame (Domenico Ranalli, Regina, Saskatchewan, Canada) using the point interception method (Floyd and Anderson, 1987). The frame was 30cm high with a length of 36cm and a width of 36cm, and it contained 16 equally spaced rods (6mm diameter) (Figure 5). Each time the living above ground biomass touched a pin it was recorded with a value of one. If at least one live plant was present in the module but did not touch a pin, it was recorded as one. Pin frame data was recorded once every two weeks until the end of the growing season. The relative growth rate (RGR) was calculated by using the pin frame data in the following formula (Harper, 1977):

$$[\mathrm{Ln}(T2) - \mathrm{Ln}(T1)] \,/\, \#\ \text{of days.}$$

A 2-way ANOVA and a Tukey Post Hoc test were used to analyze the RGR, with reference to the treatment and block. All residuals were analyzed for homogeneity with Levene's test. Plant survival was determined by a health score on a scale of 0-2 as follows: 0 (dead leaves, brown stem), 1 (mostly dead leaves, green stem) and 2 (green leaves, green stem) (Butler and Orians, 2011). There was no significant difference between blocks for the RGR.

Temperature and Volumetric Water Content (VWC)

Both the temperature (in °C) and the VWC (%) were recorded once in August and again in September using the ProCheck and a GS3 soil moisture sensor inserted into the center of each module approximately 2cm below the substrate surface. (Decagon Devices Inc., Pullman, Washington, United States). The temperature was recorded when the modules were in full sun, no more than two hours before or after solar noon. The VWC was recorded one day after a rain event and again a day later if no new showers were observed. The difference in VWC between these two days was then used to determine water loss. A 2-way ANOVA and a Tukey Post Hoc test were used to analyze the data gathered, taking into account the treatment and block. All residuals were analyzed for homogeneity with Levene's test. There was no significant difference between blocks for temperature and water loss.

Results

Survival

All three species of mosses and *Sedum,* as well as *F. rubra,* were present in all of their modules and treatments by the end of the growing season. For *P. lanugiosum,* all eight modules in the graminoid treatment contained live plants, but only six modules in the graminoid/moss treatment contained live plants. *D. flexuosa* had no survivors in the graminoid treatment and only one plant survived in the graminoid/moss treatment. *S. bicolor* had four modules with live plants in the forb treatment and five modules with live plants in the forb/moss treatment. *C. rotundifolia* had two modules with live plants in both the forb and forb/moss treatments. *A. margaritacea* had one module with a live plant in the forb treatment and no modules with surviving plants in the forb/moss treatment (Figure 6).

Health

All species of graminoids, in both treatments, decreased in health during the late July drought. Both *F. rubra* and *P. lanugiosum* recovered after the drought. However, the average of all *D. flexuosa* species remained below 1. Overall, the presence of the mosses improved the health score of *F. rubra*, decreased the health score of *P. lanugiosum and* had little to no effect on *D. flexuosa* (Figure 7). During the drought, all species of forb decreased to below 1 in health. The only group that was able to recover to a health score greater than 1 by the end of the growing season was *S. bicolor* planted with mosses. Although the health score of *C. rotundifolia* never reached greater than 1 for the rest of the growing season, those *C. rotundifolia* planted with mosses scored slightly higher. By the end of the growing season, *A. margaritacea* scored below 0.5 both with and without the mosses. Those *A. margaritacea* planted with mosses remained at 0 from August 3, 2012 until the end of the growing season (Figure 8). During the drought, the only decrease observed in both succulent treatments was from *S. acre,* which performed better during drought without mosses. *S. spurium* and *S. telephium* displayed little difference when planted with or without mosses (Figure 9).

RGR

For the mosses, the species *A. undulatum* (-0.001 ± 0.001) performed significantly worse in the moss mixture treatment when compared to all other treatments. Although not significantly different from the *A. undulatum* treatment, it had the greatest RGR in the graminoid/moss treatment (0.002 ± 0.003). For the species *P. piliferum,* only the forb/moss treatment (0.007 ± 0.004) was significantly greater than the *P. piliferum* treatment (0.003 ± 0.001). The lowest RGR for this species was recorded in the treatments for graminoid/moss (-0.003 ± 0.002) and *Sedum*/moss (0.0004 ± 0.002). For the species *P. commune,* no significant difference was observed between the four mixture treatments and the *P. commune* treatment. However, the greatest RGR was recorded in the treatments for moss (0.002 ± 0.003) and *P. commune* (0.001 ± 0.004) (Figure 10 and Table 2).

For the graminoids, only *F. rubra* in the forb/moss treatment (-0.032 ± 0.006) had a significantly greater RGR than the forb treatment (-0.055 ± 0.006). There was no significant difference in RGR values for the other two graminoid species. For all *Sedum* and forb treatments, there was no significant difference in RGR when planted with or without moss. The RGR for all species of graminoids, forbs and *Sedum* averaged a negative RGR for the 2012 growing season (Figure 11 and Table 3).

Water Loss

Water loss was calculated as the difference in VWC (%) between August 21 and August 22, 2012. Although there was no significant difference between treatments, the *P. piliferum* treatment (4.15 ± 0.966) had the greatest water loss and the forb/moss treatment had the lowest water loss (0.063 ± 2.666) (Figure 12 and Table 4). 5.1mm of rainfall was recorded on August 20, 0.1mm was recorded on August 21 and no rainfall was recorded on August 22. Measurements were taken after the rain event on August 21.

Temperature (°C)

All treatments, except for the moss treatment (32.10 ± 0.37), *P. piliferum* treatment (32.61 ± 0.78*)* and the forb treatment (32.59± 0.77) had a significantly lower temperature than the substrate-only control (34.75 ± 0.5), which recorded the highest average temperature. The lowest temperature was recorded in the graminoid/moss treatment (29.7 ± 0.62) (Figure 17 and Table 4).

<u>Discussion</u>

All graminoid and forb species, as well as *S. acre*, were negatively affected by the late July drought. All of these species except *D. flexuosa*, *A. margaritacea and C. rotundifolia* displayed signs of recovery by September. The poor performance of *D. flexuosa* may have been due to competition from *F. rubra,* which grew taller and may have recovered faster after the drought. The poor performance of the two forbs, *A. margaritacea* and *C. rotundifolia,* was most likely due to the drought. They were not as drought tolerant as *S. bicolor*.

The species affected by the presence of mosses included *F. rubra*, *S. bicolor*, *P. lanuginosum* and *S. acre*. Both *F. rubra* and *S. bicolor* performed better when planted with mosses. This may have been due to a facilitative effect, as observed in Chapter 3. However, since the temperature and water loss were not significantly different between the treatments with and without moss, it is likely that another factor was in play. One possibility is that the mosses could have increased the demand for resources, thus decreasing the ability of the other two non-moss species to survive and freeing up more resources for *S. bicolor* or *F. rubra*. *P. lanuginosum* performed better in those modules without mosses. Since a greater number of *P. lanugiosum* seedlings were observed in these modules (personal observation), this species' better performance was most likely due to decreased competition and more space. Compared to the other two grass species, *P. lanuginosum* has a very short, compact growth form that might be subject to competition for light with mosses, whereas the other grass species tend to overgrow the mosses. *S. acre's* poor performance with mosses was only observed during the late July drought, and it ultimately had a greater RGR in the *Sedum*/moss treatment. The drought occurred at the very end of *S. acre*'s flowering period (personal observation), which may have led to a lower health rating during this time frame.

Overall, the mosses survived in all treatments and in all modules. The best performer in terms of health rating and overall RGR was *P. piliferum.* This species appeared to be the most drought tolerant, which could be due to its lower growth form and lower nutrient requirements. The lowest RGR for this species was recorded in the graminoid/moss and *Sedum*/moss treatments. This may be due to increased shading in these modules, which is known to be unfavorable to this species. *P. piliferum* is commonly found in disturbed open areas, which reflects its reactions in these treatments (Ireland, 1997). *P. commune* performed best when planted alone with other mosses and as a single species. *P. commune* has a taller growth form than *P. piliferum,* which may have decreased its drought tolerance. This species is naturally found growing in bogs or wet woods (Ireland, 1997), so the lack of moisture in these modules most likely impacted its growth. *A. undulatum* had the overall lowest RGR of the three moss species. The only treatment it had the greatest RGR in was the graminoid/moss treatment. This greater performance was most likely due to increased shade, as it is found naturally growing on rich soil in moist forest conditions (Crum, 1983).

No discernible pattern was observed for water loss between those modules planted with or without mosses. However, since some moss modules had lower water loss than the substrate-only control, specific combinations could lead to decreased water loss, thereby increasing the amount of moisture available to neighbouring species. In terms of temperature, the moss mixture, *P. commune, P. piliferum and A. undulatum* treatments performed similarly to all other treatments. However, their average soil temperature was warmer than many of the other treatments. The temperature in the graminoid and forb treatments was higher than the graminoid/moss and forb/moss treatments. This was most likely due to increased coverage of the bare substrate in these modules.

Overall, the use of mosses on green roofs seems to be most beneficial in situations where there is an abundance of bare substrate. In these circumstances, mosses are able to reduce soil temperatures and hold moisture in the soil for neighbouring species. However, the type of moss used impacted both soil temperature and water loss. This indicates that moss species that naturally colonize green roofs may not be the best choice in terms of desired green roof benefits. Common colonizers should be tested and, if they do not perform as well as other species, consumers should consider adding more beneficial moss species to their green roof.

This study was limited by a number of factors which should be considered for future research. First, data was only collected from one growing season. More growing seasons are necessary to see if these trends continue. Second, the July drought had a severe impact on the survival of the vascular species, leaving some treatments without living vascular plants. This almost certainly impacted the soil temperature and water loss data. Overall, more research is necessary to determine which moss species are best suited to the climate of the roof and the demands of the consumer.

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Tables

Table 1. Vegetation used and the treatment they were involved in, as well as the number of plantings per treatment (PC = *Polytrichum commune*, PP = *Polytrichum piliferum*, AU = *Atrichum undulatum*, M = moss, F = forb, G = grass and S = *Sedum*).

Species	**Species Code**	**Origin**	**Growth Form**	**Treatment**	**Plants Per Treatment**
Polytrichum commune	*Pol. c*	Native	Moss	PC/M/FM/GM/SM	18/6/3/3/3
Polytrichum piliferum	*Pol. p*	Native	Moss	PP/M/FM/GM/SM	18/6/3/3/3
Atrichum undulatum	*Atr. u*	Native	Moss	AU/M/FM/GM/SM	18/6/3/3/3
Deschampsia flexuosa	*Des. f*	Native	Graminoid	G/GM	6/3
Festuca rubra	*Fes. r*	Native	Graminoid	G/GM	6/3
Panicum lanugiosum	*Pan. l*	Native	Graminoid	G/GM	6/3
Solidago bicolor	*Sol. b*	Native	Forb	F/FM	6/3
Campanula rotundifolia	*Cam. r*	Native	Forb	F/FM	6/3
Anaphalis margaritacea	*Ana. m*	Native	Forb	F/FM	6/3
Sedum acre	*Sed. a*	Introduced	Succulent	S/SM	6/3
Sedum spurium	*Sed. s*	Introduced	Succulent	S/SM	6/3
Sedum telephium	*Sed. t*	Introduced	Succulent	S/SM	6/3

Table 2. RGR for the mosses in the 2012 growing season (July 6 - Oct 4), separated by species and treatment. Data is displayed at the mean ± SE.

Species	Single Species	Mosses	Forbs	Sedums	Grasses
A. undulatum	-0.001±0.001	-0.008±0.003	-0.002±0.002	-0.001±0.001	0.002±0.003
P. piliferum	0.003±0.001	0.007±0.003	0.007±0.004	0.0004±0.002	-0.003±0.002
P. commune	0.001±0.004	0.002±0.003	-0.002±0.003	-0.004±0.003	-0.001±0.005

Table 3. RGR for the 2012 growing season (July 6 - Oct 4), separated by species and treatment. Data is displayed at the mean ± the standard error.

Species	With Moss	Without Moss
P. lanugiosum	-0.007±0.003	-0.001±0.003
D. flexuosa	-0.003±0.002	-0.008±0.006
F. rubra	-0.032±0.006	-0.055±0.006
S. spurium	-0.002±0.003	-0.005±0.002
S. acre	-0.012±0.003	-0.01±0.002
S. telephium	-0.008±0.002	-0.007±0.004
S. bicolor	-0.03±0.006	-0.032±0.005
C. rotundifolia	-0.004±0.003	-0.003±0.002
A. margaritacea	-0.002±0.002	-0.003±0.003

Table 4. Temperature (collected on August 4, 2012) and water loss (Difference in VWC (%) between August 21 and 22, 2012). 5.1mm of rainfall was recorded on August 20, 0.1mm was recorded on August 21 and no rainfall was recorded on August 22 (measurements were taken after the rain event on August 21). Data is separated by species and ranked from Lowest (1st) to Highest (11th). It is displayed as the mean ± SE.

	Rank	Temp	Water Loss
Lowest	1st	Grass/Moss (29.7±0.62)	Forb/Moss (0.063±2.666)
	2nd	*Sedum* (29.8±0.62)	*P. commune* (0.988±0.585)
	3rd	Grass (29.93±0.7)	Grass (1.025±0.841)
	4th	*A. undulatum* (30.55±0.47)	*A. undulatum* (2.163±0.798)
	5th	*P. commune* (30.62±0.38)	Control (2.538±0.725)
	6th	Forbs/Moss (31.49±0.82)	Forb (2.6±0.808)
	7th	Sedum/Moss (31.54±0.53)	*Sedum*/Moss (3.237±0.707)
	8th	Moss (32.10±0.37)	Grass/Moss (3.475±1.544)
	9th	Forb (32.59±0.77)	*Sedum* (3.650±1.495)
	10th	*P. piliferum* (32.61±0.78)	Moss (4.15±1.323)
Highest	11th	Control (34.75±0.5)	*P. piliferum* (4.15±0.966)

Figures

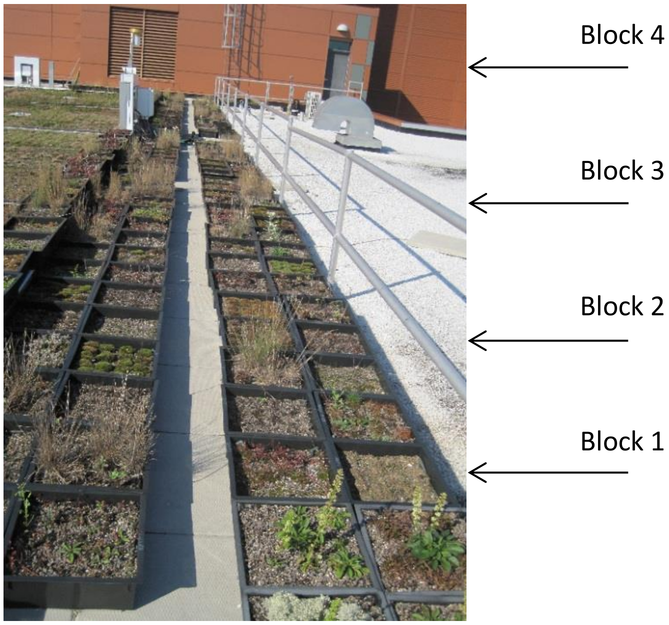

Figure 1. Layout of the treatments, with block 1 the farthest from the building and block 4 the closest.

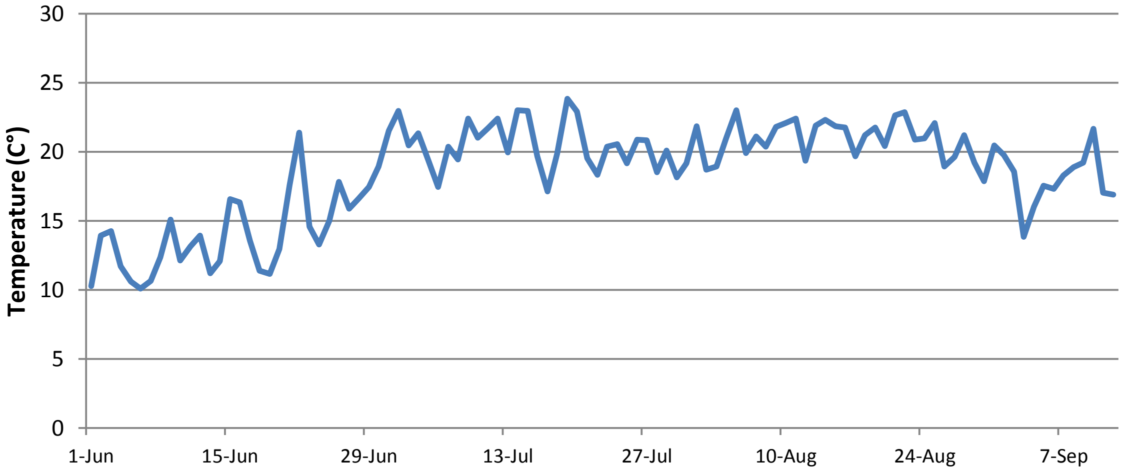

Figure 2. Average daily temperature (°C) throughout the growing season as measured by the green roof testing facility at Saint Mary's University.

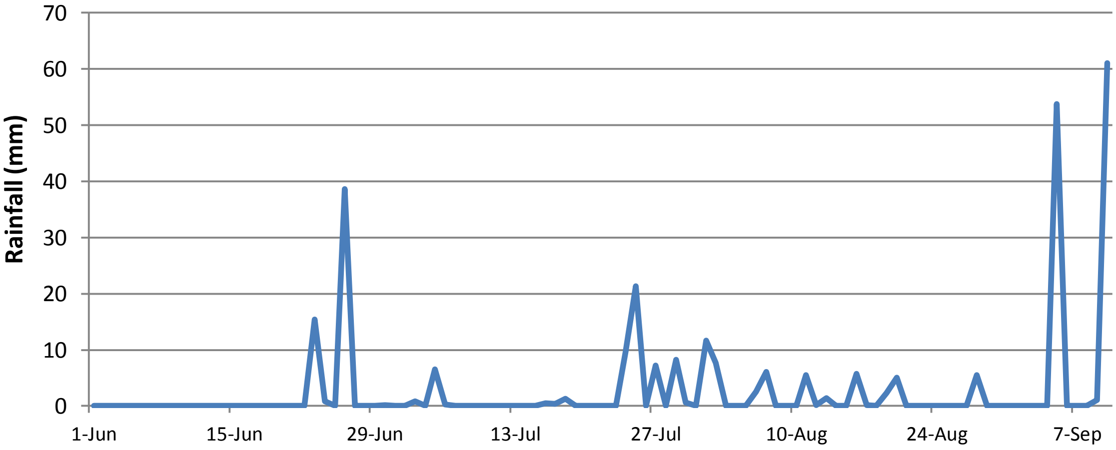

Figure 3. Daily rainfall (mm) throughout the growing season as measured by the green roof testing facility at Saint Mary's University.

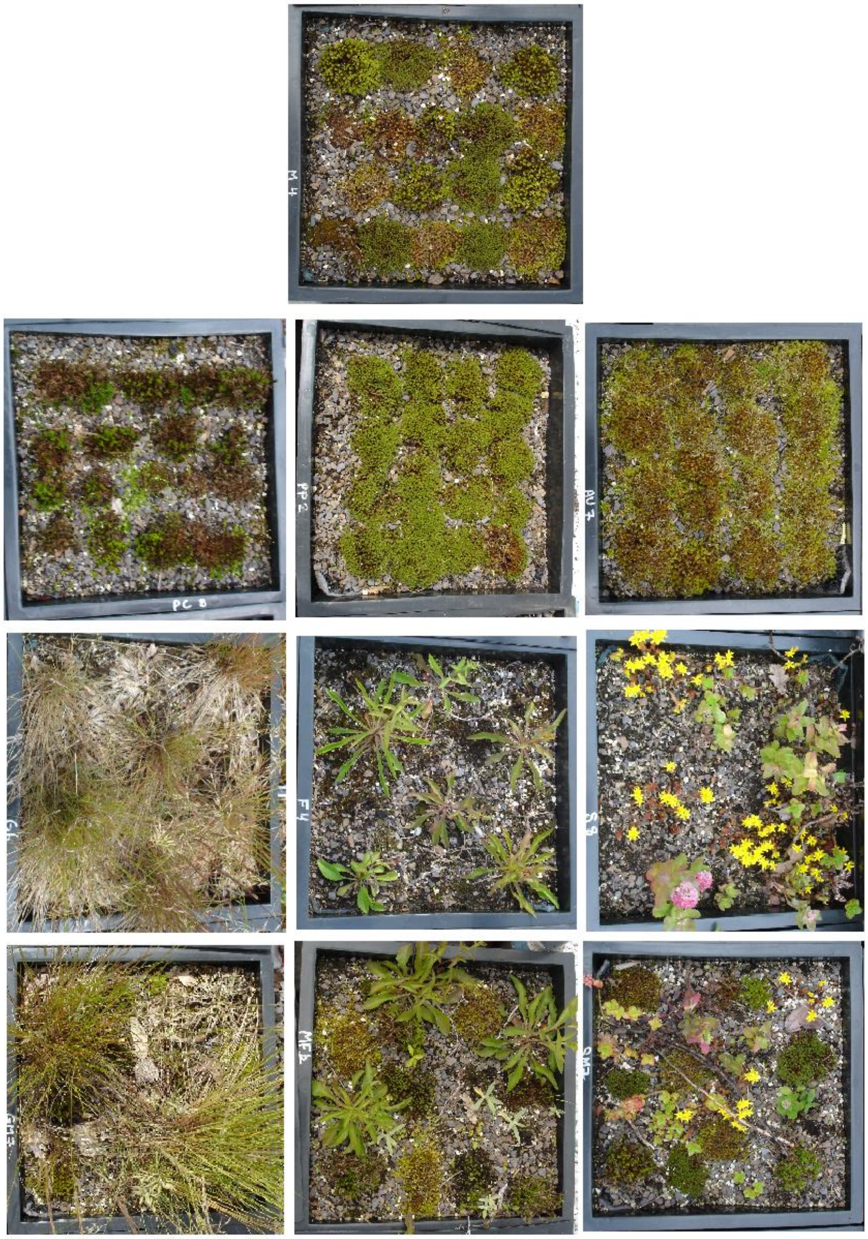

Figure 4. The different treatments used in the study. Topmost module: moss. Second row starting on the left: *P. commune, P. piliferum, A. undulatum.* Third row starting on the left: graminoid, forb, *Sedum*. Forth row starting on the left: graminoid/moss, forb/moss and *Sedum*/Moss.

Figure 5. Pin frame used to gather percent data on the modules. The base of the frame is the same size as the modules used in the study.

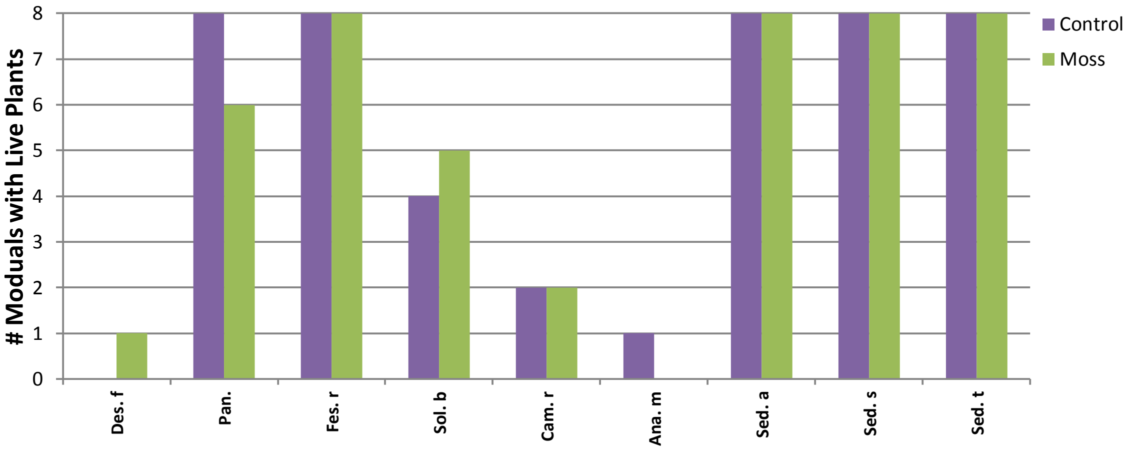

Figure 6. Number of modules containing live plants for each species except for the mosses. There were a total of eight modules per treatment (Control = modules without moss) (moss = modules with moss).

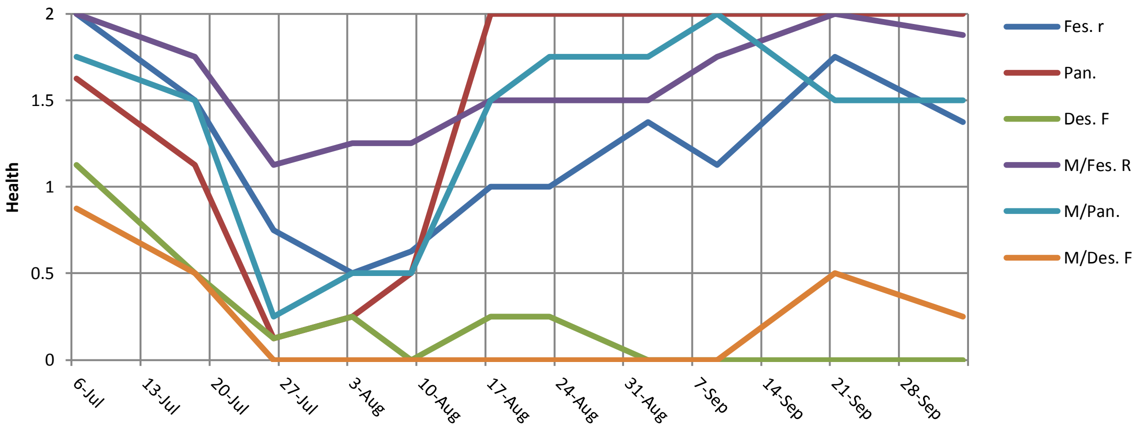

Figure 7. Health rating for the graminoids during the 2012 growing season (M = moss).

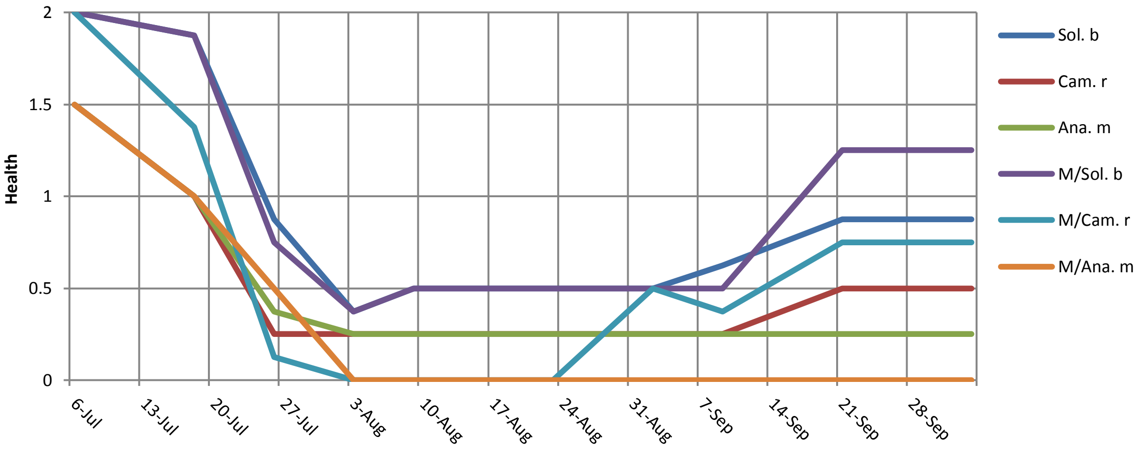

Figure 8. Health rating for the forbs during the 2012 growing season (M = moss).

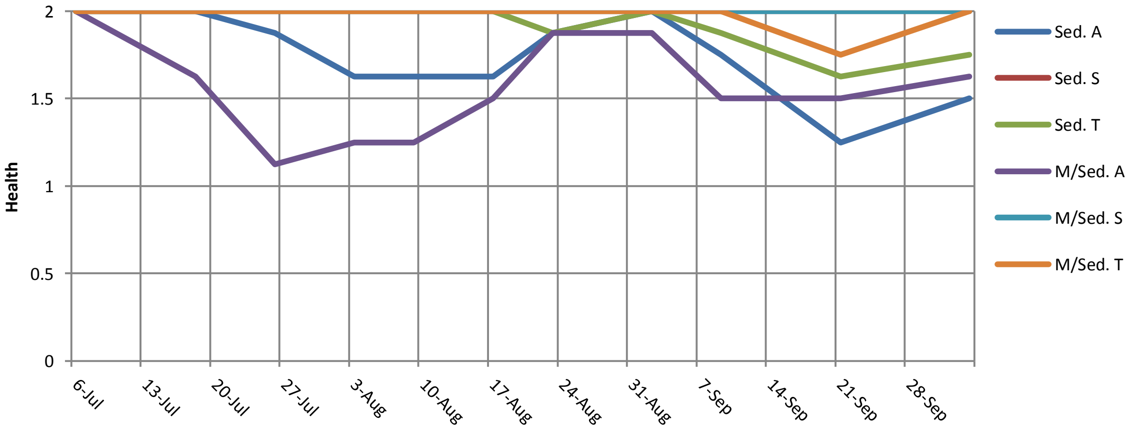

Figure 9. Health rating for the *Sedum* modules during the 2012 growing season (M = moss).

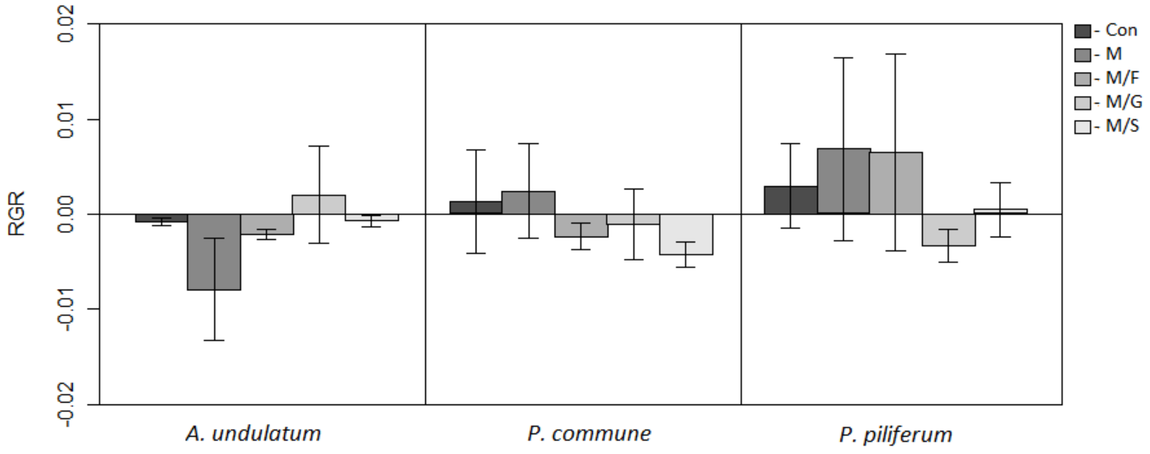

Figure 10. RGR for each species of moss in each module. The * indicates that module had significantly different RGR from the control (control = 1 species: *A. undulatum*, *P. commune* or *P. piliferum*). For *P. piliferum* the RGR had to be calculated to the 4th power before the residuals were homogeneous under Levene's test.

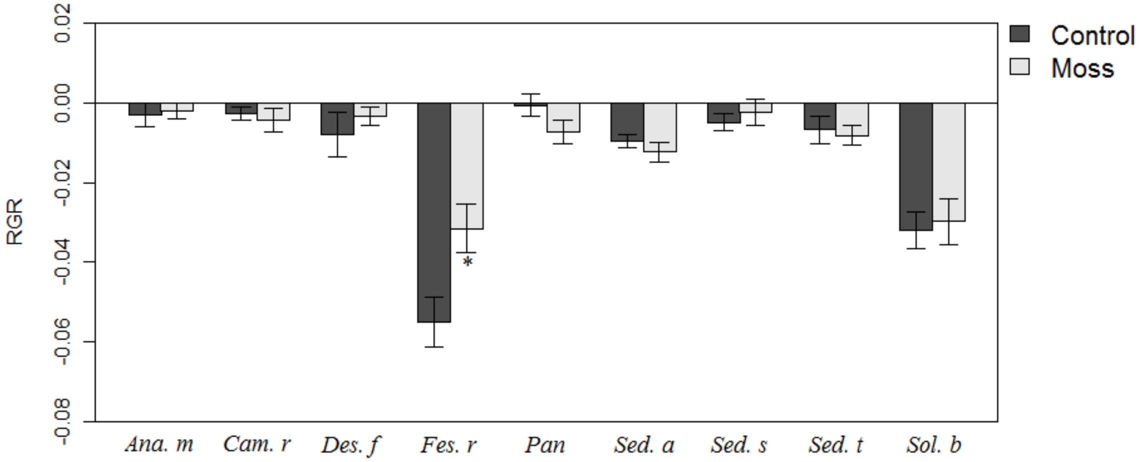

Figure 11. RGR for each species of vascular plant. The * indicates that module had significantly different RGR from the control (control = modules without moss) (moss = modules with moss).

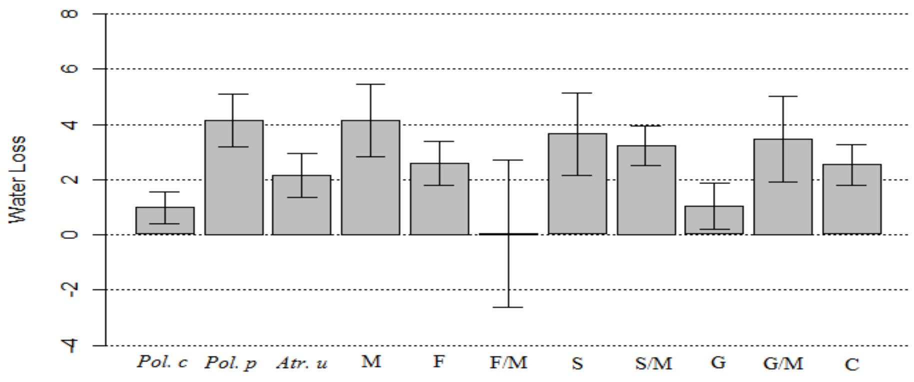

Figure 12. Average water loss as determined by the difference in VWC (%) between August 21 and August 22, 2012. No treatment was significantly different from any other treatment. 5.1mm of rainfall was recorded on August 20, 0.1mm was recorded on August 21 and no rainfall was recorded on August 22 (measurements were taken after the rain event on August 21). M = moss, F = forb, S = *Sedum*, G = grass and C = substrate-only control.

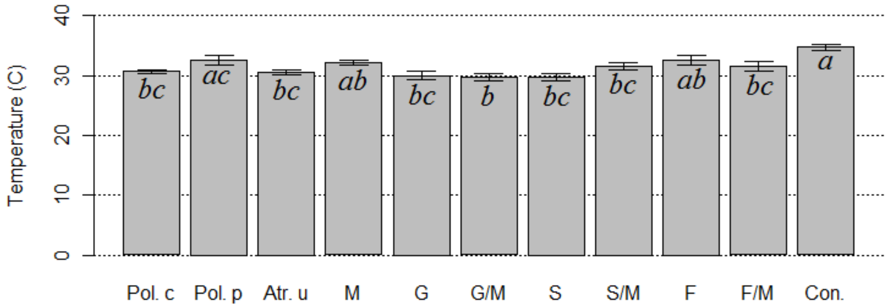

Figure 13. Average temperature (°C) for each treatment on August 21, 2012. The bars that share a letter are not significantly different. M = moss, F = forb. S = *Sedum*, G = grass, C = substrate-only control.

CHAPTER 5

SYNTHESIS: “The effects of soil depth, competition and facilitation on plant growth, soil temperature and water loss on an extensive green roof”

Thesis Synthesis

The purpose of this thesis was to examine various ways in which species diversity could be increased on an extensive green roof and how this diversity could affect soil temperature and water loss. Chapter 2 found that soil depth heterogeneity could be used to create niches allowing two species to coexist with less competition than in homogeneous soil. This method could lead to greater species diversity without increasing the weight load of the green roof. For example, a roof with a substrate depth of 10cm weighs the same as a roof with equal abundance of sections with depths of 5cm and 15cm, but the mixed substrate leads to a more equal distribution of above-ground cover between the two species. Chapter 3 examined the possible facilitative effects that mosses, lichens or bunch-grasses could have on the growth of the forb *S. bicolor*. After one growing season, the moss acted as a facilitator, the lichen had a neutral effect and the bunch-grass acted as a competitor. Overall, more research is needed to determine what mechanisms led to the facilitative effects of the moss and what other species can be used as facilitators. Finally, Chapter 4 looked at the role mosses could play on an extensive green roof in terms of species diversity, soil temperature and water loss. Overall, the presence of mosses seemed to be detrimental to certain species and assist the growth of others. In terms of reduced soil temperatures, mosses planted alone were less efficient at reducing soil temperature than graminoids, forbs and *Sedum*s. However, when the mosses were combined with these three life form groups, the temperatures were the same as when the vascular plants were used without mosses, thus any negative effect of mosses on roof cooling disappears when they are planted with vascular plants.

Soil Depth Heterogeneity

S. acre and *F. rubra* were chosen for the soil depth heterogeneity experiment due to their dissimilar reactions to drought and water uptake as shown in the greenhouse trial as well as previous research (Wolf and Lundholm, 2008; MacIvor and Lundholm, 2011). *S. acre* was one of the most drought tolerant species in the greenhouse trial and it has the potential to reduce water loss and cool soil temperatures (Wolf and Lundholm, 2008; Butler and Orians, 2011). *F. rubra* was less drought tolerant than *S. acre* in the greenhouse trial and it outperformed *S. acre* in terms of water uptake, suggesting it would promote greater storm water capture (Lundholm *et al.*, 2010). *F. rubra* is also able to create shade which is unfavorable to *S. acre*. This aspect could reduce the dominance of *S. acre* (Dunnett and Kingsbury 2004; Oberndorfer *et al.*, 2007).

The results from chapter 2 agree with previous research in that decreased soil temperatures and increased water storage are observed at deeper soil depths (Olly *et al.*, 2011). Soil temperature for both *S. acre* and *F. rubra* decreased with greater soil depths. For *F. rubra*, this is most likely due to a combination of greater canopy coverage by the plant and greater water storage capacity. This greater water storage capacity may have led to increased evapotranspiration, leading to greater cooling for the entire planter box. The decrease in temperature for *S. acre* is most likely solely due to greater water storage capacity impacting evapotranspiration.

F. rubra showed greater water loss than *S. acre* in all treatments. The 10cm soil depth recorded the greatest water usage for both species. This could have been due to the time at which the VWC was recorded; those modules with a greater biomass may have absorbed more water than those modules with a smaller biomass during the time between the rainfall ending and the measurements being taken.

In terms of growth, the percent cover of *F. rubra* increased as depth increased and the percent cover of *S. acre* (excluding the 15cm soil depth) decreased as depth increased. This trend is most likely due to greater resource availability for *F. rubra* at the deeper soil depths. Sufficient resources were available for both species at the 15cm soil depth and so the effects of competition were not apparent during the first growing season. However, as depth decreased so did the performance of *F. rubra*. This would have led to greater resource availability for *S. acre* leading to an increase in percent cover. Initial results indicate that heterogeneous soil depth can create higher evenness in cover between the two species when compared to the homogeneous treatment at the same average soil depth. More growing seasons are necessary to determine long term coexistence. If coexistence between species can be achieved in this manner then it could lead to increased diversity without increasing the weight of the green roof.

Interspecies Facilitation

When comparing the differences in *S. bicolor* growth, it was evident that the *P. commune* treatment had a facilitative effect, the *Cladonia* and easter grass treatments had a neutral effect and the conspecific and *D. spicata* treatments had a competitive effect for the first growing season. The *S. bicolor* in the *P. commune* treatments had the longest leaves, tallest plants and the greatest number of leaves and capitulescence, indicating a facilitative effect. This facilitative effect could be due to the decreased temperatures observed in these modules (the *P. commune* treatments had the second lowest soil temperature) as well as increased moisture availability as observed in previous studies (Casanova-Katny and Cavieres, 2012; Sand-Jensen and Hammer, 2012). However, since the *P. commune* treatment was not the best performer in terms of soil temperature or water loss, the observed facilitative effect could be due to an unanalyzed aspect of this relationship.

The neutral effect the *Cladonia* treatment had on the growth of *S. bicolor* indicates that these two species should be able to coexist. Since the *Cladonia* treatment was the best performer in terms of soil temperature and water loss, this association would increase the aesthetic value of the roof as well as improve the overall function.

The lichen trial found that the *Cladonia* modules were cooler and lost less water than the substrate-only control. This indicates that this genus could be a good candidate for interspecies facilitation. It is important to note that, since the initial results for the *Cladonia* neighbour treatment in the facilitation experiment were neutral, this facilitative effect could be species-specific or based on initial establishment. For example, instances of species growing out of these

Cladonia mats is a natural occurrence on the coastal barrens of Nova Scotia and, during the trial, seedlings of trees and grasses were observed growing out of these modules. If seeds are sown directly into lichen modules it may lead to greater interspecies facilitation than observed in the facilitation study. However, industrial use of lichen on a green roof is not currently feasible, as the main method for establishment is harvesting it from local ecosystems. In addition to this, lichen species, such as *Cladonia,* are sensitive to air pollution and would perform poorly in many dense urban centers (Brodo *et al.,* 2001). Overall, more research is necessary to determine what species associations lead to the greatest biodiversity and roof function.

Moss on an Extensive Green Roof

A drought that occurred in late July may have affected the results recorded in this study. All species except for *S. spurium* and *S. telephium* were negatively impacted by this drought. All other species except *D. flexuosa, A. margaritacea and C. rotundifolia* displayed signs of recovery by the end of the growing season.

Both *F. rubra* and *S. bicolor* performed better when planted with mosses. Since the temperature and water loss were not significant between the control and life form/moss treatments, the improved performance by these species may have been due to increased resource demand reducing the survival of the other grass or forb species. Only *P. lanugiosum* performed better without mosses in terms of health and relative growth rate (RGR). The greater performance of *P. lanugiosum* was most likely due to decreased competition and greater resource availability.

By the end of the growing season the mosses were present in all their treatments and modules. The best moss in terms of drought tolerance and growth was *P. piliferum*. This species only performed poorly in those modules with high shade (graminoid and *Sedum* treatments) indicating that it could be successful on shallow extensive green roofs exposed to full sun.

In terms of temperature, the moss treatment and controls were not significantly different from the forb, graminoid or *Sedum* treatments. However, the average soil temperature in the mosses-only modules was warmer than that of the other treatments. When the graminoids and forbs were planted with mosses it resulted in a lower soil temperature, most likely due to increased substrate coverage. In terms of water loss there was no notable pattern. Modules with mosses were recorded as both the best and worst performers in terms of water loss.

Conclusion

The kind of vegetation typically used on extensive green roofs is limited. If the number of viable species could be increased, it could lead to a number of benefits, including greater roof efficacy (in terms of roof cooling and reduced storm water runoff) and a greater aesthetic value. The different methods to increase plant growth and survival explored in this thesis could be applied to current green roof construction. Creating soil depth heterogeneity is a method that directly relates to those consumers with a roof that can only support a limited weight. Traditionally, these roofs are mainly planted with species of *Sedum* which can subsist in this extremely harsh environment (Dunnett and Kingsbury, 2004; Wolf and Lundholm, 2008; MacIvor and Lundholm, 2011). Soil depth heterogeneity could increase the possible species available to the consumer without increasing the weight load of the roof. The second method explored in this thesis, interspecific facilitation, has been shown, both naturally and experimentally, to increase plant survival (Butler and Orians, 2011). This thesis provides further evidence of interspecific facilitation and future research is necessary to determine what plant combinations are best suited for the consumer and climate. Overall, it should be possible to increase the number of viable species for use on extensive green roofs so long as specific methods are used.

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Appendix

Appendix 1. The weight (g) of each individual plant before transplanting in the greenhouse experiment.

	Sedum acre		*Sedum sperium*		*Solidago bicolor*		*Carex argyranthra*		*Festuca rubra*		*Sibbaldiopsis tridentata*		*Cladonia Terranova*	
	wet	**Dry**	**Wet**	**Dry**	**Wet**	**Dry**	**Wet**	**Dry**	**Wet**	**Dry**	**Wet**	**Dry**	**Wet**	**Dry**
5cm														
1	4.341	10.176	5.667	3.257	0.334	1.464	7.718	6.565	2.57	5.148	0.403	0.249	21.429	17.947
2	13.804	12.476	5.124	6.751	1.021	3.542	10.353	4.935	1.632	3.661	0.572	0.533	16.823	10.247
3	8.083	6.947	4.192	3.124	0.526	4.499	10.851	1.59	2.831	2.172	0.486	0.529	14.497	10.39
4	7.497	13.056	4.297	4.433	2.443	1.07	7.572	2.344	6.023	2.606	0.866	0.266	11.368	12.073
5	14.47	6.142	5.416	4.293	4.2	1.95	6.358	2.743	5.206	1.632	1.307	0.477	11.795	13.13
7.5cm														
1	10.877	10.69	5.694	3.852	0.26	6.041	10.293	5.367	2.45	4.111	0.606	1.023		
2	13.183	7.649	4.501	7.959	0.491	6.117	6.467	10.159	2.801	4.86	0.292	4.758		
3	5.880	9.673	3.825	2.449	1.473	2.263	10.081	9.69	1.918	1.961	1.118	0.634		
4	7.024	4.701	3.905	2.968	0.821	1.301	9.462	6.881	2.211	4.600	1.655	0.495		
5	14.47	10.211	2.935	6.748	1.837	0.638	6.193	4.393	2.238	6.574	0.828	1.196		
15cm														
1	8.906	7.001	3.795	2.448	0.873	3.683	7.669	4.815	2.112	9.659	1.501	0.107		
2	10.998	6.405	2.825	2.277	0.325	2.479	4.954	13.387	1.344	10.818	0.296	0.065		
3	7.387	10.192	5.013	4.184	0.925	1.56	10.906	5.172	4.716	7.311	1.969	0.076		
4	11.91	9.807	1.965	1.72	1.442	2.337	7.139	10.269	4.207	5.91	0.291	0.462		
5	9.93	10.344	2.785	10.473	1.89	3.985	9.240	8.026	1.685	5.394	0.952	0.352		

Appendix 2. A soil test conducted by Nova Scotia Agriculture describing the elements present in the Soprema X 2011 substrate

Soprema X 2011	**Sample 1**	**Sample 2**	**Sample 3**	**Average**
PH	7.7	7.7	7.7	7.7
Organic Matter (%)	5.8	6	5.9	5.9
P205(kg/ha)	669	727	739	711.7
K2O(Kg/ha)	1606	1586	1720	1637.3
Ca(kg/ha)	4542	4860	4806	4736
Mg(kg/ha)	860	902	912	891.3
Na(kg/ha)	317	309	340	322
sulfer(kg/ha)	463	424	552	479.7
Al(ppm)	311.85	414.78	452.07	392.9
Fe(ppm)	111	125	134	123.3
Mn(ppm)	30	34	35	33
Cu(ppm)	1.79	1.94	1.99	1.9
Zn(ppm)	6.6	6.5	6.7	6.6
B(ppm)	1.27	1.29	1.28	1.28
Nitrate - N (ppm)	41.3	33.2	44.7	39.7
% Nitrogen	0.39	0.41	0.35	0.4
Salt (mhos x10)				
CEC (meq/100gm)	17.4	18.3	18.5	18.1
Base Sat. K(%)	9.8	9.2	9.9	9.6
Base Sat. Ca (%)	65.2	66.2	65.1	65.5
Base Sat. Mg(%)	20.6	20.5	20.6	20.6
Base Sat. Na(%)	4	3.7	4	3.9
Base Sat. H(%)	0.5	0.4	0.4	0.4
Lime Required (t/ha)	6	6	6	6

Appendix 3. A soil test conducted by Nova Scotia Agriculture describing the elements present in the Soprema X 2012 substrate

Soprema X 2012	**Sample 1**	**Sample 2**	**Sample 3**	**Average**
PH	7.1	7.4	7.1	7.2
Organic Matter (%)	6.5	7.7	6.9	7
P205(kg/ha)	873	916	961	916.7
K2O(Kg/ha)	1765	1567	1762	1698
Ca(kg/ha)	4998	5119	5268	5128.3
Mg(kg/ha)	753	690	721	721.3
Na(kg/ha)	355	276	334	321.7
sulfer(kg/ha)	668	297	476	480.3
Al(ppm)	519.28	568.69	615.98	568
Fe(ppm)	140	154	148	147.3
Mn(ppm)	27	31	29	29
Cu(ppm)	1.28	1.43	1.33	1.3
Zn(ppm)	6.7	7.5	7.4	7.2
B(ppm)	1.17	1.19	1.25	1.2
Nitrate - N (ppm)	157.2	68.6	127.2	117.7
% Nitrogen	0.42	0.35	0.35	0.4
Salt (mhos x10)				
CEC (meq/100gm)	18.7	18	19.2	18.6
Base Sat. K(%)	10	9.2	9.7	9.6
Base Sat. Ca (%)	66.9	71	68.7	68.9
Base Sat. Mg(%)	16.8	16	15.7	16.2
Base Sat. Na(%)	4.1	3.3	3.8	3.7
Base Sat. H(%)	2.1	0.4	2.1	1.5
Lime Required (t/ha)	6	6	6	6

Apendix 4. Initial weights (g) of the target *S. bicolor* in the facilitation experiment collected on May 15, 2012.

Treatment	**Control**	***S. bicolor***	***Cladonia***	***P. commune***	***D. Spicata***	**Easter grass**
1	12.341	10.149	12.216	29.88	3.11	1.725
2	42.46	2.61	6.199	7.09	4.27	1.602
3	28.092	35.9	31.696	1.39	3.9	6.213
4	1.89	2.153	7.262	3.28	5.96	3.958
5	4.956	0.926	3.787	1.905	6.43	
6	8.172	3.16	4.951	4.947	2.62	
7	4.56	11.56	18.141	6.894	20.76	
8	3.056	3.6	35.671	35.671	34.49	
9	2.159	22.634	3.394	17.54	16.14	
10	28.76	21.19	2.037	11.22	10.89	

Appendix 5. Average daily temperature (°C) as measured by the lower green roof testing facility at Saint Mary's University throughout the 2012 growing season.

Day	**June**	**July**	**August**	**September**
1	10.3	21.51	21.87	19.77
2	13.96	22.98	18.7	18.58
3	14.27	20.45	18.95	13.83
4	11.71	21.35	20.96	16
5	10.63	19.33	23	17.56
6	10.11	17.45	19.93	17.3
7	10.64	20.39	21.12	18.3
8	12.36	19.45	20.36	18.88
9	15.1	22.39	21.79	19.22
10	12.13	21.03	22.08	21.67
11	13.17	21.73	22.39	17.02
12	13.93	22.43	19.37	16.88
13	11.22	19.97	21.88	17.47
14	12.08	22.99	22.3	17.07
15	16.59	22.95	21.85	17.66
16	16.34	19.7	21.75	17.53
17	13.58	17.13	19.68	15.11
18	11.38	19.87	21.19	14.99
19	11.15	23.84	21.74	14.76
20	12.98	22.9	20.4	19.12
21	17.61	19.53	22.65	14.09
22	21.37	18.32	22.89	18.64
23	14.58	20.37	20.9	18.71
24	13.29	20.56	20.97	19.71
25	15.01	19.19	22.08	16.38
26	17.82	20.88	18.92	14.23
27	15.86	20.85	19.61	16.37
28	16.62	18.51	21.22	16.39
29	17.45	20.11	19.21	12.07
30	18.94	18.16	17.85	15.08
31		19.15	20.48	

Appendix 6. Average daily rainfall (mm) as measured by the lower green roof testing facility at Saint Mary's University throughout the 2012 growing season.

Day	June	July	August	September
1	0	0	11.7	0
2	0	0.1	7.7	0
3	0	0.8	0	0
4	0	0	0	0
5	0	6.5	0	53.8
6	0	0.24	2.6	0
7	0	0	6.1	0
8	0	0	0	0
9	0	0	0	1.1
10	0	0	0	61
11	0	0	5.5	0
12	0	0	0.2	0
13	0	0	1.4	0
14	0	0	0	0
15	0	0	0	5
16	0	0.5	5.8	2
17	0	0.4	0.2	0
18	0	1.3	0	0
19	0	0	2.3	1.5
20	0	0	5.1	0
21	0	0	0.1	0
22	0.1	0	0	4.9
23	15.4	0	0	5.5
24	0.8	9.6	0	17
25	0	21.3	0	0.2
26	38.6	0	0	0
27	0.1	7.2	0	0
28	0	0	5.5	0
29	0	8.2	0	1.4
30	0.2	0.6	0	1.5
31		0	0	0

Appendix 7. 2-way ANOVA for the water uptake of all species in the wet treatment for the greenhouse trial

Water Uptake	**Df**	**Sum Sq**	**Mean Sq**	**F value**	**Pr(>F)**
Species	7	0.125347	0.0179067	12.7939	3.73e-11
Depth	1	0.000008	0.0000083	0.0060	0.93863
Species: Depth	6	0.017726	0.0029544	2.1108	0.06011
Residuals	86	0.120368	0.0013996		

Appendix 8. 3-way ANOVA for the dry shoot weight in the greenhouse trial. IW refers to the weight of the plants when potted.

S. acre	**Df**	**Sum Sq**	**Mean Sq**	**F value**	**Pr(>F)**
Shoot	1	0.068	0.068	0.0195	0.8903
Water	1	95.056	95.056	27.2013	3.131e-05
IW	1	1.303	1.303	0.3729	0.5477
Shoot: Water	1	0.002	0.002	0.0006	0.9809
Shoot: IW	1	0.613	0.613	0.1754	0.6794
Water: IW	1	0.072	0.072	0.0207	0.8869
Shoot: Water: IW	1	0.604	0.604	0.1728	0.6816
Residuals	22	76.880	3.495		

S. spurium	**Df**	**Sum Sq**	**Mean Sq**	**F value**	**Pr(>F)**
Shoot	1	7.3385	7.3385	14.0423	0.0011148
Water	1	1.6068	1.6068	3.0747	0.0934430
IW	1	0.0920	0.0920	0.1761	0.6788500
Shoot: Water	1	7.9644	7.9644	15.2399	0.0007623
Shoot: IW	1	0.2931	0.2931	0.5608	0.4618550
Water: IW	1	0.1995	0.1995	0.3817	0.5430264
Shoot: Water: IW	1	0.7602	0.7602	1.4546	0.2405992
Residuals	22	11.4972	0.5226		

C. argyranthra	**Df**	**Sum Sq**	**Mean Sq**	**F value**	**Pr(>F)**
Shoot	1	1.6336	1.6336	32.7175	9.403e-06
Water	1	4.2994	4.2994	86.1070	4.623e-09
IW	1	0.1321	0.1321	2.6460	0.11805
Shoot: Water	1	0.1284	0.1284	2.5722	0.12302
Shoot: IW	1	0.1373	0.1373	2.7498	0.11146
Water: IW	1	0.0001	0.0001	0.0023	0.96209
Shoot: Water: IW	1	0.1626	0.1626	3.2563	0.08486
Residuals	22	1.0985	0.0499		

F. rubra	**Df**	**Sum Sq**	**Mean Sq**	**F value**	**Pr(>F)**
Shoot	1	1.74676	1.74676	33.1435	8.614e-06
Water	1	0.25928	0.25928	4.9197	0.03719
IW	1	0.00471	0.00471	0.0893	0.76790
Shoot: Water	1	0.00032	0.00032	0.0062	0.93820
Shoot: IW	1	0.40594	0.40594	7.7023	0.01104
Water: IW	1	0.36580	0.36580	6.9408	0.01514
Shoot: Water: IW	1	0.23145	0.23145	4.3917	0.04784
Residuals	22	1.15947	0.05270		

S. bicolor	**Df**	**Sum Sq**	**Mean Sq**	**F value**	**Pr(>F)**
Shoot	1	0.13140	0.131397	2.9454	0.10017
Water	1	0.18929	0.189290	4.2432	0.05143
IW	1	0.12297	0.122969	2.7565	0.11105
Shoot: Water	1	0.08965	0.089651	2.0097	0.17031
Shoot: IW	1	0.05024	0.050237	1.1261	0.30011
Water: IW	1	0.01512	0.015121	0.3390	0.56635
Shoot: Water: IW	1	0.03193	0.031929	0.7157	0.40666
Residuals	22	0.98142	0.044610		

Appendix 9. 3-way ANOVA for the dry shoot weight in the greenhouse trial. IW refers to the weight of the plants when potted.

S. tridentata	**Df**	**Sum Sq**	**Mean Sq**	**F value**	**Pr(>F)**
Shoot	1	0.28377	0.28377	2.5156	0.126998
Water	1	0.41395	0.41395	3.6696	0.068501
IW	1	0.27044	0.27044	2.3974	0.135804
Shoot: Water	1	0.39849	0.39849	3.5325	0.073488
Shoot: IW	1	0.87891	0.87891	7.7913	0.010644
Water: IW	1	0.20379	0.20379	1.8065	0.192621
Shoot: Water: IW	1	1.16921	1.16921	10.3648	0.003947
Residuals	22	2.48173	0.11281		

Appendix 10. 3-way ANOVA for the dry root weight in the greenhouse trial. IW refers to the weight of the plants when potted.

S. acre	**Df**	**Sum Sq**	**Mean Sq**	**F value**	**Pr(>F)**
Depth	1	1.971	1.971	0.8726	0.3603663
Water	1	43.469	43.469	19.2466	0.0002344
IW	1	2.286	2.286	1.0122	0.3253234
Root: Water	1	0.475	0.475	0.2102	0.6511167
Root: IW	1	1.966	1.966	0.8706	0.3609289
Water: IW	1	4.527	4.527	2.0044	0.1708434
Root: Water: IW	1	0.299	0.299	0.1322	0.7195973
Residuals	22	49.688	2.259		

S. spurium	**Df**	**Sum Sq**	**Mean Sq**	**F value**	**Pr(>F)**
Root	1	37.401	37.401	6.9236	0.01525
Water	1	8.165	8.165	1.5115	0.23189
IW	1	0.751	0.751	0.1391	0.71277
Root: Water	1	0.028	0.028	0.0051	0.94356
Root: IW	1	0.331	0.331	0.0612	0.80683
Water: IW	1	2.557	2.557	0.4733	0.49865
Root: Water: IW	1	15.030	15.030	2.7824	0.10948
Residuals	22	118.843	5.402		

C. argyranthra	**Df**	**Sum Sq**	**Mean Sq**	**F value**	**Pr(>F)**
Root	1	1442.03	1442.03	22.2255	0.0001054
Water	1	2821.21	2821.21	43.4821	1.245e-06
IW	1	6.09	6.09	0.0938	0.7622268
Root: Water	1	890.14	890.14	13.7194	0.0012381
Root: IW	1	126.58	126.58	1.9509	0.1764213
Water: IW	1	0.65	0.65	0.0100	0.9210577
Root: Water: IW	1	174.36	174.36	2.6873	0.1153740
Residuals	22	1427.40	64.88		

F. rubra	**Df**	**Sum Sq**	**Mean Sq**	**F value**	**Pr(>F)**
Root	1	486.46	486.46	30.8909	1.380e-05
Water	1	599.41	599.41	38.0631	3.288e-06
IW	1	9.72	9.72	0.6174	0.4403979
Root: Water	1	254.34	254.34	16.1510	0.0005761
Root: IW	1	2.66	2.66	0.1688	0.6851673
Water: IW	1	2.63	2.63	0.1668	0.6868948
Root: Water: IW	1	7.48	7.48	0.4751	0.4978730
Residuals	22	346.45	15.75		

S. bicolor	**Df**	**Sum Sq**	**Mean Sq**	**F value**	**Pr(>F)**
SB	1	10.7199	10.7199	35.6296	5.238e-06
Water	1	3.6757	3.6757	12.2169	0.002047
IW	1	0.5068	0.5068	1.6843	0.207793
SB: Water	1	12.1300	12.1300	40.3162	2.173e-06
SB: IW	1	2.0698	2.0698	6.8795	0.015537
Water: IW	1	0.9113	0.9113	3.0289	0.095766
SB: Water: IW	1	1.0517	1.0517	3.4957	0.074898
Residuals	22	6.6192	0.3009		

Appendix 11. 3-way ANOVA for the dry root weight in the greenhouse trial. IW refers to the weight of the plants when potted.

S. tridentata	**Df**	**Sum Sq**	**Mean Sq**	**F value**	**Pr(>F)**
Root	1	0.00259	0.00259	0.1151	0.737598
Water	1	0.07321	0.07321	3.2560	0.084870
IW	1	0.88012	0.88012	39.1429	2.69e-06
Root: Water	1	0.00195	0.00195	0.0867	0.771194
Root: IW	1	0.19255	0.19255	8.5635	0.007817
Water: IW	1	0.00964	0.00964	0.4286	0.519468
Root: Water: IW	1	0.01654	0.01654	0.7357	0.400299
Residuals	22	0.49466	0.02248		

Appendix 12. 1-way ANOVA for the growth of *F. rubra* and *S. acre*, as well as the average soil temperature (°C) in each planter box for the soil heterogeneity experiment.

RGR *F. rubra*	**Df**	**Sum Sq**	**Mean Sq**	**F value**	**Pr(>F)**
Depth	3	0.0033956	0.00113188	18.693	5.087e-06
Residuals	20	0.0012110	0.00006055		

RGR *S. acre*	**Df**	**Sum Sq**	**Mean Sq**	**F value**	**Pr(>F)**
Depth	3	1.0998e-05	3.6659e-06	2.6577	0.07616
Residuals	20	2.7587e-05	1.3793e-06		

Final % Cover *F. rubra*	**Df**	**Sum Sq**	**Mean Sq**	**F value**	**Pr(>F)**
Depth	3	0.38685	0.128951	68.073	1.131e-10
Residuals	20	0.03789	0.001894		

Final % Cover *S. acre*	**Df**	**Sum Sq**	**Mean Sq**	**F value**	**Pr(>F)**
Depth	3	0.034724	0.0115747	3.8247	0.02576
Residuals	20	0.060525	0.0030263		

F. rubra* / *S. acre	**Df**	**Sum Sq**	**Mean Sq**	**F value**	**Pr(>F)**
Depth	3	2.01076	0.67025	41.681	8.599e-09
Residuals	20	0.32161	0.01608		

Temperature (°C)	**Df**	**Sum Sq**	**Mean Sq**	**F value**	**Pr(>F)**
Depth	3	48.651	16.217	6.2111	0.003719
Residuals	20	52.219	2.611		

Appendix 13. 2-way ANOVA for the temperature (°C) (taken on July 1, 2012) and the water loss (%) (Measured September 11 and 12, 2012) for *F. rubra* and *S. acre* in each treatment for the soil heterogeneity experiment.

Temperature (°C)	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Species	1	1.541	1.541	0.3993	0.5306996
Depth	1	69.439	69.439	17.9966	0.0001121
Species: Depth	1	0.529	0.529	0.1372	0.7128795
Residuals	44	169.771	3.858		

Water Loss (%)	Df	Sum Sq	Mean Sq	F value	Pr(>F)
Species	1	54.19	54.187	5.8566	0.01972
Depth	1	8.01	8.012	0.8659	0.35717
Species: Depth	1	1.51	1.507	0.1629	0.68850
Residuals	44	407.11	9.252		

Appendix 14. 1-way ANOVA for the initial weight for all target *S. bicolor*, the final growth for all target *S. bicolor* as well as water loss (%) recorded on August 21 and 24, 2012) and soil temperature in °C (recorded on July 1, 2012) in the facilitation experiment.

Initial Weight	**Df**	**Sum Sq**	**Mean Sq**	**F value**	**Pr(>F)**
treatment	6	384.9	64.148	0.4668	0.8297
Residuals	52	7146.0	137.423		

Leaf Length	**Value**	**Std.Error**	**DF**	**t-value**	**p-value**
Control	10.840000	1.465928	51	7.394633	0.0000
Easter Grass	0.679699	1.365498	51	0.497767	0.6208
D. spicata	-3.040000	1.026233	51	-2.962290	0.0046
Cladonia.	-0.460000	1.026233	51	-0.448241	0.6559
P. commune	1.990000	1.026233	51	1.939131	0.0580
S. bicolor	-3.640000	1.026233	51	-3.546953	0.0008

Leaf Width	**Value**	**Std.Error**	**DF**	**t-value**	**p-value**
Control	3.1600000	0.2469652	51	12.795323	0.0000
Easter Grass	1.2349053	0.4107709	51	3.006311	0.0041
D. spicata	-1.1700000	0.3093430	51	-3.782209	0.0004
Cladonia.	-0.4100000	0.3093430	51	-1.325390	0.1909
P. commune	-0.1400000	0.3093430	51	-0.452572	0.6528
S. bicolor	-1.0000000	0.3093430	51	-3.232658	0.0022

Height	**Value**	**Std.Error**	**DF**	**t-value**	**p-value**
Control	6.580	2.699095	51	2.437854	0.0183
Easter Grass	1.245	5.049545	51	0.246557	0.8062
D. spicata	7.830	3.817097	51	2.051297	0.0454
Cladonia.	5.420	3.817097	51	1.419927	0.1617
P. commune	12.780	3.817097	51	3.348094	0.0015
S. bicolor	8.100	3.817097	51	2.122031	0.0387

Leaf Count	**Value**	**Std.Error**	**DF**	**t-value**	**p-value**
Control	84.2	6.978869	51	12.064992	0.0000
Easter Grass	-8.2	13.056269	51	-0.628051	0.5328
D. spicata	-28.2	9.869611	51	-2.857255	0.0062
Cladonia.	-4.4	9.869611	51	-0.445813	0.6576
P. commune	1.4	9.869611	51	0.141850	0.8878
S. bicolor	-46.0	9.869611	51	-4.660771	0.0000

Capitulescence	**Value**	**Std.Error**	**DF**	**t-value**	**p-value**
Control	68.700	74.18659	51	0.9260433	0.3588
Easter Grass	-79.420	60.89828	51	-1.3041419	0.1980
D. spicata	19.700	45.76385	51	0.4304708	0.6687
Cladonia.	-16.100	45.76385	51	-0.3518061	0.7264
P. commune	140.400	45.76385	51	3.0679238	0.0034
S. bicolor	-47.400	45.76385	51	-1.0357520	0.3052

Temperature (°C)	**Value**	**Std.Error**	**DF**	**t-value**	**p-value**
Control	36.53000	1.6870585	51	21.653072	0.0000
Easter Grass	-0.71902	1.0383928	51	-0.692432	0.4918
D. spicata	-1.38000	0.7802422	51	-1.768682	0.0829
Cladonia.	-5.54000	0.7802422	51	-7.100360	0.0000
P. commune	-3.40000	0.7802422	51	-4.357621	0.0001
S. bicolor	0.30000	0.7802422	51	0.384496	0.7022

Appendix 15. 1-way ANOVA for the initial weight for all target *S. bicolor*, the final growth for all target *S. bicolor* as well as water loss (%) recorded on August 21 and 24, 2012) and soil temperature in °C (recorded on July 1, 2012) in the facilitation experiment.

Water Loss (%)	**Value**	**Std.Error**	**DF**	**t-value**	**p-value**
Control	3.980000	1.714611	51	2.3212267	0.0243
Easter Grass	1.042578	1.835917	51	0.5678784	0.5726
D. spicata	2.990000	1.379971	51	2.1667123	0.0350
Cladonia.	0.100000	1.379971	51	0.0724653	0.9425
P. commune	2.050000	1.379971	51	1.4855385	0.1436
S. bicolor	2.720000	1.379971	51	1.9710560	0.0542

Appendix 16. 2-way ANOVA for the RII, final percent cover and RGR (IC = initial cover).

RII	**Df**	**Sum Sq**	**Mean Sq**	**F value**	**Pr(>F)**
Treatment	5	2.53934	0.50787	22.7093	2.353e-10
Block	1	0.15107	0.15107	6.7552	0.01335
Treatment: Block	5	0.05851	0.01170	0.5233	0.75705
Residuals	37	0.82746	0.02236		

Final % Cover	**Value**	**Std.Error**	**DF**	**t-value**	**p-value**
Control	0.2651694	0.0375133	44	7.068678	0.0000
Easter Grass	-0.0705177	0.0674101	44	-1.046101	0.3012
D. spicata	-0.1661065	0.0459921	44	-3.611635	0.0008
Cladonia.	-0.1491767	0.0456677	44	-3.266571	0.0021
P. *commune*	0.0424576	0.0419062	44	1.013159	0.3165
S. bicolor	-0.2231529	0.0354644	44	-6.292313	0.0000
IC	0.1208125	0.5076954	44	0.237963	0.8130
Easter Grass: IC	2.0202142	2.3637345	44	0.854671	0.3974
D. spicata: IC	-0.0679435	1.1401974	44	-0.059589	0.9528
Cladonia.: IC	1.9193275	1.1177954	44	1.717065	0.0930
P. commune:IC	0.2680802	0.8791197	44	0.304942	0.7618
S. bicolor: IC	1.2454488	0.7820830	44	1.592477	0.1184

RGR	**Value**	**Std.Error**	**DF**	**t-value**	**p-value**
Control	0.03274548	0.0049568	44	6.606160	0.0000
Easter Grass	0.00280549	0.0116914	44	0.239963	0.8115
D. spicata	-0.01205966	0.0079643	44	-1.514215	0.1371
Cladonia.	-0.00738950	0.0079265	44	-0.932251	0.3563
P. *commune*	0.00305707	0.0072726	44	0.420356	0.6763
S. bicolor	-0.02443128	0.0061590	44	-3.966775	0.0003
IC	-0.25124847	0.0881799	44	-2.849271	0.0066
Easter Grass: IC	-0.14920621	0.4102429	44	-0.363702	0.7178
D. spicata: IC	-0.01679784	0.1972216	44	-0.085172	0.9325
Cladonia.: IC	0.05532274	0.1939649	44	0.285220	0.7768
P. commune:IC	-0.05408984	0.1525234	44	-0.354633	0.7246
S. bicolor: IC	0.23960126	0.1358072	44	1.764275	0.0846

Appendix 17. Welch Two Sample t-test for the soil temperature (°C) recorded on July 1, 2012 and water loss (%) recorded between August 21 and 22, 2012 recorded for the lichen trial.

Temperature (°C)		
t = -8.4837	**df** = 4.477	**p-value** = 0.0006351
	Control	***Cladonia***
Confidence Interval	-15.222947	-7.947886
Mean	26.68333	38.26875

Water Loss (%)		
t = 1.1692	**df** = 7.023	**p-value** = 0.2805
	Control	***Cladonia***
Confidence Interval	-1.557239	4.607239
Mean	3.350	1.825

Appendix 18. 1-way ANOVA comparing the RGR for each species in each treatment for the moss study.

F. rubra	**Value**	**Std.Error**	**DF**	**t-value**	**p-value**
Control	-0.05501473	0.006218384	11	-8.847109	0.0000
Moss	0.02340592	0.008794123	11	2.661541	0.0221

D. flexuosa	**Value**	**Std.Error**	**DF**	**t-value**	**p-value**
Control	-0.007978855	0.005082522	11	-1.5698612	0.1447
Moss	0.004636020	0.005081926	11	0.9122566	0.3812

P. lanugiosum	**Value**	**Std.Error**	**DF**	**t-value**	**p-value**
Control	-0.00053672	0.002949516	11	-0.1819689	0.8589
Moss	-0.00668567	0.004171245	11	-1.6027995	0.1373

A. margaritacea	**Value**	**Std.Error**	**DF**	**t-value**	**p-value**
Control	-0.0030026826	0.002974317	11	-1.0095367	0.3344
Moss	0.0009530329	0.003140095	11	0.3035045	0.7672

C. rotundifolia	**Value**	**Std.Error**	**DF**	**t-value**	**p-value**
Control	-0.002586370	0.002524690	11	-1.0244306	0.3276
Moss	-0.001709498	0.003495587	11	-0.4890444	0.6344

S. bicolor	**Value**	**Std.Error**	**DF**	**t-value**	**p-value**
Control	-0.03198641	0.006079604	11	-5.261265	0.0003
Moss	0.00215988	0.006147320	11	0.351354	0.7320

S. acre	**Value**	**Std.Error**	**DF**	**t-value**	**p-value**
Control	0.002739147	0.002812711	11	0.973846	0.3511
Moss	-0.012342572	0.002368310	11	-5.211552	0.0003

S. spurium	**Value**	**Std.Error**	**DF**	**t-value**	**p-value**
Control	-0.002465962	0.003219560	11	-0.7659314	0.4598
Moss	-0.002389802	0.003249832	11	-0.7353617	0.4775

S. telephium	**Value**	**Std.Error**	**DF**	**t-value**	**p-value**
Control	0.001463454	0.004316609	11	0.3390285	0.7410
Moss	-0.008172435	0.003052304	11	-2.6774647	0.0215

P. commune	**Value**	**Std.Error**	**DF**	**t-value**	**p-value**
Control	0.001288971	0.003737645	32	0.3448617	0.7325
Forb	-0.003634981	0.005285829	32	-0.6876843	0.4966
Moss	0.001149293	0.005285829	32	0.2174291	0.8293
Graminoid	-0.002385588	0.005285829	32	-0.4513176	0.6548
Sedum	-0.005555457	0.005285829	32	-1.0510097	0.3011

P. piliferum	**Value**	**Std.Error**	**DF**	**t-value**	**p-value**
Control	2.601380e-09	1.249614e-08	32	0.2081749	0.8364
Forb	4.189732e-08	1.767221e-08	32	2.3708019	0.0239
Moss	2.180890e-08	1.767221e-08	32	1.2340788	0.2262
Graminoid	-8.128600e-10	1.767221e-08	32	-0.0459967	0.9636
Sedum	1.288890e-09	1.767221e-08	32	0.0729332	0.9423

A. undulatum	**Value**	**Std.Error**	**DF**	**t-value**	**p-value**
Control	-0.000796084	0.002104461	32	-0.3782840	0.7077
Forb	-0.001302665	0.002840491	32	-0.4586056	0.6496
Moss	-0.007106750	0.002840491	32	-2.5019437	0.0177
Graminoid	0.002830868	0.002840491	32	0.9966119	0.3264
Sedum	0.000073853	0.002840491	32	0.0259999	0.9794

Appendix 19. 2-way ANOVA for the soil temperature (°C) on July 1, 2012 and the water loss (%) between August 21 and 22, 2012.

Water Loss (%)	**Df**	**Sum Sq**	**Mean Sq**	**F value**	**Pr(>F)**
Treatment	10	150.13	15.013	1.1254	0.3572
Block	1	34.89	34.889	2.6155	0.1106
Treatment: Block	10	80.09	8.009	0.6004	0.8079
Residuals	66	880.41	13.340		

Temperature (°C)	**Df**	**Sum Sq**	**Mean Sq**	**F value**	**Pr(>F)**
Treatment	10	159.925	15.9925	3.9433	0.0003071
Block	1	0.306	0.3058	0.0754	0.7844801
Treatment: Block	10	42.771	4.2771	1.0546	0.4094278
Residuals	66	267.671	4.0556		