GIS-based Analysis to Understand the Effects of Environmental Variability on the Growth and Success of Native Plants on Green Roofs

by

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Abstract: Green roofs have a number of realized benefits including reducing stormwater runoff, saving building energy costs, and reducing the urban heat island effect. However, more research is needed to understand the effects of environmental variability on plants growing in these dynamic systems. In this study, Geographic Information Systems were used in conjunction with statistical analysis to uncover some of these relationships. 69 *Sibbaldiopsis tridentata* plants and 72 *Solidago bicolor* plants were monitored across an extensive green roof located in Halifax, Nova Scotia, from June 5th to November 10th, 2014. Plants were measured based on growth, survival, and reproductive potential and environmental data were also collected. Spatial information was obtained from the plants by turning the roof into a grid system. Additionally, a 3D model of the roof was constructed in ArcGIS. The model was then used in GIS to calculate a solar radiation model of the roof surface and this was incorporated into the analysis. Both species achieved faster growth, but had a greater risk of mortality, where there was low cover of vascular plants. Plant growth and survival were also greater with higher soil moisture, lower soil temperatures, and deeper soil. There were also species differences in responses to environmental conditions. The data show that significant spatial environmental variability occurred across the green roof system. Furthermore, certain building features, such as the Atrium Triangle, created detectable microclimates that influenced many plant and environmental variables. The data suggest that these microclimates were beneficial for plants growing on the extensive green roof. Geographic Information Systems not only provided the ability to visualize important spatial relationships but it also contributed significantly to the data analysis and ultimately to an increased understanding of the dynamic nature of the green roof system.

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1.1: Green Roof Technology

We are in an era where climate change, environmental pollution, and loss of global biodiversity are just a few of the many problems occurring around the world (Vitousek et al., 1997). Many of these global issues are without a doubt anthropogenic (Vitousek et al., 1997; Goudie, 2013). To address these issues we must look towards new technologies and ways of living to help suppress the effects of human activities on the environment. One major activity that causes such issues is urban development (Vitousek et al., 1997). The process of urbanization involves replacing the original land surface, usually containing soils and vegetation that provide many ecosystem functions (Nowak et al., 2002), with impervious surfaces, such as roads and buildings with shingled roofs (Pauleit et al., 2005). This results in adding pollution to the environment (Goudie, 2013), issues with controlling stormwater runoff (Scholz-Barth, 2001), and less habitat for organisms (Pauleit et al., 2005) which further results in a loss in ecosystem functioning (Alberti, 2005). Although it would be difficult to eliminate this activity, there are ways to mitigate this type of impact caused by urban development, for example by using green roofs (Dunnett and Kingsbury, 2004). Green roofs provide a layer of “soil” and vegetation to offset the original loss of these landscape features.

Green roofs are by no means a new technology – they have been built throughout human civilization, dating back to 2100 B.C. in ancient Mesopotamia (Velazquez, 2005). The sloping walls of the Ziggurat of Nanna (located in present-day Iraq) grew trees and shrubs and allowed people to cool down from the hot weather according to Velazquez (2005) and Magill et al. (2011). The Hanging Gardens of Babylon was another example of ancient green roofs, where lush rooftop gardens were also displayed. Later, sod roofs were built in cold climates, like Canada, by the Vikings to help protect their homes and provide insulation (Magill et al., 2011). In the 20th Century, Germany took the lead in developing green roofs to be used as a sustainable roofing alternative (Velazquez, 2005). In the 1980s, the European market accepted green roofs for commercial applications once technologies such as root barriers were developed to guarantee the longevity and safety of buildings beneath these vegetated roof systems. Today, green roofs are being built all over the world (Dunnett and Kingsbury, 2004).

Green roofs can be divided into two main groups: intensive and extensive green roofs (Dunnett and Kingsbury, 2004). Intensive green roofs have deep substrate which allows them to support a wide diversity of plants including trees and shrubs. Due to the great weight of intensive green roofs, however, these types of roofing systems are limited to being built on rooftops that can withstand the structural loading. Extensive green roofs are shallow, often supporting less than 15 cm of soil depth (Dunnett and Kingsbury, 2004). Although these modern green roof systems result in less structural loading than intensive green roofs, the shallow substrate limits the plant species that can be grown on them. Since there is much less soil, growing conditions on extensive green roofs tend to be much harsher for plants, as there tends to be less water availability and room for roots to grow (Wolf and Lundholm, 2008). Nevertheless, there has been some research examining what plant varieties can be grown in such harsh environments, including native plants (Monterusso et al., 2005; MacIvor and Lundholm, 2011). Extensive green roofs remain the focus of green roof research due to their lower cost, use of fewer materials, and the fact that they can be retrofitted on many pre-existing buildings with little or no additional structural support needed, which offers the possibility of widespread use (Dunnett and Kingsbury, 2004).

The installation of a green roof system has been shown to realize a number of benefits that alleviate many of the effects of urban development. Some of these benefits include: reducing stormwater runoff (MacIvor and Lundholm, 2011); removing CO_2 and harmful pollutants from the atmosphere (Currie and Bass, 2008; Getter et al., 2009; Speak et al., 2012); reducing the ‘urban heat island’ effect (Susca et al., 2011); extending the life of roof membranes (roof membranes are a common type of roofing system and are generally used to waterproof buildings) (Liu and Baskaran, 2003); providing habitat to wildlife to increase biodiversity (Dunnett and Kingsbury, 2004; Gedge and Kadas, 2005) ; and reducing heating and cooling costs in buildings (Liu and Baskaran, 2003; Wong et al., 2003; Dunnett and Kingsbury, 2004). Green roofs also provide a vegetative space to grow medicinal or edible plants, such as vegetables or berry bushes, hence the alternate name ‘rooftop garden’ (Dunnett and Kingsbury, 2004). Lastly, green roofs can also be considered aesthetically pleasing, compared to conventional roofing, which could potentially add value to a business by attracting customers (Dunnett and Kingsbury, 2004).

Environmental conditions on an extensive green roof can be dynamic and harsh for plants (Dunnett and Kingsbury, 2004). The shallow soil depth means that root exploration will be compromised and thus water availability will be limited. Furthermore, green roofs tend to be exposed to high amounts of wind and periods of drought that would exacerbate this condition (Dunnett and Kingsbury, 2004). In climates similar to the Maritimes, freeze-thaw cycles can be a major issue for plants growing on green roofs and can cause death if the plants are not adapted to handling such stress (Thomashow, 1998). It is also common for green roofs to have variable exposure to solar radiation when surrounding buildings shade certain parts of the roofs at different times of the day (Getter et al., 2009; MacIvor and Lundholm, 2011). Getter et al. (2009) showed that shaded parts of green roofs will hold more moisture than areas exposed to the sun. This is likely due to increased evaporation in sun-exposed areas, suggesting that moisture levels across a roof would rarely be uniform. In view of the many variables and stress-inducing factors, it is clear that plants must have certain adaptations and traits in order to survive, become established, and develop vegetative cover on green roofs.

Plants ideally suited to growing in these conditions would be fast-establishing and have a low-growing, mat-forming or compact growth form (Dunnett and Kingsbury, 2004; Oberndorfer et al., 2007). In order to deal with drought conditions plants would ideally have drought-tolerant adaptations such as succulent leaves, CAM-photosynthesis or other methods for reducing water loss. Plants grown on extensive green roofs should develop a shallow root system. Ruderal species (‘Weedy’ species; plants that colonize disturbed areas) are also known for doing well on green roofs as they tend to rapidly colonize habitat that was recently disturbed or subject to stressful conditions that other plants cannot tolerate (Oberndorfer et al., 2007).

Sedum species are the most common choice for extensive green roof systems and are considered to be the best commercial plant species for growing on green roofs (Dunnett and Kingsbury, 2004). They are often grown as monocultures and are known for their hardiness. *Sedum* have shallow roots and succulent leaves for storing water. However, many *Sedum* used by the green roof industry in Canada are not native to the regions they are used in and there are some concerns about the continuous use of *Sedum* monocultures (Sutton, 2008). Overuse of these plants as monocultures could lead to complications, such as widespread disease and pest infestation. An alternative to this issue is planting roofs with greater biodiversity and incorporating the use of native plant species accustomed to the microclimates of green roofs.

Native plants are an attractive option for green roofs as they are already adapted to the existing climate where the green roof is located (Monterusso et al., 2005). For example, native plants in the Maritimes would likely be adapted to freezing temperatures, whereas non-native species may not have adaptations for handling such stresses. Native plants can also have morphological traits, like succulent leaves (e.g. rose root, *Rhodiola rosea*), that can make them suitable for use on green roofs (Monterusso et al., 2005;

MacIvor and Lundholm, 2011). Using native plants may result in less irrigation and roof maintenance, as well as increased pollination by native pollinators (MacIvor and Lundholm, 2011). However, the city environment can cause harsh conditions compared to the countryside so there is no guarantee that natives will be suited for green roof conditions.

1.3: Current Research on Green Roofs

1.3.1: Two Major Benefits of Green Roofs

To date, most research in the green roof industry has tried to quantify and evaluate a number of ecosystem services that green roofs provide. Among these services or benefits are stormwater retention and energy conservation (Oberndorfer et al., 2007).

1.3.1.a: Stormwater Retention

Stormwater retention is an important benefit that green roofs can provide because preventing stormwater runoff from entering sewage systems can save costs in cities in a number of ways (Scholz-Barth, 2001; Dunnett and Kingsbury, 2004). In urban areas, around 75% of rainfall becomes direct runoff, often redirected by gutters to sewage systems (Scholz-Barth, 2001). This can be compared to a forested habitat that would only have about 5% runoff. One consequence of rainfall becoming direct runoff in urban areas has been seen in England, where heavy rainfall events caused major flooding in counties like Sussex and Kent in 2000 and 2001, causing major economic loss (Marsh and Dale, 2002). This was likely due to such heavy amounts of stormwater being redirected to the sewage systems and rivers in a very short amount of time. Another consequence of stormwater not being captured in cities is the added cost of water treatment by sewage treatment plants (Scholz-Barth, 2001).

Since rooftops may account for 40-50% of impervious surfaces within a city, green roofs are becoming an attractive option as a strategy for stormwater management (Stovin et al., 2012). One study in the UK found that their green roof test bed containing *Sedum* was able to retain approximately 50.2% of overall rainfall (Stovin et al., 2012). MacIvor and Lundholm (2011) compared 15 different native plant species from the Maritimes which were grown as monocultures in modular arrays on a green roof in Halifax, Nova Scotia. They found that the top performing species retained up to 75.3% of experimentally added stormwater. Dunnett and Kingsbury (2004) suggest that most research indicates that green roofs can retain between 60-80% of stormwater. Plants growing on green roofs can assist with stormwater retention by absorbing the water, using it for processes such as growth and photosynthesis, and transpiring it back into the atmosphere (Taiz and Zeiger, 2006). The physical properties of the soil substrate, the soil depth, and the type and thickness of the vegetation all play key roles in determining the performance of green roofs for retaining stormwater (Dunnett and Kingsbury, 2004; MacIvor and Lundholm 2011).

The installation of a green roof has also been shown to aid with energy conservation for the building supporting the roof (Dunnett and Kingsbury, 2004). More specifically, green roofs are known for their ability to reduce heating and cooling costs. Green roofs have been shown to keep the indoor temperature of buildings stable by providing protection from large temperature fluctuations and extreme temperatures (Fioretti et al., 2010; Teemusk and Mander, 2010: Jaffal et al., 2012). This is because green roofs influence energy flux through the building surface in several ways including direct shading of the roof by vegetation, evaporative cooling from the plants and green roof substrate, insulation from the vegetation, and the thermal mass effects from the soil substrate (Liu and Baskaran, 2003).

In a study from Ottawa, Canada, Liu and Baskaran (2003) observed that an extensive green roof was able to reduce the energy demand for air conditioning in summer months by over 75% compared to a light grey “reference roof” which represented a conventional rooftop. It should be noted that a building with a green roof in a hot climate is likely to save more energy on cooling compared to a building with a green roof in a cold climate saving energy on heating, in particular where freezing would occur. This is because green roofs are better at cooling in hot weather than insulating in cold weather (Liu and Baskaran, 2003; Dunnett and Kingsbury, 2004). The insulating properties of a green roof, however, should not be overlooked. According to Peck et al. (2003), 20cm of soil substrate with 20-40cm of grass vegetation has an equivalent insulation value to 15cm thick of mineral wool insulation.

Similar to stormwater retention, the thermal performance of a green roof depends on both the depth of the soil substrate and the thickness of vegetation; a deeper soil substrate and thicker vegetation on a green roof will result in better thermal performance (Dunnett and Kingsbury, 2004). This suggests that low-growing plants like the commercial *Sedum* species might not be as good for thermal performance on green roofs as some other plants, such as graminoids (grasses). Lundholm et al. (2014) found that some species of graminoids were able to reduce the amount of heat loss from study roofs during a winter study in Halifax, Nova Scotia. This shows further support for choosing native plant species for green roofs rather than the traditional low-growing, non-native *Sedum*.

1.3.2: Environmental Variability on Green Roofs

Although most research on green roofs focuses on trying to quantify the thermal and water retention properties of green roofs, very little research has considered how environmental variability can affect these benefits. Variability in environmental conditions can cause adverse spatial and temporal effects on a rooftop. For example, nearby buildings or surrounding trees could provide shelter from harsh winds or heavy amounts of sunlight on certain parts of a rooftop but not others. Also, Dunnett and Kingsbury (2004) suggest that atmospheric pressure varies across the surface of a flat roof; the centre will have relatively low pressure while the edges and corners experience relatively high pressure.

In a study mentioned earlier by MacIvor and Lundholm (2011), it was found when measuring stormwater retention and surface temperatures of experimental plant modules that there was a significant influence on the results caused by shading from the surrounding buildings. This effect was so strong that in some cases the position of the modules on the roof was more significant than the plant species treatment. Their study concluded that environmental conditions greatly influence extensive green roof performance and that further research should consider environmental variability across a rooftop. Köhler (2006) found similar results while evaluating vegetation dynamics on 10 “sub-roofs” over the period of 20 years. It was found that some tall trees growing near the study roofs provided greater heterogeneity of habitat exposure and promoted biodiversity on the rooftops. This was caused by trees creating shaded and semi-shaded microenvironments on the roofs which allowed for shade plants to thrive alongside sun-loving plants.

Getter et al. (2009) realized that differences in solar radiation can change plant community structure and can affect soil moisture levels in soil substrate. They found that shaded areas on a green roof held more moisture than areas exposed to high amounts of solar radiation. This was likely due to increased evaporation and transpiration in areas with higher solar exposure. In one more example, Piana and Carlisle (2014) collected spatially explicit vegetation data on an experimental green roof in New York and produced various kinds of visual maps. Some of these maps depicted changes in vegetation over time and temperature profiles of the roof. This type of spatial and temporal analysis may be a useful for assessing the conditions on a green roof.

It is known that abiotic factors, such as exposure to wind and different amounts of solar radiation, will affect the growth and composition plants (Hoefs and Shay, 1981; Chapin et. al, 1987; Theodosiou, 2003; Getter et al., 2009). Responses by plants to variability in environmental conditions will likely result in physiological and morphological differences across a green roof since, as explained above, the conditions on green roofs are rarely uniform. According to Boardman (1977), various morphological and physiological differences have been observed within a plant species growing in shaded areas compared to highly exposed areas. For example, plants species adapted to shaded areas cannot perform high rates of photosynthesis but are very efficient in low light intensities, while plant species that typically grow in high light intensities have a greater capacity for photosynthesis but may not be as efficient if exposed to lower light levels. Furthermore, a plant that has developed in a shaded area compared to a plant of the same species in a highly exposed area might have longer and narrower leaves, larger chloroplasts and contain a higher proportion of chlorophyll b to chlorophyll a.

If we want to improve our understanding of the ecological services provided by green roofs and how they can be optimized, we need to gain a better understanding in the relationship between spatial and temporal environmental variability on green roofs and how different plant species respond in these systems. One of the best ways to study spatial and temporal relationships is by using Geographic Information Systems (GIS), which will be discussed in the next section.

1.3.3: Spatial and GIS-based Analysis of Green Roofs

Spatial data are characterized by having geographic coordinates or other spatial identifiers which allows the data to be located in geographic space (Jensen and Jensen, 2013). Geographic Information Systems (GIS) have been developed to store, organize, edit, visualize, and analyze spatial and even non-spatial data. GIS is a powerful tool and is ultimately used to help understand spatial relationships and gain new information from spatial data. Displaying data in the form of maps can be useful as this type of visualization can reveal patterns and relationships that might not be apparent by traditional methods of data analysis (Piana and Carlisle, 2014). Visualizing spatial data can also be useful for communication and collaboration in scientific research (Jensen and Jensen, 2013).

Incorporation of spatial and GIS-based analysis in scientific research is becoming commonplace (Jensen and Jensen, 2013) and it is one of the most popular growing fields in the study of ecology (Fortin and Dale, 2005). A number of recent studies are showing the usefulness and sheer power of spatial and GIS-based analysis. Iverson and Prasad (1998) used GIS to analyze plant species data provided by the Illinois Plant Information Network, a species database containing all information known about the distribution of vascular flora in Illinois. Using GIS and spatial statistics allowed the study to identify important patterns in species richness and biodiversity. Wong and Jusuf (2008) demonstrated the usefulness of GIS-based analysis by assessing and analyzing greenery conditions in 3D and predicted temperature changes across a university campus in Singapore. Schröder and Pesch (2004) used GIS and spatial statistics to evaluate the spatial distribution of metal accumulation in mosses across Germany. The study demonstrated a number of novel techniques for spatial analysis including spatial interpolation of moss monitoring data by using a method known as Kriging. Kriging is a method of spatial interpolation whereby unknown values of a target location are predicted based primarily on observed values from sample locations (Matheson, 1963). This produced visual maps depicting zones of high and low amounts of metal accumulation in mosses across Germany.

In green roof research, however, spatial and GIS-based analysis has seldom been used (Piana and Carlisle, 2014). One of the only studies to look at the use of GIS-based analysis for green roof research was done by Luo et al. (2011) who proposed a simple framework for how GIS and Google Earth might be used in the study of green roofs. As mentioned earlier, Piana and Carlisle (2014) also conducted a study that incorporated the use of spatial analysis on green roofs. Their study proposed a methodology for collecting spatially explicit vegetation data on a green roof which involved dividing the roof into 2 square meter sections. Field note diagrams depicting plant species footprints would be drawn at each square section and then transcribed and compiled into Adobe Illustrator

Software. This methodology provided a good means for studying vegetation dynamics overtime and appears to have strong potential in future green roof research. Still, to date no research has effectively used GIS-based analysis to visualize, analyze and ultimately gain new information about how green roof plants respond to spatial environmental variability and how this affects the ecological services provided by green roofs.

In this study, a methodology is proposed for collecting spatial data on a green roof system. This methodology was used to achieve one of the study's main objectives: to show how GIS can be incorporated into green roof research. Additionally, a novel technique for reconstructing buildings and green roofs in 3D is proposed. One specific goal from creating the 3D model of the green roof and adjacent buildings was to be able to model the differential shading that occurs across the green roof caused by nearby building features. These techniques are used to understand how spatial environmental variability affects plants growing in an extensive green roof system.

2.1: The Study Roof

Spatial environmental variability and plant performance was assessed on an extensive green roof located on top of the Atrium building at Saint Mary's University, Halifax, NS. This study roof was installed in the spring of 2010. The green roof is non-irrigated and measures 24m x 9m in the shape of a rectangle. The green roof system consists of: 7.5cm of commercial substrate used for extensive green roofs (Sopraflor X, Soprema Inc., Drummondville, Quebec); extensive green roof drainage containers (ELT EasyGreen, Brant-ford, Ontario); a roof membrane; a 2.5cm thick plywood protection board; and rigid polyisocyanurate (R = 5 per 2.5 cm) with a thickness ranging from 5-15cm, which sits on top of the steel roof deck. The roof is subdivided into eight sections which measure approximately 6m x 4.5m. Each section has its own roof drain and sections are separated by metal edging and rubber pond liners. This prevents water from moving between sections. Each section is further subdivided into three more subsections, measuring approximately 2m x 4.5m. Plugs of various plant treatments were originally planted into the 24 green roof subsections. The plugs were spaced apart by 15cm. Within several years, plants became established and approximately 50% cover of vascular plants was achieved.

Before this study began, it was observed that certain building features, such as the Atrium Triangle and the wall of the Science building, provide differential shading across the green roof during different times of the day (see Figure 1 below). Since this study looks at how spatial environmental variability affects plants growing in a green roof system, it was one of the goals of this study to try and model this shading.

Figure 1. A photograph taken on August 20th, 2014 of the extensive green roof located on top of the Atrium building at Saint Mary's University, Halifax, NS. It was observed prior to the study that certain building features, like the Atrium Triangle, provide differential shading on the green roof.

2.2: Sampling Design

To understand how spatial environmental variability affects the performance of plants on a green roof, the plants should be considered in a spatial context as well. In order to do this, a sampling design was made to select and monitor individual plants growing on the extensive green roof. Spatial information was taken from each study plant and growth, survivorship, and reproductive potential was monitored over a six month period.

Two plant species were selected for observation on the green roof: *Sibbaldiopsis tridentata* (three-toothed cinquefoil) and *Solidago bicolor* (white goldenrod). Both species are native to North America and naturally occur in Atlantic Canada. These species are characterized as being low-growing, perennial, herbaceous forbs (USDA, 2014). These two species were planted well before the study began and they were selected primarily due to the fact that they were the most abundant on the study roof compared to the other plant species. They also have simple morphologies that make them ideal for observing and measuring growth, survival, and reproduction.

To have a sampling distribution that covers the greatest range of environmental conditions, it was decided that nine plants would be selected within each of the eight sections of the green roof, totaling a maximum number of 72 individuals per species. In each section, three of the nine plants would be within three feet of green roof edging; three more plants would be in the center of the section; and the final three plants would be on the side of the section opposite to the edging. The sampling design can be seen in Figure 2 A below. This formation was chosen because it provides good coverage for each section of the green roof in addition to allowing the study to take into account plants growing near the edges of the roof, which were hypothesized to create different microclimates and influence the growth of plants.

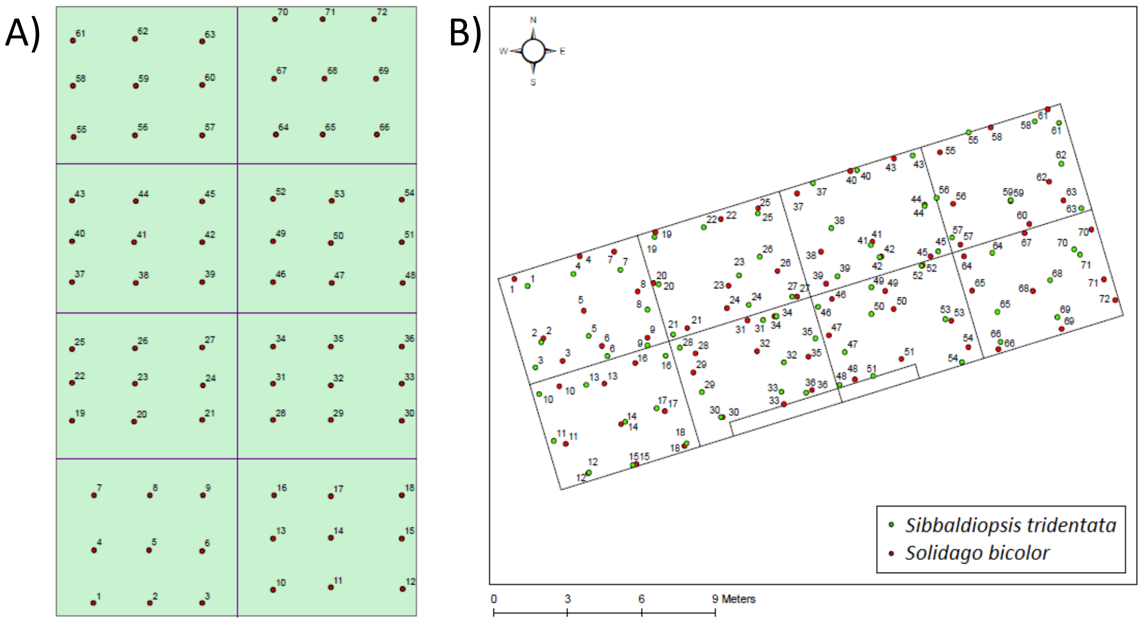


Figure 2. A) The sampling design used to select plant individuals on the Atrium green roof at Saint Mary's University, Halifax, NS. Nine plants of each species (*S. tridentata* and *S. bicolor*) were selected in each of the eight sections to provide a good sampling cover of the roof. **B)** The positions of the study plants across the Atrium green roof at Saint Mary's University, Halifax, NS. Location data were obtained from the plants by creating a grid system across the green roof and positions were spatially adjusted using ArcGIS.

Individual plants were selected based on a number of selection criteria. Each individual selected for observation would have to be within a three-foot radius of the sampling location indicated in the sampling design (see Figure 2 A above). If a plant of that species could not be found within that area, no data would be taken for that location. Secondly, selected plants would represent the local vegetation. For example, if the majority of the plants appeared to be quite small within a subsection, a large plant should not have been selected. Lastly, during the course of this study, a separate study was being conducted which involved creating various topographic changes and microclimates (i.e. introducing logs and small piles of white rocks) across the roof. Due to the potential effects that these changes might have on the individual plants chosen for this study, additional criteria were made: plants must be at least six inches from any log or rock pile; and if the sampling location falls on a region that had undergone topographic changes, the chosen plant should be in the area with the least amount of disturbance. It was decided that if any study plant showed that they were being influenced by these features, they should be removed from the dataset.

After sampling for plant individuals based on the criteria above, 72 *Solidago bicolor* plants and 69 *Sibbaldiopsis tridentata* plants were selected for the study (three sampling locations were void of *Sibbaldiopsis tridentata*). Once plants were selected, a tag containing the ID number for the plant was placed into the soil next to the individual so that it could be easily found for data collection.

2.3: Obtaining Spatial Information from the Plants

I obtained location data from the plants by creating a grid system out of measure tapes for each of the eight sections of the green roof. Tape measures were laid out along the horizontal and vertical sides of each section and the coordinates of each study plant were recorded to a spatial resolution of approximately ten centimeters. Using the Spatial Adjustment tool in ArcGIS (ArcGIS 10.2.2, Environmental Research Systems Institute, Redlands, California), I compiled and georeferenced the plant locations within each section to form a complete map of the plant locations across the green roof (see Figure 2

B above). The full method is outlined in section 2.5.1: Mapping the Positions of the Plants.

2.4: Data Collection

2.4.1: Plant Measurements

Both species were measured on a monthly basis from June 5th to November 10th, 2014. Measurements were based on three distinct categories: growth, health, and reproductive potential. Growth was assessed for *S. tridentata* by measuring the height of the plant (cm) and counting the number of leaves. For *S. bicolor*, growth was measured by taking the length and width of its longest leaf (cm). Height was also measured for this species, however this parameter was not used in this study to indicate growth because it was found to be too dependent on whether or not the plant flowered. Relative growth rates were calculated by using a formula that is described in Section 2.6: Statistical Analysis. The health of both species was assessed using a health score (Butler and Orians, 2011) ranging from 0 to 2: a score of 2 suggested that the plant had green stems and green leaves and was healthy; a score of 1 meant that the plant was unhealthy with only a green stem and little or no green leaves; and a score of 0 suggested the plant had died. Lastly, reproductive potential for *S. tridentata* was measured based on the date that the plant flowered and the number of flowers the plant had at a given time. For *S. bicolor*, reproductive potential was measured based on the date the plant flowered and the length and width of the plant's flower stalk (cm) (Heim and Lundholm, 2014).

Soil moisture and temperature data were collected on July 18th and July 23rd, 2014. Data collection on July 18th occurred shortly after a heavy rainfall. Data were also collected on July 23rd since there was an extended period of drying between July 18th and the 23rd. In the Maritimes, July tends to be one of the warmest months and is likely the time in which plants on a green roof would be at the highest risk for heat and water stress. Sampling shortly after a rain event acted as a control for the moisture levels, since a rainfall would theoretically homogenize the soil moisture levels across the green roof. Drying periods would allow for detection of arid regions of the green roof as well as areas that retained more moisture, which may influence plant survival. Both sampling events were conducted mid-day and in full sun. Measurements were taken at each plant location on the extensive green roof. Soil moisture data were collected by placing a moisture probe (GS3 Ruggedized Soil Moisture, Temperature, EC, Hoskin Scientific Limited, Burlington, Ontario) into the soil substrate within ten centimeters of each plant; soil temperatures were recorded by placing a temperature probe (9878E Pocket Digital Thermometer, Taylor, Oakbrook, Illinois) into the substrate by each plant in a similar fashion to the moisture probe. Soil depth in centimeters was also measured at each plant location.

On August 1st, 2014, photographs of each study plant were taken using a Nikon Coolpix L110 camera. A two-foot diameter ring (see Figure 3 below) was placed around each plant, indicating the likely area around the plant in which competition for resources, such as sunlight, soil, and nutrients, would occur. These photos were analyzed in

JMicroVision (JMicroVision 1.2.7, Geneva, Switzerland) using the Point Counting feature. A sampling grid of 300 points was used to assess the percentage of vascular plant cover, moss cover, and substrate cover within the sampling ring. The purpose of these photographs was to assess the local neighbourhood for each study plant and to assess the overall vascular plant cover of the extensive green roof.

Figure 3. A photograph of a study plant (*S. tridentata)* on the Atrium green roof at Saint Mary's University, Halifax, NS taken on August 1st, 2014. A two-foot diameter ring was placed around each study plant so that vascular plant cover, moss cover, and substrate cover could be assessed using JMicroVision software.

GIS was used to generate two sets of data: solar radiation (see section 2.5.4: Modeling Solar Radiation) and the distance from the green roof edge. The distance from the green roof edge dataset indicated how far each study plant was located from the nearest green roof edge (in meters), in order to assess whether the edge altered the microclimate.

2.5.1: Mapping the Positions of the Plants

In a blank map in ArcGIS (with no specified coordinate system), an excel file containing the species, ID number, and X and Y coordinates (in inches) was uploaded (see section 2.3 for how this data was collected). In addition to the plant coordinates, four more coordinates were added to represent the four corners of the green roof section. The reason for this will be explained. Using the command “Display XY Data” resulted in the creation of an Events Layer which displayed points representing the positions of the plants with no geographic coordinate system. This layer was then exported as a shapefile. Shapefiles can store geometry and attribute information of a dataset (Jensen and Jensen, 2013). Once a shapefile was made, the points were spatially adjusted to an AutoCAD drawing of the Atrium green roof, which was already georeferenced, by using the Spatial Adjustment tool in ArcGIS.

The Spatial Adjustment tool operates by creating displacement links between two features. I used the Spatial Adjustment tool to link the four corner points of each green roof section to the corresponding corners of each section of the georeferenced AutoCAD drawing. After selecting “Adjust”, the corner points and all of the plant positions within the corners were moved to their correct positions within the georeferenced AutoCAD drawing. The corner points were then removed from the shapefiles so that only the plant positions remained. Lastly, the command “Calculate Geometry”, within the attribute table of each shapefile, was used to calculate the geographic coordinates (Northings and

Eastings) of each study plant. These geographic coordinates were used for the remainder of the study. The resulting map of the plant positions can be seen in Figure 2 B.

2.5.2: Digitizing the Roof in 3D

Having a 3D model of the green roof and adjacent buildings is not only useful for visualization, but in GIS one gains access to a very large array of statistical tools and analyses that can generate valuable information about the 3D model. For instance, one tool has the ability to calculate incoming solar radiation (WH/m^2) across a 3D surface. Since this study aims to study the relationships between environmental conditions on a green roof and how plants respond to these conditions, this tool could be very useful.

As it is a common theme in GIS, there are a number of ways one can digitize a building in 3D. The chosen method should be based on how much accuracy is desired, the amount of information available, and the amount of time required for completion. I devised a methodology for modeling a building with a green roof in 3D based on information from building blue-prints, an AutoCAD drawing, and a campus survey that georeferenced the foot-print of the campus buildings - all of which were provided by Saint Mary’s University. Although some steps involved in this methodology can be quite time-consuming, the result is a highly accurate 3D representation of the study roof and surrounding building features.

In ArcGIS, an AutoCAD drawing containing scaled rooftop features of the Atrium and Science buildings from Saint Mary's University's campus was uploaded. The AutoCAD drawing did not contain a spatial reference, meaning it could not be placed on a map with a geographical context, so the drawing first had to be spatially adjusted which was done by using the Spatial Adjustment tool. As mentioned above, this tool operates by creating displacement links between locations from an unreferenced feature to the corresponding locations on another feature. I created displacement links from all of the corners of the AutoCAD drawing to the corresponding corners of the georeferenced campus survey drawing. The reason that the campus survey wasn't used instead of the AutoCAD drawing was that it did not contain as much detail. For example, the campus survey only contained the building footprint, while the AutoCAD drawing contained important internal features within the footprint such as the outline of the green roof being studied. When all the links were made, "Adjust" was then used to spatially adjust the AutoCAD drawing.

The following series of steps involved creating a framework of the building in 3D. This is best done using ArcScene (one of the software components of ArcGIS) which can interactively view 3D data. ArcMap can also be used, however it can only view data in two dimensions. I began by creating a 3D point feature class. Using the Editor tool, points were added to all of the corners of the features within the spatially adjusted AutoCAD drawing. Elevations of each 3D point were adjusted by using "Edit Vertices" within the Editor tool. Elevations of each feature were determined by the blue print drawings provided by Saint Mary's University. Once all of the 3D points were created and adjusted, I created 3D line feature classes. It should be noted that 3D polygons can also work, but it was found that 3D lines produced the best results. To allow for the fewest computational errors in the upcoming steps, 3D line feature classes were designated for specific sections of the Atrium and Science buildings. For example, one feature class was created for the Atrium skylight next to the green roof, as seen in Figure 4 below. Using the 3D Editor tool in ArcScene, lines were created by creating line vertices at each of the 3D points, creating the 3D features of the buildings. To ensure accuracy, the vertices of the lines were manually adjusted to the exact coordinates of the 3D points. It should be noted that for computational purposes, only the features of the roof need to be digitized - adding features such as walls and flooring is useful for visualizing, however the added information can increase the chance of errors when creating a Triangulated Irregular Network (TIN) or raster surface.

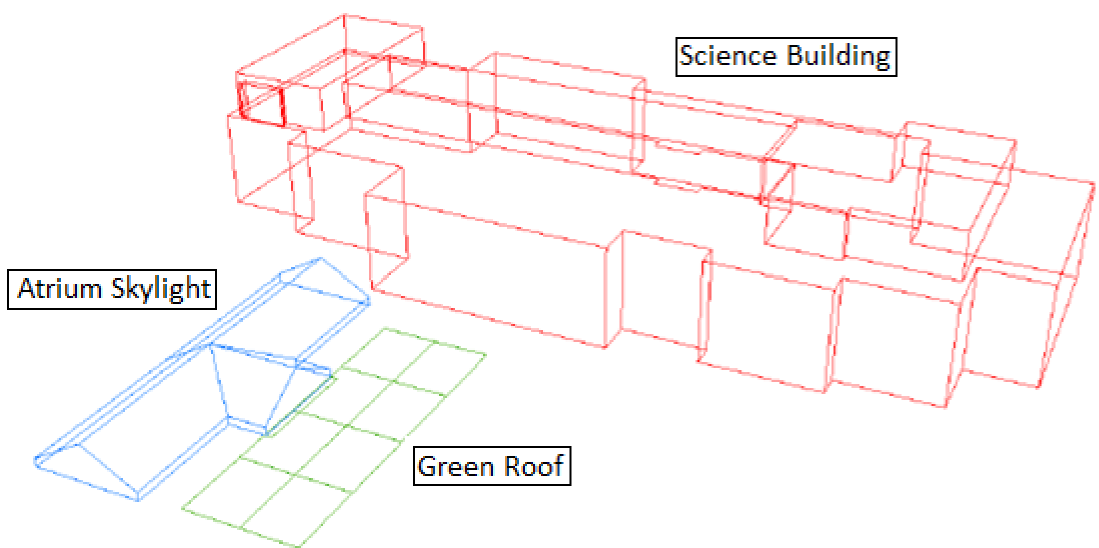


Figure 4. A 3D framework of the green roof and surrounding building features of the Atrium and Science buildings at Saint Mary's University, Halifax, NS. These 3D line feature classes were created in ArcGIS and were later used to create the final 3D model.

Once the 3D line feature classes were completed, the Create TIN (3D Analyst) tool was used to create 3D surfaces for each of the building sections. Next, the TIN to Raster tool was used to convert the TIN surfaces into raster surfaces. A raster surface is a grid of cells, where each cell is assigned a value (Jensen and Jensen, 2013), in this case an elevation value in meters above sea level. Rasters are one of the most commonly used file formats for analyzing surfaces in 3D. Lastly, the Mosaic to New Raster tool was used to compile all of the building sections into one raster file (see Figure 5 A below). The final 3D model, which includes the green roof, the Atrium building, and the Science building, can be seen in Figure 5 B.

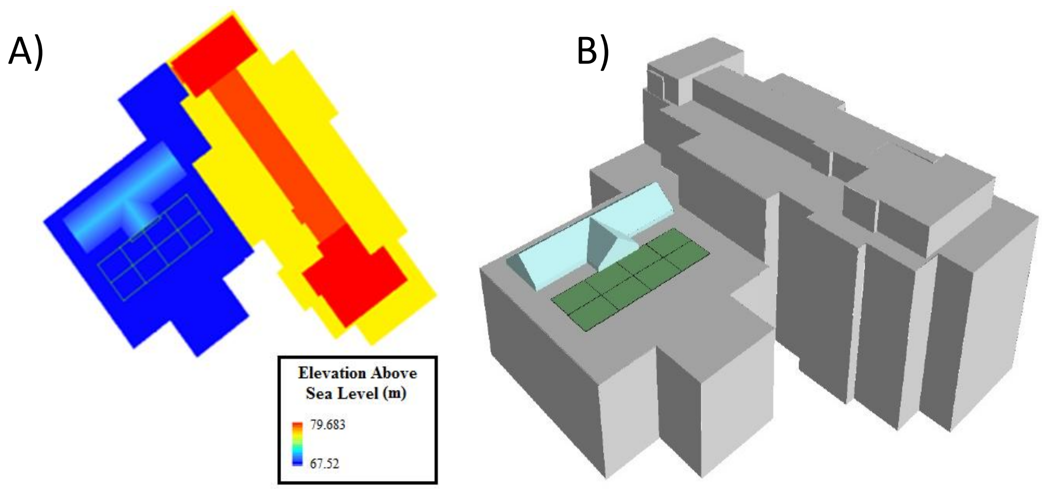


Figure 5. A) A raster surface/digital elevation model of the green roof, Atrium building, and Science building at Saint Mary's University, Halifax, NS. This raster surface was built using ArcGIS. **B)** The final 3D model of the green roof, Atrium building, and Science building at Saint Mary's University, Halifax, NS. This model was built in ArcGIS and viewed in 3D using ArcScene.

2.5.3: Mapping Spatial Data

Once the geographic coordinates of the plant positions were established, excel files were created with columns containing the plant Ids, geographic coordinates, and the data collected for the corresponding plants (e.g. soil moisture and temperature). One file was designated for *S. tridentata*, the other for *S. bicolor*. These tables were uploaded into ArcGIS and were turned into shapefiles by selecting "Display XY Data" followed by exporting the events layer as a shapefile. This feature class containing points was capable of being spatially analyzed by a number of tools within ArcGIS, including the Kriging (Spatial Analyst) tool, which interpolates a raster surface based on values from sample points. By using these techniques, a number of maps were generated to help understand the complex patterns and relationships derived by the spatial data.

2.5.4: Modeling Solar Radiation

As part of analyzing the spatial environmental variability occurring across the extensive green roof, a specific tool built by ArcGIS was incorporated into the study: Area Solar Radiation (Spatial Analyst). In general, this tool uses a raster surface/digital elevation model (DEM) to derive incoming amounts of solar radiation in watt hours per square meter. One of the main purposes for digitizing the study roof into a raster surface was to utilize this tool, since it accepts no other file format. It should be noted that the tool assumes that the values of the raster surface are elevations in meters. This tool is very powerful and takes into consideration the position of the raster/DEM on the surface of the earth (latitude and longitude), the date and/or time of day, and the clarity of the sky (i.e. clear or overcast). There are a number of options for time periods when calculating the solar radiation model: over the course of a year, month, week, day, hour, or even at a single moment in time. It is important to note that in order to accurately calculate solar radiation values within a day (for example, at 12pm on June 1st, 2014) using this tool, Local Standard Time must be used when setting the start and end times, as well as inputting the longitude of the DEM in degrees decimal minutes. In addition to this, the tool does not account for daylight savings time, so one hour may need to be subtracted during this period. For example, in Halifax, NS, between March 9th and November 2nd, 2014 (daylight savings) the time zone value should be set to -3 instead of -4, and the desired time left as normal.

For this study, a single model of solar radiation, depicting the total amounts of incoming solar radiation received (WH/m^2), was calculated from June 5th to September 5th, 2014. This time period was chosen because it encompasses the portion of the growing season in 2014 during which plant measurements were taken. Once the solar radiation model was generated, relationships and patterns were observed by comparing the model to other maps, such as maps of spatial data interpolated by Kriging (Spatial Analyst). In addition, the Extract Values to Points (Spatial Analyst) tool was used to extract solar radiation values (WH/m^2) at each plant location by using the shapefile containing plant coordinates. This added another variable for statistical analysis.

To test the accuracy of the solar radiation model, a time lapse camera was mounted in front of the green roof on August 20th, 2014. The camera took photos of the green roof every 15 minutes for the entire day. Several time points during the day were selected for comparison and those same time points were used to calculate individual solar radiation models in GIS using the Area Solar Radiation (Spatial Analyst) tool. No significant errors were observed when comparing the angles of the shadows in both photos. This suggests that both the 3D model of the buildings and the Area Solar Radiation (Spatial Analyst) tool are very accurate (see time-lapse comparisons in Figure 6 below).

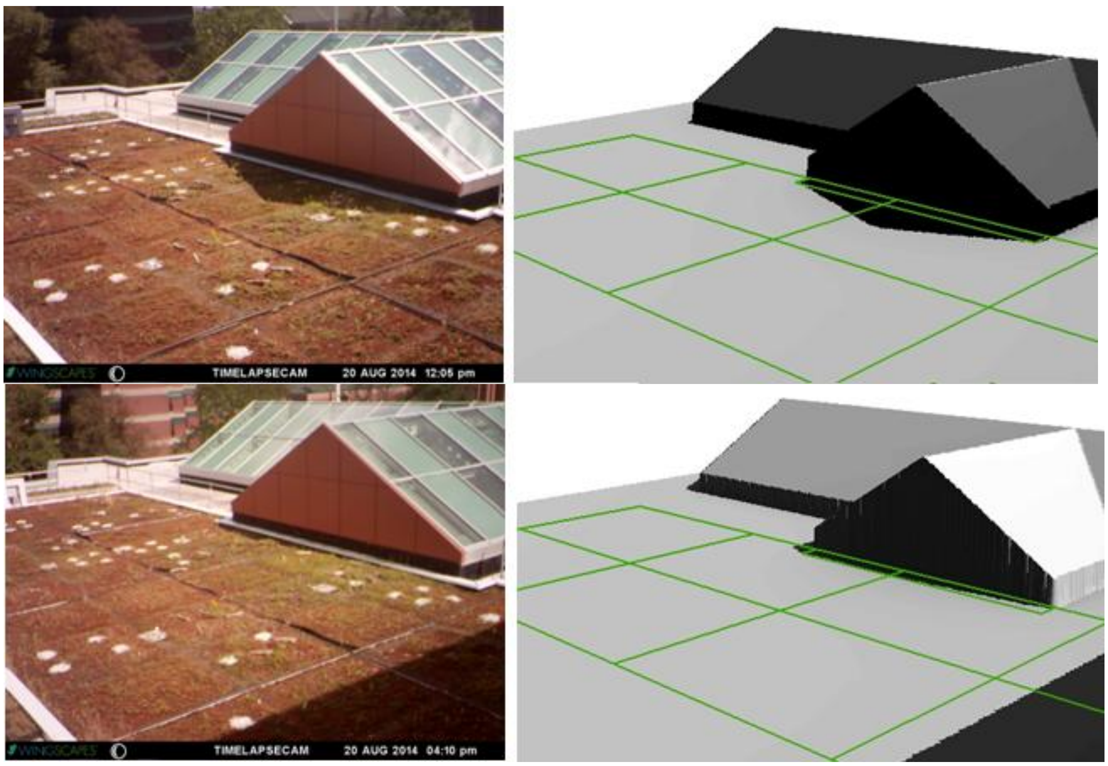


Figure 6. A time-lapse camera was mounted on the Atrium green roof at Saint Mary's University, Halifax, NS on August 20th, 2014 to test the accuracy of the solar radiation models created in ArcGIS. The photos on the left are the real time lapse photos (the top photograph is 12:05pm; the bottom photograph is 4:10pm) and on the right are the solar radiation models calculated at the corresponding times.

2.6: Statistical Analysis

Data were analyzed using RStudio (RStudio 0.98.1060, Boston, Massachusetts). Multiple linear regression analysis, generalized linear regression analysis, and two-sample t-tests were the primary methods for statistical analysis. StepAIC was used to perform stepwise model selection for both the multiple linear regression and generalized linear regression models. This method for model selection uses backward and forward stepwise regression in combination with Akaike Information Criterion (AIC) values to rank the models. The model with the lowest AIC value was selected as the model of best fit.

To calculate relative growth rates, for example the relative change in the number of leaves for *S. tridentata,* a formula was used from Harper (1977): [ln(Time 2) – ln(Time 1)] / the number of days (ln = natural logarithm). This formula accounts for differences in plant sizes so that relative growth rates can be compared among individuals.

3.1: Plant Growth

Multiple regression analysis showed that *S. tridentata* achieved fastest growth in areas with lower neighbouring vascular plant cover, deeper soil, lower solar radiation, and higher soil moisture (see Table 1 below). Low vascular plant cover was the most significant predictor of both the change in number of leaves and the change in height of the plants. Multiple regression models were statistically significant for both the change in number of leaves (R^2=0.26; P<0.05) and the change in height (R^2=0.22; P<0.05) in *S. tridentata*. Maps of the change in number of leaves and change in height of *S. tridentata* can be seen below in Figure 7 A and B respectively.

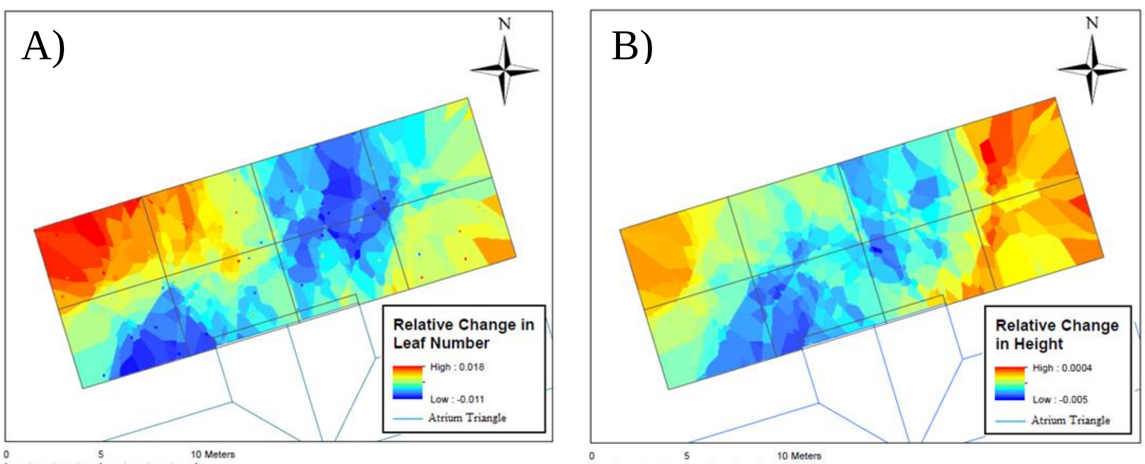


Figure 7. The relative change in leaf number (**A**) and height (**B**) for *S. tridentata* plants on the Atrium green roof at Saint Mary's University, Halifax, NS from June 5th to September 5th, 2014. A formula was used to account for differences in plant sizes so that relative growth rates can be compared among individuals (Harper, 1977).
Note: All data in **A)** to **B)** were interpolated using Kriging in ArcGIS.

S. bicolor plants achieved the fastest leaf growth in areas with lower vascular plant cover and lower temperatures (see Table 2 below). Positive changes in the change in leaf width were also observed in shallower soils. Multiple regression models were statistically significant for the change in leaf width (R^2=0.37; P<0.01), change in leaf length (R^2=0.18; P<0.05), and change in width x length (R^2=0.34; P<0.01). Maps of *S. bicolor*’s change in leaf length, leaf width, and leaf width x length can be seen below in Figure 8 A, B, and C respectively.

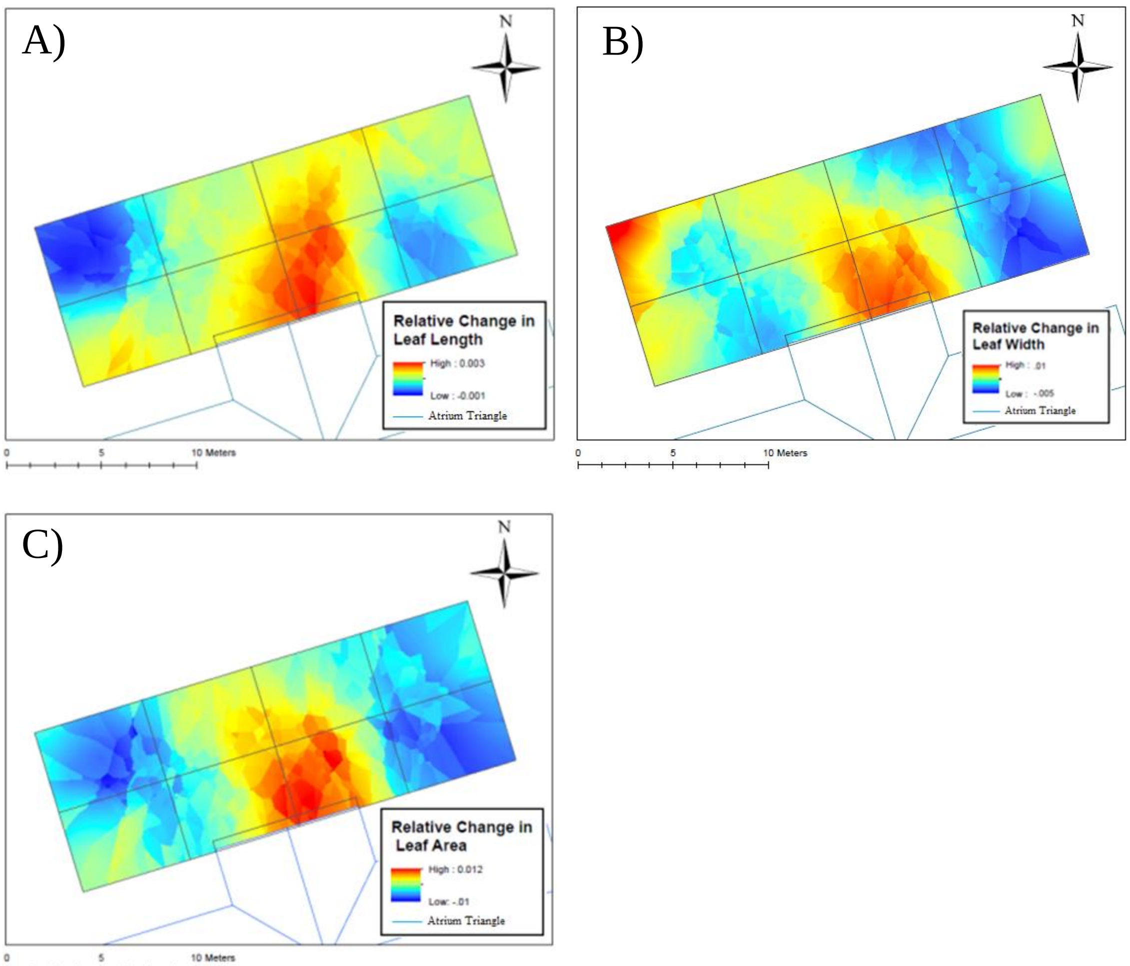


Figure 8. The relative change in leaf length (**A**), leaf width (**B**), and leaf area **C**) for *S. bicolor* plants on the Atrium green roof at Saint Mary’s University, Halifax, NS from June 5th to September 5th, 2014. A formula was used to account for differences in plant sizes so that relative growth rates can be compared among individuals (Harper, 1977). Note: All data in **A)** to **C)** were interpolated using Kriging in ArcGIS.

Variable	R-Square Value	P-value	Model of Best Fit
Number of Leaves	0.257	0.011	-Vascular Plant Cover**, +Soil Depth**, -Solar Radiation*, -Flower*, +Health, +Distance from Edge, +Moisture
Height (cm)	0.2194	0.009	-Vascular Plant Cover***, -Moss Cover*, +Moisture, +Soil Depth, +Health
Leaf Width (cm)	0.1684	0.008	-Vascular Plant Cover**, -Temperature*, +Change in Moisture
Leaf Width x Length (cm)	0.1873	0.011	-Vascular Plant Cover**, +Change in Moisture, -Temperature, +Moisture
Vascular Plant Cover (%)	0.5482	2.98E-11	-Temperature***, +Moisture**, +Soil Depth
Change in Soil Moisture (%)	0.4288	9.16E-07	+Moss Cover**, +Solar Radiation**, -Distance from Edge**, -Soil Depth*, +Substrate Cover
Soil Moisture (%)	0.4598	1.50E-09	+Vascular Plant Cover***, -Solar Radiation**
Soil Temperature (°C)	0.7546	< 2.2e-16	+Solar Radiation***, -Soil Depth***, +Substrate Cover***, +Moss Cover**, -Change in Moisture
Moss Cover (%)	0.4482	8.39E-08	+Change in Moisture**, +Distance from Edge*, +Solar Radiation, +Temperature
Substrate Cover (%)	0.1208	0.014	-Soil Depth*, -Moisture

Table 1. Multiple linear regression results for data collected at *S. tridentata* plant locations during the study in 2014 on the Atrium green roof at Saint Mary's University, Halifax, NS. Note that for some of the items listed under Model of Best Fit: Flower refers to whether or not the plant flowered during the study in 2014; Health refers to the health scores recorded for the plants between June 5th and September 5th, 2014; Distance from Edge refers to the distance of the plant in meters from the nearest green roof edge.

Variable	R-Square Value	P-value	Model of Best Fit
Leaf Width (cm)	0.365	0.0001	-Vascular Plant Cover**, -Temperature**, -Moss Cover**, -Soil Depth*, +Health, -Substrate Cover
Leaf Length (cm)	0.1844	0.014	-Moss Cover**, +Health**, -Vascular Plant Cover**, -Substrate Cover*
Leaf Width x Length (cm²)	0.3399	0.0004	-Vascular Plant Cover***, -Moss Cover**, +Health**, -Substrate Cover*, -Temperature*, -Soil Depth
Flower Stalk Volume (cm³)	0.2695	0.203	-Temperature, -Health, -Solar Radiation, Moss Cover
Vascular Plant Cover (%)	0.6518	1.02E-14	-Temperature***, +Soil Depth*, +Moisture, -Distance from Edge
Change in Soil Moisture (%)	0.4259	2.83E-08	+Solar Radiation***, -Distance from Edge***, -Vascular Plant Cover**
Soil Moisture (%)	0.6454	1.86E-14	-Temperature***, -Distance from Edge**, -Solar Radiation**, -Substrate Cover*
Soil Temperature (°C)	0.7038	< 2.2e-16	-Vascular Plant Cover***, +Solar Radiation**, -Moisture*, -Soil Depth*
Moss Cover (%)	0.4043	1.73E-08	+Temperature***, +Solar Radiation
Substrate Cover (%)	0.2177	0.0008	-Moisture***, -Change in Moisture, -Soil Depth

Table 2. Multiple linear regression results for data collected at *S. bicolor* plant locations during the study in 2014 on the Atrium green roof at Saint Mary's University, Halifax, NS. Note that for some of the items listed under Model of Best Fit: Health refers to the health scores recorded for the plants between June 5th and September 5th, 2014; Distance from Edge refers to the distance of the plant in meters from the nearest green roof edge.

3.2: Health Scores

Out of 69 *S. tridentata* plants, only 2 received health scores of 0 (death) by September 5th, 2014 (see map in Figure 9 A below). This translated into approximately 3% mortality between the months of June through to September.

Out of 72 *S. bicolor* plants 7 plants received health scores of 0 (death) and 1 plant received a health score of 1 (poor health) by September 5th, 2014 (see map in Figure 9 B). This translated into approximately 10% mortality between the months of June through to September. Generalized linear regression analysis showed that plants were likely to be healthy in areas with lower soil temperatures and deeper soil (see Table 5 below). Two-sample t-tests showed that there was a significant difference between the sample means of plants that died compared to plants that were healthy for many of the environmental variables (see Table 3 below), including soil depth (5cm compared to 7cm), soil temperature (35.2^{o}C compared to 31.6^{o}C), soil moisture (9.8% compared to 14.2%), change in soil moisture (20.5% compared to 17.1%), solar radiation (455906 WH/m^2 compared to 428154 WH/m^2), vascular plant cover (5.6% compared to 27%), moss cover (56.7% compared to 42.7), and substrate cover (35.8% compared to 25.8%).

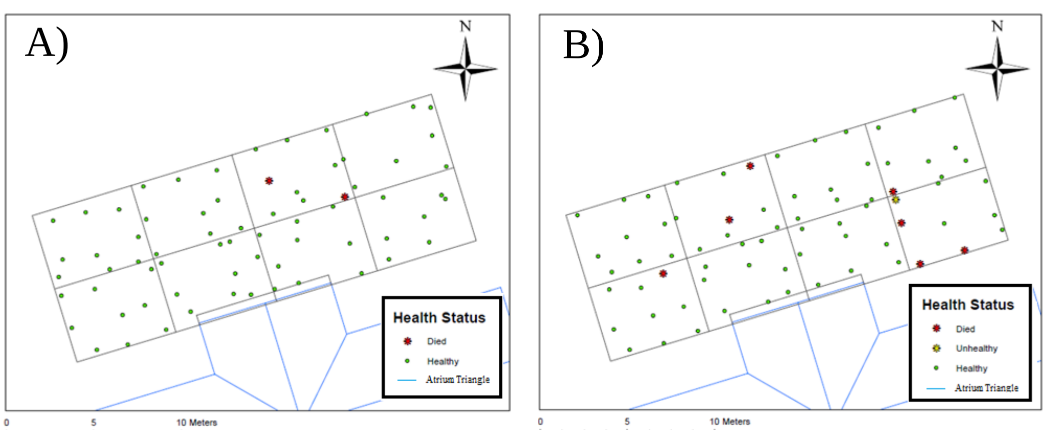


Figure 9. Health scores of *S. tridentata* (**A**) and *S. bicolor* (**B**) study plants on the Atrium green roof at Saint Mary's University, Halifax, NS on September 5th, 2014.

Environmental Variable	Mean of Plants that Died	Mean of Healthy Plants	P-value	95% Confidence Interval
Soil Depth (cm)	5	7	0.00003	-2.6 to 1.3
Soil temperature (°C)	35.2	31.6	0.00012	24.3 to 29.2
Soil Moisture (%)	9.8	14.2	0.00046	-1.7 to -1.2
Change in Soil Moisture (%)	20.5	17.1	0.00658	6.7 to 14.3
Solar Radiation (WH/m²)	455906	428154	0.01372	6122 to 49384
Vascular Plant Cover (%)	5.6	27	0.00191	-2.1 to -1.2
Moss Cover (%)	56.7	42.7	0.00237	6.1 to 21.9
Substrate Cover (%)	35.8	25.8	0.04712	0.2 to 19.8

Table 3. Results from two-sample t-tests comparing the mean values of environmental variables from two distinct groups in *S. bicolor*: plants that died compared to plants that were healthy.

Variable	Model of Best Fit
Health Score	+Moisture, +Change in Moisture, -Soil Depth, -Moss Cover
Flower (Y/N)	-Solar Radiation, +Soil Depth

Table 4. Results of generalized linear regression analysis on health scores (from June 5th to September 5th, 2014) and flowering data (during the study in 2014) of *S. tridentata* plants growing the Atrium green roof at Saint Mary's University, Halifax, NS.

Variable	Model of Best Fit
Health Score	+Soil Depth, -Change in Moisture, -Temperature
Flower (Y/N)	+Moisture, +Temperature, +Health, +Moss Cover

Table 5. Results of generalized linear regression analysis on health scores (from June 5th to September 5th, 2014) and flowering data (during the study in 2014) of *S. bicolor* plants growing the Atrium green roof at Saint Mary's University, Halifax, NS.

3.3: Reproductive Potential

During the study, 11 out of 69 *S. tridentata* plants flowered (see map in Figure 10 A below). This translated into an approximate flowering rate of 16% across the green roof. Logistic regression analysis indicated that plants were more likely to flower in areas with deeper soil and lower solar radiation (see Table 4). In contrast, 23 out 72 *S. bicolor* plants flowered (see map in Figure 10 B below). This translated into an approximate flowering rate of 32% across the green roof. Logistic regression analysis indicated that *S. bicolor* plants were more likely to flower in areas with higher soil moisture and higher soil temperatures (see Table 5).

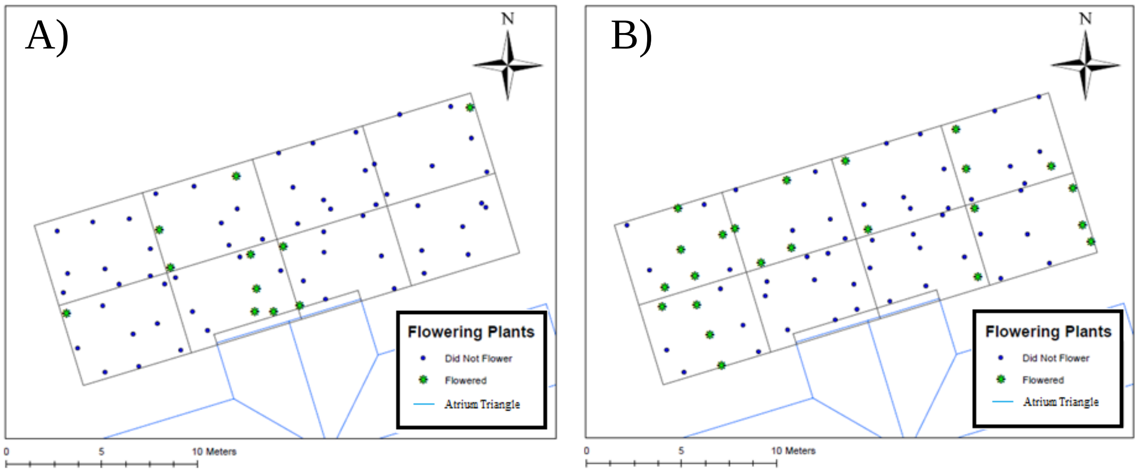


Figure 10. *S. tridentata* (**A**) and *S. bicolor* (**B**) plants that flowered on the Atrium green roof at Saint Mary's University, Halifax, NS during the study in 2014.

3.4: Vascular Plant Cover

Multiple regression analysis indicated that higher vascular plant cover occurred in areas with lower soil temperatures, higher soil moisture, deeper soil, and areas closer to the edges of the green roof (see Tables 1 and 2). The multiple regression models were statistically significant for vascular plant cover for both *S. tridentata* locations (R^2=0.55; P<0.01) and *S. bicolor* locations (R^2=0.65; P<0.01). The most significant predictor for vascular plant cover was soil temperature (see scatter plot in Figure 12 A below; R= -0.70). A map of vascular plant cover can be seen in Figure 11 A below.

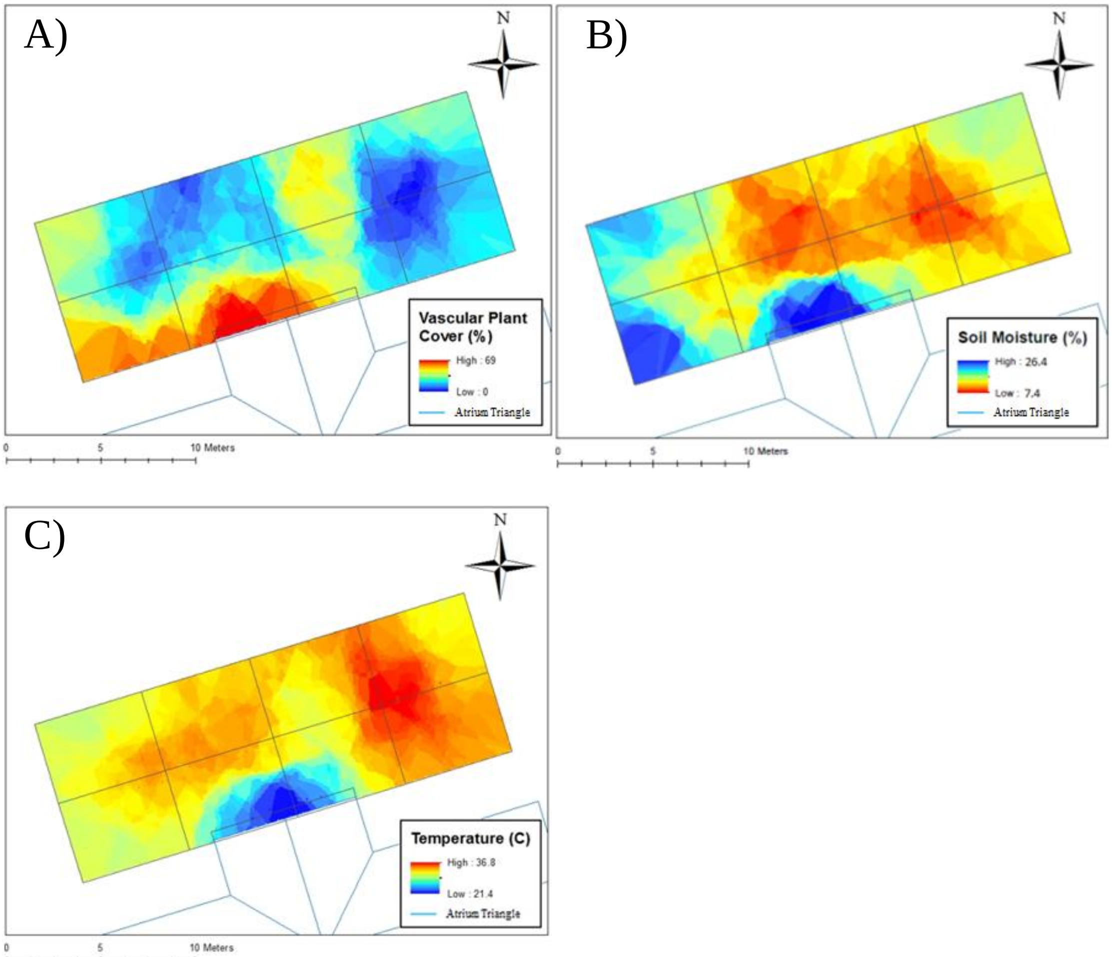
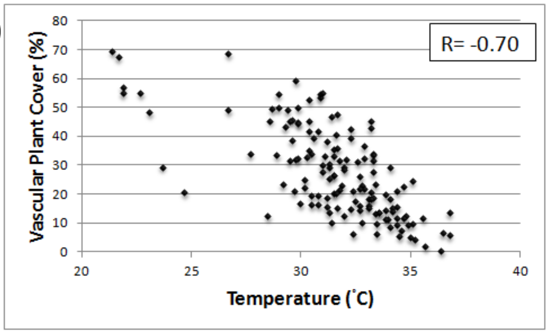
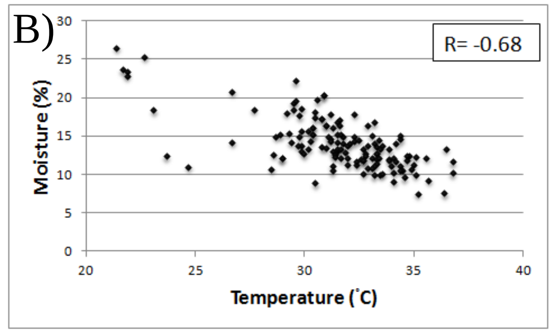


Figure 11. A) Vascular plant cover was assessed on the Atrium green roof at Saint Mary's University, Halifax, NS by analyzing photographs using JMicroVision 1.2.7. A two-foot diameter ring was placed around each plant, which designated the sampling area when analyzing vascular plant cover. Photographs of each plant were taken on August 1st, 2014. **B)** Soil moisture data were collected on the Atrium green roof at Saint Mary's University, Halifax, NS at each plant location at noon on July 23rd, 2014. **C)** Soil temperature data were collected on the Atrium green roof at Saint Mary's University, Halifax, NS at each plant location at noon on July 18th, 2014.
Note: All data in **A)** to **C)** were interpolated using Kriging in ArcGIS.

A)



B)



C)

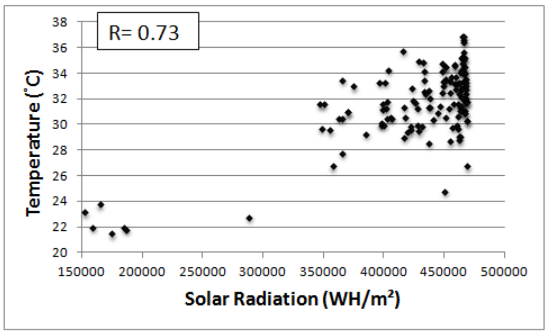


Figure 12. A) The relationship between soil temperature (collected on July 18th, 2014) and vascular plant cover (assessed by analyzing photographs taken on August 1st, 2014 using JMicroVision 1.2.7) on the Atrium green roof at Saint Mary's University, Halifax, NS. **B)** The relationship between soil temperature (collected on July 18th, 2014) and soil moisture (collected on July 23rd, 2014) on the Atrium green roof at Saint Mary's University, Halifax, NS. **C)** The relationship between solar radiation (calculated using the Area Solar Radiation (Spatial Analyst) tool in ArcGIS) and soil temperature (collected on July 18th, 2014) on the Atrium green roof at Saint Mary's University, Halifax, NS.

<u>3.5: Soil Moisture</u>

Multiple regression analysis indicated that higher soil moisture content was found in areas with lower soil temperatures, lower solar radiation, higher vascular plant cover, and in areas closer to the green roof edges (see Tables 1 and 2). The multiple regression models were statistically significant for soil moisture for both *S. tridentata* locations (R^2=0.46; P<0.01) and *S. bicolor* locations (R^2=0.65; P<0.01). The most significant predictor for soil moisture was temperature (see scatterplot in Figure 12 B; R= -0.68). A map of soil moisture can be seen in Figure 11 B.

Multiple regression analysis showed that higher soil temperatures were found in areas with higher amounts of solar radiation, shallower soils, areas with a greater change in soil moisture, lower soil moisture, higher moss cover, higher substrate cover, and lastly lower vascular plant cover (see Tables 1 and 2). The multiple regression models were statistically significant for soil temperature for both *S. tridentata* locations (R^2=0.75; P<0.01) and *S. bicolor* locations (R^2=0.70; P<0.01). The most significant predictor for soil temperature was solar radiation (see scatterplot in Figure 12 C; R= 0.73). A map of soil temperatures can be seen in Figure 11 C.

3.7: Solar Radiation

A model of solar radiation from June 5th to September 5th, 2014 can be seen in Figure 13 below. Solar radiation calculated from the model was significantly correlated with measured soil temperatures (see scatterplot in Figure 12 C; R= 0.73)

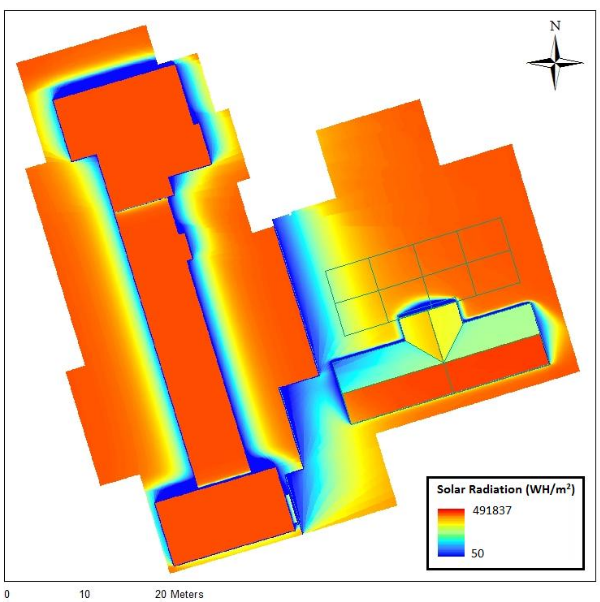


Figure 13. A solar radiation model (WH/m^2) of the Atrium and Science buildings at Saint Mary's University, Halifax, NS calculated from June 5th to September 5th, 2014. This model was calculated in ArcGIS using the Area Solar Radiation tool.

4.1: Plant Growth and Environmental Conditions

Understanding how plants will respond to environmental conditions can be important for green roof research. Durhman et al. (2007) showed by studying 25 different green roof plant taxa that in general, plants that grew faster were more likely to provide the best cover. Therefore, knowledge of how plant growth rates are influenced by environmental conditions can be used to achieve the best cover on a green roof. Cover on a green roof is important because theoretically the more plants growing on a green roof the better the roof will perform its ecological services, since the services for the most part come from the plants themselves.

The presence of nearby vascular plants appeared to be the strongest factor that negatively affected the growth of both plant species. This was likely due to competition for resources among nearby plants. Competition is well known to negatively impact the growth of plants (Casper and Jackson, 1997; Poorter and Navas, 2003; Paradis et al., 2014). This makes sense because the study plants were growing in shallow substrate so nutrient availability, water availability, and root exploration would have been limited. Although it appears as though competition reduced growth rates in both species, there is no evidence that it caused mortality. In fact, all of the plants that died actually had significantly low levels of competition, likely because the environmental conditions were so unfavourable in those locations.

As one might have predicted, deeper substrate and higher soil moisture content were favourable conditions for growth in both species on the green roof. Interestingly, lower soil temperatures and solar radiation also were favourable for plant growth. Although plants require sunlight as the active ingredient for photosynthesis, which would normally lead to increased plant growth, areas that experienced high temperatures and high amounts of solar radiation on the green roof likely experienced the highest rates of soil moisture loss. This is supported by a study done by Getter et al. (2009) which showed that areas that experience lower amounts of solar radiation on a green roof hold more soil moisture. Since water availability is more limiting than sun exposure on a green roof, it makes sense that both species achieved faster growth in areas with high soil moisture, low soil temperatures and low solar radiation rather than the other way around. This is clear when the maps of *S. bicolor* leaf growth (see Figure 8 A, B, and C), soil moisture (see Figure 11 B), and soil temperature (see Figure 11 C) are compared.

Some of the highest growth rates of *S. bicolor* occurred within or near the shaded region of the green roof caused by the Atrium Triangle. A study that evaluated the effects of shading on blueberry plants growing in Manitoba, Canada had similar findings: blueberry plants grew faster, had larger leaves, and had a better water economy under intermediate shade (Hoefs and Shay, 1981). This occurred because solar radiation is the driving force for evaporation of soil moisture on green roofs, so where there is less incoming solar radiation, there will be less evaporation and in turn more soil moisture.

When viewing the maps of plant growth for both species, it is quite evident that the growth responses of these species are complex, even when compared to maps of abiotic factors such as soil moisture and soil temperature. Chapin and Shaver (1985) conducted a study that compares individualistic growth responses of a number of species of Tundra plants over a two-year period. Their research suggests that no single factor equally limits the growth of all species. One of the aims of this study was to understand how abiotic factors might affect plants growing on a green roof, however there are likely many other factors that weren't considered, such as wind exposure, salinity, and nutrient availability. We expect that with more abiotic factors taken into consideration, patterns of plant responses on green roofs will become more evident and predictable.

4.2: Survival and Environmental Conditions

Identifying areas of high risk for the establishment of plants on green roofs is important for green roof research. In order for a green roof to optimize its ecological services, one of the most important factors would be having the largest number of plants growing in the system as possible (i.e. high cover). Since green roof conditions tend to be harsh for plants, understanding areas of high risk is therefore essential to achieving optimal performance of a green roof.

The environmental conditions for the *S. bicolor* plants that died during the study were significantly different compared to those that remained healthy. Soil depth was 2cm shallower than the rest of the plants, soil temperatures were several degrees higher, and not surprisingly soil moisture was 4.4% lower. Based on these findings, plants were at greater risk for mortality in hotter, drier, and shallower soils. This is clear when observing a map of soil temperatures that is overlayed with a map of plant mortality (see Figure 14 below).

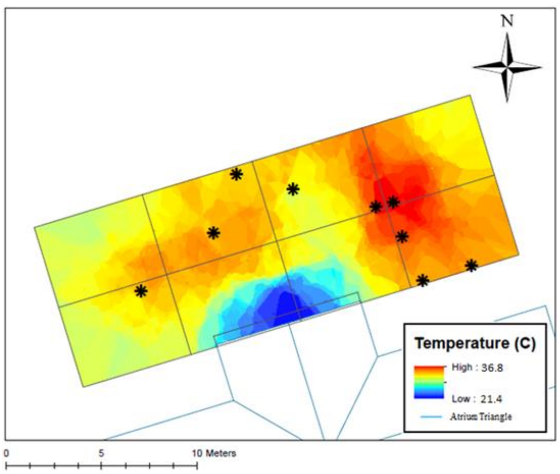


Figure 14. Soil temperatures overlayed with plant mortality of both *S. tridentata* and *S. bicolor* plants on September 5th, 2014. Soil temperature data were collected on the Atrium green roof at Saint Mary's University, Halifax, NS at each plant location at noon on July 18th, 2014.
Note: Soil temperature data were interpolated using Kriging in ArcGIS.

The finding that shallow soils are linked to high rates of plant mortality is supported by a study done by Durhman et al. (2007). Growth, cover, and survival were assessed for 25 different succulent plants by controlling substrate depths (2.5cm, 5cm, and 7.5cm). They show that shallow soils not only reduce survival during a growing season, but also reduce the chance of successfully overwintering. It is speculated that deeper soils provide greater retention of moisture, reduce large fluctuations in soil temperatures, and provide a greater space for root exploration.

Survival of plants on the green roof during this study did not seem to be dependent on one particular environmental factor. Instead, it appears that in most cases, it was a combination of unfavourable conditions that tipped the balance and led to mortality. For example, even though the average soil depth of plants that died was 5cm, we still saw a few plants remaining relatively healthy below that level of soil depth (see Figure 15 below). More than a 15 degree temperature difference was observed across the green roof on July 18th, 2014 (see Figure 11 C). Plant growth and survival for both study species were highest in conditions with lower temperatures. It is possible that having a combination of low soil depth with higher than average soil temperatures and lower soil moisture could be more stressful to a plant than each condition considered individually.

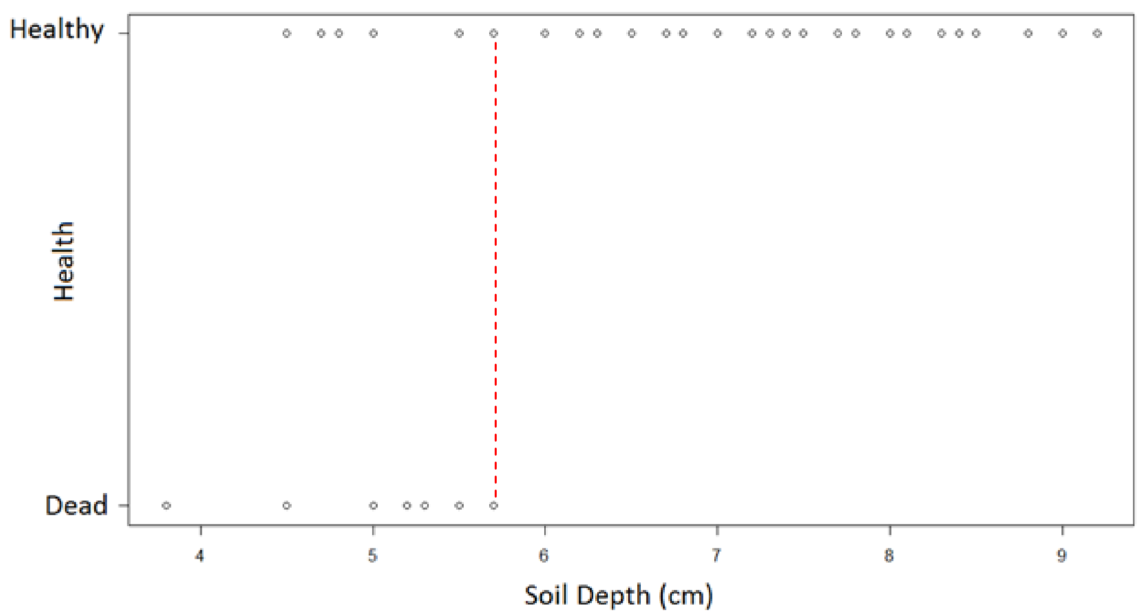


Figure 15. The relationship between soil depth (cm) and health scores (collected on September 5th, 2014) of *S. bicolor* on the Atrium green roof at Saint Mary's University, Halifax. The dotted red line depicts the soil depth level (5.7 cm) in which we begin to see plant mortality for this species.

Although it appears as though competition reduced growth rates in both species, there is no evidence that that competition caused mortality. In fact, all of the plants that died actually had significantly low levels of competition. This is likely because the environmental conditions were unfavourable for plants to survive in those locations.

4.3: Reproductive Potential and Environmental Conditions

Whether or not a species flowers on a green roof may determine long-term persistence of that species. If reproduction of a particular species on a green roof is unsuccessful, it is possible that sooner or later the roof will be void of that species. Therefore, it is important to understand what conditions on a green roof make plants of a particular species more likely to flower.

In this study, it appears that there are some species-specific preferences for environmental conditions in order to flower. This is supported by a study in England that looked at the relationships between flowering dates and temperatures from a 36-yearold database of 243 angiosperms and gymnosperms (Fitter et al., 1995). They show that the date in which a plant species first flowers is quite variable among species. Moreover, some species rely on certain temperatures several months before they flower while other species are affected by temperatures from the previous autumn. The study concludes that higher temperatures would advance the flowering in some species but would retard it in others. This finding is supported in Figure 16 A and B below: *S. tridentata* appears to flower in the shaded and more cooler parts of the green roof while *S. bicolor* essentially flowered everywhere on the green roof except in the shaded region caused by the Atrium Triangle.

Although most flowering plants undergo photoperiodic flowering (when flowering is dependent on the duration of day/night periods) or vernalization (when flowering is dependent on temperature), it has been observed that some plants may flower as a result of being very stressed, which is known as stress-induced flowering (Wada and Takeno, 2010). It is likely that stress-induced flowering is an adaptive emergency response to preserve the species during times of uncertainty. So the question becomes: did plants on the green roof flower due to photoperiodic flowering, vernalization, or stress-induced flowering? Since it was not within the aims of this study to determine whether or not plants undergo stress-induced flowering, vernalization, or photoperiodic flowering on a green roof, we can only speculate. Based on the data, it seems as though the environmental conditions were generally favourable for plants that flowered compared to those that didn’t. This suggests that it was likely not stress-induced flowering that caused these plants to flower, but this is only speculation and would be worth investigating in future green roof studies.

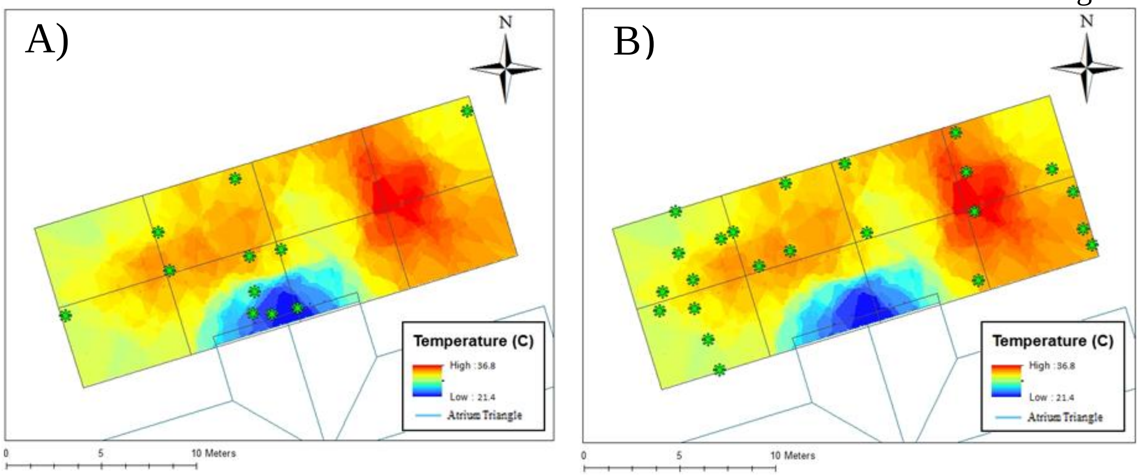


Figure 16. Soil temperatures overlayed with plants that flowered (depicted by green dots) for *S. tridentata* (**A**) and *S. bicolor* (**B**) during the study in 2014. Soil temperature data were collected on the Atrium green roof at Saint Mary's University, Halifax, NS at each plant location at noon on July 18th, 2014.
Note: Soil temperature data were interpolated using Kriging in ArcGIS.

<u>4.4: Vascular Plant Cover and Environmental Conditions</u>

Achieving maximum plant cover on a green roof is necessary in order for a green roof to effectively provide its desired ecological services. Therefore, having an understanding of how to achieve maximum plant cover would be powerful knowledge. The data from this study show that the most important environmental factors for achieving highest plant cover in this green roof system is soil temperature, soil moisture, and soil depth. The relationships between vascular plant cover and soil moisture and soil temperature are indeed strong and can be seen when comparing the maps in Figures 11 A, B, and C. In general, it seems that where there were lower soil temperatures and higher soil moisture on the green roof, there was higher vascular plant cover.

What is more, the area of the green roof encompassed by the shadow cast by the Atrium Triangle had the highest amount of vascular plant cover observed in this green roof system. This is likely because this area also had the lowest temperatures and highest soil moisture recorded on the green roof (see Figures 11 B & C and Figure 13). Water availability on green roofs is often very limiting and is required for the vital functioning of plants (Dunnett and Kingsbury, 2004; Taiz and Zeiger, 2006). This suggests that the Atrium Triangle created a beneficial microclimate.

These findings may suggest that having structures on or near a green roof that intentionally create shading could be beneficial for the green roof and assist with achieving maximum plant cover. Furthermore, technologies that may have seemed incompatible, such as green roofs and solar panels, may actually work very well together. This is supported in a study by Slabe and Bousselot (2013) that showed that photovoltaic panels on top of a green roof promote plant cover, increase the chance of plants to overwinter from 60% in exposed areas to 95% in shaded areas, promote habitat heterogeneity, and lastly increase the potential for species diversity. The study also points out that photovoltaic panels function better at less extreme temperatures, and since plants are known for their cooling properties, for example through evapotranspiration, it is possible that the relationship between green roofs and photovoltaic panels could be synergistic.

It also makes sense that deeper soil was favourable for achieving higher vascular plant cover. Deeper soil would allow a larger space for roots to explore and would likely reduce competition amongst nearby plants since root exploration would not be so limited.

This is supported by a study mentioned earlier by Durhman et al. (2007), where they show that deeper soils promote plant growth and plant cover.

4.5: Application of GIS to Green Roofs

Building a 3D model of the green roof and nearby buildings using GIS was not only useful for visualizing the building features and their interactions with the green roof, but it also allowed me to create various solar radiation models of the roof, one of which was incorporated into the statistical analysis of this study. This solar radiation model was useful for predicting soil temperatures (compare maps in Figure 11 C and Figure 13; see scatterplot in Figure 12 C; R=0.73). However, soil temperatures are likely a function of not only incoming solar radiation, but also the depth of the soil and the albedo. For example, soil with vegetation growing on top will likely require more solar radiation to achieve the same soil temperature as bare substrate. This is because plants will not only reflect more solar radiation than the soil substrate, due to differences in albedo, but they will also absorb some of the energy and convert it to a different state using photosynthesis. The data show that soil temperatures were significantly linked to both soil moisture and vascular plant cover, so if the solar radiation model serves as a good predictor for soil temperatures, it could also be useful for predicting relative moisture levels and vascular plant cover across a green roof. Creating models, such as solar radiation, in GIS for a green roof could be useful for predicting its environmental conditions and provide insight into how plants may respond in certain areas of the green roof, even before the green roof is established.

Using the time-lapse camera was a good way to test the accuracy of both the solar radiation model and the 3D model of the buildings (which was generated in GIS by using blue prints and scaled drawings). This is because the solar radiation model was calculated based on the different angles and elevations from the 3D model. This means that if either the Area Solar Radiation tool or the 3D model of the buildings were inaccurate, it would have become apparent when comparing the angles of the shadows from the real photographs taken from the time-lapse camera of the roof, to the shadows generated by the solar radiation model in GIS. The results showed that the models were surprisingly accurate: no significant errors were observed between the time-lapse photographs and the models generated by the Area Solar Radiation tool (see time-lapse comparisons in Figure 6). This suggested that there were no issues in accuracy in either of the models. Furthermore, for the first time, the methodology used in this study to create a 3D model of the green roof and nearby buildings showed that the model can be very accurate and could be applied to other green roof projects and buildings for future studies.

Mapping the positions of the plants using GIS was essential to visualizing and analyzing the spatial relationships in the data. Knowing the exact position of each study plant on a map made finding them much easier during data collection. Even though the plants were tagged, having to find over a hundred study plants amongst thousands across the green roof each month would have been a very onerous task without the use of a map. Having a map of plant positions in GIS also allowed me to calculate a novel dataset that was useful in statistical analysis: the distance from the nearest green roof edge. This dataset was useful in explaining some of the variation in the data and also showed that there was more soil moisture located towards the edges of the green roof. Lastly, having spatial data from each study plant allowed for various kinds of data that were collected during the study to be mapped through use of Kriging interpolation. Using Kriging proved to be very useful for comparing relationships across the extensive green roof between plant growth, survival, reproduction, vascular plant cover, and other environmental factors. Using the methodology in this study to collect spatial data on a green roof can be quick and efficient, and once one has spatial data, the possibilities for analysis and visualization are extensive.

For the first time, this study proposed a methodology to incorporate Geographic Information Systems (GIS) into green roof research. The first part of the methodology proposed a way to collect spatial data on a green roof and showed how this data can be brought into GIS to visualize and analyze spatial relationships in the data. The second part of the methodology included a novel technique for creating a 3D model of a green roof system and adjacent buildings using GIS. Having this 3D model not only allowed for visualization of the green roof and surrounding building features, but it also allowed us to gain new information about the environmental conditions on the green roof by gaining access to 3D analysis tools in GIS – one such tool created a solar radiation model of the building roofs. Using photographs from a time-lapse camera, it was shown that these models are very accurate with no significant error observed. These methods for incorporating GIS into green roof research were used to understand how spatial environmental variability affects plants growing in an extensive green roof system.

The data show that there is significant environmental variability occurring across the green roof system. It was found that this spatial variability in environmental conditions significantly affected plant growth, survival, reproductive potential, and plant community structure. This is an important finding because most green roof research assumes that conditions across a green roof system are homogeneous, which is clearly incorrect. It was also found that certain building features, such as the Atrium Triangle and the edges of the green roof, create detectable microclimates on the green roof. Furthermore, the data show that these microclimates are beneficial to the plants growing on this green roof. Since green roofs require healthy plants and maximum plant cover to perform their ecological services at an optimal level, further investigation into using building features on green roofs to create favourable microclimates may prove to be important, particularly for commercial ventures that rely on their moderating influence.

In conclusion, using GIS-based analysis was essential to understanding how spatial environmental variability affected plants growing in this extensive green roof system. These novel methods for incorporating GIS into research on green roofs were very useful for visualizing and analyzing spatial relationships in both environmental data and vegetation data across the green roof, and these methods can certainly be applied to other buildings with green roofs.

- How do different environmental conditions affect the ecological services performed by green roofs (i.e. stormwater retention and reducing building energy costs)?
- How does shading on a green roof affect these ecological services?
- How does shading on a green roof affect the accumulation of snow in cold climates?
- How does wind exposure affect different plant species growing on a green roof?
- How variable is soil chemistry (i.e nutrients, salinity, pH) across a green roof?
- Quantify the effects on a green roof system of having solar panels place on top of the vegetation.
- Strategies for effectively creating shading across a green roof and quantify the effects that this shading has on ecological services, plant growth, survival, reproduction, biodiversity, and species richness potential across the green roof.

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