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Evapotranspiration from extensive green roofs: influence of climatological conditions, vegetation type, and substrate depth

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Abstract

Green roofs are gaining popularity worldwide as a low impact development tool to mitigate increasing stormwater runoff within dense urban areas. Evapotranspiration (ET) is the key hydrologic process governing the capacity of a green roof to retain rainfall as it regenerates available water storage space in the green roof substrate (soil) between rainfall events. To date, there are limited data on how the interaction between different climatological conditions and design parameters (e.g., vegetation type, substrate depth) affect ET rates. This currently limits the ability to optimize green roof design for stormwater management. In this field study, the impact of climatological conditions, vegetation type, and substrate depth on ET rates were evaluated from experimental, modular extensive green roofs installed in three climate regions in Canada: Calgary AB (Prairies), London ON (Great Lakes/ St. Lawrence), and Halifax NS (Atlantic/ Maritime). Daily ET rates and cumulative ET over the field season were calculated from daily (n = 40) and continuous (n = 2 to n = 4) module weight data recorded from May to September in 2013 and 2014. The modular set-up of the green roof at all sites consisted of two module depth treatments (10 cm and 15 cm substrate depth), substrate only treatments (no vegetation), and four vegetation treatments (monoculture treatments of *Sedum spurium*, *Sporobolus heterolepis*, and *Aquilegia canadensis*, and a mixed species treatment consisting of the three aforementioned species). The plant coverage and root mass distribution were characterized for all vegetation treatments. The percentage of cumulative rainfall returned to the atmosphere by ET over the 2013 and 2014 field seasons was greater for Calgary (73%) and London (67%) compared with Halifax (33%). ET rates in Calgary and London were found to be limited by the available moisture in the substrate, whereas the results suggested that the other climatological variables or atmospheric forcing rather than available moisture may have been the limiting factor controlling ET rates in Halifax. Data revealed that green roofs with only *Sedum spurium* or a mixture of *Sedum spurium*, *Sporobolus heterolepis*, and *Aquielgia canadensis* had higher ET rates, and thus will be able to restore the retention capacity of the green roof substrate faster than a green roof with no vegetation, *Sporobolus heterolepis* or *Aquilegia canadensis*. The optimum substrate depth differed among vegetation types and study site. To optimize the hydrologic performance of green roofs (i.e., retention capacity), this study found that plant characteristics, such as plant coverage and root mass distribution, should be considered when selecting vegetation type and substrate depth. This study provided valuable insight on the sensitivity of ET rates to climatological conditions and green roof design parameters (i.e., vegetation type and substrate depth), with the study findings needed to make informed decisions on the design and optimization of the hydrologic benefits for green roofs installed in different climatological conditions.

Keywords

Evapotranspiration, vegetation type, substrate depth, climatological conditions, water saturation, extensive green roof, drying period, retention capacity, hydrologic performance

Co-Authorship Statement

Under the supervision of Dr. Denis M. O’Carroll and Dr. Clare Robinson, the candidate interpreted and analyzed experimental data which were collected during the field monitoring seasons. The contributions of the co-authors for the manuscript draft of Chapter 3 are outlined below.

Chapter 3: Evapotranspiration from extensive green roofs: influence of climatological conditions, vegetation type, and substrate depth

Authors: Maria Eloisa Sia, Denis M. O’Carroll, Clare Robinson, Charles Chris Smart, James A. Voogt, Danielle A. Way

Contributions:

Dr. Denis M. O’Carroll and Dr. Clare Robinson initiated the research project, designed the methodology (i.e. instrumentation and site layout), advised on the interpretation and analysis of data, and provided feedback and suggestions on the drafts of the thesis.

Dr. Charles Chris Smart and Dr. James A. Voogt initiated the research project, designed the methodology (i.e. instrumentation and site layout), and advised on the interpretation and analysis of data.

Dr. Danielle A. Way provided resources for the collection of plant traits data and advised on the interpretation of the data.

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Chapter 1

1 Introduction

1.1 Background

Stormwater management solutions are needed to increase resiliency within urban areas and to decrease the adverse effects of urbanization on receiving waters within the watershed. Large impervious areas from urban development results in the loss of vegetated surfaces which leads to an increase in direct stormwater runoff (e.g., Paul & Meyer 2001). Stormwater management solutions are implemented by municipalities to remediate the adverse effects of altering the natural hydrologic cycle including flooding, erosion, and deterioration of downstream water quality (Ministry of the Environment 2003). Within the urban area, conventional roofs cover 40-50% of the impervious surfaces (Dunnett and Kingsbury 2004). Green roofs, also known as vegetated roofs, provide a non-intrusive solution to mitigate against excessive stormwater runoff (Stovin 2010), and as a result are becoming an increasingly popular low impact development (LID) tool. In the late 1960s and early 1970s, Germany modernized the sod roof design by engineering the green roof substrate (soil) to be lightweight and highly porous decreasing the design structural load requirements of green roofs and improving their ability to retain rainfall (Osmundson 1999). As a result, green roofs can be designed to have a relatively shallow substrate depth without losing their ability to retain rainfall, and therefore mitigate stormwater runoff. Green roofs with shallow substrate depth (< 150 mm) are commonly referred to as extensive green roofs (Oberndorfer et al. 2007). The modernized extensive green roof design allows for wider implementation when retrofitting existing infrastructures due to the lower structural load requirement (Stovin 2010).

Green roofs are able to reduce the volume and attenuate roof stormwater runoff by re-introducing vegetation onto urban rooftops (e.g., Mentens et al. 2006; Berghage et al. 2007; Fassman-Beck et al. 2013). Green roofs are also a rapidly growing sustainable solution for decreasing building energy consumption (e.g., Ouldboukhitine et al. 2011) and mitigating the urban heat island effect (e.g., Takebayashi & Moriyama 2007). Within the past decade, an increasing amount of research has been conducted worldwide to quantify thermal green roof performance under varying climatological conditions and design configuration to assess their suitability for building energy conservation from a thermal performance perspective (e.g., Jaffal, Ouldboukhitine, and Belarbi 2012), and to assess their suitability as a low impact development tool from a hydrologic performance perspective (see Li & Babcock 2014 for a review). The hydrologic and thermal benefits of green roofs can be attributed to their enhancement of evapotranspiration (ET) in urban areas. ET from green roofs reduces stormwater runoff by returning captured rainfall to the atmosphere as water vapour. Through this hydrologic process, the capacity of the green roof substrate to retain rainfall is regenerated (e.g., Berretta et al. 2014). Concurrently, the transfer of latent heat from the evaporation of water from the substrate and the vegetated surface provides a cooling effect which reduces the ambient air temperature of the roof (Oke 1987; Takebayashi and Moriyama 2007). Quantifying ET from green roofs is therefore critical to green roof design (e.g., vegetation type and substrate depth), and the optimization of green roof hydrologic and thermal performance. While many studies have now demonstrated the effectiveness of green roofs in reducing stormwater runoff (e.g., Roehr & Kong 2010; Mentens et al. 2006; Nagase & Dunnett 2012; Fassman-Beck et al. 2013), little field research has been done on directly quantifying ET and evaluating the effects of climatological conditions, substrate depth, and vegetation type on ET from green roofs (e.g., Wadzuk et al. 2013; Berretta et al. 2014; Marasco et al. 2014; Poe et al. 2015). More specifically, there is a lack of actual ET data from green roofs built under the Canadian climate, limiting the development of optimal green roof design under these types of climatological conditions.

1.2 Research Objectives

The aim of this research is to evaluate the sensitivity of ET rates to green roof design parameters when exposed to distinct climatological conditions at three sites across Canada (Calgary AB, London ON, and Halifax NS). More specifically, the two design parameters which will be assessed are the vegetation type and substrate depth. To date, no field research has examined these parameters using the same green roof design installed in three different climatological conditions. It should be noted that this research assesses ET from extensive green roofs using a water balance approach; therefore, the objectives of this research are focused on stormwater management. The understanding developed from this research is critical to making informed decisions on the selection of vegetation and substrate depth during the design of green roofs in different climatological conditions. This improvement in the design process will allow for the optimization of ET, subsequently enhancing the rainfall retention performance of the green roof. The research questions that this study aims to answer are outlined below.

1) Is there a difference in the ET rates measured at the three study sites? If there is a difference, what are the climatological factors that cause the difference in ET rates?
2) Is the cumulative moisture loss and daily average ET rate different:
    i. among the three single species vegetation treatments?
    ii. between the mixed species and single species treatments?
    iii. between the bare substrate (no vegetation) treatment and the vegetation treatments?
3) Is there a difference in the cumulative moisture loss and daily average ET rate when the substrate depth is varied?

1.3 Thesis Outline

This thesis is written in “Integrate Article Format”. A brief description of each chapter is presented below.

Chapter 1 introduces the research topic and corresponding knowledge gaps related to assessing climatological and design parameters which influence ET from green roofs.

Chapter 2 reviews the findings reported from past research related to the influence of climatological conditions, substrate depth and type, and vegetation type on ET from green roofs. The knowledge gaps within this field of research are highlighted at the end of the chapter.

Chapter 3 presents the methodology, field data analysis, and findings pertaining to the research objectives for this study.

Chapter 4 summarizes the findings for the research objectives and outlines recommendations for future work.

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Chapter 2

2 Literature Review

2.1 Introduction to Green Roofs

2.1.1 Benefits of Green Roofs

Green roofs or vegetated roofs are constructed ecosystems built within the urban environment to provide ecosystem services including: (1) the mitigation of the stormwater runoff quantity (e.g., Fassman-Beck et al. 2013; Schroll et al. 2011; Roehr & Kong 2010; Mentens et al. 2006; VanWoert et al. 2005) and quality (e.g., Morgan et al. 2013; Berndtsson et al. 2006; Beecham & Razzaghmanesh 2015); (2) reduction of building energy usage (e.g., Ouldboukhitine et al. 2011; Jaffal et al. 2011; Takakura et al. 2000); (3) mitigation of the urban heat island effect (e.g., Takebayashi & Moriyama 2007; Santamouris 2014); (4) reduction of air pollution and carbon sequestration (Getter et al. 2009; Rowe 2011; Jim & Chen 2008); (5) extension of the life of the roof membrane (Getter & Rowe 2006); and (6) provision of an aesthetic environment (Getter & Rowe 2006). The key motivation for the installation of green roofs is often for the thermal and hydrologic benefits they provide (Banting et al. 2005; Toronto and Region Conservation 2007). Vegetation is the key design component that makes it possible for green roofs to provide these two benefits (Lundholm & Williams 2015). By re-introducing vegetation on the impermeable traditional roof surface, the evapotranspirative component of the hydrologic cycle is recovered, effectively decreasing the roof surface temperature (e.g., Wolf & Lundholm 2008) and roof stormwater runoff (e.g., Schroll et al. 2011). Evapotranspiration (ET) is the key process that governs both the thermal and hydrologic benefits of the green roof. From a stormwater management perspective, green roofs have been shown to significantly decrease roof stormwater runoff volumes and reduce peak flow rates (Fassman-Beck et al. 2013; Voyde et al. 2010). Green roofs are able to hold a finite amount of rainfall within their substrate (soil) and vegetation layer, with the water storage volume available for retaining stormwater dependent on the amount of water returned to the atmosphere by ET between rain events. Green roofs also provide considerable insulation with the presence of a green roof found to decrease the building’s energy consumption through evaporative cooling providing energy savings for the building in warm and cooler climates (Castleton et al. 2010; Lundholm et al. 2010). At a larger scale, green roofs are thought to mitigate the urban heat island effect (e.g., Takebayashi & Moriyama 2007; Santamouris 2014), which is the increase in air temperature within urban areas relative to the adjacent rural areas.

2.1.2 Green roof history

Green roofs are not a new engineering concept. In fact, green roofs have slowly evolved throughout the years from the addition of plants and trees for aesthetic value in ancient Mesopotamia, to roofs covered with sod for insulation during the Middle Age and Viking eras, and to what is seen today as the modernized green roof (Osmundson 1999). In the late 1960s and the early 1970s, Germany modernized the ancient vegetated roof design by engineering the green roof substrate to be lightweight and highly porous (Osmundson 1999). Reinhard Bornkamm, a researcher at Berlin's Free University is known internationally as the father of modern green roofs. He played an important role in building one of the earliest examples of a modern green roof in Stuttgart, Germany. In 1975, a green roof organization known as The German Landscape Research, Development & Construction Society, also known as Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau e.V. (FLL), was founded by professional organizations (FLL 2002). FLL developed an influential green roof manual and guideline for green roof design and installation. To this day, the FLL manual and guideline continues to be cited as the basis for green roof design policy and standards for various municipalities across Canada and United States, and in other countries worldwide (Lawlor et al. 2006).

Today, municipalities worldwide are implementing low impact development (LID) tools to mitigate the adverse effects of urbanization on water resources (e.g., City of Toronto 2013; Lawlor et al. 2006). The implementation of LID tools serve to bring the present urban hydrologic cycle closer to the pre-development hydrologic cycle by increasing infiltration and ET, thereby decreasing stormwater runoff volume and peak stormwater flow rates (Ministry of the Environment 2003). With roof area accounting for close to 50% of the impervious surface area within developed areas (Dunnett & Kingsbury 2004), there is a potential for roofs to be a host for LID tools, such as green roofs (Mentens et al. 2006).

The motivation for the recent re-emergence in green roof research is to develop process level understanding of the impact of green roofs on the urban hydrologic cycle in order to optimize the green roof design process.

2.1.3 Green roof design

Within a city and among different geographic regions, green roofs can have different design configurations as the design considerations often differ based on environmental conditions, site conditions, and stakeholder preferences (Doshi et al. n.d.; Mentens et al. 2006; Getter & Rowe 2006; FLL 2002). Within the same city, the environmental conditions at roof sites may vary due to different local microclimatic conditions (e.g., Doshi et al. n.d.; Peck et al. 1999). Among different geographic regions, the environmental conditions can differ in annual precipitation and other climatological conditions (i.e. average temperature and relative humidity) (Mentens et al. 2006). Site conditions which may vary include the building's roof load capacity, roof shading due to adjacent buildings, roof slope, and wind tunneling due to adjacent buildings (Getter & Rowe 2006). Finally, different stakeholders have different reasons for installing the green roofs (e.g., preferred ecologic and economic benefits from a green roof); therefore, the stakeholder's preferences can influence green roof design configuration (e.g., Doshi et al. n.d.; Peck et al. 1999).

Green roofs fall under three main categories: extensive, semi-intensive, and intensive (Oberndorfer et al. 2007). The main difference among these green roof types is the substrate depth (Oberndorfer et al. 2007), which subsequently impacts the type of vegetation which can be planted on the green roof (Heim & Lundholm 2014b; Thuring et al. 2010). The different green roof design configurations ultimately result in differences in the structural load on a building (Oberndorfer et al. 2007). Intensive green roofs typically have greater than 150 mm of substrate depth, and host vegetables, shrubs, and trees since these vegetation types require a deeper root zone (Oberndorfer et al. 2007). With a large substrate depth and vegetation types which often require external irrigation, intensive green roofs have a larger structural load requirement (Oberndorfer et al. 2007). In contrast, extensive green roofs have a lower load requirement since these roofs have a shallower substrate depth (typically ranging from 50 to 150 mm) and host vegetation types which require negligible artificial irrigation (Getter & Rowe 2006). Extensive green roofs are the popular choice when retrofitting an existing building with a green roof due to their low structural load and low maintenance requirements (Getter & Rowe 2006). This thesis, including the following sections in this Chapter, focuses primarily on extensive green roofs.

The design configuration of extensive green roofs varies widely. The three well known types of extensive green roof set-ups include modular systems, pre-cultivated vegetation blanket systems, and complete systems (Oberndorfer et al. 2007). The modular system involves the use of square or rectangular containers (e.g., made of recycled polypropylene) which are filled with green roof substrate (e.g., LiveRoof 2012). The substrate filled modules are planted with vegetation plugs ex-situ prior to installation onto a roof surface covered with a root protection membrane. The green roof module design allows different substrate depths to be used. LiveRoof® is one of the green roof companies which has developed a modular type of extensive green roof set up (LiveRoof 2012). The pre-cultivated system involves the use of pre-grown vegetated mats with varying substrate depth (e.g., Xero Flor America n.d.). The vegetated mat is rolled out onto the roof surface covered with root protection membrane (Oberndorfer et al. 2007).The complete system involves the installation of the green roof components, including the roof membrane, as the primary part of the roof (Oberndorfer et al. 2007). Despite the variations in the installation method and the design configuration, the main components of an extensive green roof are similar and mainly include the: root protection membrane, drainage layer, substrate layer, and vegetation layer. Together, these components function to provide the ecologic and economic benefits required from green roofs. Prior literature studies have examined the function and processes of the different green roof components in order to optimize the benefits of green roofs (Lundholm et al. 2015; Poe et al. 2015; Ouldboukhitine et al. 2012; Ouldboukhitine et al. 2011; VanWoert et al. 2005; Boivin et al. 2001). Researchers have varied different aspects of the green roof component (e.g., depth and type of substrate) and measured the associated impact on green roof benefits (e.g., stormwater retention) to better understand how to optimize the green roof design (Feitosa & Wilkinson 2016; Poe et al. 2015; Fassman-Beck et al. 2013; VanWoert et al. 2005).

The depth and type of substrate and the type of vegetation used on green roofs are major components of the design configuration which play a role in the thermal and hydrologic performance of the green roof. These design parameters can be varied to optimize green roof performance. The main role of the substrate is to retain rainfall and provide support for plant life. The substrate used on green roofs generally adheres to the FLL guidelines which outline in detail the suggested granulometric distribution, organic content, frost resistivity, structural and bedding stability, water permeability, maximum water capacity (i.e. water available for vegetation), air content, pH value, carbonate content, salt content, and nutrient content (FLL 2002). The engineered green roof substrate consists mostly of inorganics, such as lightweight aggregates (e.g., pumice and expanded clay or slate), and a small content of organics (e.g., peat and humus). The substrate type and depth influences the type of vegetation which can be grown (Brown & Lundholm 2015; Berretta et al. 2014; Poë et al. 2015). One of the challenges for the implementation of green roofs is selecting suitable vegetation types which grow well with relatively shallow substrate depth that has low organic and nutrient content, and little to no external irrigation (Thuring et al. 2010). The main role of vegetation is to provide surface cooling and increase substrate stormwater retention by transpiring stored pore water back to the atmosphere, as well as improving the aesthetics of the roof environment. Succulents (e.g., various Sedum species) and graminoids (e.g., various grass species) are commonly used on green roofs as they are able to survive under the harsh microclimatic conditions on the roof. The other design parameters of the green roof which have not garnered as much attention within the green roof literature are the drainage layer and the root protection membrane. Among the green roof companies, the drainage layer can come in different designs. The main purpose of the drainage layer is to retain excess rainfall which has percolated through the substrate but could not be retained, and then direct this volume of stormwater towards outlets and roof drains. The root protection membrane is placed directly above the conventional roof membrane. This membrane acts as a root barrier to prevent roots from permeating through the building's roof. The remainder of this Chapter focuses on the impact of substrate depth and type, and vegetation type on ET from green roofs.

2.2 Evapotranspiration from green roofs

2.2.1 What is evapotranspiration?

ET is the process through which solid and liquid water from the Earth’s surface is transformed into water vapour and returned back to the atmosphere (Jones 2014b). ET is the combination of two physical processes occurring simultaneously: evaporation of water from the substrate and leaf surface, and the transpiration of water through the stomatal cavities of the plant (Jones 2014b). Evaporation is a diffusive process which is controlled by the amount of moisture available in the substrate or on a leaf surface relative to the water vapour concentration in the atmosphere (Penman 1948). The vapour pressure difference between the substrate or leaf surface and the atmosphere is the driving force for evaporation (Dingman 2002). Transpiration is driven by the potential-energy gradients that originate in the movement of water vapour into the air through the stomatal openings of a plant in response to the vapour pressure difference (Monteith 1965; Meinzer 1993). A vapour pressure gradient between the leaf surface and the inner leaf environment, as well as a vapour pressure gradient between the inner leaf environment and the root zone is required for transpiration to occur (Dingman 2002). Transpiration has a physiological control over the size of the stomatal opening, regulating the amount of water loss from the inner leaf environment (Meinzer 1993). ET rate is typically expressed in millimeters (mm) per unit time. From a stormwater management perspective, ET is the fundamental hydrologic process for increasing rainfall retention and decreasing peak flow rates from green roofs, as the loss of water to the atmosphere between rainfall events provides available storage space in the green roof substrate for water storage during subsequent rainfall events (Berretta et al. 2014).

2.2.2 Climatological factors influencing evapotranspiration

Solar radiation, air temperature, relative humidity, and wind speed are the main climatological factors that influence ET (Dingman 2002). Solar radiation typically provides the energy required to enable the phase change of water molecules from liquid water (i.e. pore water) to water vapour (Allen et al. 1998; Jones 2014b). The driving force of the transfer of water from the vegetated and substrate surface to the atmosphere is a function of the vapour pressure deficit (VPD) (Dingman 2002). The climatological factors which govern VPD are air temperature and relative humidity. VPD is a measure of the difference between the amount of moisture in the air and the amount of moisture the air can hold at a given temperature. As ET proceeds, the surrounding air gradually becomes saturated. The replacement of the saturated air with the drier air depends on the wind speed (Allen et al. 1998). Therefore, all four climatological factors (i.e. solar radiation, air temperature, relative humidity, and wind speed) interact with each other, and these interactions govern the overall ET rates from the vegetated surfaces (Allen et al. 1998). Past studies have quantified the interacting relationships between these climatological factors and developed predictive ET formulas indicating that ET is a function of all these aforementioned climatological factors (i.e. combination methods; e.g., Penman-Monteith; Penman 1948; Monteith 1965; Allen et al. 1998, ASCE; Walter et al. 2001) or only some of the climatological factors (e.g., temperature-based method; e.g., Hargreaves & Samani 1985). Regardless of which factors are considered in the predictive ET equations, the relationships between ET and a climatological factor is the same among all predictive equations. Past green roof studies on ET have observed diurnal and seasonal fluctuations in ET in response to daily and seasonal changes in climatological conditions, respectively (Berretta et al. 2014; Marasco et al. 2014). A general observation made by these studies is that ET rates are higher during warmer (summer) conditions and lower during cooler (spring) conditions (Berretta et al. 2014; Marasco et al. 2014). For instance, Berretta et al. (2014) reported double the moisture loss (ET) during warmer drying periods with an average ET of 1.83 mm/ day compared to relatively cooler drying periods with an average ET of 0.76 mm/ day. Drying periods are defined as a duration during which there is no rainfall and drainage to or from the green roof.

In addition to being governed by the climatological factors described above, ET rates are also influenced by the moisture content in the substrate (Berretta et al. 2014). As the moisture content in the substrate decreases during drying periods, the soil moisture that can be evapotranspired becomes limited. Under lab conditions where the climatological conditions (e.g., temperature and relative humidity) are kept constant, this drying and decrease in moisture content results in an exponentially decaying trend in ET (Voyde et al. 2010). However, under field conditions the exponential decay in ET rate is often not as apparent as it is generally masked by the varying climatological conditions (Berretta et al. 2014). For predictive ET equations, such as the ASCE or Hargreaves methods, water saturated conditions are assumed and ET is estimated based solely on the climatological conditions. Despite favourable climatological conditions, the actual ET rate from a green roof may not equal the ET predicted from these equations due to available moisture limitations. A recent study conducted by Berretta et al. (2014) concluded that a moisture content factor needs to be applied on the predictive ET equations in order to accurately capture the decrease in ET rates with the decrease in moisture content. Therefore, the synergistic effects of the variation in climatological conditions and the moisture content during drying periods influence the ET rate.

2.3 Green roof design factors influencing evapotranspiration

2.3.1 Influence of substrate characteristics and depth

Particle size and void size distributions are substrate characteristics which influence the substrate's porosity, thereby influencing the substrate's field capacity (Beattie & Berghage 2004). Field capacity is the point at which soil capillary pressure can no longer permanently store water in the soil, and drainage from the soil occurs (Dingman 2002). Consequently, these substrate characteristics influence the ability of a green roof to retain rainfall, and by extension determines the maximum amount of water which can be evaporated and transpired from a green roof (Poë et al. 2015). One of the commonly used engineered green roof substrate is brick-based with small particles and a well-graded grain size distribution. With these substrate characteristics, the substrate is engineered to have a high porosity (e.g., 0.39 to 0.41) and a low permeability (e.g., 2.41 to 14.8 mm/ min) (Poë et al. 2015). A well-graded distribution is desirable because it increases the tortuosity of the path through which water flows through the substrate prior to becoming roof runoff – this may increase the stormwater detention time within the green roof (Poë & Stovin 2011; Poë et al. 2015). Berretta et al. (2014) compared the cumulative moisture loss (ET) of three vegetated extensive green roof treatments, where two treatments used brick-based substrate and one used a volcanic-based (or LECA-based) substrate over the same drying duration (~ 10 days). Compared to the brick-based substrate, the LECA-based substrate had larger particles and a poorly graded distribution (Berretta et al. 2014). From this study, both brick-based substrate treatments were found to have greater cumulative moisture loss over the a ten day drying period compared to the LECA-based substrate treatment (Berretta et al. 2014). This difference in retention performance between the substrate types was attributed to the differences in the substrate's characteristics (Berretta et al. 2014). This study highlighted that substrate characteristics can influence both the rainfall retention capacity of the substrate and the rate of moisture loss via ET (Berretta et al. 2014).

From an ecological perspective, optimizing the field capacity of the substrate is important for the plants since this storage capacity determines the upper water content limit from which water can be made available to plants (Cassel & Nielsen 1986). The total available water to the plants is the amount of water released between the field capacity and permanent wilting point of the substrate (Cassel & Nielsen 1986). To date, there is a limited understanding on the viability and growth of plants in various green roof substrates. A previous study found that for particular herbaceous species (*Dianthus deltoids* and *Petrorhagia saxifrage,* and a succulent species (e.g., *Sedum sexangulare*)), plant growth was significantly higher in the expanded clay substrate treatments compared to the expanded shale substrate treatments (Thuring et al. 2010). The higher plant performance in the expanded clay treatment was attributed to the higher field capacity of clay aggregates (31.7%) compared to the shale aggregates (27.5%) (Thuring et al. 2010).

The rainfall retention performance of green roofs with different substrate depths has been assessed in previous studies (VanWoert et al. 2005; Yilmaz et al. 2016). These studies found that rainfall retention improved as substrate depth increased (VanWoert et al. 2005; Yilmaz et al. 2016). For example, Yilmaz et al. (2016) recently reported a 10% increase in retention for a substrate depth of 12 cm compared with 8 cm. While these prior studies have quantified the impact of substrate depth on rainfall retention amounts, no study to date has explicitly assessed the impact of varying substrate depths on ET rates. The substrate depth is typically kept constant within a single green roof ET study, ranging from shallow depths of 6.5 cm (East North America, Maritime climate; MacIvor & Lundholm 2011; Lundholm et al. 2010; Lundholm et al. 2014) to greater depths of 19 cm (Australia, Mediterranean climate; Farrell et al. 2013). It is difficult to compare the ET rates among these past studies due to differences in climatological conditions and green roof configuration (e.g., substrate type, substrate depth, plant type, etc.) among the studies.

From a plant health perspective, previous green roof studies have reported that substrate depth can influence the growth, drought stress, and drought tolerance of green roof vegetation. These past studies have similar recommendations in that greater substrate depth can increase the chances of survival for different plant types, including various Sedum species (e.g., Van Mechelen et al. 2015; Thuring et al. 2010; Boivin et al. 2001). For example, Van Mechelen et al. (2015) reported that deepest substrate of 10 cm resulted in the highest plant cover, abundance values, and species richness. For semi-arid climates, other studies have also recommended deeper substrate depth ranging from 6 cm to 20 cm (Benvenuti & Bacci 2010; Thuring et al. 2010). In Quebec, Boivin et al. (2001) found that substrate depth can influence freezing injury for certain herbaceous perrennials and recommended a minimum substrate depth of 10 cm should be used for green roofs installed in northern latitudes (e.g. Canada). Additional data from green roofs which have a substrate depth greater than 10 cm is required as a substrate depth greater than 10 cm is recommended for green roofs in Canada to prevent the green roof plants from experiencing freezing injury during the winter months when temperatures reach below 0°C (Boivin et al. 2001).

2.3.2 Influence of vegetation type on green roof performance

Plant species which have been used on green roofs can be categorized into the life-form groups: succulents, graminoids, and forbs (Lundholm & Williams 2015). Each life-form group consists of species with similar ecological strategies which are reflected by their morphological, anatomical, physiological, and phenology features (Lundholm & Williams 2015). Plant species from the succulent life-form group have been widely used in green roofs in North America since they are known to survive and thrive on green roofs (Berghage et al. 2007; Villarreal & Bengtsson 2005; Lu et al. 2014). Although Sedum species are widely used on green roofs and are known to be suitable for the harsh roof environment, recent research has focused on optimizing the ecosystem services provided by green roofs by selecting plants on a plant-trait based approach (Farrell et al. 2013; Farrell et al. 2015; Lundholm et al. 2014; Lundholm et al. 2015; Van Mechelen, Van Meerbeek, et al. 2015). A plant-trait based approach selects plants based on their physiological, anatomical, and morphological traits (Van Mechelen, Van Meerbeek, et al. 2015; Farrell et al. 2013; Farrell et al. 2015; Lundholm et al. 2015). These plants traits include, but are not limited to: stomatal conductance, specific leaf area, plant height, leaf area index, plant coverage, and high root biomass (Lundholm & Williams 2015). Researchers suggest that green roof performance, including the thermal and hydrologic performance, can be optimized by understanding how plant traits optimize specific functions of the green roof (Ouldboukhitine et al. 2011; Ouldboukhitine et al. 2014; Tabares-Velasco & Srebric 2012; Lundholm et al. 2010; Lundholm et al. 2015). Knowledge of these traits allows the stakeholder to make informed decisions on selecting plants which can optimize the key benefits desired from a green roof. Knowledge of the appropriate plant traits allows the stakeholder to choose plants available in specific regions and climates where the green roof is being installed that fit the plant-trait criteria required to perform a given green roof function (Farrell et al. 2015). Key plant traits that affect ET rates, and thus the hydrologic performance of green roofs, are leaf and canopy structure, and root distribution (Lundholm & Williams 2015).

The water vapour and CO_2 exchange occurs through the pores on plant leaves which are known as stomata. The anatomical, morphological, and physiological features of stomata vary among different life-form groups and among plant species within the same life-form groups. The stomatal structure and density differ for different plant species. Plants which have stomata restricted to the lower epidermis are referred to as hypostomatous, whereas plants which have stomata on both sides are called amphistomatous (Jones 2014a). The two main types of stomata found in higher plants are the elliptical type and the graminaceous type (Jones 2014a). The differences in stomatal patterns and behaviour are important to understand because it provides insight on the plant's water use strategy under different physiological and environmental conditions. In the case of green roofs, this is important information because it gives us insight into the water use strategies the species will use when water is available and when water is limited. To improve the hydrologic performance of green roofs, species which effectively use the water when it is available and conserve water when it is not available are the ideal types of species to use because they are able to survive drought conditions that can occur on extensive green roof conditions, where external irrigation is not typically provided (Farrell et al. 2013).

The characteristics of the aboveground structure of a plant species, such as the leaf and canopy area, are important parameters to quantify as they provide an indication of the total area through which gas exchange can occur. For predictive ET equations, such as Penman-Monteith, the measurement for the total canopy area which actively receives photosynthetically active radiation over the measured ground area (commonly referred to as the leaf area index) is required to empirically derive the stomatal resistance for a plant type under varying climatological conditions (Monteith 1965). Given this relationship between canopy area and transpiration, it can be expected that species with a greater canopy area will have greater transpiration rates, assuming that the climatological conditions remain constant and soil moisture is not limited. In past green roof studies, the canopy area can be described as aboveground biomass or plant coverage (Lundholm et al. 2010; Berretta et al. 2014). For the remainder of this thesis, the term plant coverage will be used to describe canopy area. The presence of low growing mat-like plants, such as Sedum species, has been suggested to decrease evaporation rates, which can hinder the regeneration of the retention capacity for subsequent rain events (Berretta et al. 2014); however, water loss through transpiration was suggested to likely cancel out this effect (Lundholm et al. 2010). From a biodiversity perspective, the addition of Sedum species in mixed species treatments was found to positively influence the survival of other plant species which did not have high plant coverage due to the lower evaporation rates maintaining a wetter moisture content throughout the drying period (Wolf & Lundholm 2008). In addition to spatial plant coverage, temporal stability in plant coverage was found to positively influence water capture (Lundholm et al. 2010). Greater plant coverage has also been found to improve the thermal functioning of the green roof, especially when the plant species has leaves with high reflectivity (Lundholm et al. 2010) and low stomatal resistance (Tabares-Velasco & Srebric 2012). Therefore, plant coverage is an important parameter for optimizing the hydrologic and thermal functioning of green roofs.

Plant physiology is the study of the functions and processes occurring within the plant. This includes various aspects such as the plant's metabolism and water transport processes.

Plant metabolic process affects how these anatomical features respond to external environmental conditions (e.g., climatological conditions). Plant species can be classified to have one or two of the three metabolic processes: C3, C4, and crassulacean acid metabolism (CAM) (Starry et al. 2014). Plants with a C3 and C4 metabolism open their stomata in response to the light during the day and close in the dark. The stomata for plants with the CAM pathway do the reverse, and open during the dark when the temperature is cooler and close during the day (Jones 2014c). CAM pathway allows plants to reduce the amount of moisture loss, and to conserve water use when it is limited (Starry et al. 2014). When selecting plant types for green roofs, it is beneficial to choose plants which utilize water when it is available and conserve water when it is limited (Berghage et al. 2007; Farrell et al. 2012).

The spatial distribution of the roots, including the root length and mass, influences the root’s water uptake which can in turn influence transpiration rates. It has been shown that when plants are placed under water stress, they increase their root to shoot biomass to increase their water uptake preventing the plant from experiencing water deficiencies (Lu et al. 2014). As an example, plants exposed to irrigation deficit during the development phase were found to better adapt to drought stress at the maturation stage due the development of specific root characteristics (i.e., increase in root to shoot biomass) compared to plants which had sufficient water irrigation throughout their development phase (Lu et al. 2014). The root characteristics among different species vary, some plants have high root biomass with great length (e.g. grass species), whereas other roots are made to be fibrous and short (e.g. Sedum species) (Nagase & Dunnett 2012). Within the green roof literature, the root distribution of different plant types and how this distribution interacts with the substrate depth to influence the ET rate has not been examined. Given the importance of water uptake by roots, better understanding of the influence of roots on the ET rate from green roofs is required. This knowledge can also help improve the plant selection process to better match the substrate configuration by including substrate depth in the green roof design process. Within green roof design policy, there is currently no mention of ensuring that the root distribution of the plant should match the substrate depth chosen for the green roof.

To maximize the number of benefits provided by green roofs, past studies have recommended the installation of a mixture of species with different and yet complementary plant traits (Lundholm 2015; Lundholm et al. 2015; Lundholm et al. 2010; Nagase & Dunnett 2012; Heim & Lundholm 2014a). Some of these past studies have examined the effect of green roofs designed with a mixture of species and those with only one species (monoculture) on stormwater retention from green roofs (Lundholm et al. 2015; Lundholm et al. 2010; Nagase & Dunnett 2012; Dunnett et al. 2008; MacIvor & Lundholm 2011). Until recently, it was unclear whether a mixed species design would outperform a monoculture design, or vice versa, in the amount of stormwater capture due to discrepancies in the results reported in past studies (Dunnett er al., 2008a, MacIvor er al., 2011, Lundholm et al., 2010, Nagase and Dunnett, 2012). Some studies reported no additional benefits from having a mixture of species (Dunnett et al. 2008; Nagase & Dunnett 2012), whereas other studies found some positive benefits on stormwater retention (Lundholm et al. 2010) and substrate cooling (MacIvor & Lundholm 2011). To optimize green roof performance and its provision of economically valuable benefits, it is best to have a mixture of high performing species with complementing functional traits compared to mixing poor performing species with non-complementing traits (Lundholm 2015). For example, Lundholm et al. (2010) recommended a mixture of species from the life-form groups succulents, grasses, and tall forbs to optimize two green roof benefits, surface temperature cooling and stormwater capture. The aboveground and belowground traits from each species optimized the water uptake, surface reflectivity, and surface cooling (Lundholm et al. 2010). Sedum species provided temporal stability in the aboveground biomass (i.e. plant coverage), the grass species maximized the aboveground biomass and belowground biomass (i.e. root mass distribution), and one of the tall forbs species (*Solidago bicolor*) was characterized to have large, flat leaves which also contributed to the aboveground biomass (Lundholm et al. 2010). The large biomass aboveground increased the total area for gas exchange, thereby maximizing water loss through evapotranspiration and by extension surface cooling (Lundholm et al. 2010). The mixture of the spatial root distribution belowground from the mixed species was not quantified in this study, but past researchers suggested that belowground spatial complementarity can maximize water uptake (Wolf & Lundholm 2008; Lundholm et al. 2010).

2.4 Knowledge gaps

While the depth and type of the green roof substrate determines the finite capacity of rainfall which can be retained, the ET rate between rainfall events determines the amount of water storage space replenished. The ET rate depends on various factors including the physical traits of the vegetation type and vegetation's physiological response to varying climatological and moisture conditions. The relationships between key climatological factors and ET have long been established by past studies (e.g., Penman 1948; Monteith 1965; Hargreaves & Samani 1985). Solar radiation, air temperature, relative humidity, and wind speed are the main interacting climatological factors which drive the phase change and transfer of stored pore water into water vapour from within the green roof substrate and into the overlying urban atmosphere. For an extensive green roof setting, ET rates are more limited by moisture content due to the shallow substrate depth in comparison to other vegetated systems which have greater substrate depths (Stovin et al. 2013; Berretta et al. 2014).

Over the past decade, there has been a growing database of ET rates from varying green roof configurations under different climatological conditions (Poe et al. 2015; Berretta et al. 2014; Marasco et al. 2014; Wadzuk et al. 2013; Voyde et al. 2010; Lundholm et al. 2010; Berghage et al. 2007). However, it is difficult to compare different green roof studies to quantify the impact of green roof vegetation types and substrate (type and depth) on ET because studies differ in green roof design parameters and climatological conditions. As a result of these differences, ET rates from one study may not be easily be compared with ET rates at a different site with the same design configuration and different climatological conditions, or vice versa. To date, no study has evaluated the sensitivity of ET rates under different climatological conditions from the same green roof design. By maintaining a constant green roof design and varying only the climatological factors, a more detailed understanding of the effects of various climatological factors and moisture content on hydrologic and thermal performance is gained. This knowledge gap needs to be addressed to provide insight on how climatological factors impact the hydrologic and thermal performance of similar green roofs installed in different climates (e.g., differ in annual rainfall, and seasonal average temperature and relative humidity).

Furthermore, optimizing green roof design requires detailed understanding of the impacts of various parameters on ET. Prior green roof studies, both those which assessed the thermal and hydrologic performance of green roofs, focused on using plants which were known to survive and thrive under the harsh roof conditions, which were namely succulents (e.g., Monterusso et al. 2005; VanWoert et al. 2005; Wolf & Lundholm 2008). However, recent green roof plant studies have shown that it is important to consider the benefits that other plant species can provide (MacIvor & Lundholm 2011; Monterusso et al. 2005). New plant species include those that are native or plant species with known adaptive strategies that may be beneficial under a roof environment (e.g., Thuring et al. 2010). The benefits that these other plants can provide in terms of the hydrologic and thermal performance of green roofs requires further investigation as there are only a limited number of studies which have assessed the characteristics of green roof plants and measured ET within the same study (Farrell et al. 2013; Lundholm et al. 2010; Lundholm et al. 2015; Tabares-Velasco & Srebric 2012; Ouldboukhitine et al. 2014). Quantifying plant characteristics can help make the plant selection process more quantifiable instead of it being based on the plant’s species and its aesthetics. A combined understanding of the plant functional traits and how they influence ET rates is currently lacking within the green roof literature. This knowledge gap needs to be addressed in order to optimize the hydrologic performance of green roofs in terms of how plants can help in regenerating the retention capacity of the green roof substrate.

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Chapter 3

3 Evapotranspiration from extensive green roofs: influence of climatological conditions, vegetation type, and substrate depth

3.1 Introduction

With urbanization comes the need to mitigate increasing stormwater runoff volumes. Given the limited ground space within dense urban areas, retrofitting the available roof space of existing buildings with extensive green roofs provides a non-intrusive solution to mitigate against the impact of excessive stormwater runoff (Stovin 2010). Literature studies to date have primarily focused on the extent to which green roofs can retain precipitation (e.g., VanWoert et al. 2005; Roehr & Kong 2010; Villarreal & Bengtsson 2005; Carter & Jackson 2007; Mentens et al. 2006). The extent to which green roofs retain precipitation, however, is governed by evapotranspiration (ET) as it frees up water storage space for precipitation retention in green roof substrate (soil). The enhancement of ET from green roofs also provides thermal benefits through the decrease in the building's roof surface temperature, as a result of evaporative cooling (e.g., Tabares-Velasco & Srebric 2012; Lundholm et al. 2010). To date, the impact of different green roof design parameters including vegetation type on ET rates has received limited attention.

ET is the process through which soil moisture held within the plant and green roof substrate is transferred as water vapour to the atmosphere (Dingman 2002). ET is the combination of two physical processes occurring simultaneously: evaporation of water from the substrate and leaf surface, and transpiration of water through the stomatal cavities of the plant (Jones 2014). Evaporation is regulated by the ambient weather conditions, such as the vapor pressure gradient between the atmosphere and the substrate, as well as the available moisture content in the substrate (Penman 1948). Transpiration is regulated by the plant's metabolic process and adaptive strategies, available moisture content, in addition to the vapour pressure gradient between the leaf surface and the overlying atmosphere (Monteith 1965). During transpiration, water travels from the deep root zone to the shallow root zone due to hydraulic lift where it then travels through the xylem and into the plant’s stomatal cavity (Norton & Hart 1998).

Studies examining ET from green roofs have been completed around the world, including Europe (e.g., Sheffield, UK; Stovin et al. 2013; Poe & Stovin 2011; Poe et al. 2015; Berretta et al. 2014), USA (e.g., New York City, NY; Marasco et al. 2014; Marasco et al. 2015), and Canada (e.g., Halifax, NS; Lundholm et al. 2015). Prior studies were either conducted under controlled conditions, such as those conducted in a laboratory or green house setting (e.g., Poe et al. 2015), or under field conditions where climatological conditions and rainfall are not controlled (e.g., Berretta et al. 2014). Under controlled conditions, the initial moisture content, ambient weather conditions, and duration of a drying period (defined as a period with no rainfall and no drainage) can easily be manipulated. Under field conditions, the moisture content at the start of a drying period (referred to as initial moisture content) depends on the amount of rainfall immediately preceding the drying period and the antecedent moisture content before the rainfall occurred. The antecedent moisture content is defined as the soil moisture within the substrate at the end of a drying period (i.e., before a rainfall event begins). Comparison of ET results between prior studies is difficult because both the climatological conditions (i.e., temperature, relative humidity, precipitation) and green roof design (i.e., substrate type and depth, plant type) differ. No green roof study has investigated the impact of climatological conditions on ET using the same green roof design under field conditions. The impact of climatological variables on ET has only previously been shown by investigating the seasonal effects on ET at the same site (Metselaar 2012; Berretta et al. 2014; Marasco et al. 2014; Poë et al. 2015). For instance, under conditions when water was not limited, Berretta et al. (2014) found that ET rates were higher during the summer months when there was more available energy for ET. In contrast, ET rates in the spring, under well-watered conditions were found to be lower due to lower available energy for ET and relatively cooler conditions (Berretta et al. 2014).

A series of green roof studies at the University of Sheffield assessed the impact of substrate and vegetation type on the hydrologic performance of green roofs (Berretta et al. 2014; Poe et al. 2015). They reported ET rates ranging from 0.52 mm/ day to 2.7 mm/ day for green roof treatments with 8 cm substrate depth and conducted under similar climatological conditions (i.e., spring and summer conditions in Sheffield, UK) (Berretta et al. 2014; Poë et al. 2015). ET rates from another study at The Pennsylvania State University, which used a substrate depth of 8.9 cm and conducted under a different climatological conditions (i.e., greenhouse conditions), varied from 0.84 mm/ day and 2.2 mm/ day (Berghage et al. 2007). The University of Sheffield group also found that green roof substrate with a field capacity between 0.39 to 0.41 and a permeability between 2.41 to 14.8 mm/ min had higher cumulative moisture loss (ET), and therefore greater rainfall retention capacity (Poë et al. 2015). The depth of substrate is another important green roof design parameter that may considerably affect ET rates. While prior studies have shown that substrate depth affects rainfall retention (e.g., VanWoert et al. 2005; Feitosa & Wilkinson 2016), to our knowledge no studies have explicitly examined the effect of varying substrate depth on ET rates under the same climatological conditions. The individual green roof ET studies which were conducted under varying climatological conditions and with different vegetation types typically keep the substrate depth constant. The substrate depth among these past green roof ET studies ranges from 6.5 cm (East North America, Maritime climate; MacIvor & Lundholm 2011; Lundholm et al. 2010; Lundholm et al. 2014) to 19 cm (Australia, Mediterranean climate; Farrell et al. 2013).

Plant selection is an important design consideration when optimizing ET and subsequently the green roof rainfall retention capacity. In past green roof studies, Sedum species (succulents) were typically selected based on their ability to survive and grow under harsh roof microclimatic conditions (VanWoert et al. 2005). However, most Sedum species are non-native to North America, as such there is an interest in adopting native species in green roof installations (Monterusso et al. 200; Wolf & Lundholm 2008; MacIvor & Lundholm 2011; Whittinghill et al. 2014). Recent research conducted in a Canadian Atlantic/ Maritime climate found that certain grass species (e.g., *Poa compressa*) outperformed non-native species, such as *Sedum acre* and *Sedum x rubrotinctum*, by having a greater cumulative ET during an experimental “dry treatment” where vegetated treatments only received irrigation every 24 days (Wolf & Lundholm 2008). Furthermore, in the past decade, green roof research has moved towards selecting plants based on their functional traits to optimize the ecologic and economic benefits provided by green roofs (Farrell et al.

2013; Farrell et al. 2015; Van Mechelen et al. 2015; Heim & Lundholm 2014; Lundholm et al. 2015; Lundholm & Williams 2015; J. Lundholm et al. 2014). These traits can include morphological (e.g., leaf shape), anatomical (e.g., stomata density, stomata aperture), physiological (e.g., metabolic process), and phenological (e.g., seasonal flowering stage) features (Lundholm & Williams 2015). Plants with high root biomass (Nagase & Dunnett 2012), high specific leaf area (SLA) (Lundholm et al. 2015), and low stomatal resistance (Tabares-Velasco & Srebric 2012; Sendo 2010) have been shown to influence the rainfall retention and the cooling performance of green roofs. Previous research found that grass species (e.g., *Anthoxanthum odoratum* and *Trisetum flavescens*) improved green roof retention performance better than the forbs and Sedum species due to greater root growth (and greater plant diameter and height) resulting in greater water capture in the substrate (and interception) (Nagase & Dunnett 2012). SLA was found to be positively correlated to canopy density which indirectly influenced the thermal benefits of the green roof, whereby species with high SLA corresponded to lower summer substrate temperatures (Lundholm et al. 2015). Differences in the stomatal resistance between grass species (50 s/ m) and Sedum species (350 – 700 s/ m) was found to influence the predicted ET from a green roof in a modelling study, whereby grass species had ET rates 3-4 times greater than Sedum species (Tabares-Velasco & Srebric 2012).

A plant's ability to readily transpire water following a rainfall event is a desirable functional trait as it allows for faster regeneration of water storage within the green roof substrate (Farrell et al. 2013). Sedum species have traditionally been classified to have a carbon fixation pathway known as crassulacean acid metabolism (CAM); however, recent research has found that some Sedum species may be classified under two carbon fixation pathways, C3 and CAM (Starry et al. 2014). While differences in water use (i.e., water lost through evaporation and transpiration), and thus ET rates, from individual green roof plant species have been examined by previous studies (Farrell et al. 2013; Starry et al. 2014), there is limited understanding of the impact of plant traits, and thus green roof vegetation type, on ET rates under different climatological conditions (Lundholm et al. 2015; Lundholm et al. 2010; Van Mechelen et al. 2015; Wolf & Lundholm 2008; MacIvor & Lundholm 2011). Furthermore, there is currently no consensus on whether increasing the number of plant species and plant traits can increase green roof performance, or specifically rainfall retention (Lundholm & Williams 2015; Dunnett et al. 2008; MacIvor & Lundholm 2011; Lundholm et al. 2010). One study has indicated that on average the thermal and hydrologic green roof performance (measured based on surface temperature cooling and stormwater capture, respectively) was higher from treatments with a mixture of species from three to five life-form groups compared to treatments with lower diversity (Lundholm et al. 2010). This past study recommended a mixture of succulents, grasses, and tall forbs as these mixtures were found to optimize both surface temperature cooling and rainfall retention (Lundholm et al. 2010). In continuation of this former study, a more recent study found that species within life-form groupings vary in their functional traits resulting in differences in the species' ability to provide thermal and hydrologic benefits (Lundholm 2015). Of the mixed species treatments, a mixture of high performing species with complementary functional traits were found to enhance the effectiveness at which green roofs provided ecosystem services compared to a mixture of poor performing species with non-complementary traits (Lundholm 2015). Therefore, selecting plants based on their functional traits is still an important consideration when increasing the species diversity within a green roof (Lundholm 2015). For example, installing three plant species which have different water use strategies allows for the green roof to regenerate the water storage space available in the substrate during drying periods by having plants which effectively transpire water in the substrate when it is abundant (e.g., C3 species) and when it is limited (e.g., C4 and CAM species).

The climatological and design parameters synergistically affect ET rates in that various vegetation types respond to ambient weather conditions differently, and various plant root structures can also interact with substrate depths differently. To date, there is limited knowledge on the rate at which the retention capacity is regenerated (i.e., ET rate) for green roofs with different vegetation types planted in varying substrate depths. This is hindering the design process in optimizing the hydrologic performance of green roofs. The novel experimental design of this study makes it one of the first studies to quantitatively investigate the influence of different green roof plants and substrate depths on ET rates from extensive modular green roofs in different climate regions. The aim of this study is to evaluate how green roof ET varies in response to different green roof design configurations (i.e., substrate depth and vegetation type) in different climatological conditions. This understanding is needed to inform green roof design aimed at enhancing stormwater retention performance of this increasingly popular low impact development option for urban areas.

3.2 Materials and Methodology

3.2.1 Site description

Three experimental green roofs with identical extensive modular design were built in London ON, Calgary AB, and Halifax NS in July 2012 (Figure 1; Table 1). In London ON, the green roof was installed on the 4th floor of Talbot College at the University of Western Ontario campus. In Calgary AB, the green roof was installed on the 3rd floor of the Earth Sciences building at the University of Calgary campus. In Halifax NS, the green roof was located on an office building in a business park. The extensive modular design consisted of square module casings at 30 cm x 30 cm with a substrate depth of 10 cm or 15 cm. All green roof modules and substrate used at each site were supplied by LiveRoof® (Nunica, MI). These green roof modules included built-in drainage flow paths at the base of the module to facilitate drainage. The green roof substrate was a mixture of fine and coarse hadite, crushed dolostone, bark, peat moss, and some fertilizer (LiveRoof®, Nunica, MI). The substrate satisfied the requirements set out by the German FLL for green roofs (Agricultural Analytical Services Laboratory 2008). The center of the experimental green roof array was elevated at a height of 0.2 m. Surrounding the elevated array were modules sloped at 12°, which were then bordered by other modules lying flat on the building’s roof surface.

Figure 1: Site layout of the experimental modular extensive green roof at the three study sites.

Table 1: Site and climate characteristics for each green roof.

	Calgary, AB	London, ON	Halifax, NS
Latitude, Longitude	51.08, -114.13	43.01, -81.27	44.70, -63.58
Rooftop surface	Gravel ballast	Conventional asphalt	White
Green roof area (m^2)	65	52	55
Plant hardiness rating*	3a	5b - 6a	6a
Climate region**	Prairie	Great Lakes/ St. Lawrence	Atlantic/ Maritime
Climate type**	Cool, arid; extreme temperatures year round	Warm summers, cool winters	Warm winters, cool summers

* (Agriculture and Agri-Food Canada 2015)
** (Environment Canada 2014)

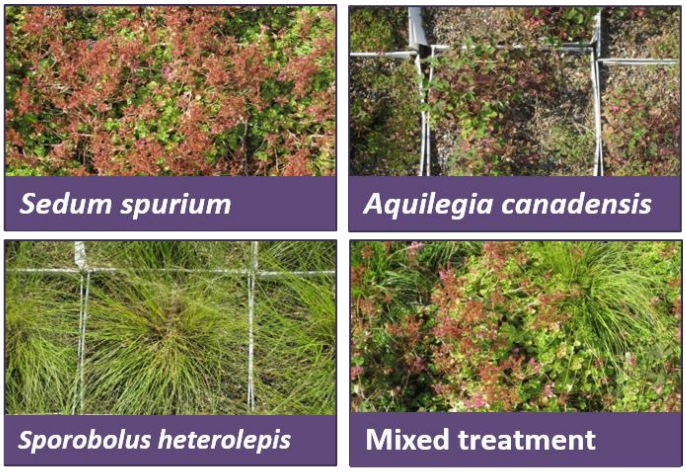

Figure 2: Plan view single species treatments (*S. spurium* (top left), *A. canadensis* (top right), *S. heterolepis* (bottom left), and the mixed species treatment (bottom right).

The green roof array consists of four different vegetated module treatments and two substrate depth treatments. The vegetated module treatments include three single species treatments of *Sedum spurium* 'John Creech' (*S. spurium*), *Aquilegia canadensis* (*A.*

canadensis), and *Sporobolus heterolepis* (*S. heterolepis*), and one mixed species treatment which has a combination of all aforementioned species (Figure 2). For all vegetated treatments, there are modules with substrate depths of 10 cm and 15 cm. The number of replicates for each treatment is summarized in Table 3. It should be noted that all plants were grown in the nursery as plant plugs prior to being transplanted into the green roof modules.

3.2.2 Evapotranspiration measurements

ET rates were determined by continuously weighing a number of modules at each site as well as daily manual weighing of select additional modules. ET rates were quantified based on the change in weight of a module over a given time period (Δt) (Eq. 1):

$$ET = \frac{w_i - w_{i+1}}{\rho_w A_c \Delta t} \qquad [1]$$

where w_i and w_{i+1} are the module weights at the start and end of the time period, ρ_w is the density of water, and A_c is the surface area of a module. ET rates were only calculated for drying periods which are defined as periods during which there is a decrease in module weight as a result of moisture loss from ET, and as periods during which there is no precipitation or drainage. Individual drying periods are separated by precipitation events and associated periods where water continued to be lost by drainage from the module.

Two to four individual *S. spurium* module treatments were weighed continuously at each site during the 2013 and 2014 field season which extended from May to September. The duration of the data collection varied slightly between the sites due to instrument malfunction and availability of site personnel (Table 2). Module weights were continuously measured by placing individual modules on custom made weighing lysimeters that were connected to the CR3000 datalogger (Campbell Scientific, Edmonton AB). The sampling interval for the lysimeter was one second which was then averaged for every one-minute interval. The lysimeters were built with one metal plate (30 cm x 30 cm) centered on the top of one load cell (Interface SPI-25 or Interface SPI-50; Durham Instruments, Pickering ON) and another metal plate (30 cm x 30 cm) centered below the load cell.

Table 2: Duration of the continuous lysimeter measurements and daily module weighing measurements in 2013 and 2014 at each site for the vegetated and bare module treatments. The number of days with measurement considers days during drying periods only (i.e., when there was no precipitation or drainage from the modules).

Site	Year	Treatment	Duration		Days with continuous measurement	Days with manual measurement
			From	To		
Calgary	2013	Vegetated	16-May	1-Oct	123	79
	2014	Vegetated	1-May	1-Oct	148	64
		Bare			-	48
London	2013	Vegetated	1-May	1-Oct	130	98
	2014	Vegetated	1-May	1-Oct	136	134
		Bare			-	134
Halifax	2013	Vegetated	10-May	1-Oct	122	27
	2014	Vegetated	22-May	1-Oct	119	59
		Bare			-	59

Approximately 40 vegetated treatments modules in London, Halifax, and Calgary were weighed manually each day during the 2013 and 2014 field season using a portable electronic scale (Lee Valley Tools Ltd. and Veritas Tools Inc., London ON). In 2014, two to four bare module treatments (i.e., substrate only with no vegetation) were added to the green roof array and manual daily weight measurements were also taken for these modules. Daily weight measurements were taken between 9 am to 10 am to ensure that module weights were recorded prior to solar noon, which is when the ET rate would be expected to peak. Consistently measuring the weight of the module treatments at the same time prior to solar noon allowed for unbiased calculation of the daily ET rates during drying periods.

3.2.3 Climatological measurements: precipitation, temperature, and relative humidity

At each site, precipitation was continuously measured using two rain gauges (TE525WS; Texas Electronics Inc., Dallas TX) installed at the height of the vegetation within the elevated green roof array. Another rain gauge was installed adjacent to the green roof array to quantify any spatial variability in precipitation. A weather station with a relative humidity and temperature probe (HC2-S3; Campbell Scientific, Edmonton AB) was also deployed on each roof to collect microclimate data at five-minute intervals. Instruments on-site were connected to a CR3000 data logger for continuous data collection.

3.2.4 Plant trait measurements

The plant coverage and the root mass distribution were two plant traits which were quantitatively measured in this study. The pin frame method was used to quantitatively assess the plant coverage for individual modules for all vegetated treatments monthly over the 2013 field season and biweekly over the 2014 field season. The pin frame method has been previously used by Lundholm et al. (2010). The pin frame sampling area (30 cm x 30 cm) was divided evenly into 16 sampling points, and the total number of leaves touched from each point was used to estimate the plant coverage for each module treatment. Destructive root mass analysis was conducted at the end of the 2014 field season in London ON using one 15 cm substrate depth module of each vegetation type. The method used was similar to Kabganian et al. (2002). Here, each module was sectioned into four quadrants which was then sectioned into four depth intervals: 0-5 cm, 5-10 cm, 10-13 cm, and 13-15 cm. For each depth interval, the substrate was rinsed off the roots, and then oven-dried at 70°C until the root mass remained constant. The dry weights from each depth interval were used for the root mass analysis.

3.3 Results and Discussion

3.3.1 Influence of climatological conditions on evapotranspiration rates

Cumulative moisture loss through ET provided a means to compare the total ET over the field seasons (May to September) for each city and, as such, assess the impact of climatological conditions on ET. Monthly climatological data for the three cities over the field seasons are provided in Appendix A (Figure A 1). In this analysis, continuous data from the weighing lysimeters placed under 15 cm depth *S. spurium* treatments were used as the dataset provides nearly continuous quantification of ET over the field seasons. For this analysis, moisture gain due to precipitation and moisture loss due to drainage was filtered out. Cumulative ET from May to September averaged over the two years (i.e., 2013 and 2014) were similar in Calgary and Halifax, at approximately 250 mm (Figure 3a). Due to instrument issues in Halifax, data for May 2014 as well as June and July 2013 were unavailable. For months when data were not available, ET in the year with data available was assumed to be representative of both years. Average cumulative ET for London from the 2013 and 2014 field seasons was notably larger (average 360 mm) than Halifax (average 246 mm) and Calgary (average 251 mm) (Figure 3a). Averaged over the two field seasons, this represents an ET rate of ~ 2.4 mm/ day for London and ~ 1.6 mm/ day for Halifax and Calgary. These ranges in ET rates are comparable to Wadzuk et al. (2013) who reported monthly average ET rates of 1 to 7 mm/ day from a green roof in Philadelphia, PA based on weighing lysimeter data. As discussed earlier, ET frees up storage space in the substrate for rainfall retention as well as provides evaporative cooling. As such, the proportion of ET relative to precipitation is important. Over May to September 2013 and 2014, London had a cumulative ET of 720 mm and received 1081 mm rainfall, as such ET represents 67% of the rainfall received. Similarly, cumulative ET in Calgary from both field seasons (501 mm) represented 73% of the 682 mm rainfall received. Finally, from the available rainfall and ET data, Halifax received 1102 mm rainfall with cumulative ET from both field seasons (364 mm) representing 33% of the rainfall. Halifax experienced differing rainfall amounts in both years in addition to instrument issues, resulting in notable differences in the ratio of ET relative to rainfall between 2013 and 2014. For example, for May, June, and September 2013, ET represented 22% of the 765 mm rainfall received in Halifax. In June through September 2014, ET represented 57% of the 337 mm rainfall. These data suggest that for all cities, ET returned a large amount of rainfall to the urban atmosphere, reducing the volume of water that may have been discharged to storm sewers and providing evaporative cooling. It further suggests that climatological conditions may have had a strong impact on ET rates, with ET in London 50% greater than Calgary and Halifax.

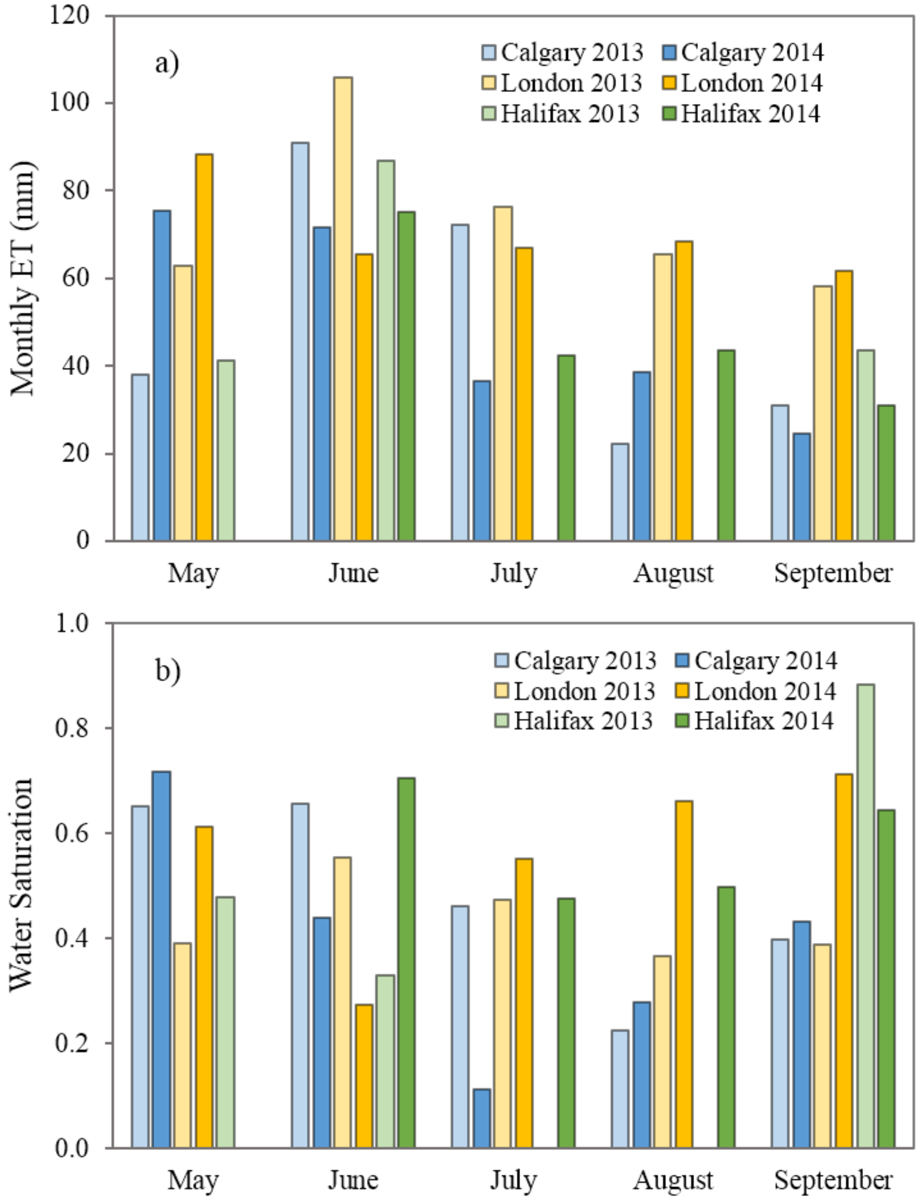

Figure 3: a) Cumulative monthly ET and b) water saturation in the three cities for 2013 and 2014 field seasons. Data not available in Halifax for May 2014 as well as July and August 2013.

As expected, ET was not constant during the field seasons due to changes in climatological conditions (e.g., average air temperature, relative humidity, rainfall volume, and rainfall frequency) and available soil moisture. Cumulative monthly ET, averaged over the three cities, decreased from 83 mm +/– 11 mm in June to 42 mm +/– 11 mm in September (Figure 3a). The extent to which cumulative monthly ET decreased through the field seasons differed in each city. For example, average cumulative ET decreased from 86 mm in June to 60 mm in September in London. Decreases in Halifax (i.e., from 81 mm to 28 mm) and Calgary (i.e., from 81 mm to 37 mm) were larger (Figure 3a). Daily ET rates were ranked to quantify the distribution of ET rates during the observation periods (Figure 4a). This analysis suggests that daily ET rates are generally similar for Calgary and Halifax, as would be expected given similar cumulative ET. For example, daily ET rates were less than 2.0 mm/ day 70% and 64% of the time in Calgary and Halifax, respectively (Figure 4a). Daily ET rates were consistently larger in London with daily ET rates less than 2.0 mm/ day in London for only 46% of the reporting days (Figure 4a). The difference in the proportion of high daily ET rates (e.g., greater than 2.0 mm/ day) and low daily ET rates (e.g., less than 2.0 mm/ day) among the sites was likely due to variability in rainfall volume and antecedent soil moisture. Rainfall volume influences the amount of rainfall retained in the substrate and the moisture content at the start of a drying period. The antecedent soil moisture is defined as the soil moisture within the substrate pores at the end of a drying period (i.e., before a rainfall event begins). If a rain event is large enough to bring the moisture level back up in the substrate, then the ET rates at the start of a drying period were typically high. However, small rain events did not typically result in high ET rates at the start of a drying period. For relatively small rain events (e.g., < 2mm), it is possible that most of the rainfall was intercepted by the plant canopy and evaporated back to the atmosphere directly off the leaf surface (Berretta et al. 2014). A previous study found that wetting of the underlying soil was not detected during minor rainfall events for vegetated green roofs with > 85% of plant coverage (Berretta et al. 2014).

Water saturation provides a quantitative means to determine the amount of water available in the substrate for ET. In this study water saturation is defined as:

$$Water\ saturation = \frac{h - h_{wp}}{h_{fc} - h_{wp}} \qquad [2]$$

where h is the moisture available in the green roof module, h_{wp} is wilting point, and h_{fc} is the field capacity. Wilting point and field capacity were determined from field data. Average water saturation, for the three cities, decreased from 0.57 in May to 0.41 in August but increased in September to 0.58 (Figure 3b). Similar to ET, water saturation differed in each city, with Calgary systematically exhibiting the driest conditions (Figure 3b, 4b). For example, 78% of measured water saturations were less than 0.5 in Calgary, in comparison to 45% of measured water saturations in London, and 43% of measured water saturations in Halifax (Figure 4b). A regression analysis, conducted through Minitab® 17.1.0, was used to determine the extent to which water saturation impacted daily ET rates for the three cities. Assuming that ET is a linear function of water saturation, water saturation was found to have a significant effect on daily ET rates in Calgary and London ($P < 0.005$), but not Halifax ($P = 0.358$). ET rates were moderately and positively correlated to water saturation in Calgary ($r = 0.572$); however, in London, water saturation impacted ET rates to a lesser extent ($r = 0.302$). The largest range of antecedent soil moisture was observed in Calgary due to the large range of rainfall event size and rainfall frequency. In 2013 and 2014, from the end of June to the end of August, the green roof in Calgary experienced long duration drying periods, with greater than 50% of the 6 drying periods lasting longer than nine days. In July and August, when the long drying periods occurred, soil moisture did not reach field capacity after rainfall events as the size of the rainfall events were relatively small and preceded by low antecedent soil moisture. Each city is located in distinct climate regions with Calgary located within the Prairie climate region, London the Great Lakes/ St. Lawrence climate region, and Halifax the Atlantic/ Maritime climate region (Environment Canada 2014). As such, Halifax is characterized by a cool and humid climate resulting in relatively high water saturation. Given that ET was not correlated with water saturation in Halifax but was correlated to water saturation in Calgary, and that both cities exhibited similar ET rates, suggests that other climatological variables (e.g., atmospheric forcing) likely influenced the ET rates in Halifax. However, further investigation is required to determine the role of other climatological variables and atmospheric forcing in the variability of ET rates in Halifax. Also of note is that average water saturation across all cities in September (0.58) was relatively large (Figure 3b), yet average cumulative monthly ET in September was relatively small (42 mm) (Figure 3a). These results suggest the importance of climatological variables and substrate water saturation in governing ET rates.

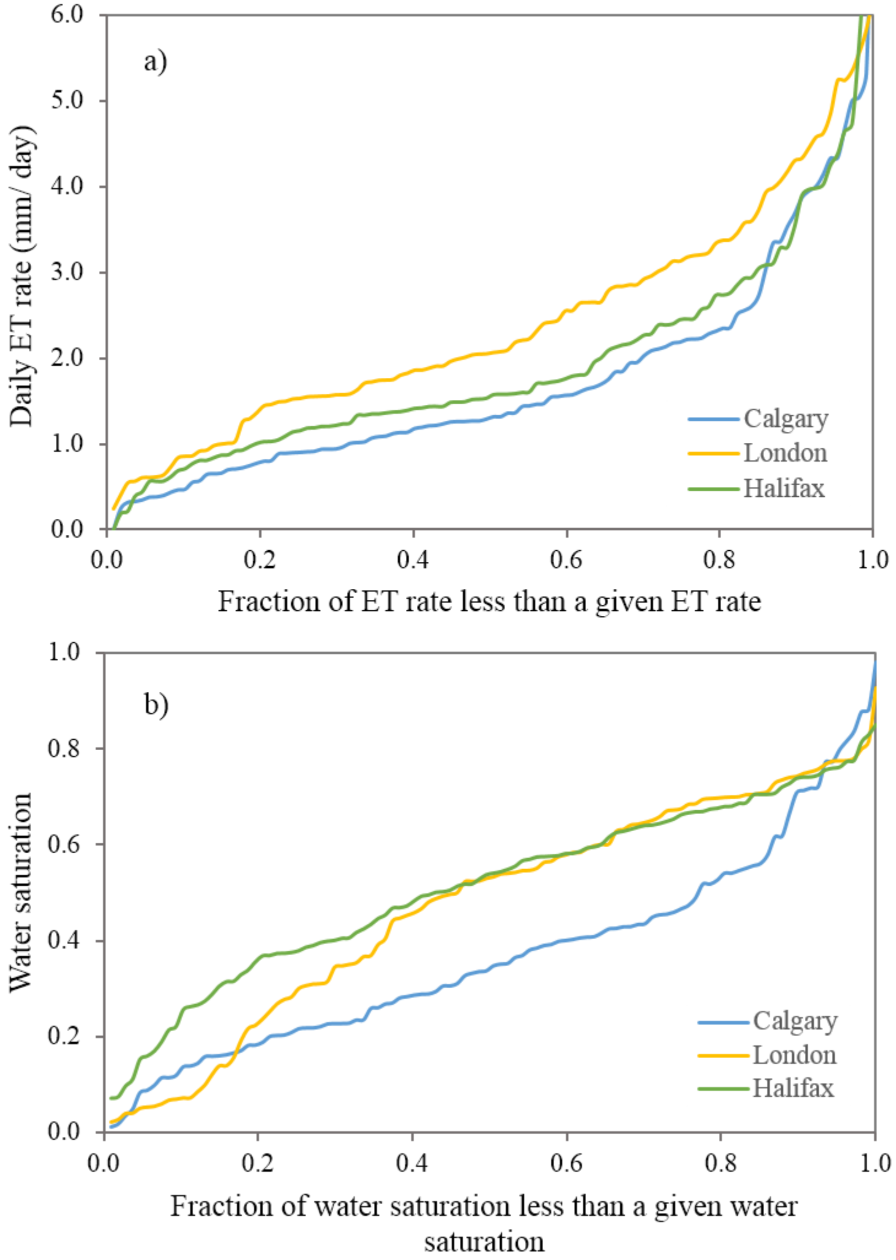

Figure 4: Distribution of a) daily ET rate and b) water saturation for Calgary, London and Halifax for the 2013 and 2014 field seasons when measurements were available in all three cities.

3.3.2 Influence of vegetation and substrate depth treatments on evapotranspiration rates

Leaf morphology, plant coverage, and the root structure differ among the plant species used in this study: *S. spurium*, *S. heterolepis*, and *A. canadensis*. *S. spurium* is a succulent, low lying species with an upright branch structure and relatively small, broad leaves. *A. canadensis* is an herbaceous species with upright branches and has relatively larger leaves which spans over a smaller total leaf area compared to *S. spurium. S. heterolepis* is a densely tufted graminoid species with a mixture of short upright thin leaves and longer drooping leaves. Although the leaf angular distribution (LAD) was not quantified in this study, visual observations suggest that *S. spurium* and *A. canadensis* on average have leaves which are relatively parallel to the ground (planophile LAD) and *S. heterolepis* has vertically angled leaves (erectophile LAD).

Quantification of plant coverage is an important aboveground feature because this is one of the primary plant parameters which influences the fraction of evaporation and transpiration within the total ET process (Allen et al. 1998). In this study, plant coverage, quantified through pin frame measurements, was compared among vegetation treatments within the individual sites. This method allowed for quantitative comparisons of the canopy structure between vegetation treatments. The plant coverage was generally similar for the monoculture *S. spurium* treatment and the mixed species treatment since the foliage in the mixed treatment was predominantly *S. spurium* (Appendix B). It is noted that plant coverage was denser for the mixed species treatments (e.g. peak of 125 leaf points in 2014) in London in comparison to *S. spurium* treatments (e.g. peak of 76 leaf points in 2014) for the 15 cm depth treatments (Appendix B: Figure B 1c, B 1d). In comparison, plant coverage for *A. canadensis* and *S. heterolepis* 15 cm depth treatments in London were sparser (e.g. peak of 50 and 62 leaf points in 2014, respectively) than the *S. spurium* and mixed species treatments, indicating less canopy coverage (Appendix B). Similar plant coverage trends were noted among the vegetation treatments planted in both depth treatments in Halifax and Calgary. The plant coverage data indicated that the peak values in plant coverage at each site generally occurs between June to July in 2013 and 2014 (Appendix B), with the exception of London in 2013 (Appendix B: Figure B 1c). The variation in plant coverage for the vegetation treatments in London ON over the 2014 field season is qualitatively shown in Figure 5.

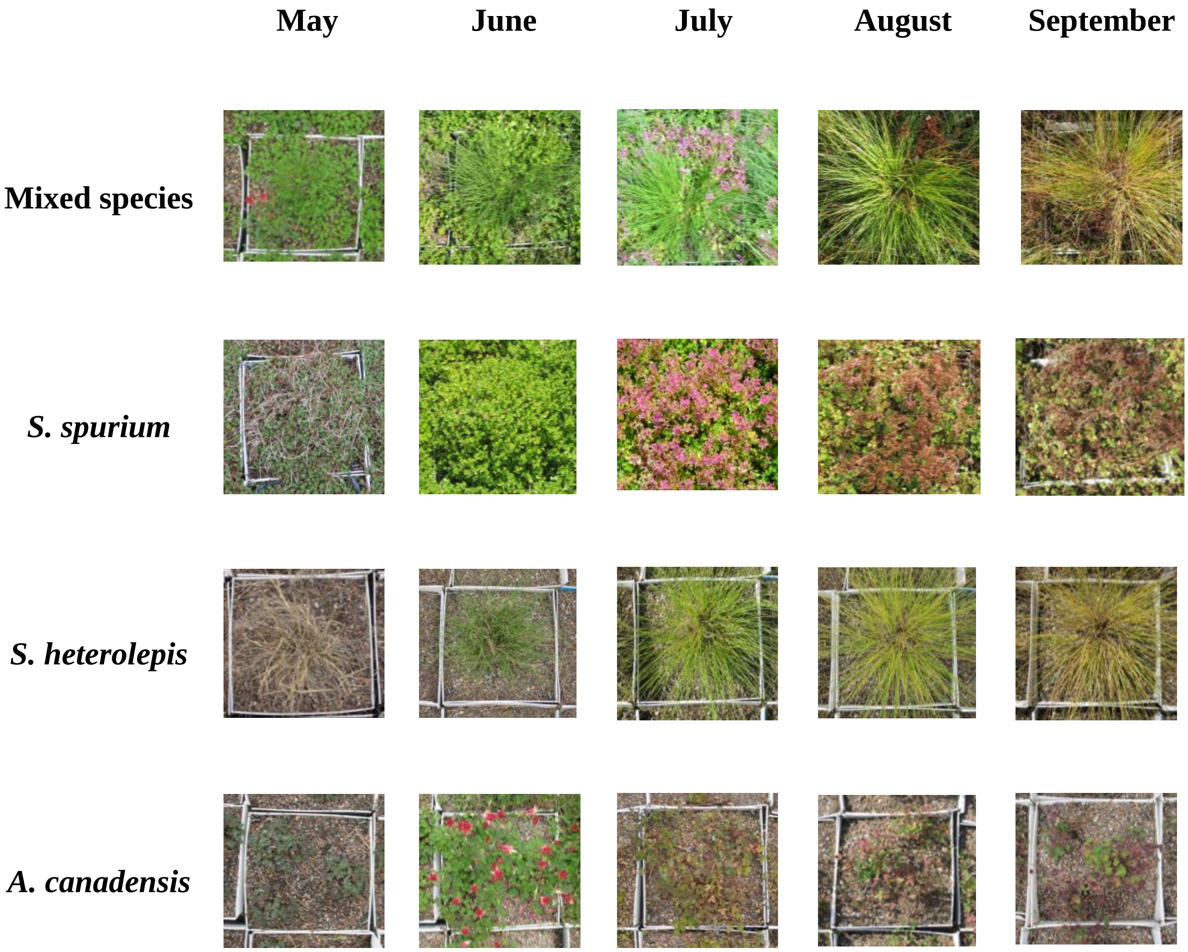

Figure 5: Plan view of the plant growth stages of the vegetation treatments from May to September capturing the changes in plant coverage throughout the 2014 field season in London ON.

The difference in root structure belowground can affect the distribution of pore water from the roots and up the plant's xylem, and subsequently the transpiration rates. As expected, root mass decreased with depth for all vegetation treatments (Figure 6). While the *S. spurium* and the mixed species treatments were found to have a similar aboveground structure (i.e. plant coverage), their belowground structure, specifically their root structure (Figure 6), differed. For the monoculture *S. spurium* treatment, the majority of the roots were within the top 10 cm of the substrate as it has shallow, fibrous roots (Figure 6). These root characteristics have been previously been noted for Sedum species (Nagase & Dunnett 2012; Lu et al. 2014). In comparison, the root mass distribution for the mixed species treatment indicated that roots are present from the substrate surface to the 15 cm depth (Figure 6). The root mass for the monoculture *S. heterolepis* treatment had a similar profile trend to the mixed species treatment from the 5 cm to 15 cm depth (Figure 6). Within the first 5 cm depth of substrate, the *S. heterolepis* treatment (10.29 ± 3.01 g) had a lower root mass compared to the mixed species treatment due to the lack of *S. spurium* which was found to have a root mass of 25.78 ± 3.15 g within this depth (Figure 6). At a substrate depth deeper than 5 cm, the presence of *S. heterolepis* in the mixed species treatment resulted in an increase in root biomass due to the deep, dense root biomass of *S. heterolepis* (Figure 6).

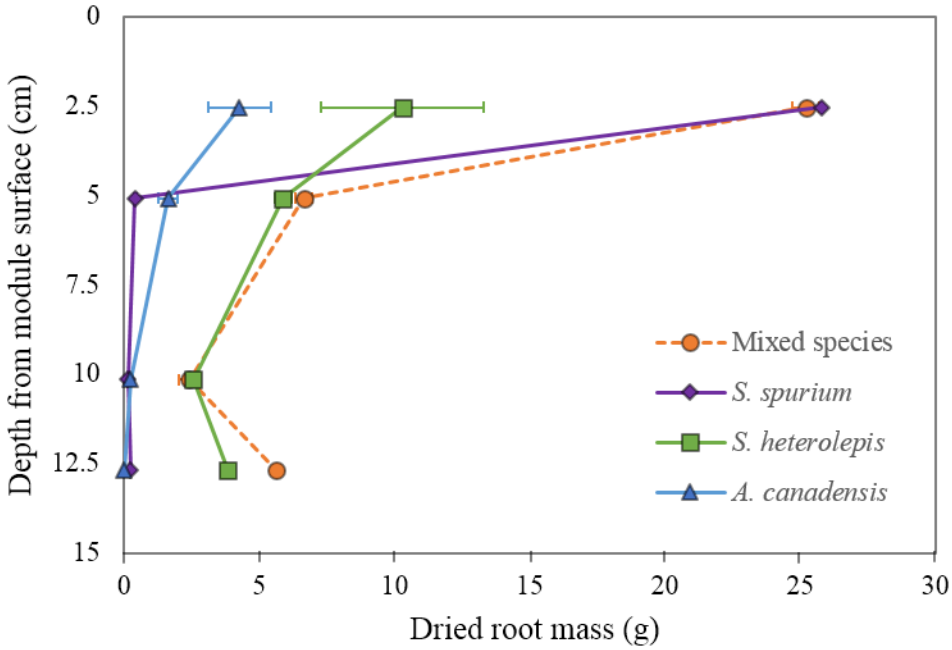

Figure 6: Distribution of the oven-dried root mass from four depth intervals, within a 15 cm substrate depth module, among the vegetation treatments: *S. spurium*, *A. canadensis*, *S. heterolepis*, and mixed species. The error bars represent the standard error of the mean.

Table 3: Mean cumulative moisture loss (in mm) for the different vegetation treatments and substrate depth treatments at each site in 2013 and 2014. Uncertainty values are the standard error of the mean, and the number of replications is provided in the brackets below each result.

Site	**Year**	**Measurement Period**	**Mixed (3 species)**		***S. spurium***		***S. heterolepis***		***A. canadensis***		***Bare (Control)***	
			10 cm	**15 cm**	**10 cm**	**15 cm**	**10 cm**	**15 cm**	**10 cm**	**15 cm**	**10 cm**	**15 cm**
Calgary	**2013**	**7 Jun – 16 Sep**	89 ± 1.9 (3)	105 ± 1.9 (4)	82 ± 1.5 (3)	89 ± 1.5 (12)	72 ± 0.3 (3)	86 ± 1.2 (4)		81 ± 2.9 (2)		
	2014	**20 Jun – 7 Sep**	95 ± 0.8 (3)	110 ± 1.0 (4)	91 ± 1.6 (3)	97 ± 1.2 (12)		92 (1)		85 (1)		
		18 Jul – 17 Sep	55 ± 1.3 (3)	56 ± 0.3 (4)	51 ± 0.5 (3)	48 ± 0.6 (12)		55 (1)		48 (1)	55 ± 1.3 (3)	53 ± 2.3 (4)
London	**2013**	**21 May – 3 Oct**	215 ± 3.4 (4)	241 ± 4.8 (3)	233 ± 7.6 (3)	202 ± 3.1 (12)	179 ± 5.2 (4)	186 ± 8.4 (3)	172 ± 3.0 (4)	193 ± 4.8 (7)		
	2014	**5 Apr – 3 Sep**	209 ± 4.5 (4)	224 ± 3.4 (3)	201 ± 1.9 (3)	187 ± 3.0 (12)	177 ± 4.4 (4)	197 ± 2.0 (3)	175 ± 2.6 (4)	182 ± 10.1 (7)	154 ± 6.7 (2)	177 ± 4.2 (2)
Halifax	**2013**	**5 May – 15 Aug**	104 ± 4.4 (3)	119 ± 3.9 (4)	94 ± 4.3 (3)	108 ± 2.9 (14)	78 ± 2.1 (3)	92 ± 0.4 (4)	91 ± 5.8 (3)	106 ± 4.8 (4)		
	2014	**20 May – 27 Aug**	124 ± 1.2 (3)	144 ± 1.2 (4)	116 ± 1.7 (3)	133 ± 1.8 (14)	94 ± 3.0 (3)	111 ± 1.6 (4)	96 ± 1.9 (3)	119 ± 2.3 (4)		98 ± 2.2 (2)

Manually weighed modules were used to evaluate the impact of vegetation type on ET as only select *S. spurium* modules were continually weighed on lysimeters at each site. Manual weighing was not consistently conducted on a daily basis, and in some cases drying periods were missed. As such cumulative moisture loss quantified from the lysimeter measurements cannot be directly compared to manually weighed data, however, manual weighing data were ideal for comparison of ET from different vegetation types in a given city. There were notable differences in cumulative ET among the vegetation and substrate depth treatments (Table 3). For the 15 cm substrate depth, the mixed species treatments consistently had the highest cumulative ET (e.g., ~ 224 mm in London 2014) compared to the monoculture species (e.g., ~ 182-197 mm in London 2014) (Table 3). *S. spurium* (e.g., 187 ± 3.0 mm in London 2014) consistently had the second highest cumulative ET, with the exception of London 2014 15 cm depth treatments, where cumulative ET was slightly larger for *S. heterolepis* (197 ± 2.0 mm), and *A. canadensis* (182 ± 10.1 mm) (Table 3). With the exception of London 2014 15 cm depth treatments, the monoculture treatments of *S. heterolepis* and *A. canadensis* generally had the lowest seasonal cumulative ET (Table 3). Trends in cumulative ET between the different vegetation types for the 10 cm depths were similar to that of the 15 cm treatments, with the exception of cumulative ET from the *S. spurium* treatment (233 ± 7.6 mm) in London 2013, which was larger than the mixed species treatment (215 ± 3.4 mm) (Table 3).

Cumulative ET from the 15 cm depth treatments were consistently larger than that quantified from the 10 cm treatments with the exception of *S. spurium* treatment in London 2013 and London 2014 (Table 3). The enhancement of ET for the deeper treatment depth was consistently greater for the mixed species treatment (e.g., ~ 144 mm cumulative ET in Halifax 2014) in comparison to *S. spurium* (e.g., ~ 133 mm cumulative ET in Halifax 2014), irrespective of the city or year (Table 3). Interestingly the ET enhancement for the 15 cm depth treatments was greater for three cases (i.e., London 2013 and 2014; Halifax 2014) out of the four cases for *A. canadensis* treatments in comparison to the mixed species treatments (Table 3). For the fourth case (i.e., Halifax 2013), ET enhancement due to deeper depth for mixed species and *A. canadensis* treatments were similar (Table 3). Increased water stress conditions in Calgary resulted in permanent wilting of *A. canadensis* and *S. heterolepis*. For both plant species, no 10 cm treatments survived both field seasons. Freezing during the winter months may have also played a role in decreasing the viability of both species. It should be noted that both *A. canadensis* and *S. heterolepis* survived in the mixed treatments for a longer duration than in the monoculture treatments. These observations suggest that *A. canadensis* and *S. heterolepis* are not suitable for installation on green roofs in Calgary with shallow substrate depth due to its harsh climatological conditions.

The Wilcoxon signed rank test, conducted through Minitab® 17.1.0, was used to determine if daily ET rates were statistically different between vegetation treatments (Appendix C). Daily ET rates for each vegetation treatments for both years were analyzed together as one dataset (Appendix C). Significant differences between mixed species and *S. spurium* treatments were observed in all cities for the 15 cm substrate depth, with daily ET rates higher for the mixed species treatments (Appendix C). For example, for the 15 cm depth treatments in London, the median difference in daily ET rate between the mixed species treatment and the *S. spurium* treatment over both field seasons was 0.36 mm/day. Daily ET rates for *S. heterolepis* and *A. canadensis* treatments were significantly lower than the mixed treatments for the 15 cm treatments (Appendix C: Table C 1b). For example, for the 15 cm depth treatments in London, the median difference in daily ET rate between the mixed species treatment and the *S. heterolepis* and *A. canadensis* treatments over both field seasons were 0.47 mm/day and 0.50 mm/day, respectively. For the 15 cm depth treatments in Halifax, the daily ET rates for *S. spurium* treatments were significantly greater than *S. heterolepis* treatment rates (0.25 mm/ day median difference; *P* = 0.003), however, the daily ET rates were not significantly different between these two treatments in London and Calgary (Appendix C: Table C 1b). With regards to *A. canadensis* 15 cm depth treatments, *S. spurium* (15 cm depth) daily ET rates were significantly greater for London (0.19 mm/ day median difference; *P* = 0.001) and Calgary (0.10 mm/ day median difference; *P* = 0.03); however, ET rates were not significantly different between these two treatments in Halifax (Appendix C: Table C 1b). *S. heterolepis* and *A. canadensis* 15 cm depth treatments only exhibited significantly different daily ET rates in Halifax, with *A. canadensis* having greater ET rates (0.18 mm/ day median difference; *P* = 0.003) (Appendix C: Table C 1b).

It is noted that these two treatments (i.e., *S. heterolepis* and *A. canadensis* 15 cm treatment depths) could not be statistically compared in Calgary for the 2014 field season since only one replicate from each treatment survived the field season. For the 10 cm depth treatments in Calgary and Halifax, the daily ET rate was significantly greater for the mixed species treatment in comparison to the *S. spurium* treatment with a median difference of 0.11 mm/ day between the two treatments at both sites (P < 0.005) (Appendix C: Table C 1a); however, in London there was no significant difference between these two treatments (Appendix C: Table C 1a). *S. heterolepis* and *A. canadensis* 10 cm depth treatments exhibited statistically significant lower daily ET rates in comparison to the mixed species and *S. spurium* treatments with the exception of *A. canadensis* in Halifax (Appendix C: Table C 1a). Among the 10 cm depth treatments which exhibited lower daily ET rates, *A. canadensis* had significantly larger daily ET rates in comparison to *S. heterolepis* in Halifax (0.13 mm/ day median difference; P = 0.01), but not in London (Appendix C: Table C 1a). These data suggest that in Halifax, which had less moisture limitations, *A. canadensis* outperformed *S. heterolepis* in terms of ET. Differences in daily ET rates and cumulative ET among the vegetation treatments may be attributed to differences in plant coverage and root mass distribution.

Given that the ET governs antecedent moisture condition and subsequently rainfall retention, trends observed in prior studies focused on rainfall retention can be compared to our observed ET trends. A previous study showed that plant species with extremely dense fibrous roots retained less water (MacIvor & Lundholm 2011), however, other studies have found that the addition of roots results in higher porosity, enhancing retention (Dunnett et al. 2008; Nagase & Dunnett 2012) and detention (Poë et al. 2015). In this study, the mixed species treatments had the greatest root biomass as well as the greatest ET (Figure 6; Table 3). *S. spurium* had the largest root biomass at the surface, but *S. heterolepis* had greater root biomass with depth (Figure 6). Given that *S. spurium* had significantly greater ET rates but had a root mass distribution similar to that of *A. canadensis* suggests that root mass distribution alone is not a good predictor of ET rates. This is further supported by the fact that *S. heterolepis* and *A. canadensis* generally had similar ET rates, but *A. canadensis* had a relatively lower root mass. As indicated from the pin frame results, plant coverage was greater for the mixed species and *S. spurium* treatments in comparison to the *S. heterolepis* and *A. canadensis*, which is consistent with higher observed cumulative ET (Table 3) and daily ET rates for these treatments (Appendix C: Table C 1). Due to their higher plant coverage, *S. spurium* and the mixed species treatments may continue to lose moisture through transpiration once the substrate water saturation decreases. In comparison, *A. canadensis* and *S. heterolepis* may generally have lower cumulative ET because the evaporation rates decrease as the substrate water content decreases and the transpiration rates were low to begin with due to the low canopy coverage. Quantifying the extent to which the greater plant coverage enhanced ET due to higher transpiration rates is difficult as the modules with less plant coverage would have a greater proportion of bare media exposed at the surface, potentially enhancing evaporation.

Further work needs to be completed to explore the cause of the higher ET observed for the mixed species treatment modules compared to the monoculture treatments. The movement of water from different depths of substrate to the surface was not quantified in this study. Greater ET rates for the mixed species treatment could be due to the greater canopy coverage for the mixed species, particularly in London, as well as pore water from deeper substrate layers being distributed to the shallower layers by the deep *S. heterolepis* roots during prolonged drying periods. Through hydraulic lift, the deep *S. heterolepis* roots would provide water to shallow *S. spurium* roots for subsequent transpiration after shallow pore water from a rainfall event was transpired. The combination of shallow and deep roots in the mixed species treatment provides additional insight to the importance of selecting green roof plants with complementary functional traits to optimize the regeneration of the substrate's retention capacity during drying periods through ET.

3.3.3 Comparing evapotranspiration between bare (no vegetation) and vegetated treatments

The extent to which plants enhance ET was quantified through comparison of cumulative ET (Table 3) and daily ET rates (Appendix C: Table C 2) for vegetated treatments and bare modules (i.e., no plants) for the 2014 field season. For London and Halifax, cumulative ET was greater for vegetated treatments than for bare modules for both 10 cm and 15 cm treatment depths (Table 3). In London and Halifax, daily ET rates were significantly larger for all vegetated treatments in comparison to the bare modules ($P < 0.02$), with the exception of the 15 cm *A. canadensis* in London ($P = 0.10$) (Appendix C: Table C 2). In Calgary, cumulative ET and daily ET rates were similar for both vegetated and bare modules (Table 3). In the case of *A. canadensis* and *S. heterolepis*, the vegetated treatments were similar to a bare treatment due to the decrease in plant coverage from plant stress in Calgary. In Calgary, a region with limited water availability for green roofs (in the absence of additional irrigation), the lack of significant difference in ET between the vegetation and the bare treatments was likely due to the moisture limited conditions resulting in decreased plant health and therefore transpiration rates. Given this dataset, it is difficult to definitively determine the rate limiting process. For example, the bare modules do not have a canopy shading the substrate surface, so it is in direct contact with the incoming radiation energy and the overlying atmospheric conditions. As such, it is likely that evaporation is greater for the bare modules. For the vegetated modules, a combination of evaporation and transpiration contributes to the observed ET. Given the enhanced ET from the vegetated treatments compared with the bare modules in London and Halifax, it can be concluded that plants provide significant benefits in regenerating the retention capacity of the substrate, particularly through prolonged drying periods when the moisture conditions become limited. These findings are similar to those observed in a previous field study which also found that the effects of vegetation in decreasing substrate moisture are most prominent under decreased moisture conditions and not under well-watered conditions (Berretta et al. 2014)

3.4 Conclusions

With 11 distinct climate regions in Canada (Environment Canada 2014), it is important to choose vegetation types which are suitable for the climate region and the harsh microclimatic conditions on the urban roof environment. The three Canadian cities chosen for this study, Calgary AB, London ON, and Halifax NS, are found in three different climate regions: Prairies, Great Lakes/ St. Lawrence, and Atlantic/ Maritime, respectively. This research has provided insight on how climatological conditions influence cumulative ET and daily ET rates from extensive green roofs in the specified regions. Cumulative ET, calculated from the continuous lysimeter data for the 15 cm depth *S. spurium* treatments, was found to be greater in London over the 2013 and 2014 field seasons compared to Calgary and Halifax which experienced similar cumulative moisture loss. The percentage of cumulative rainfall that was returned to the atmosphere by ET, however, was greater for Calgary (73%) and London (67%) compared with Halifax (33%). Available moisture in the green roof substrate was found to limit ET rates in Calgary and London, whereas results suggest that other climatological variables (e.g., atmospheric forcing) rather than moisture content may have potentially influenced the ET rates in Halifax where the climate is wet and humid.

This study also illustrated the importance of selecting suitable vegetation types to optimize ET, and subsequently the hydrologic performance of green roofs. Of the vegetation treatments used in this study, *S. spurium* and the mixed species treatment are recommended for use in all three Canadian sites. At each site and for both depth treatments, both of these aforementioned vegetation treatments generally had higher ET rates than *A. canadensis* and *S. heterolepis* throughout the field season. Therefore, green roofs with a monoculture of *S. spurium* or mixture of *S. spurium*, *S. heterolepis*, and *A. canadensis* will be able to restore the retention capacity of the green roof substrate faster than a green roof with only *S. heterolepis* and *A. canadensis*. These results suggest that to optimize the hydrologic performance of green roofs (i.e., retention capacity), it is important to consider plant characteristics, such as plant coverage and root mass distribution. The study findings indicate that the ET from a green roof, and thus retention performance of a green roof, varies depending on the vegetation type and substrate depth. In London, it is recommended that a green roof is planted with *S. spurium* in 10 cm substrate depth, and a mixed species treatment in 15 cm substrate depth to optimize retention performance. In order to decrease the total cost associated with the green roof substrate, as well as reduce the structural load associated with the green roof, this finding indicates that it may be best to limit the substrate depth to 10 cm when S. spurium is used on a green roof in London. In Calgary and Halifax, it is recommended that a green roof is planted with mixed species treatments in 15 cm substrate depth to optimize retention performance. Finally, this study indicates the need to consider plant health and survivability in different climates as decreasing plant health, such as that observed in Calgary, decreases the effectiveness of vegetation in enhancing ET, and subsequently improving the hydrologic performance of the green roof system.

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Chapter 4

4 Summary and Recommendations

4.1 Summary

Evapotranspiration (ET) plays a key role in the hydrologic and thermal benefits provided by green roofs. For instance, the capacity of a green roof to retain rainfall is largely governed by the rate at which moisture within the pores of the substrate is evapotranspired back to the urban atmosphere. While climatological conditions and green roof design parameters (e.g., vegetation and substrate type) have been shown to impact ET rates (e.g., Lundholm et al. 2010; Lundholm et al. 2015; Dunnett et al. 2008; Marasco et al. 2014; Berretta et al. 2014; Poe et al. 2015), to date the impact of these factors (i.e., climatological conditions, vegetation type, and substrate depth) have not been studied from three replicate extensive green roof design installed in distinct climatological conditions. The aim of this research was to develop a better understanding of how climatological conditions, vegetation type, and substrate depth impact ET to inform decisions on the design of green roofs installed in different Canadian climatological conditions.

The first research question focused on evaluating the impact of climatological conditions on ET from green roofs. Identical experimental green roofs were installed and monitored in three Canadian cities, Calgary AB, London ON, and Halifax NS. These cities are located in three different climate regions: Prairies, Great Lakes/ St. Lawrence, and Atlantic/ Maritime, respectively. Using weighing lysimeters, daily ET was calculated from continuous weight measurements of 15 cm depth *S. spurium* module replicates at each site. From calculated daily ET rates, the cumulative moisture loss for two field seasons (May to September in 2013 and 2014) were calculated and averaged at each site. In Calgary and Halifax, the average ET rate were similar (~ 1.6 mm/ day) whereas it was found to be higher in London (~ 2.4 mm/ day). While Calgary and Halifax had similar average ET rates, it was found that ET was significantly ($P < 0.005$) influenced by water saturation in Calgary, but not in Halifax ($P = 0.358$). This finding suggests that ET rates in Halifax were not limited by water saturation but may have been influenced by other climatological variables (e.g., atmospheric forcing) which were not evaluated in this study. Of note, the ET rates in London were also found to be significantly influenced by water saturation (*P* < 0.005). Additionally, the findings from this study support previous findings that green roofs are able to mitigate stormwater runoff. Through ET, 73%, 67%, and 33% of the total rainfall received in Calgary, London, and Halifax, respectively, over the field seasons were returned back to the atmosphere. The novelty of the findings from this section of the study stems from the fact that this was the first study in North America to evaluate ET from extensive green roofs across three climatological conditions under a field setting.

With 11 distinct climate regions in Canada (Environment Canada 2014), it is important to select vegetation types which are suitable for the climate region and the harsh microclimate conditions on the urban roof environment, as well as optimize the desired benefits of the green roof installation (e.g., hydrologic, thermal, and/ or aesthetic benefits). The second research question focused on investigating the impact of four vegetation treatments on ET (single species *S. spurium*, *A. canadensis*, and *S. heterolepis*, and a mixture of all three species), and the third question focused on the impact of varying the substrate depths on ET. Species of Sedum and grass are commonly used on green roofs, however, due to the variability in the plant functional traits (e.g., metabolic process) among species within these two life form groups, the ET rates measured for one species from one study may not necessarily be transferrable to a different species, regardless of the species originating from the same life-form group. Of the three species, *S. spurium* is the most commonly used vegetation type on green roofs, and therefore it is the most commonly studied species within the green roof literature (e.g., Wolf & Lundholm 2008; VanWoert et al. 2005). This current work was the first to investigate the impact of all four vegetation treatments on ET, under similar green roof design (i.e. substrate depth), and in three different climatological conditions. This research provided insight on which of the four vegetation types were best suited for extensive green roofs installed in the three selected study sites. This study found that plant coverage and root structure are two plant traits which should be considered during the vegetation and substrate depth selection process. The vegetation treatment (i.e. *S. spurium* and the mixed species treatment) with a dense plant coverage had higher ET rates compared to sparsely covered vegetation treatments (i.e. *A. canadensis* and *S. heterolepis*). In London, all four vegetation treatments were suitable; however, *S. spurium* planted in 10 cm substrate depth and the mixed species treatments planted in 15 cm substrate depth were the two treatments which had the highest ET rates. In Calgary and Halifax, *S. heterolepis* and *A. canadensis* were not suitable for the climatological conditions or the roof conditions. Of the vegetation type and substrate depth treatments evaluated in this study, the mixed species treatment planted in 15 cm substrate depth is recommended for extensive green roofs in Calgary and Halifax. The notable finding from this study was the role of root structure in influencing the ET rates when the substrate depth was varied between 10 cm and 15 cm. In London, data indicated that the vegetation type with a dense plant coverage and a root depth which was similar to the substrate depth selected had the highest cumulative ET. This effect was notable when comparing the cumulative ET between the 10 cm and 15 cm depth treatments of *S. spurium*, which has shallow, fibrous roots that reached a maximum depth of 10 cm or less in London. For the 2013 and 2014 field seasons, the average cumulative ET was greater for the 10 cm depth (average of 217 mm) compared to the 15 cm depth (average of 195 mm) treatment. This finding suggests that the retention capacity for the 15 cm depth may not necessarily be larger than the 10 cm depth following a drying period since the ET rates in the shallower substrate are higher. Therefore, it is important to ensure that the root structure (i.e., mass and depth profile) of the vegetation type matches the substrate depth to maximize the substrate area from which water uptake occurs. This design can be achieved by mixing plant species with different root structures (i.e. mixed species treatment). This was one of the first studies known to investigate the impact of substrate depth on ET and to quantify the root structure of three green roof vegetation species.

4.2 Recommendations

This thesis has shown the impact of climatological conditions, vegetation type, and substrate depth on ET rates from green roofs. Recommendations for future work include:

- Compare measured ET rates at the three green roof sites with ET predictions made using the ASCE, Hargreaves, and Penman-Monteith models with the moisture content correction factor. The measured data could be used to calibrate and validate these predictive ET models. Validated models should be applied to provide insight into the potential ET at all sites and the importance of soil moisture limitations.

- Quantify additional plant traits that influence transpiration rates including stomatal conductance and leaf area index (LAI) values for each plant type used in this study: *S. spurium*, *A. canadensis*, and *S. heterolepis*. These measurements are required as input parameters for predictive ET models including the Penman-Monteith method, and would also provide additional understanding of the ET differences observed.
- The development of predictive ET models for each site and plant type would provide valuable information on how each plant species would perform under varying climatological conditions – this may not have been fully captured with data from two field seasons only. Insight into plant suitability for different climatological conditions would inform decisions on plant selection and substrate depth selection to optimize the ET and thus the stormwater benefits provided by green roofs.
- Apply validated ET models for the three sites to compare predicted ET for the 10 cm and 15 cm substrate depth to provide additional insight on the impact of substrate depth on ET under vary climate conditions. The impact of substrate depth on ET was not consistent between years in Halifax and this may have been due to the limited number of measurement days as well as the different precipitation amounts in Halifax between 2013 and 2014.
- ET rates affect both the water and energy balance on green roofs. Additional work is required to determine how the ET rates for different plant types affect the energy balance on the green roof. For instance, reflective properties (albedo) and heat flux below the different plant types should be measured at the three sites through the growing season.
- The transport of water through the roots and within the substrate depth during a drying period was not examined. A better understanding of the root and substrate depth interaction would improve the plant selection process as it would provide more informed decision on which plants are better suited for certain substrate depths.

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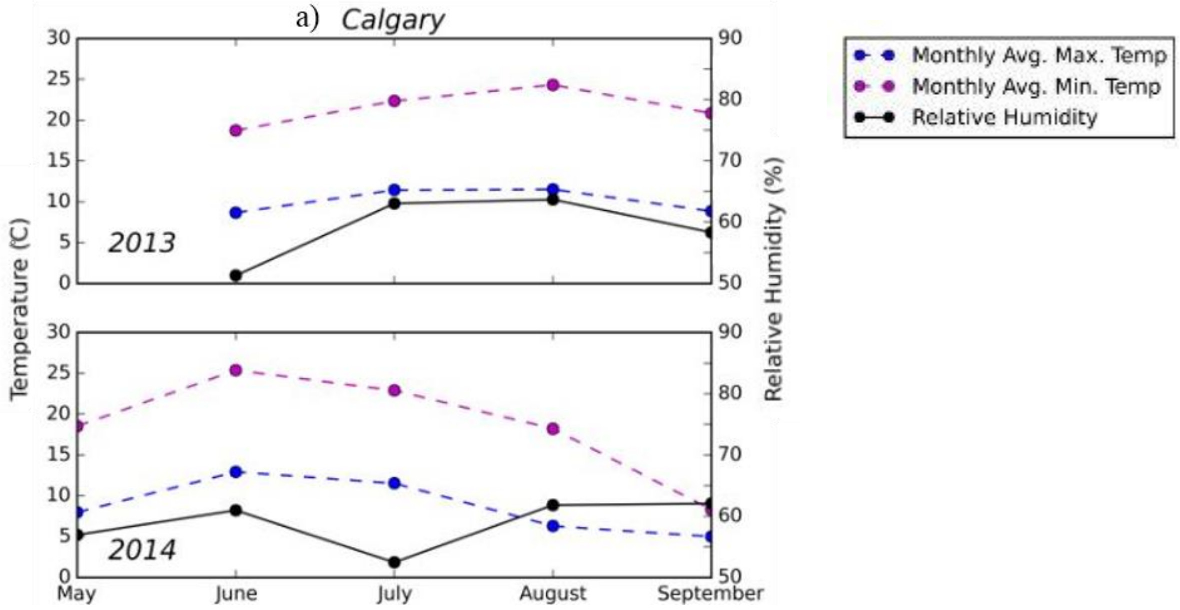
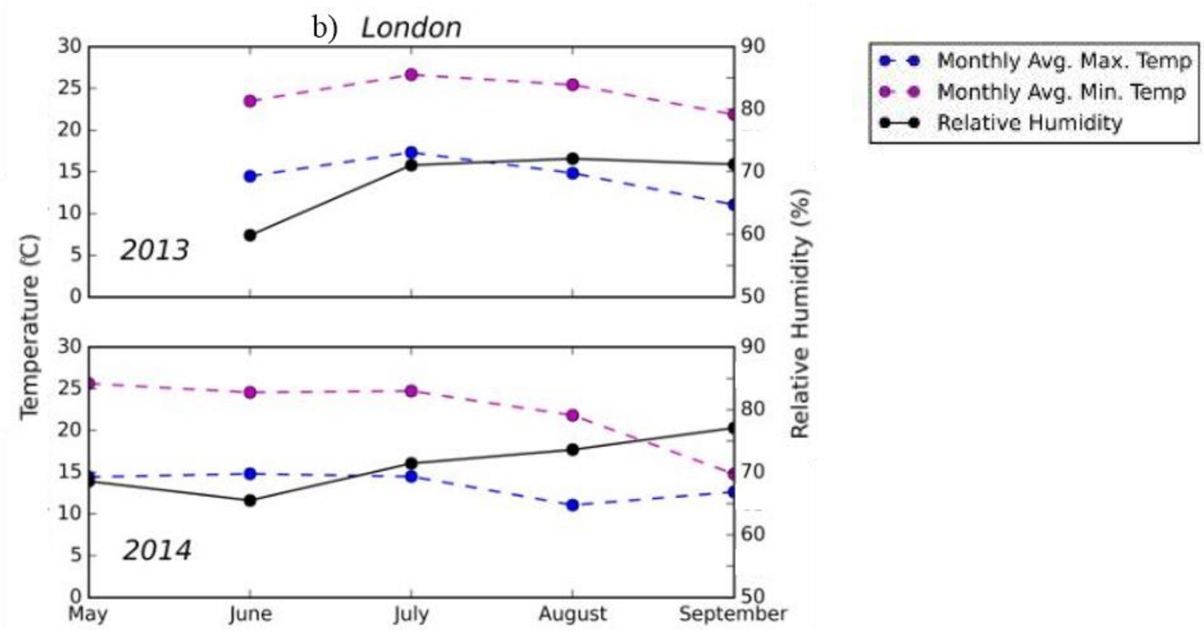
Appendices

Appendix A: Monthly climatological data for the 2013 and 2014 field season





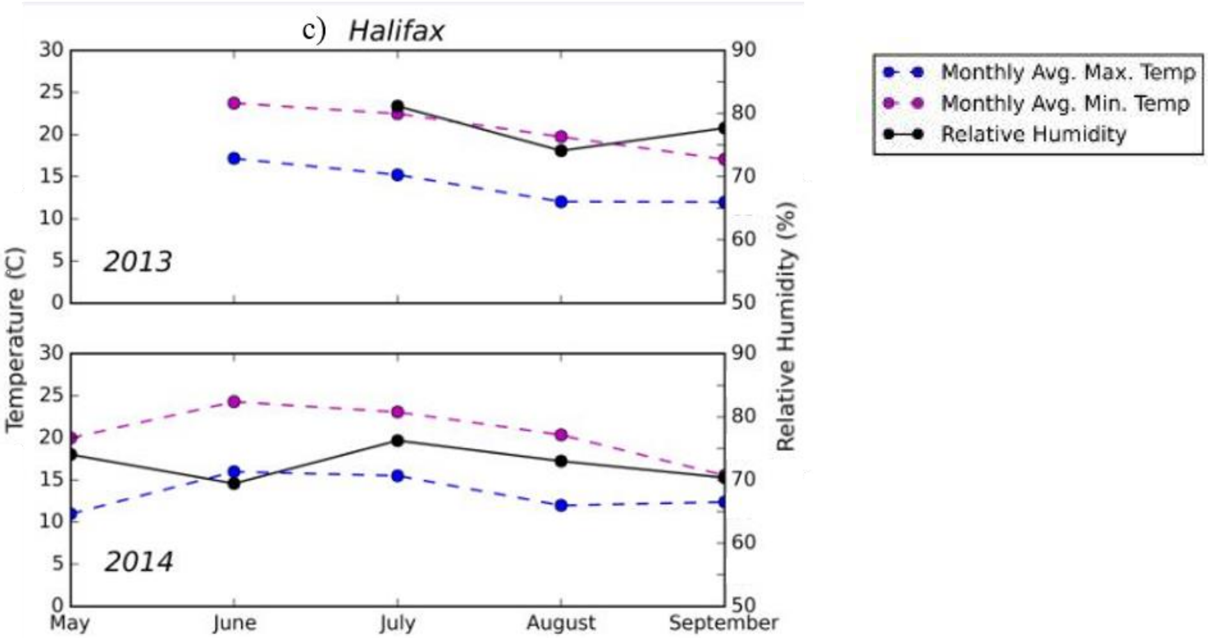
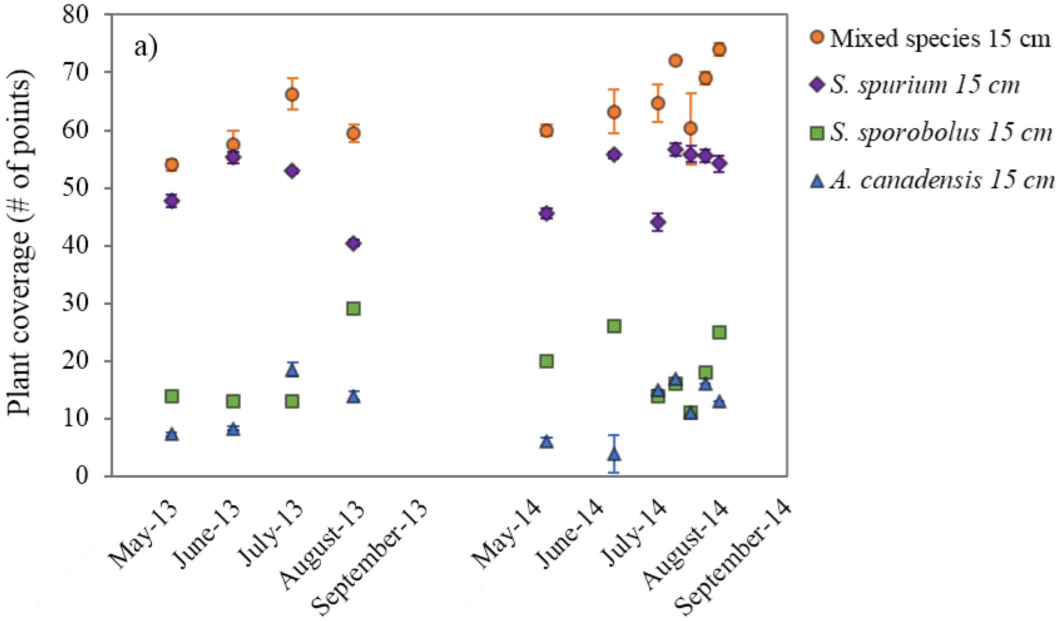
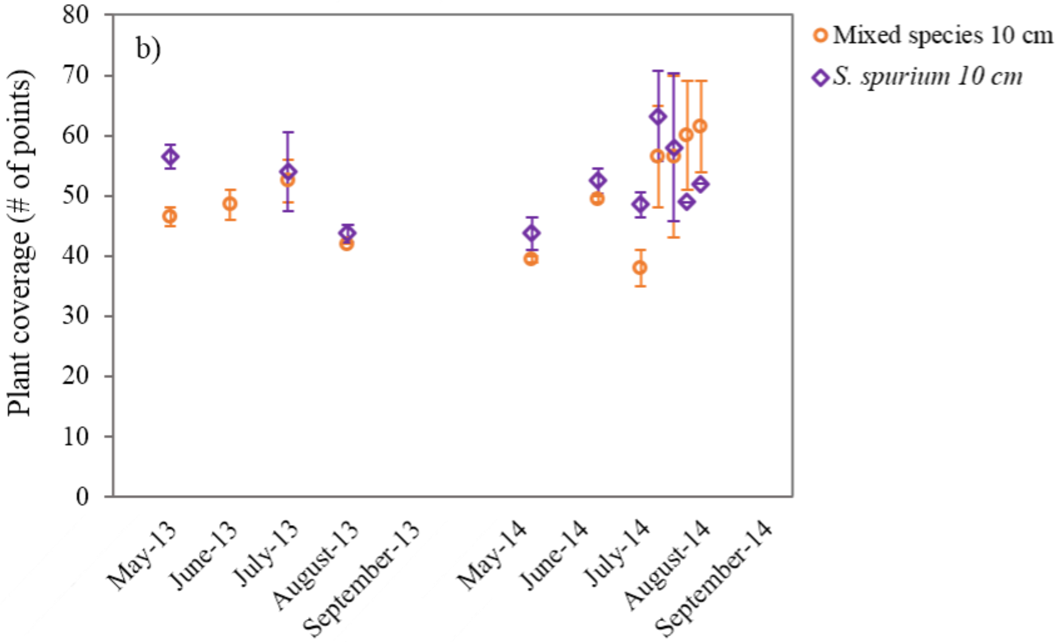
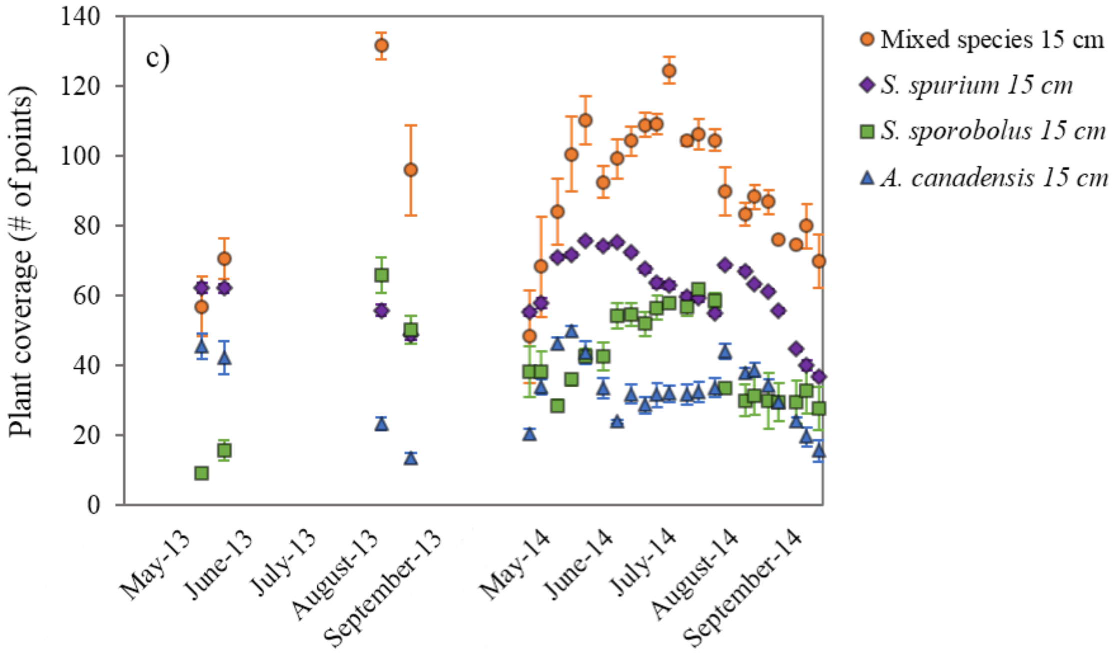


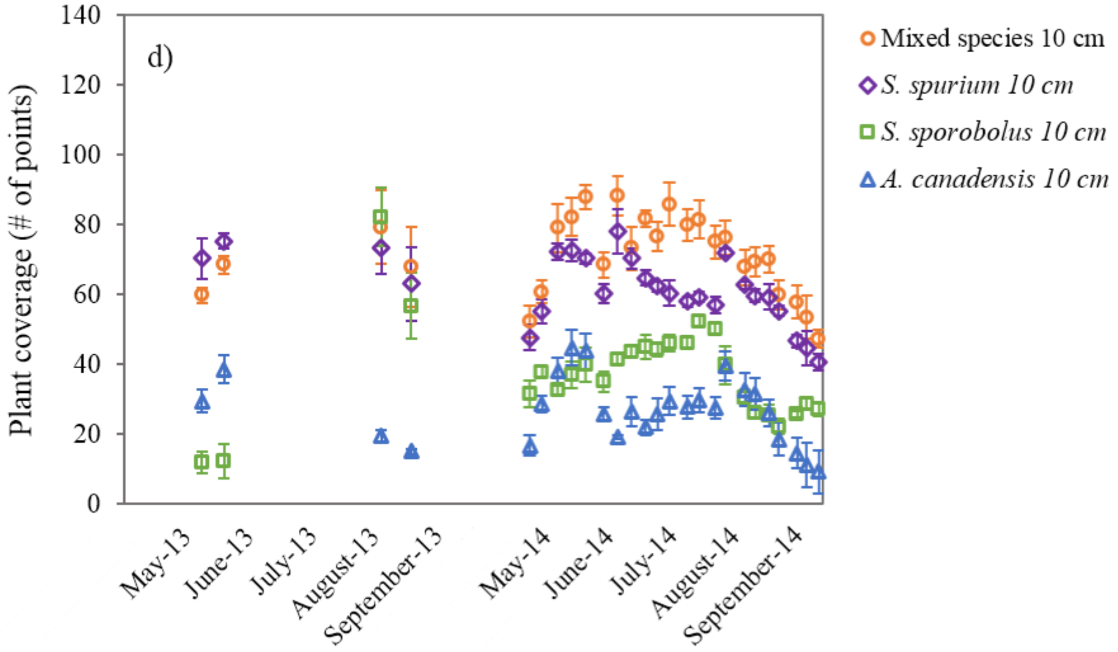
Figure A 1: Monthly climatological data (i.e., maximum temperature, minimum temperature, and relative humidity) from May to September for the 2013 and 2014 field season in (a) Calgary AB, (b) London ON, and (c) Halifax NS.

Appendix B: Pin frame data for 2013 and 2014 field season






c)
Plant coverage (# of points)
0
20
40
60
80
100
120
140
May-13
June-13
July-13
August-13
September-13
May-14
June-14
July-14
August-14
September-14
● Mixed species 15 cm
◆ *S. spurium 15 cm*
■ *S. sporobolus 15 cm*
▲ *A. canadensis 15 cm*


d)
Plant coverage (# of points)
0
20
40
60
80
100
120
140
May-13
June-13
July-13
August-13
September-13
May-14
June-14
July-14
August-14
September-14
○ Mixed species 10 cm
◇ *S. spurium 10 cm*
□ *S. sporobolus 10 cm*
△ *A. canadensis 10 cm*

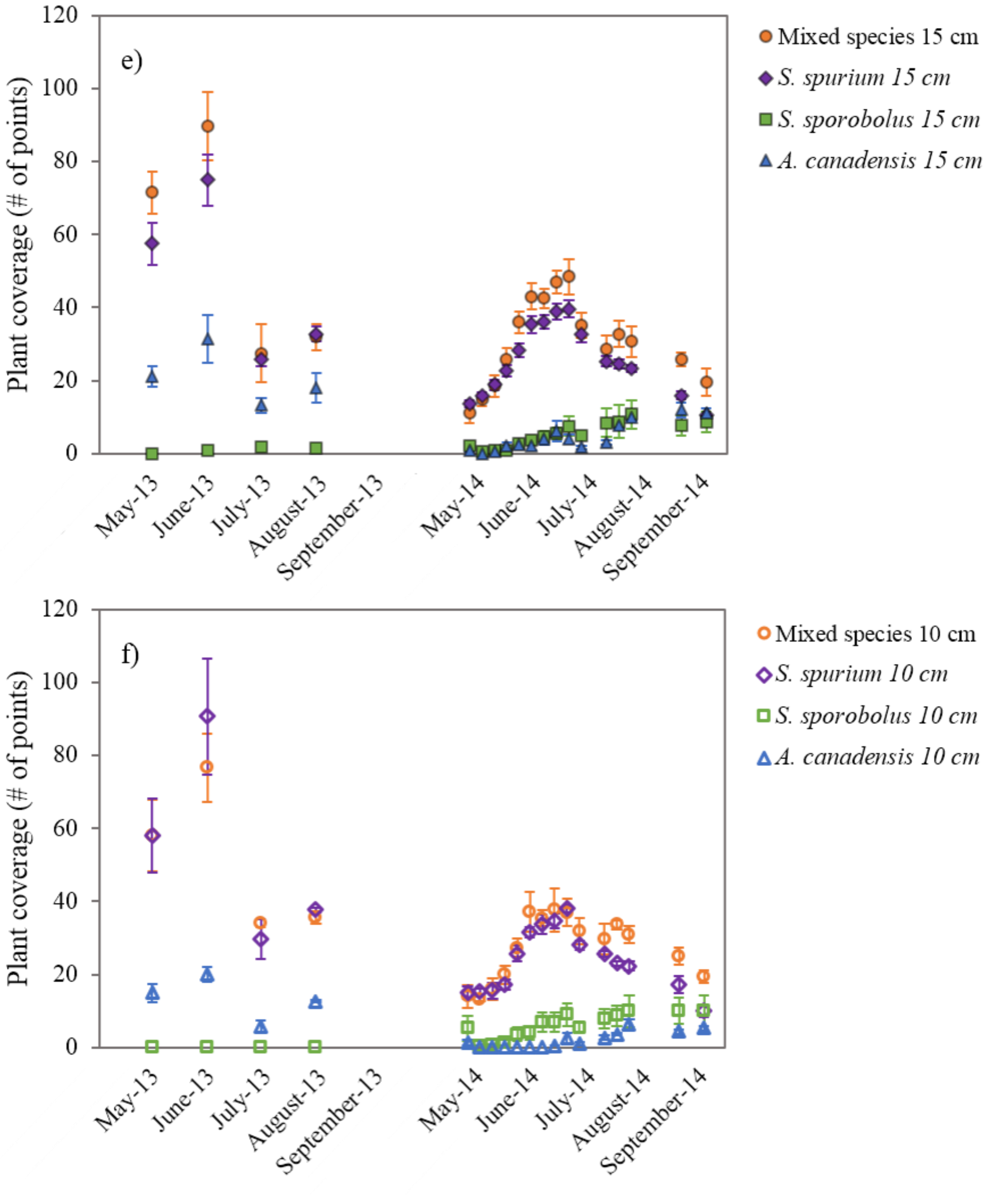


Figure B 1: Seasonal trends of the plant coverage (measured using the pin frame method) for vegetation treatments for the 2013 and 2014 field seasons in: Calgary AB [a) 15 cm depth and b) 10 cm depth], London ON [c) 15 cm depth and d) 10 cm depth], and Halifax NS [e) 15 cm depth and f) 10 cm depth]. The x-axis indicates the month and year the data were collected. The error bars represent the standard error of the mean.

Appendix C: Comparing daily ET rates between vegetation type and substrate depth treatments using the Wilcoxon signed rank test

Table C 1: Comparing the daily ET rates between the vegetation treatments planted in: (a) 10 cm vs. 10 cm substrate depth, (b) 15 cm vs. 15 cm substrate depth, and (c) 10 cm vs. 15 cm substrate depth for all three sites in 2013 and 2014 using the Wilcoxon signed rank test (*P* < 0.05). The significant *P* values and not significant *P* values calculated for the individual vegetation treatment comparisons are coloured as green boxes and red boxes, respectively.

a)

	10 cm Treatment								
vs.	*S. spurium*			*A. canadensis*			*S. heterolepis*		
10 cm Treatment	Calgary	London	Halifax	Calgary	London	Halifax	Calgary	London	Halifax
A. canadensis	-	0.001	0.110						
S. heterolepis	-	0.001	0.001	-	0.875	0.014			
Mixed species	0.001	0.120	0.005	-	0.001	0.007	-	0.001	0.001

b)

	15 cm Treatment								
vs.	*S. spurium*			*A. canadensis*			*S. heterolepis*		
15 cm Treatment	Calgary	London	Halifax	Calgary	London	Halifax	Calgary	London	Halifax
A. canadensis	0.025	0.001	0.218						
S. heterolepis	0.138	0.063	0.003	0.311	0.43	0.003			
Mixed species	0.001	0.001	0.001	0.001	0.001	0.002	0.001	0.001	0.001

c)

	10 cm Treatment											
vs.	*S. spurium*			*A. canadensis*			*S. heterolepis*			Mixed species		
15 cm Treatment	Calgary	London	Halifax	Calgary	London	Halifax	Calgary	London	Halifax	Calgary	London	Halifax
S. spurium	0.001	0.022	0.001									
A. canadensis				-	0.013	0.001						
S. heterolepis							-	0.001	0.001			
Mixed species										0.001	0.002	0.001

Table C 2: Comparing the daily ET rates calculated between the vegetation and bare (no vegetation) treatments planted in a) 10 cm vs. 10 cm substrate depth, b) 15 cm vs. 15 cm substrate depth, and c) 10 cm vs. 15 cm substrate depth for all three sites in 2014 using the Wilcoxon signed rank test (*P* < 0.05). The significant *P* values and not significant *P* values calculated for the individual vegetation treatment comparisons are coloured as green boxes and red boxes, respectively.

	a) 10 cm Bare vs. 10 cm Treatment			b) 15 cm Bare vs. 15 cm Treatment			c) 10 cm Bare vs. 15 cm Treatment		
Treatment	Calgary	London	Halifax	Calgary	London	Halifax	Calgary	London	Halifax
S. spurium	0.55	0.005	-	0.21	0.02	0.007			
A. canadensis	-	0.01	-	0.57	0.10	0.005			
S. heterolepis	-	0.01	-	0.42	0.005	0.009			
Mixed species	0.77	0.005	-	0.19	0.005	0.005			
Bare							0.44	0.47	-

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