Climate and Plant Traits as Influences on Green Roof Performance

By
Stephanie Tran

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

June 2017, Halifax, Nova Scotia

Approved:	Dr. Jeremy Lundholm Supervisor Department of Biology and Environmental Science
Approved:	Dr. Tracey Mackenzie External Examiner Department of Plant, Food, and Environmental Sciences Dalhousie University
Approved:	Dr. Zhongmin Dong Supervisory Committee Member Department of Biology
Approved:	Dr. James Steenberg Supervisory Committee Member Department of Resource and Environmental Studies Dalhousie University
Approved:	Dr. Sam Veres Graduate Studies Representative
Date:	June 16, 2017

ABSTRACT

CLIMATE AND PLANT TRAITS AS INFLUENCES ON GREEN ROOF PERFORMANCE

Stephanie Tran

Green roofs are being introduced and installed in varying climates worldwide to benefit from green roof services. Services of thermal cooling and stormwater capture reduce building energy consumption and strain on infrastucture. Across North America, green roofs often make use of a limited set of plants, but the effects of different climates on survival and growth are unknown while survival often outranks optimization of services. To identify the impact of climate on plant performance, I installed an identical green roof system in three Canadian cities. To investigate the relationship between plant traits and green roof services, I measured service provision and analyzed for correlation. A moderate climate supported the best growth and performance, but in all climates, mixture plantings performed well over the two growing seasons. Plant traits of specific leaf area and plant height were predictive, through vegetation characteristics, of stormwater capture and green roof surface cooling.

June 16, 2017

ACKNOWLEDGEMENTS

Thank you deeply to my thesis supervisor - Dr. Jeremy Lundholm - for the opportunity of this research work and study. I am grateful for the guidance, the statistics talks, the e-mail reminders, the encouragement and the wide-ranging views and connections to ecology. Thank you to the Lundholm Lab for being thought-provoking, inclusive and expansive.

Thank you to all the members of my committee: Tracey Mackenzie, Zhongmin Dong, and James Steenberg. The careful reading and the willingness to discuss ecology and research and all of the related implications was much appreciated, and turned out to be fun.

Many many thanks to Caitlin Porter. For trips to jaw-droppingly beautiful locations. For never-ending laughs. For guidance to R statistics books. For knowing the struggle.

Most memories and love to Robert William.

Thank you to my family and especially my partner Sean Lamb. This thesis would have been insurmountable without your support and interest, your willingness to be my sounding board, and your frustration with my dragging feet.

And a massive thank you to everyone that brought Nova Scotia to life for me: Lauren Matheson, Guylaine Williams, Brin Jones, Hana Ogasawara, Steph Boulton, Miranda Cobb, Evan Cervelli, Mathieu Arsenault, Xan Hawes, Karen Schaffer, Michael Stone and Karen Mombourquette.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Chapter 2:

LIST OF APPENDICES

Chapter 1

Introduction: Climate and plant traits as influences on green roof performance

Introduction

Urban environments are characterized as having more impervious surface compared to rural or wild areas and are quickly expanding due to growing populations. Roads, parking lots, sidewalks and rooftops make up horizontal impervious surfaces which change normal hydrology (USEPA 2003) and contribute to the urban heat island effect (Rizwan et al. 2008). While roads, sidewalks and parking lots serve functions for city inhabitants, rooftops, which account for 20–30% of a city's impervious surfaces, are under-utilized spaces (Banting et al. 2005, Carter and Jackson 2007, Akbari and Rose 2008). Green roofs, as porous systems, are being promoted for their benefit to the environment in urban centres such as Berlin, Portland, and Tokyo (Earth Pledge 2005). Large-scale, citywide benefits include mitigation of the urban heat island (Bass and Baskaran 2003, Wong et al. 2003, Getter and Rowe 2006), stormwater runoff reduction (Carter and Jackson 2007, Getter et al. 2007), provision of habitat for insects and birds (Brenneisen 2006), air quality improvement (Currie and Bass 2008), and aesthetic value (Getter and Rowe 2006, Oberndorfer et al. 2007, Berndtsson 2010). Green roof benefits also extend to the building-level, increasing roof longevity (Monterusso et al. 2005) and reducing energy consumption through summer cooling (Theodosiou 2003).

Green roofs are an engineered ecosystem composed of a drainage layer, filter membrane and water retention layer, lightweight growing media and vegetation (Dunnett and Kingsbury 2004, Oberndorfer et al. 2007). They are categorized based on the growing medium (or substrate) depth with extensive green roofs having depths of less than 15 to 20 cm while intensive green roofs have substrate depths greater than 15 or 20 cm. Extensive green roofs have lower structural loading requirements, lower installation costs and require less maintenance (Dunnett and Kingsbury 2004). For these reasons, extensive green rooftops are more often considered for implementation. However, extensive green roofs present challenging conditions for vegetation. In general, green roofs are subject to high wind speeds which promote desiccation of both the substrate and vegetation. They experience higher summer temperatures and are prone to periods of drought (Snodgrass and Snodgrass 2006). Along with drought conditions, green roofs can quickly shift to being waterlogged (Wolf and Lundholm 2008) due to the limited water-holding capacity of shallow substrate depths. The physical parameters of the green roof along with climate conditions create a difficult environment and limit plant selection for green roof use. At minimum, plants must be able to survive the intended climate and have a rooting system compatible with the substrate depth. Climate factors affecting green roof plant survival include summer maximum temperatures, humidity, and soil moisture while differences in the climate affect plant height and relative growth rate (Gazol and Camerero 2012) and with timing and amount of precipitation impacting plant growth and competition (Aerts 1993, Knapp et al. 2002, Heisler and Weltzin 2006). The green roof industry has relied heavily on *Sedum* spp. plants for green roof plantings as they have proven adaptable to many climates and have shallow rooting systems. *Sedums* are capable of withstanding drought and quickly creating coverage, however they have limited survival in climates with extreme winter or summer temperatures (Boivin et al. 2001, Livingston et al. 2004). While researchers in the green roof field often investigate survival of different test species within a given location, no studies have looked at the impact climate has upon plant performance within the same species. Green roof studies vary in location and corresponding climate, substrate depths and composition, and vegetation types. Understanding climate impact on green roof systems is crucial as climate impacts green roof services of stormwater capture and thermal cooling and also influences plant performance which in turn impacts green roof service provision.

Stormwater runoff is a concern especially in cities with a combined sewer system. In a combined sewer system, stormwater is drained from roadways and led to pipes also collecting wastewater. During heavy rain events, sewer system capacity can be exceeded resulting in a combined sewer overflow event where rainwater and raw sewage are released at relief points. These relief points typically lead into surface waters such as rivers, lakes and oceans. In New York

City, half of the rainfall events result in combined sewer overflow and surface waters receive 40 billion gallons of untreated sewage annually (Cheney 2005). Replacing sewer pipes to increase water storage capacity is an expensive, time-consuming and disruptive process. Green rooftops relieve stress on the stormwater system by reducing the amount of runoff entering the sewer system, delaying runoff start and releasing runoff over a longer period of time (VanWoert et al. 2005, Carter and Rasmussen 2006, Mentens et al. 2006, Getter et al. 2007, Teemusk and Mander 2007). Climate factors of temperature, rainfall duration, quantity and intensity (Speak et al. 2013), and preceding dry duration (Villarreal and Bengtsson 2005, Mentens et al., 2006, Getter et al. 2007) modulate stormwater capture amounts by green roofs.

Thermal cooling by green rooftops reduces the required energy used to cool the building during summer months (Del Barrio 1998, Niachou et al. 2001, Liu and Minor 2005). Green rooftops delay and reduce the daily temperature extremes experienced (Liu and Baskaran 2003). With lower surface temperatures, less heat is then transferred through the roof into the building interior, lowering cooling energy demands. Green roofs reduce heat flux by increasing albedo (Alexandri and Jones 2008), evapotranspiration (Onmura et al. 2001, Lazarrin et al. 2005) and the rooftop insulation value (Niachou et al. 2001). Thermal cooling is related to climate factors, influenced by temperatures and rainfall (Lin et al. 2013). Higher temperatures result in greater thermal cooling performance while rain reduces cooling ability relative to conventional roofs. Aside from ambient temperature and rainfall, humidity, wind speed and solar radiation intensity also influence thermal performance by green roofs (Theodosiou 2003, Santamouris 2012). Theodosiou (2003) found relative humidity to be the most important climatic factor in green roof temperatures, where higher humidity levels reduced cooling processes of transpiration and evaporative cooling.

Green roof services of thermal cooling and stormwater capture can be considered ecosystem services as they are considered valuable to us. Ecosystem services are valued products ranging from cultural services (inspiration, iconography, social effects) to productive soils to water purification to fuel resources. They are generated from ecosystem functions, which represent processes arising between components of an ecosystem, such as biological production, nutrient cycling and decomposition. Ecosystem functions such as plant biomass generation affect the ecosystem services of green roof stormwater capture and thermal cooling. Each plant species performs functions to varying degrees (Hector and Bagchi 2007) and some species outperform the industry standard *Sedum* spp. in stormwater capture. Wolf and Lundholm (2008) found grasses to remove water from the substrate more quickly than *Sedums*. Over repeated rainfalls, grasses would remove more water, creating drier antecedent conditions and thereby allowing the green roof system to retain more subsequent stormwater than *Sedum* plantings (Lundholm et al. 2010). Overall, herbaceous plants can outperform *Sedums* in terms of stormwater management (Dvorak and Volder 2010). With higher transpiration rates in herbaceous plants, there is potential for greater cooling effects through evaporative cooling (Dvorak and Volder 2010). Blanusa et al. (2013) reported better cooling of the substrate surface by *Stachys byzantina* over other herbaceous plants and an industry *Sedum* mix.

Green roof service provision of stormwater capture and thermal cooling is influenced by a number of physical and physiological vegetation traits. Stormwater capture is proposed to be linked to transpiration rates (DeNardo et al. 2005) and shown to be influenced by canopy features that slow the rate of water reaching the substrate (Dunnett et al. 2008). Thermal cooling depends in part by reducing heat flux through the roof, with the plant canopy playing a role by shading the substrate surface (DeNardo et al. 2005) and performing evaporative cooling (Jim and Tsang 2011). The canopy architecture may also differentially change thermal performance (Dunnett and Kingsbury 2010) with canopy architecture being highly varied and comprised from a wide array of traits, including branching characteristics, leaf angle and branch angle (Ollinger 2011). Canopy features and evaporative processes are all derived from inherent plant traits. Plant traits are morphological and physiological characteristics, independent of taxonomic identity, that relate to plant function, survival and fitness. From the understanding of plant function through plant traits, a range of ecological questions can be answered. Ecological questions probing vegetative response to climate, climate change, landuse and disturbance or atmospheric chemistry have been investigated (Gross et al. 2008, Lavorel and Grigulis 2012). Questions can also be answered on a large scale, at the ecosystem, landscape or biome level, as archetypal values of plant traits are systematically found in similar environments.

The most useful plant traits are those relatively easy to measure for the widest number of plant species and those that most strongly predict ecosystem processes (Cornelissen et al. 2003). For my purpose, within the green roof system, stormwater capture and thermal cooling can be considered ecosystem processes. Use of plant traits for description and prediction of green roof functions has begun to be adopted by researchers. Functional plant traits for green roofs were defined by Cook-Patton and Bauerle (2012) as "traits that contribute to a green roof's ability to provide services to an urban area," while Farrell et al. (2013) utilized physiological traits to screen for potential green roof plants, looking for drought tolerance, and to investigate green roof vegetation water use. With the ability to measure trait data for a large number of species and the correlation of traits to ecosystem processes, there exists the opportunity for green roof researchers to expand the palette of suitable and optimal green roof plants. Expanding the green roof plant palette and increasing green roof plant diversity can develop resilience of green roofs (Cook-Patton and Bauerle 2012) and potentially optimize green roof service provision (Lundholm et al. 2010). Diverse green roof plantings can, depending on the incorporated species, better withstand conditions of drought (Butler and Orians 2011) and better perform stormwater capture and thermal cooling (Kolb and Schwarz 1986, Lundholm et al. 2010).

The goal of this thesis was to investigate the impact climate has upon green roof plant performance, and to suggest a method for screening plants to optimize green roof service provision of stormwater capture or thermal cooling. The specific objectives addressed were:

Chapter 2: Determining the impact of climate upon green roof plants in growth performance measures; and

Chapter 3: Identifying the relationship between plant traits and green roof services of thermal cooling and stormwater capture.

For Chapter 2, identical green roof systems were installed in Calgary, Alberta; London, Ontario; and Halifax, Nova Scotia; cities which receive different weather. *Sedum spurium* (a succulent), *Aquilegia canadensis* (a forb) and *Sporobolus heterolepis* (a graminoid) were grown in monoculture and combined in a mixture planting. The objective was to discern whether plant performance of leafing density, plant height and establishment and persistence rates differed between sites, indicating influence of climate.

For Chapter 3, test plant species were grown in monoculture on a modular green roof system in Halifax, NS and included local, native species previously shown to survive on extensive green roof systems (Lundholm et al. 2010, MacIvor and Lundholm 2011). Traits were obtained for these 21 test species and relationships to their corresponding stormwater capture and surface temperatures were analyzed using path analysis.

References

Aerts, R., Berendse, F., de Caluwe, H., Schmitz, M., 1990. Competition in heathland along an experimental gradient of nutrient availability. Oikos 57, 310e318.

Akbari, H., Rose, L.S. 2008. Urban surfaces and heat island mitigation potentials. Journal of the Human-Environmental System, 11: 85–101.

Alexandri, E., Jones, P. 2008. Temperature decreases in an urban canyon due to green roofs in diverse climates. Building and Environment, 43: 480 – 493.

Banting, D., Doshi, H.H., Li, J., Missios, P. 2005. Report on the Environmental Benefits and Costs of Green Roof Technology for the City of Toronto. City of Toronto and Ontario Centres for Excellence-Earth and Environmental Technologies, Toronto.

Bass, B., Baskaran, B., 2003. Evaluating rooftop and vertical gardens as an adaptation strategy for urban areas. Institute for Research and Construction, National Research Council, Canada, p. 111.

Berndtsson, J.C. 2010. Green roof performance towards management of runoff water quantity and quality: a review. Ecological Engineering, 36: 351 – 360.

Blanusa, T., Vaz Monteiro, M.M., Fantozzi, F., Vysini, E., Li, Y., Cameron, R.W.F. 2012. Alternatives to *Sedum* on green roofs: can broad leaf perennial plants offer better 'cooling service'? Building and Environment, 59: 99 – 106.

Bovin, M., Lamy, M., Gosselin, A., Dansereau, B. 2001. Effect of artificial substrate depth on freezing injury of six herbaceous perennials grown in a green roof system. HortTechnology, 11: 409 – 412.

Brenneisen, S. 2006. Space for urban wildlife: designing green roofs as habitats in Switzerland. Urban Habitats, 4: 27 – 36.

Butler, C., Orians, C.M., 2011. Sedum cools soil and can improve neighboring plant performance during water deficit on a green roof. Ecological Engineering, 37: 1796-1803.

Carter, T.L., Rasmussen, T.C. 2006. Hydrologic behavior of vegetated roofs. Journal of the

American Water Resources Assosciation, 45: 1261 – 1274.

Carter, T., Jackson, C.R. 2007. Vegetated roofs for stormwater management at multiple spatial scales. Landscape and Urban Planning, 80: 84 – 94.

Cheney, C. 2005. New York City: Greening Gotham's rooftops, p. 130-133. In Earth Pledge. Green roofs: Ecological Design and Construction. Schiffer Books, Atglen, PA.

Cornelissen, J.H.C., Lavorel, S., Garnier, E., Díaz, S., Buchmann, N., Gurvich, D.E., Reich, P.B., ter Steege, H., Morgan, H.D., van der Heijden, M.G.A., Pausas, J.G., Poorter, H. 2003. A handbook of protocols for standardized and easy measurement of plant functional traits worldwide. Australian Journal of Botany, 51: 335 – 380.

Cook-Patton, S.C., Bauerle, T.L. 2012. Potential benefits of plant diversity on vegetated roofs: a literature review. Journal of Environmental Management, 106: 85 – 92.

Currie, B.A., Bass, B. 2008. Estimates of air pollution mitigation with green plants and green roofs using the UFORE model. Urban Ecosystems, 11: 409 – 422.

Del Barrio, E.P. 1998. Analysis of the green roofs cooling potential in buildings. Energy and Buildings, 27: 179 – 193.

DeNardo, J.C., Jarrett, A.R., Manbeck, H.B., Beattie, D.J., Berghage, R.D., 2005. Stormwater mitigation and surface temperature reduction by green roofs. Transactions of the ASAE, 48: 1491-1496.

Dunnett, N., Kingsbury, N. 2004. Planting Green Roofs and Living Walls. Timber Press, Portland, OR.

Dunnet, N., Kingsbury, N. 2010. Planting Green Roofs and Living Walls, 2nd Ed. Timber Press, Portland.

Dunnett, N., Nagase, A., Booth, R., Grime, P., 2008. Influence of vegetation composition on runoff in two simulated green roof experiments. Urban Ecosystems, 11: 385-398.

Dvorak, B., Volder, A. 2010. Green roof vegetation for North American ecoregions: a literature review. Landscape and Urban Planning, 96: 197 – 213.

Earth Pledge, 2005. Green roofs: ecological design & construction. Schiffer Books, Atglen, PA.

Gazol, A., Camarero, J. 2012. The performance of Mediterranean subshrubs depends more on microsite than on regional climate conditions. Journal of Vegetation Science, 23: 1062-1070.

Getter, K.L., Rowe, D.B. 2006. The role of extensive green roofs in sustainable development. HortScience, 41: 1276 – 1285.

Getter, K.L., Rowe, D.B., Andresen, J.A. 2007. Quantifying the effect of slope on extensive green roof stormwater retention. Ecological Engineering, 31: 225 – 231.

Gross, N., Robson, T.M., Lavorel, S., Albert, C., Le Bagousse-Pinguet, Y., Guillemin, R., 2008. Plant response traits mediate the effects of subalpine grasslands on soil moisture. New Phytologist, 180: 652-662.

Hector, A., Bagchi, R. 2007. Biodiversity and ecosystem multifunctionality. Nature, 448: 188 – 191.

Heinze, W. 1985. Results of an experiment on extensive growth of vegetation on roofs. Rasen Grünflachen Begrünungen, 16: 80 – 88.

Heisler, J.A., Weltzin, J.F. 2006. Variability matters: towards a perspective on the influence of precipitation on terrestrial ecosystems. New Phytologist, 172: 189-192.

Jim, C.Y., Tsang, S.W., 2011. Biophysical properties and thermal performance of an intensive green roof. Building and Environment, 46: 1263-1274.

Knapp, A.K., Fay, P.A., Blair, J.M., Collins, S.L., Smith, M.D., Carlistre, J.D., Harper, C.W., Danner, B.T., Lett, M.S., McCarron, J.K. 2002. Rainfall variability, carbon cycling, and plant species diversity in a mesic grassland. Science, 298: 2202-2205.

Kolb, W., Schwarz, T. 1986. Zum Klimatisierungseffekt von Pflanzbeständen auf Dächern, Teil I. Zeitschrift für Vegetationstechnick 9. Republished in Veitshoechheimer Berichte, Heft 39, Dachbegrünung. (cf. Dunnett and Kingsbury 2004).

Lavorel, S., Grigulis, K., 2012. How fundamental plant function trait relationships scale-up to trade-offs and synergies in ecosystem services. Journal of Ecology, 100: 128-140.

Lazarrin, R.M., Castellotti, F., Busato, F. 2005. Experimental measurements and numerical modeling of a green roof. Energy and Buildings, 37: 1260 – 1267.

Livingston, E.H., Miller, C., Lohr, M. 2004. Green roof design and implementation in Florida. In: Proceedings of the 2nd North American Green Roof Conference: Greening rooftops for sustainable communities, Portland, OR, The Cardinal Group, Toronto.

Lui, K., Baskaran, B. 2003. Thermal performance of green roofs through field evaluation – Ottawa. Ottawa (Canada): National Research Council Canada, Institute for Research in Construction. Report no. NRCC-46412.

Liu, K., Minor, J. 2005. Performance evaluation of an extensive green roof. In: Proceedings of 3rd North American Green Roof Conference: Greening rooftops for sustainable communities, Washington, DC, The Cardinal Group, Toronto.

Lundholm, J., MacIvor, J.S., MacDougall, Z., Ranalli, M. 2010. Plant species and functional group combinations affect green roof ecosystem functions. PLoS ONE, 5: e9677.

MacIvor, J.S., Lundholm, J. 2011. Performance evaluation of native plants suited to extensive green roof conditions in a maritime climate. Ecological Engineering, 37: 407 – 417.

Mentens, J., Raes, D., Hermy, M. 2006. Green roofs as a tool for solving the rainwater runoff problem in the urbanized 21st century? Landscape and Urban Planning, 77: 217 – 226.

Monterusso, M.A., Rowe, D.B., Rugh, C.L. 2005. Establishment and persistence of *Sedum* spp. and native taxa for green roof applications. HortScience, 40:391 – 396.

Niachou, A., Papakonstantinou, K., Santamouris, M., Tsangrassoulis, A., Mihalakakou, G. 2001. Analysis of the green roof thermal properties and investigation of its energy performance. Energy and Buildings, 33: 719 – 729.

Oberndorfer, E., Lundholm, J., Bass, B., Coffman, R.R., Doshi, H., Dunnett, N., Gaffin, S., Köhler, M., Liu, K.K.Y, Rowe, B. 2007. Green roofs as urban ecosystems: ecological structures, functions and services. BioScience, 57: 823 – 833.

Ollinger, S.V., 2011. Sources of variability in canopy reflectance and the convergent properties of plants. New Phytologist, 189: 375-394.

Onmura, S., Matsumoto, M., Hokoi, S. 2001. Study on evaporative cooling effect on roof lawn gardens. Energy and Buildings, 33: 653 – 666.

Rizwan, A., Dennis, Y., Liu, C. 2008. A review on the generation, determination, mitigation of Urban Heat Island. Journal of Environmental Sciences, 20: 120 – 128.

Santamouris, M. 2012. Cooling the cities - a review of reflective and green roof mitigation technologies to fight heat island and improve comfort in urban environments. Solar Energy, 103: 682-703.

Snodgrass, E.C., Snodgrass, L.L. 2006. Green Roof Plants: A Resource and Planting Guide. Timber Press, Portland, OR.

Speak, A.F., Rothwell, J.J., Lindley, S.J., Smith, C.L. 2013. Rainwater runoff retention on an aged intensive green roof. Science of the Total Environment, 461-462: 28-38.

Teemusk, A., Mander, Ü. 2007. Rainwater runoff quantity and quality performance from a greenroof: the effects of short-term events. Ecological Engineering, 30: 271 – 277.

Theodosiou, T.G. 2003. Summer period analysis of the performance of a planted roof as a passive cooling technique. Energy and Buildings, 35: 909 – 917.

USEPA. 2003. Protecting water quality from urban runoff. EPA 841-F-03-003. USEPA, Washington, DC.

VanWoert, N.D., Rowe, D.B., Andresen, J.A., Rugh, C.L., Fernandez, R.T., Xiao, L. 2005. Green roof stormwater retention: effects of roof surface, slope and media depth. Journal of Environmental Quality, 34: 1036 – 1044.

Villarreal, E.L., Bengtsson, L. 2005. Response of a *Sedum* green-roof to individual rain events. Ecological Engineering, 25: 1-7.

Wolf, D., Lundholm, J.T. 2008. Water uptake in green roof microcosms: effects of plant species and water availability. Ecological Engineering, 33: 179 – 186.

Wong, N.H., Chen, Y., Ong, C.L., Sia, A., 2003. Investigation of thermal benefits of rooftop garden in the tropical environment. Building and Environment, 38: 261-270.

Chapter 2

Green roof plant performance across three climate contexts of Canada

Abstract

Green rooftops are being introduced and installed in varying climates worldwide to benefit from green roof services. Across North America, green roofs often make use of the same limited set of plant species, but the effects of different climates on survival and growth on different plant species is unknown. To identify the impact of climate on green roof plant performance, we installed an identical green roof system in three Canadian cities that experience different climate conditions: Calgary, Alberta; London, Ontario; and Halifax, Nova Scotia. The green roofs were monitored across three growing seasons for plant survival, plant height, and canopy density of three species grown in monoculture: *Aquilegia canadensis*, *Sporobolus heterolepis*, and *Sedum spurium*, in addition to a mixture planting incorporating all three species. I found green roof canopy density, plant height and calculated establishment and persistence rates, components of green roof performance, to be significantly influenced by the green roof site. Experimental factors of site, plant species and planting type (monoculture or mixture treatment), significantly impacted plant growth variables. I found a moderate climate, as experienced in London, supported the best green roof growth and performance as compared to the cooler, drier Calgary and the rainier Halifax. Between sites, plant species also exhibited different phenologies. Mixture treatments performed better than monoculture plantings at each site in canopy density measures but were not significantly greater in plant height measures. The persistence rate for mixture treatments was greatest, indicating greater potential for long term survival and performance of mixture plantings.

Keywords: Extensive green roof; monoculture; mixture; climate; canopy density

Introduction

Between 2005 and 2012, thirteen cities across North America implemented policy or incentive programs regarding green roof installation (GRHC 2013), often to promote stormwater capture, but green roofs also provide habitat provision, increase roof membrane longevity and urban heat island mitigation, among others benefits (Getter and Rowe 2006, Oberndorfer et al. 2007). While green rooftops provide benefits to the city and the building itself through its material components and its living plants, growing conditions for plants on rooftops are considerably harsher than comparative ground level conditions. Green roofs are restricted in substrate depth and are typically subject to greater solar radiation and wind speeds (Dunnett and Kingsbury 2010). Greater solar radiation and wind speeds quicken water loss through evaporation (Santamouris 2012) while restricted substrate depth limits maximum water availability (Berndtsson 2010), contributing to creating drought conditions. For extensive green roofs, especially of substrate depth less than 15 cm, these growing conditions limit plant selection to those that can withstand periodic drought if supplementary irrigation is not available and to those with shallow, non-penetrating root systems.

Research and industry experience from Europe and North America have found the *Sedum* genus well suited to green roof conditions. *Sedums* are drought tolerant succulents, able to survive in a wide range of climates and in very shallow substrate depths, shown to endure down to a substrate depth of 5 cm (Dvorak and Volder 2010). However, *Sedums* are not suitable across all climates. Boivin et al. (2001) found *Sedum x hybridum* in 5 cm deep substrate to be susceptible to root damage following winters with minimum temperatures of -0.4 and -5.4°C in Laval, Quebec, Canada. At the other climate extreme, Livingston et al. (2004) found *Sedums* susceptible to hot, humid environments. Furthermore, provision of green roof services isn't necessarily optimized by *Sedum* species. Their drought tolerant nature and mat growth form prevents high water capture ability as compared to other plant species (Wolf and Lundholm 2008). Lundholm et al. (2010) and Farrell et al. (2013) have found some plant species to outperform *Sedums* in water capture and transpiration rate.

The use of mixture plantings has shown evidence of enhancing plant survival and green roof performance. Butler and Orians (2011) found survival of herbaceous species in extensive green roof modules to be greater during drought conditions when co-planted with *Sedum* species through facilitation. Nagase and Dunnett (2010) similarly found greater plant survival in dry conditions when plantings included multiple species. Co-planting, or mixture plantings, can also potentially boost green roof service provision. Lundholm et al. (2010) found increased roof cooling and stormwater capture services with a mixture planting incorporating a tall forb, a grass and a succulent life form. Cook-Patton and Bauerle (2012) reports findings from Kolb and Schwarz (1986) that diverse plantings had greater roof cooling abilities than monocultures. Instead of industry reliance on *Sedums*, there exists great potential for plantings incorporating different species and different growth forms to maximize green roof service provision. The ability to maximize green roof ecosystem functioning through plant selection would enhance environmental benefits and create increased visual diversity on green roofs, an aesthetic marker (Dunnett et al. 2008).

Incorporating taller plants on green roofs could be one strategy of green roof optimization. Plants with taller foliage allow for better maintenance of the insulating air pocket between the substrate surface and the vegetation layer (Theodosiou 2003). This air pocket reduces temperatures at the substrate surface compared to atmospheric temperatures. Consequently, taller plants better reduce the temperature within the substrate (Sailor 2008). Taller plants have also been shown to perform stormwater capture better than shorter plants (Nagase and Dunnett 2012). Theodosiou (2003) mentions that low foliage plants provide better shading of the substrate surface, which contributes to reducing substrate temperatures, but overall, studies suggest taller foliage heights have better performance value on green rooftops.

Overall plant biomass contributes to green roof services of stormwater capture, thermal cooling and visual rating. Plants contribute to stormwater capture by taking water up from the substrate and performing evapotranspiration through their leaves. This removes water from the substrate material and recharges the substrate's capacity for water capture during the next storm event (Stovin 2010). Plant canopies contribute to reducing heat flux through the roof by shading the substrate surface (DeNardo et al. 2005) and through evaporative cooling (Jim and Tsang 2011).

Plant height, biomass and interaction with other plant species contribute to green roof performance. Green roofs, however, are dynamic, with plant biomass, height and coverage of the green roof shifting with time (Dunnett et al. 2008). Considering the role plants have in stormwater capture and thermal cooling, having optimal biomass and coverage throughout the growing season or year if possible would help optimize green roof service provision.

While studies have looked to expand the green roof palette to maximize green roof performance, many studies allude to the need for plant selection suited to the climate conditions the roof will experience. Monterusso et al. (2005) expressed that better understanding of the plants that will thrive in the climate range of the United States is required for the success of green roofs. Getter et al. (2009) furthered this message, writing that plant success depends upon the overall climate as well as the microclimate experienced by the roof.

For this study, I was interested in how plant growth would respond in different climate locations. I investigated if different sites would be differently affected by green roof parameters of substrate depths and planting species. To fulfill this goal, I installed an identical green roof system of two substrate depths in three Canadian cities: Calgary, Alberta; London, Ontario; and Halifax, Nova Scotia. Plant species *Sedum spurium*, *Aquilegia canadensis* and *Sporobolus heterolepis* were grown in monoculture modules and plant health and survival, canopy density, establishment and persistence rates were measured as indicators of plant performance. To investigate robustness of mixture plantings, I also compared the plant performance of the best monoculture canopy density performer from this experiment, *S. spurium*, against a mixture planting containing *S. spurium, A. canadensis* and *S. heterolepis*. The mixture planting was compared to only the best monoculture so that any added benefit from mixture planting would be clear. The goal was to identify the best approach for green roof planting, so if the mixture outperformed the best, it would follow that it also outperformed a poorer performing monoculture. In comparing these plantings, we aim to identify factors that contribute to best optimal performance for each site.

Methods

Sites

To examine plant performance variation between cities with differing climates, identical green roof systems were installed in Calgary, Alberta; London, Ontario; and Halifax, Nova Scotia, Canada. In Calgary, the green roof system was installed on the University of Calgary's Earth Sciences building, atop the second storey over an existing gravel ballast roof. To the north, the Earth Sciences building rises another eight storeys. In London, the green roof system was hosted by the University of Western Ontario. It was placed atop Talbot College, on a two storey high portion of the building where the building's third storey rises on the south face of the green roof approximately 50 feet away. The existing roof surface was covered by concrete pavers. In Halifax, the green roof was installed atop Park Place V, a five storey commercial office building approximately 5 km from Halifax's city centre. The experimental green roof system was placed on a high-reflectivity, white roof membrane with a mechanical penthouse to the east. To minimize interaction with and influence from the existing roof structures, at all locations, the experimental green roofs were installed atop 2.5 cm sheets of Styrofoam insulation.

Climatically, Calgary has a dry climate, receiving less precipitation than both London and Halifax (Table 1, Figure 1). Calgary experiences colder winter temperatures but also receives frequent chinooks, warm winds that raises temperatures and remove winter conditions for hours to days at a time. By the Köppen classification system, created considering temperatures and amount and distribution of precipitation, all three cities classify under humid continental (Dfb) with some differences within the classification. Some markers of continental climate within the Köppen classification system are a large temperature difference between summer and winter, and precipitation generally distributed throughout the year. Calgary classifies as a dry humid continental climate, while London's climate can be considered to be on the threshold between

Table 1: Thirty year climate averages from 1971 - 2010 for Calgary, Alberta, Halifax, Nova Scotia and London, Ontario.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Yearly
Calgary													
Daily Average T (°C)	-7.1	-5.4	-1.6	4.6	9.7	13.7	16.5	15.8	11	5.2	-2.4	-6.8	4.4
Precipitation (mm)	9.4	9.4	17.8	25.2	56.8	94	65.5	57	45.1	15.3	13.1	10.2	418.8
Wind Speed (km/h)	13.9	13.7	14.6	16.1	16.1	15	13.5	12.7	13.4	14	13.4	13.7	14.2
Days with wind >= 52km/h	3.1	2.1	2.2	2.2	2.6	2.1	1.8	1.7	2.1	2.5	2.1	3.1	27.7
Degree days over 15 °C	0	0	0	0.4	7.8	22.7	65.6	57.3	13.4	1.1	0	0	168.1
London													
Daily Average T (°C)	-5.6	-4.5	-0.1	6.8	13.1	18.3	20.8	19.7	15.5	9.2	3.4	-2.6	7.9
Precipitation (mm)	74.2	65.5	71.5	83.4	89.9	91.7	82.7	82.9	103	81.3	98	87.5	1011.5
Wind Speed (km/h)	17.3	16.2	16.3	16.3	14	11.9	10.6	9.7	11.1	13.4	15.6	16.5	14.1
Days with wind >= 52km/h	1.2	0.8	1.6	1.2	0.6	0.4	0.4	0.2	0.3	0.8	0.5	1.0	9.0
Degree days over 15 °C	0	0	0.9	5.3	35.6	112.3	179.3	147.7	61.1	6.8	0.3	0.1	549.2
Halifax													
Daily Average T (°C)	-5.9	-5.2	-1.3	4.4	10	15.1	18.8	18.7	14.6	8.7	3.5	-2.4	6.6
Precipitation (mm)	134.3	105.8	120.1	114.5	111.9	96.2	95.5	93.5	102	124.9	154.2	143.3	1396.2
Wind Speed (km/h)	17.7	18.3	18.5	18.3	16.5	15.2	14.2	13.2	14.4	16	17.5	18.3	16.5
Days with wind >= 52km/h	2.4	1.9	1.9	1.3	0.4	0.3	0.2	0.2	0.5	0.6	1.7	2.2	13.3
Degree days over 15 °C	0	0	0	0.1	4.6	42.8	120.6	118.4	35	3.1	0.1	0	324.6

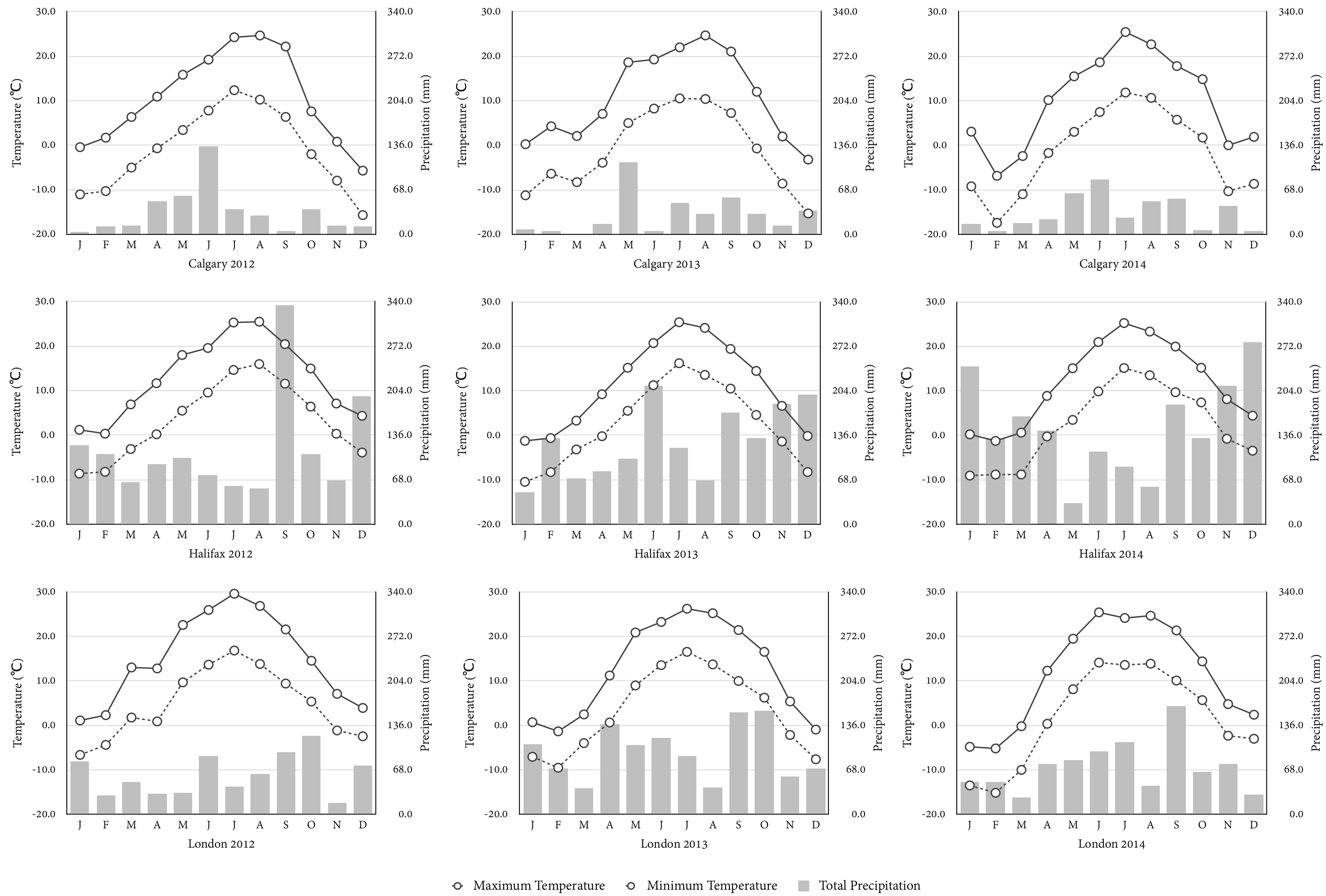

Figure 1. Minimum and maximum temperatures (°C) and precipitation (mm) for green roof sites Calgary, London and Halifax over the experimental period 2012 - 2014.

Dfb and Dfa. Dfa, a hot summer continental climate, in London is pushed to the Dfa/Dfb boundary due to a lake effect from Lake Huron. Consequently, London experiences the greatest number of >15°C degree days, 519.5 compared to 157.3 days in Calgary and 303.6 in Halifax (Table 1). Halifax receives the most annual rainfall, 1356.1 mm, with precipitation occurring even in the driest months. Halifax receives relatively mild winters from the Gulf Stream, but is overall cold and temperate, with high wind speeds.

Green Roof System

A modular green roof from LiveRoof® System was used at all locations (LiveRoof Ontario, Mount Brydges, ON, Canada). The system consists of plastic modules measuring 30 cm x 30 cm along the inside perimeter, and proprietary LiveRoof® Engineered Soil.

Plant plugs and modules for the green roof system were propagated at two plant nurseries. Eagle Lake Turf Farms, near Strathmore, AB, prepared planted modules for Calgary. The LiveRoof® nursery in Mount Brydges, ON, prepared planted modules for London. For Halifax, the Mount Brydges nursery prepared plant plugs which were trucked to Halifax and planted into modules upon arrival.

Plant species for experimentation included *Sedum spurium*, commonly used by the industry throughout North America, and two species native to Ontario: *Sporobolus heterolepis*, a grass, and *Aquilegia canadensis*, a forb. These test plant species were planted in modules as monocultures as well as incorporated into a mixture treatment. Modules with the mixture treatment combined these three growth forms, following findings from Lundholm et al. (2010) for optimal green roof performance of thermal cooling and stormwater capture. All monoculture and mixture treatments were planted at two substrate depths, 10 cm and 15 cm deep.

With the goal of achieving 80% coverage upon maturation as per FLL guidelines (FLL

2002), monoculture modules were planted with plant density of: one *S. heterolepis*; three *A. canadensis*; or five *S. spurium*. These planting densities for each species was, from literature and past experience, assumed to be sufficient to generate 80% coverage. For mixture treatment modules, a five plug planting density was created from one *A. canadensis*, one *S. heterolepis* and three *S. spurium* plugs. Following installation, 10 mL of 17-06-12 POLYON Nursery fertilizer (Agrium Advanced Technologies, Calgary, AB, Canada) was applied to the base of each plug. Modules were thoroughly watered following installation and for the subsequent two weeks. After the two foundation weeks, no supplemental irrigation was provided. Modules were weeded twice a month during the growing season to remove volunteer species.

Experimental units were created from nine modules in a 3 x 3 arrangement of the same planting type (monoculture species or mixture planting) and substrate depth. In each unit, the centre module, buffered by the other modules to reduce edge effects, was considered the test module. Data were collected only from these central, test modules.

Replicate number of experimental units were identical between Calgary and Halifax green roofs, whereas London had increased replication of *S. spurium* monoculture modules and a different allotment between shallow and deep modules of the monocultures and the mixture (Table 2).

Table 2. Final test module replication number by green roof location, planting type and substrate depth. In parentheses are the original module replication counts, where appropriate.

Site	Depth	*A. canadensis*	*S. heterolepis*	*S. spurium*	Mixture
Calgary	10 cm	0 (3)	3	3	3
	15 cm	2 (4)	4	9	4
Halifax	10 cm	3	3	3	3
	15 cm	4	4	9	4
London	10 cm	4	4	3	4
	15 cm	3	3	16	3

Data Collection

Experimental modules were assessed for plant health and survival, module canopy density and plant height. In addition, module coverage was obtained by processing overhead photographs of test modules in Image J (Image Processing and Analysis in Java, NIH, USA). Measurements of canopy density began August 2012, year 1, after the two weeks of irrigation following installation. Measurements were taken again in October. Through year 2 (2013) and year 3 (2014), measurements were taken once monthly from May to August. All measurements were made in the third week of the month. Canopy density measurements June and July year 2 for London were lost.

Plant health was rated on a scale of 0-2 (Butler and Orians 2011) where a rating of 2 corresponded to a healthy plant with green leaves and green stem, 1 dead leaves with green stem, and 0 dead leaves and dead stem. At the beginning of the year 2, treatment blocks whose centre, test module had died (health rating of 0) were removed and replaced with a LiveRoof® *Sedum* mixture. Following plant death, these test modules were removed from analysis.

Canopy density, an index of above-ground biomass, was determined using the point-interception method (Jonasson 1988). A plastic frame measuring 30 cm x 30 cm along the inside edge was subdivided into 16 sections. At each intersection, totalling nine points, a 3.75 mm diameter pin was inserted and the number of contacts made between live vegetation matter and pin recorded, measuring three dimensional density. Contacts were totalled from the nine points to provide the canopy density value. Canopy density measures over the experimental period were used to identify the best monoculture species for comparison to mixture module performance.

Plant height was obtained by using a frame measuring 30 cm x 30 cm divided into nine sections. Within each section, a ruler was placed at substrate level, and the average plant height visually assessed for the section. The nine measurements were averaged for the module.

Establishment and persistence rates were generated from August canopy density measurements over a year time period to identify a year-over-year measure of growth. Establishment rate was considered the year 1 to year 2 growth rate, determined as:

$$\text{Canopy Density}_{\text{(August year 2)}} - \text{Canopy Density}_{\text{(August year 1)}}$$

Persistence rate, considered the year 2 to year 3 growth rate, was similarly calculated as:

$$\text{Canopy Density}_{\text{(August year 3)}} - \text{Canopy Density}_{\text{(August year 2)}}$$

In both instances, positive values indicate increased canopy density over the time span.

Data Analysis

To compare green roof performance between locations over time, a repeated measures ANOVA was performed with two within-subject factors (random effects: unit nested within sampling year and month) and three-between (fixed effects: site, depth, species). Post-hoc tests were performed at each time point, with three-way ANOVAs and TukeyHSD to investigate pair-wise interactions. Variables canopy density, heights and establishment and persistence rates were investigated with factors of site, substrate depth and species type (for monoculture plantings) or planting type (when comparing mixtures to the best monoculture). Significance was determined at $p < 0.05$.

Results

Overall, plant performance was highest in all plant performance measures at the green roof site in London, Ontario and mixture plantings outperformed the best monoculture planting. Noticeably, the London roof experienced no plant death over the experimental period, whereas both the Halifax, Nova Scotia and Calgary, Alberta green roofs experienced plant death following the first, year 1, winter. The London roof had highest overall canopy density throughout all experimental growing seasons and the tallest plant height measures. Green roof performance of Calgary and Halifax were at times similar, but mid year 2 and onward, the Calgary roof outperformed the Halifax roof (plants were larger and grew faster) although the Calgary roof experienced more plant death initially.

Plant health and survival

Over the experimental period, the majority of plants survived. No plants died during the year 1 growing season, but plant death occurred over the first winter in Calgary and Halifax. In Calgary, five *A. canadensis* test modules died, three 10 cm and two 15 cm deep. Counting the non-test modules included in the treatment block to reduce edge effects, 42 *A. canadensis* and five *S. heterolepis* modules experienced plant death in Calgary. In Halifax, 11 non-test *S. heterolepis* modules died. In Calgary, for the units where the test modules died, the full unit was removed and replaced with a LiveRoof® *Sedum* mixture and removed from further measurement. No plant death occurred in any planted species in London and no further plant death was experienced after the first winter. Aside from the noted plant deaths, all subsequent plant health measurements rated 2, green stem and green leaves, across all sites throughout the experimental measurement points.

Coverage

By the end of the year 2 growing season when the green roofs were considered to be established, 4 out of the 12 site-species/planting treatment combinations achieved the target 80% module coverage (Figure 2). Only the *S. spurium* and mixture modules of Calgary and London met and exceeded 80% coverage. The mean coverage in Halifax for *S. spurium*, *A. canadensis* and mixture treatment were close to the coverage target with mean module coverage of 76.4±5.1%, 77.4±10.1% and 75.9±10.1% respectively. In no locations did *S. heterolepis* meet target coverage, with coverage 61.3±2.6% in Calgary, 62.3±13.8 in Halifax and 72.6±2.7 in London. *A. canadensis* coverage in Calgary and London was low, 47.3±5.9% and 60.3±3.3% respectively.

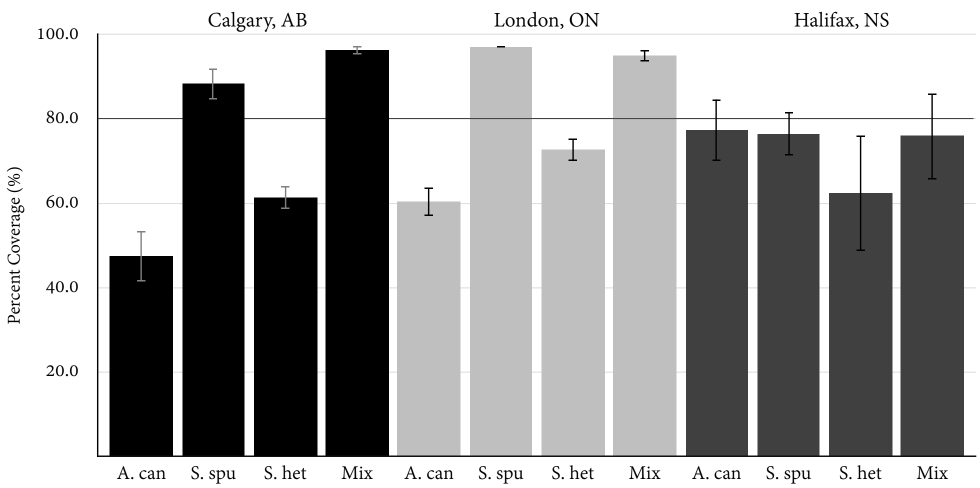

Figure 2. Mean canopy cover (%) in August year 2 by green roof location and planting type from overhead photographs processed in Image J. Error bars represent standard error (+/-).
A. can-*A. canadensis*; S. spu-*S. spurium*; S. het-*S. heterolepis*, Mix = mixture

Monoculture Planting Treatment

From the repeated measures ANOVA, time components of this experiment were significant - both the month and year of sampling by site and by species [p<0.001] (Appendix A). Overall, this experiment showed peak canopy densities in June (Figure 3). The experimental year was significant for both site [F(4,180)=50.340, p<0.0001] and species canopy density [F(4,180)=6.089, p<0.001]. Canopy density was greatest in year 2, and lowest in year 1 (Figure 4). Calgary and London overall canopy density increased year upon year, while Halifax canopy density increased from year 1 to year 2, and declined year 3. Dividing out by plant species, only *S. heterolepis* canopy density increased year upon year, while both *A. canadensis* and *S. spurium* increased in canopy density from year 1 to year 2, and declined year 3. Time interaction of month-year was also significant [F(3,160)=23.977, p<0.0001].

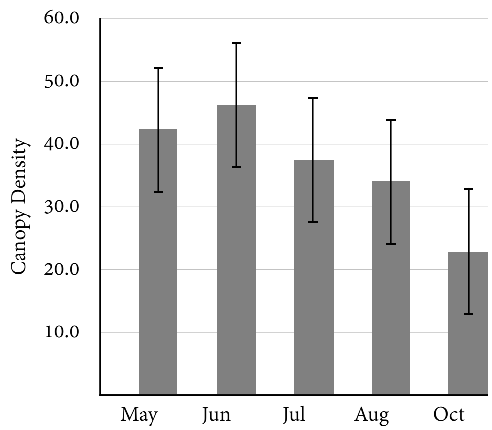

Figure 3. Mean canopy density aggregated by month over the experimental period. Error bars represent standard error (+/-).

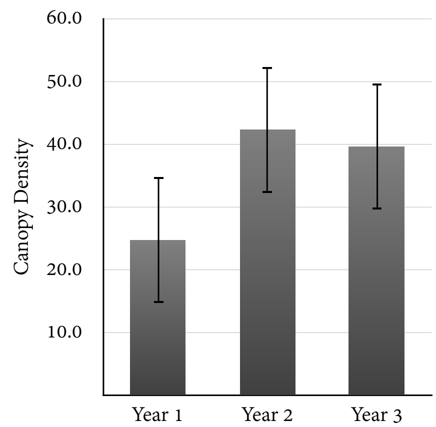

Figure 4. Mean canopy density by year of sampling. Error bars represent standard error (+/-).

When data from all sites were available, canopy densities were highest in London. Site was a significant factor at all time points [p<0.001] and all sites differed from one another [p<0.05] except at initial planting (Appendix B). In August year 1 site was a significant effect [F(2,107)=11.836, p<0.001] but Tukey HSD post-hoc comparison found London and Calgary performance similar [p=0.201] with site canopy densities of 30.0±2.4 and 26.9±2.4 respectively. Meanwhile, Halifax canopy density was significantly lower at 21.4±2.4 than both Calgary [p=0.011] and London [p=0.000] (Figure 5). For the next two time points, canopy density in

Halifax was greater than Calgary; by July year 2, Halifax canopy density was lower than Calgary's and remained so throughout year 3 (Figure 5). The London green roof held the greatest canopy density. Year 3, London outperformed the other sites significantly throughout the growing season [$p<0.05$].

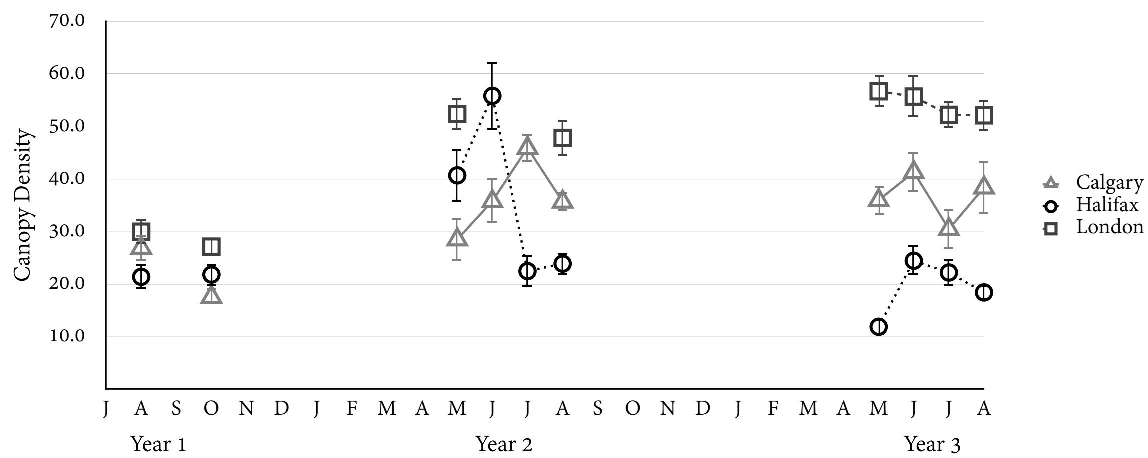

Figure 5. Mean canopy density of monoculture modules by green roof location measured August, October year 1, May through August year 2 and 3. Error bars represent standard error (+/-).

Peak canopy density timings differed over the growing seasons by site. While Halifax peak canopy density occurred in June both year 2 and year 3, Calgary's peak density shifted from July in year 2 to one month earlier in year 3. Full canopy density measures throughout the growing season were missing for London, not allowing for comparison. Measures of canopy density were highly variable in Halifax, with canopy density ranging year 2 from 55.8±6.4 to 22.5±3.2 from June to July. Meanwhile, canopy density was steadiest across year 3 in London, with a canopy density range of 52.1±2.9 to 56.7±2.9.

Plant species was a significant factor in monoculture canopy density measurement at every time point [$p<0.01$] (Appendix B). Across all time points, *S. spurium* exhibited the highest canopy density (Figure 6). From post-hoc analysis, canopy density of *S. spurium* was significantly greater than canopy density of *S. heterolepis* at all time points [p<0.01] and significantly greater than *A. canadensis* measurements at all time points [p<0.05] except July year 2 [p=0.111]. *A. canadensis* performed better than *S. heterolepis* throughout year 2, significantly so only May year 2 [p=0.004] (Figure 6). Year 3, *S. heterolepis* canopy density was significantly higher than *A. canadensis* canopy density June [p=0.000] and July [p=0.029], but *A. canadensis* outperformed *S. heterolepis* August year 3 [p=0.011].

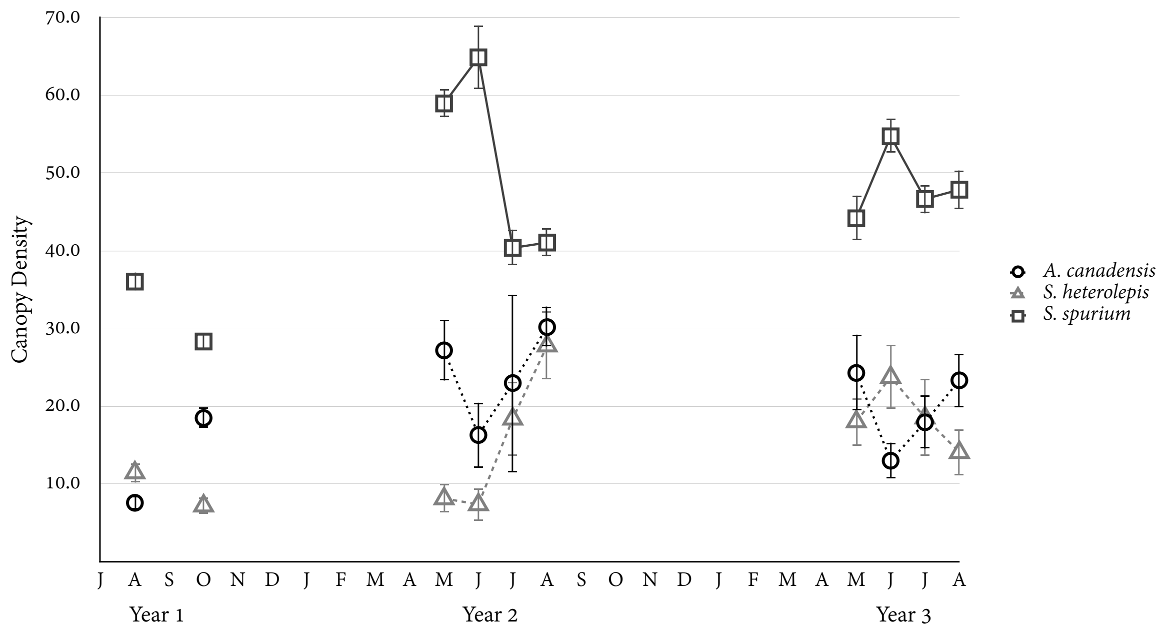

Figure 6. Mean canopy density of monoculture modules by plant species measured August, October year 1, May through August year 2 and 3. Error bars represent standard error (+/-).

Peak canopy density timings by plant species also differed over the growing season. In year 2, *A. canadensis* canopy density was highest in August yet peak *A. canadensis* canopy density moved earlier to May year 3. *S. heterolepis* peaked in August year 2 and shifted peak density in year 3 to July. *S. spurium* peak canopy density occurred consistently in June both year 2 and 3. The range in canopy density was greatest in *S. spurium* year 2, from a high of 64.9±4.1 to a low of 40.4±2.3. *S. heterolepis* canopy density measures varied the least, differing over the year 3 growing season by 9.7 points.

Site-species interaction was significant May [$F(4,97)=6.131$, $p<0.001$], June [$F(2, 63)=7.495$, $p<0.001$] and July year 2 [$F(2,62)=4.333$, $p<0.05$] and all time points through the year 3 growing season [$p<0.001$] (Appendix B). In general, all plant species grown in London outperformed those in Calgary and Halifax (Figure 7). Post-hoc comparison for May year 2 showed that London *S. spurium* outperformed Calgary *S. spurium* [$p=0.017$] with canopy density of 63.5±2.0 to 49.6±2.2 respectively. At this time point, Halifax *S. spurium* canopy density was statistically similar to *S. spurium* in London [$p=0.830$] and to *S. spurium* in Calgary [$p=0.477$]. May year 2, London *A. canadensis* outperformed Calgary *A. canadensis* [$p<0.001$] and Halifax *A. canadensis* [$p<0.001$]. Through June and July year 2, where data were missing from the London site, Halifax and Calgary canopy densities differed. *A. canadensis* did not differ in either month between the two sites. Calgary *S. heterolepis* canopy density was significantly higher in July, 31.5±5.6, outperforming Halifax, 3.4±1.6, (Figure 7). *S. spurium* canopy density differed significantly between Calgary and Halifax June and July year 2, but higher canopy density was not consistent by site during this period. June year 2, Halifax *S. spurium* canopy density of 80.0±5.6 outperformed Calgary's 49.9±4.1 while one month later, Halifax *S. spurium* dropped to 27.5±1.6 and Calgary's increased to 52.8±2.1 (Figure 7). Throughout year 3, London's *S. spurium* outperformed both Calgary [$p<0.0001$] and Halifax *S. spurium* [$p<0.000$], and Calgary's *S. spurium* outperformed Halifax's *S. spurium* May [$p=0.000$], June [$p<0.0001$] and August [$p=0.000$] year 3. *S. spurium* of Calgary and Halifax was similar July year 3 [$p=0.136$].

At all time points, modules of substrate depth 15 cm exhibited higher canopy density than 10 cm modules (Figure 8). However, substrate depth was an inconsistent factor throughout the experiment, significant at four time points: October year 1, June year 2, May year 3 and June year 3. The greatest difference in canopy density by module depth occurred June year 2, where deep

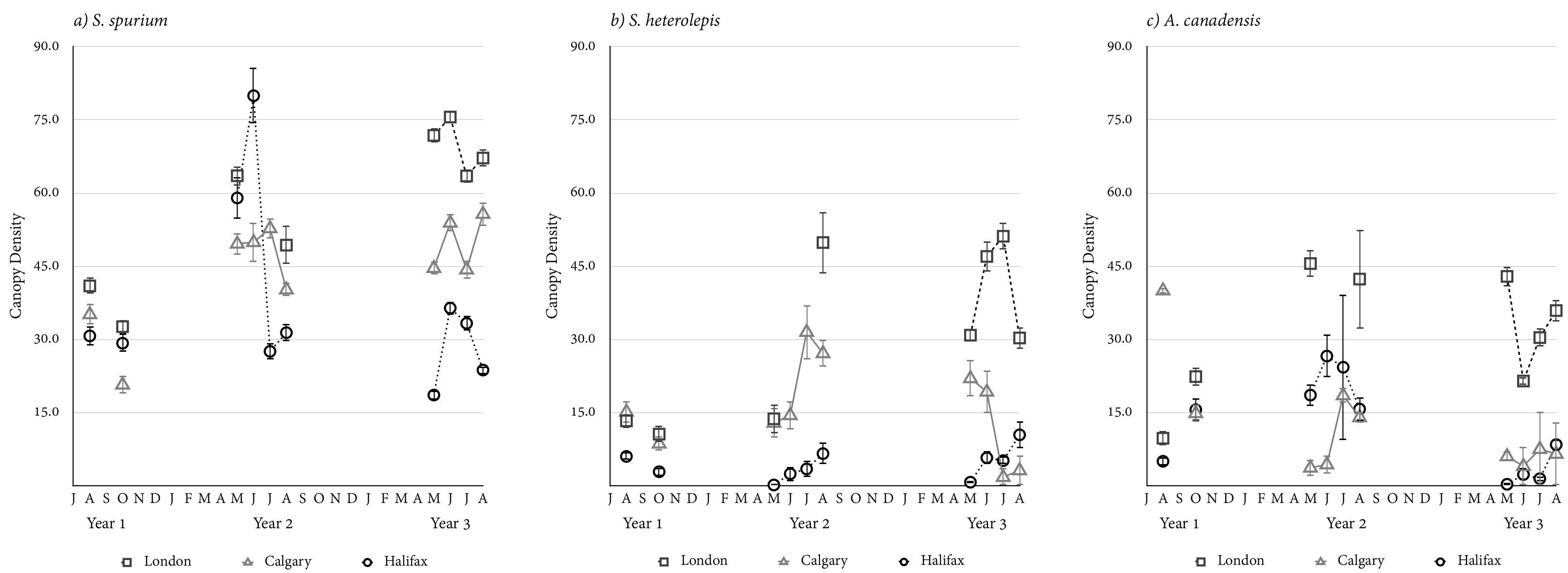

Figure 7. Mean canopy density of monoculture modules by location and plant species a) *S. spurium* b) *S. heterolepis* and c) *A. canadensis* measured August, October year 1, May through August year 2 and 3. Error bars represent standard error (+/-).

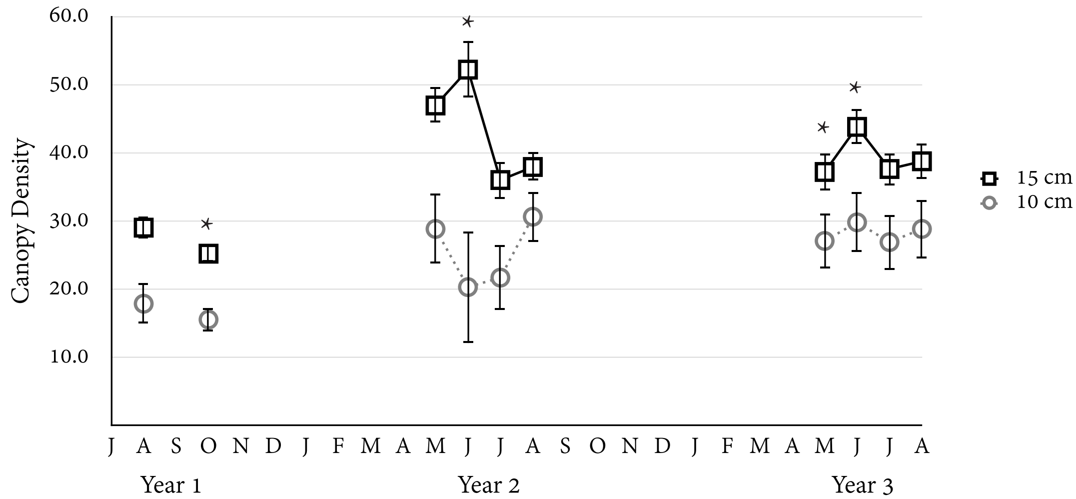

Figure 8. Mean canopy density of monoculture modules by depth measuresd August, October year 1, May through August year 2 and 3. Error bars represent standard error (+/-). Asterisks (*) indicate significant differences.

15 cm modules measured canopy density 52.2±4.2 and outperformed shallow modules canopy density of 20.3±8.1 [$F(1,63)=7.311$, $p<0.01$].

From the four time points where depth was significant, three were also significant for a site-depth interaction: June year 2; May and June year 3. From post-hoc analysis June year 2, Halifax 10 cm modules performed such that they were statistically similar to the 15 cm modules of Calgary [$p=0.125$] and Halifax [$p=0.995$]. In year 3, both May and June found all site-depth combinations significant, except for within-site for Halifax and London, where 15 cm and 10 cm deep modules had similar canopy densities.

A depth-species interaction was fleetingly significant, only in July year 2 where 15 cm *S. spurium* outperformed 15 cm *S. heterolepis,* 10 cm *A. canadensis* and 10 cm *S. heterolepis*. The three-way interaction between site, depth and species in monoculture module analysis was significant only year 2 June.

Monoculture versus Mixture Planting Treatment

From the repeated measures ANOVA, time components of both month and month-year interaction were significant for mixture and best monoculture canopy density performance [p<0.001] (Appendix C). Canopy density was highest in June, and in year 2.

Of the three monoculture species plantings in this experiment, the best performing monoculture in canopy density was determined to be *S. spurium*. However, in comparing this monoculture to mixture plantings, mixtures consistently provided greater canopy density than *S. spurium* through the experimental period. Planting treatment (monoculture versus mixture) significantly affected canopy density October year 1 [F(1,82)=4.944, p=0.029] and throughout year 3 [p<0.01] (Appendix D). In October year 1, mixture planting canopy density outperformed *S. spurium* monoculture canopy density by 4.6 points, 32.9±2.4 to 28.3±1.1 respectively [p=0.020] (Figure 9). Throughout year 3, the difference in canopy density between mixture and monoculture modules ranged from 5.7 to 16.4 points, with the largest gap in July where mixture canopy density measured 63.1±7.2 and monoculture 46.7±1.8 [p<0.0001]. In year 3, both

Figure 9. Mean canopy density of planting treatments mixture and *S. spurium* modules measured August, October year 1, May through August year 2 and 3. Error bars represent standard error (+/-).

mixture and monoculture canopy density peaked in June, with mixture planting canopy density of 63.2±5.3 outperforming *S. spurium* at 54.8±2.2 [$p<0.0001$] (Figure 9).

As with monoculture canopy densities, site was a significant factor through all eligible time points [$p<0.01$]. In year 3, all sites differed significantly from one another with canopy density highest in London, then Calgary and Halifax respectively.

Site-treatment interaction was significant in year 3, in May [$F(2,75)=4.177$, $p=0.019$], June [$F(2,75)=9.574$, $p<0.001$] and July [$F(2,75)=35.968$, $p<0.0001$]. However, post-hoc analysis found that through these time periods, mixture modules in Halifax and Calgary did not outperform the monoculture modules at their own site, only mixtures in London outperformed the monoculture plantings. Module depth was not a significant factor between *S. spurium* monoculture and mixture planting treatments early in the experiment, showing significance only in June year 2 [$F(1,54)=7.429$, $p=0.009$], and May through to July year 3 ($p<0.01$). Site-depth interaction was inconsistent, significant in June year 2 [$F(1,54)=9.435$, $p=0.003$], July year 2 [$F(1,55)=6.712$, $p=0.012$], May year 3 [$F(2,75)=3.266$, $p=0.044$] and July year 3 [$F(2,75)=3.798$, $p=0.027$]. Halifax module canopy density did not significantly differ between 10 cm and 15 cm modules at any time point, although 10 cm modules did hold greater canopy density at four time points: May year 2, and May, June, July year 3. In London, 10 cm modules outperformed 15 cm modules June and July year 3. In Calgary, 15 cm modules for the most part held greater canopy density (Figure 10), but was significantly outperformed August year 3 by 10 cm modules. In July year 3, Calgary 10 and 15 cm depths were similar.

An interaction between treatment and depth only arose in year 3, for June and July measurements. 15 cm mixture modules outperformed 10 and 15 cm *S. spurium* modules, and the 10 cm mixture modules.

For mixture versus monoculture plantings, three-way interaction between site, treatment and module depth on canopy density only was significant June and August year 2 and July year 3.

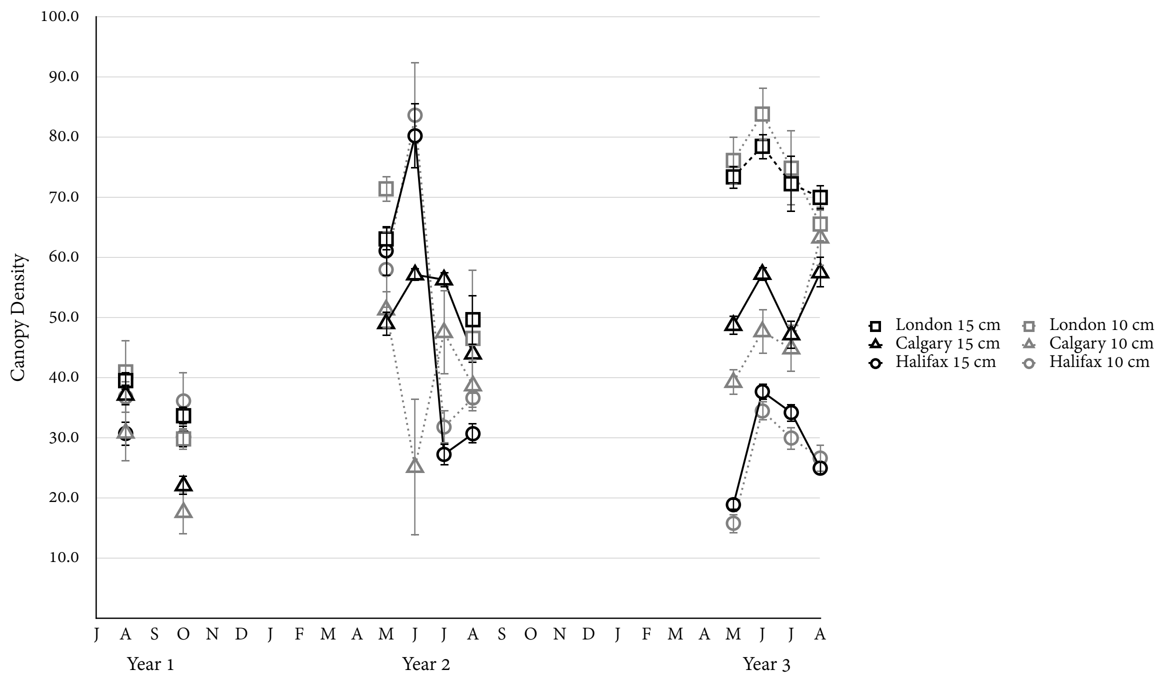

Figure 10. Mean canopy density of mixture and *S. spurium* modules by site and module depth measured August, October year 1, May through August year 2 and 3.

Plant Height

Month of sampling was a significant effect on plant height [F(1,110)=1172.373, p<0.0001) and significantly affected site, species and depth differences in planting heights from repeated measures ANOVA (Appendix E).

Plant heights exhibited a similar trend as canopy density by site hierarchy. Site was a significant factor in plant height throughout the year 3 season [p<0.0001] (Appendix F). London plants exhibited the greatest heights, followed generally by Calgary and then Halifax (Figure 11). However, from post-hoc comparison, June plant height in Halifax (6.5±0.4 cm) significantly surpassed that of Calgary (5.3±0.4 cm) [p=0.001]. In Halifax and London, plant heights from June through to August were relatively steady, with a range of 1.7 cm and 0.6 cm by site

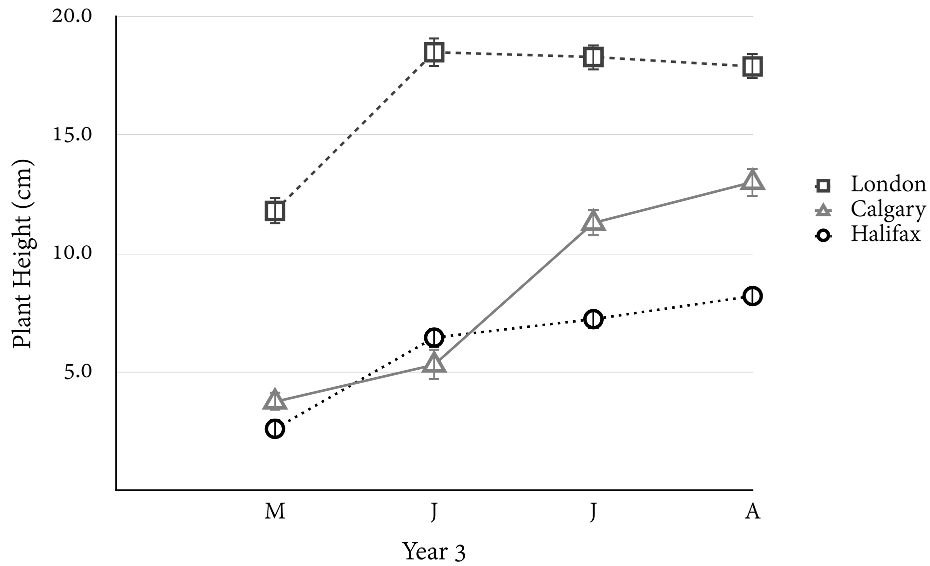

Figure 11. Mean plant height by green roof location measured May through August year 3. Error bars represent standard error (+/-).

respectively (Figure 11). Plant height in Calgary had a wider range June through August, moving from a June height of 5.3±0.4 cm, to July height 11.3±0.7 cm and August height 13.0±0.6 cm.

Plant height by planting treatment significantly differed through over time [$p<0.0001$]. Both mixture plantings and *S. heterolepis* monocultures consistently exhibited significantly taller heights than *S. spurium* (Figure 12) [$p<0.001$]. *S. heterolepis* height increased steadily through the season, peaking in August at 17.5±1.5 cm (Figure 12). *A. canadensis* height peaked in June with height 12.6±1.8 cm with height range not varying much for the season. *S. spurium* monoculture height was lowest in May (4.3±0.3 cm), but grew to 9.2±0.5 cm for June measurement and gradually reached peak height in August at 12.1±0.4 cm. Mixture plantings follow a similar profile to the grass *S. heterolepis*, but instead of continued gains in height in August as *S. heterolepis* did, mixture plantings plateaued in July and August.

While depth was a significant effect on plant height only in August [$F(1,102)=6.366$, $p=0.013$], with 15 cm modules generating taller heights than 10 cm modules (13.3±0.5 cm to

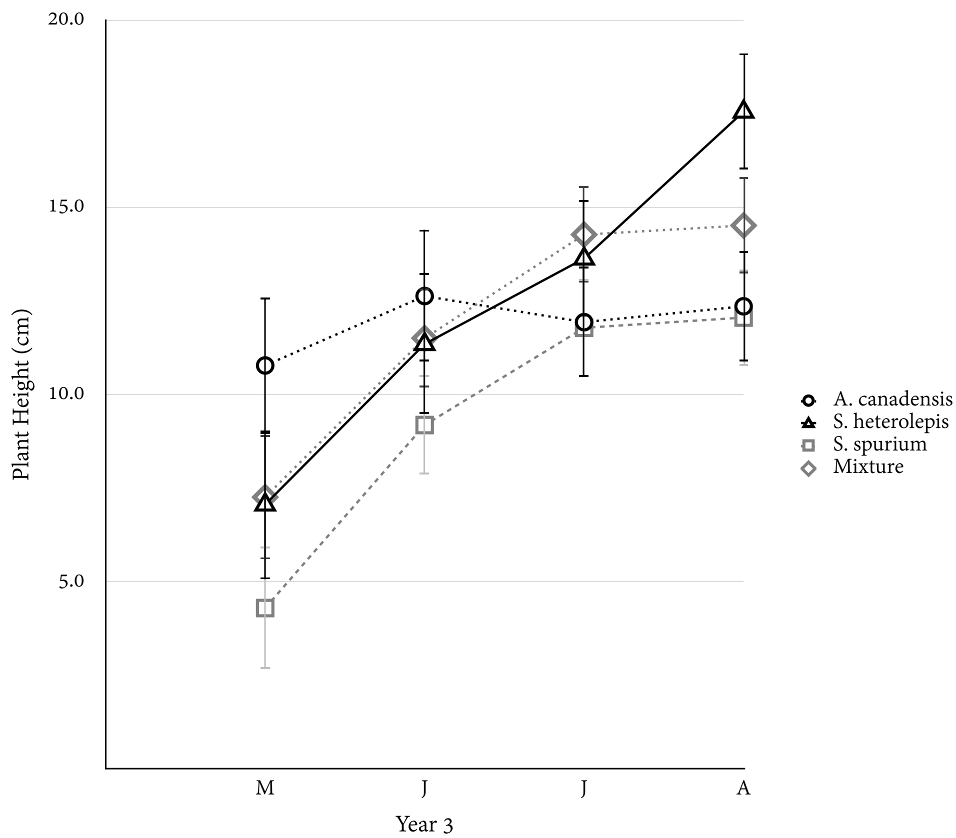

Figure 12. Mean plant height by species measured May through August year 3. Error bars represent standard error (+/-).

12.9±1.0 cm), a site-depth interaction was significant through the growing period [p<0.01]. London plant heights were similar between 15 cm and 10 cm modules and both London depths outperformed plant heights of 15 and 10 cm deep Calgary and Halifax modules [p=0.000]. Calgary 15 cm modules achieved significantly greater plant heights than 10 cm Calgary modules [p<0.01] except for measurement in May where they were similar [p=0.676], yet Halifax modules showed no difference in plant height between 10 cm and 15 cm modules through year 3. A depth-species interaction was significant in June [F(3,107)=5.798, p=0.001] and August [F(3,102)=3.328, p=0.022]. During these time points, 10 cm and 15 cm *A. canadensis* did not differ from one another; nor did 10 cm and 15 cm *S. spurium* modules. At the June time point, *S. heterolepis* 10 cm and 15 cm had similar heights, but in August, deep 15 cm modules

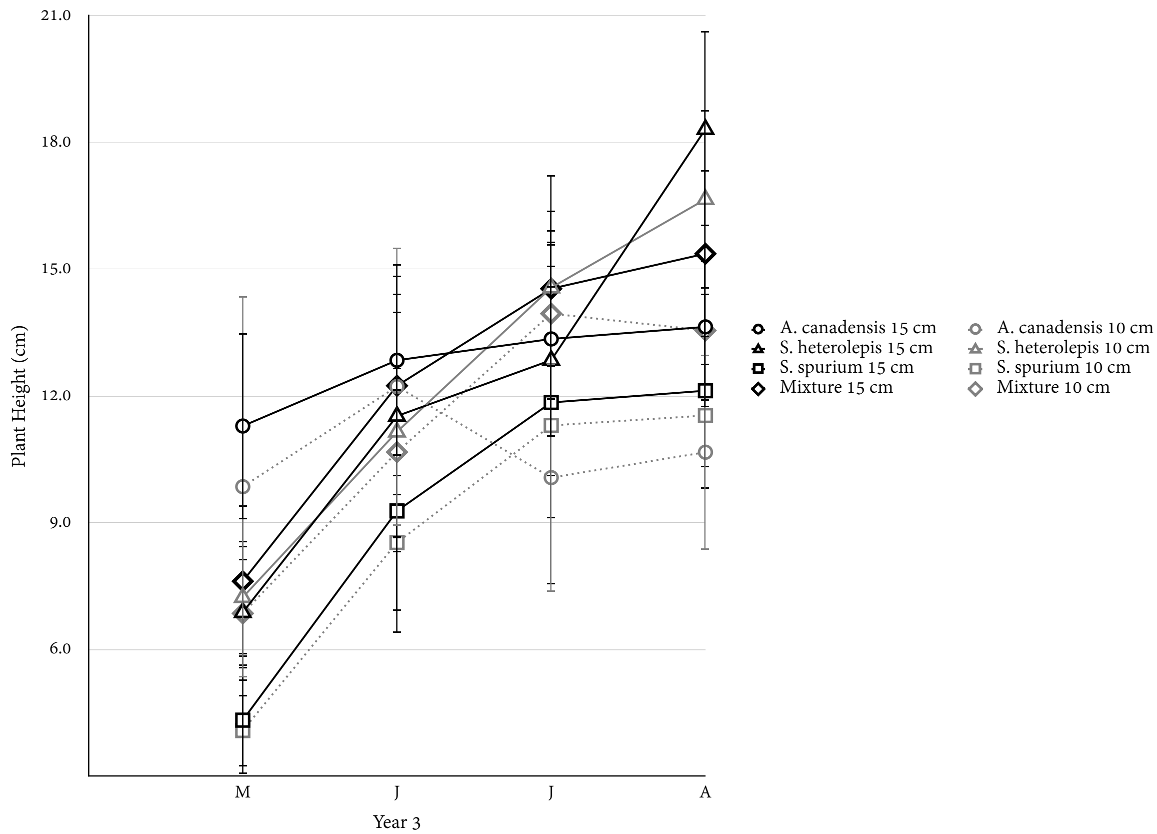

Figure 13. Mean plant height by module depth and species measures May through August year 3. Error bars represent standard error (+/-).

exhibited significantly greater heights (Figure 13). Overall, deep 15 cm mixture modules held greater heights than those in 10 cm modules (Figure 13). Site-species interaction was significant through the growing season [$p<0.0001$], while a three way interaction was significant June [$F(6,107)=3.511$, $p=0.003$].

Establishment & Persistence

Establishment rate was considered the year 1 to year 2 growth rate and was significantly influenced by green roof site [$F(2,124)=10.189$, $p<0.0001$] and plant species [$F(3,124)=4.442$, $p=0.005$] (Appendix G) for all plantings (monoculture and mixture). London held the greatest

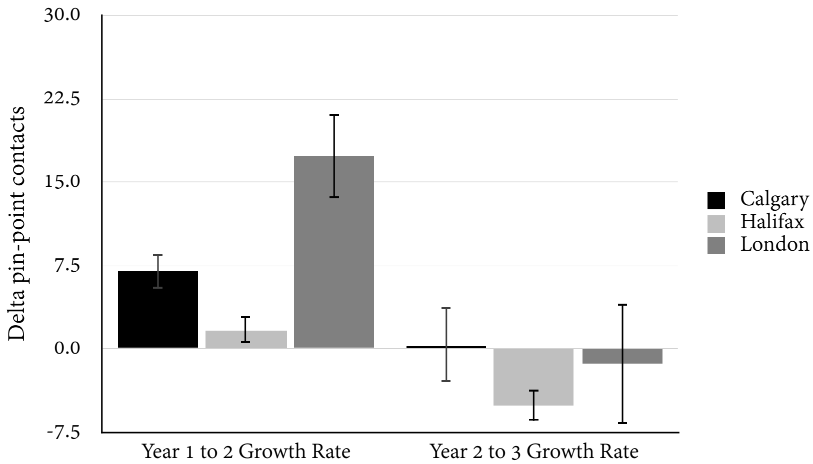

Figure 14. Year 1 to 2 growth rate (establishment) and Year 2 to 3 growth rate (persistence) by green roof location as measured over a year time period. Error bars represent standard error (+/-).

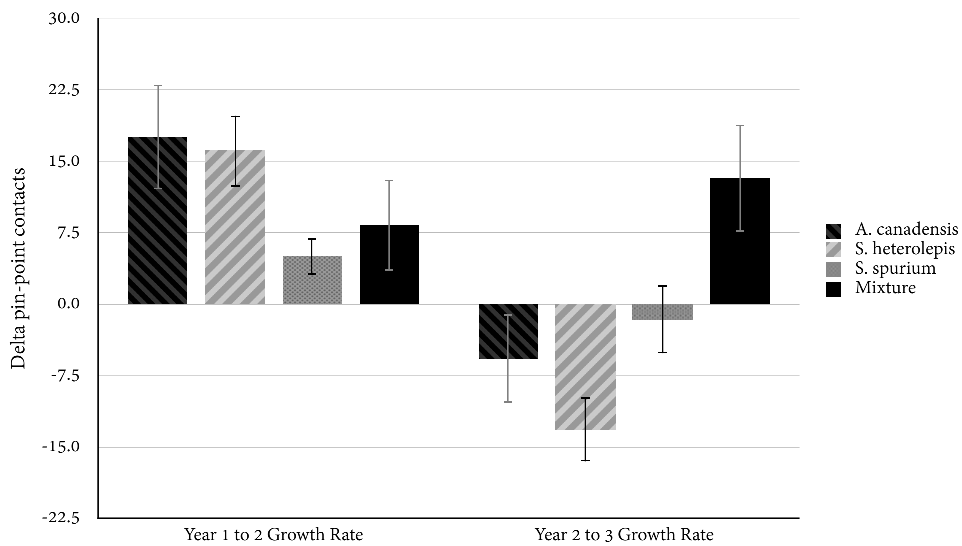

Figure 15. Year 1 to 2 growth rate (establishment) and Year 2 to 3 growth rate (persistence) by plant species as measured over a year time period. Error bars represent standard error (+/-).

year 1-2 growth rate of 17.3±3.8 canopy points, outperforming Calgary year 1-2 growth rate of 6.9±1.5 canopy points [$p=0.010$] and Halifax of 1.7±1.2 canopy points [$p<0.0001$] (Figure 14). Statistically, the year 1-2 growth rates in Calgary and Halifax were similar [$p=0.342$]. Between plant species, *A. canadensis* held the largest year 1-2 growth rate at 17.6±5.4 while *S. spurium* held the lowest rate at 5.0±1.9 canopy points (Figure 15). Establishment of *S. spurium* was significantly lower than both *A. canadensis* [p=0.035] and *S. heterolepis* [p=0.038] (Figure 15). Significant interactions in year 1-2 growth rates were site-species interaction [F(6,124)=2.823, p=0.013] where London *A. canadensis* outperformed Calgary *A. canadensis* [p=0.0133] and London *S. heterolepis* outperformed Halifax *S. heterolepis* [p=0.0216], as well as a three way site-depth-species interaction [F(6,124)=2.200, p=0.047]. Ten out of the 12 significant site-species interactions were reflections of London's higher establishment rates over Calgary and Halifax. The two others indicated that London *S. spurium* was outperformed by both London *A. canadensis* and London *S. heterolepis.*

Persistence, year 2-3 growth rate, showed a drop from year 1-2 rates, with negative persistence rates in Halifax and London (-5.0±1.4; -1.3±5.4) (Figure 14). Plant species (including mixture plantings) was the only significant factor in year 2-3 growth rate [F(3,124)=3.626, p=0.015], with *S. heterolepis* growth rate significantly lower than that of the mixture plantings [p=0.009] at rates -13.1±3.3 and 13.2±5.7 respectively (Figure 15).

Discussion

This study found a single green roof system to have differing performance outputs in terms of canopy density, plant height, establishment and persistence stage growth rates across multiple locations. I attribute the differentiation in plant performance to the different climate profiles experienced in each location. Climate factors and events impact plant performance, and microsite conditions can change plant growth rate and plant height-dimension ratios (Gazol and Camarero 2012). While I did not directly measure climate events at each green roof location, the sites differed over the experimental period in temperature profiles, amount of sunlight and precipitation. Climate measures of precipitation, average daily maximum temperature and relative humidity for the three green roof locations are described in Sims et al. (2016) and

Gebert (2015). Performance was best for all planting types and depths in London, Ontario, outperforming the Calgary, Alberta green roof, both of which outperformed the Halifax, Nova Scotia roof.

That London performed better across all planting types can potentially be attributed to the plant selection for this experiment. While *Sedums* have proven to be adaptable to green roofs in many climates and did perform best across all sites in this study, other green roof plant selection for extensive green roofs must share similar plant characteristics such as a suitably shallow rooting depth and be drought tolerant while also matching the green roof location's hardiness zone (Dunnett and Nagase 2004, VanWoert et al. 2005, Durhman et al. 2006). *Sedums*, with their shallow rooting systems and drought tolerant adaptations, are well suited to extensive green roof applications and have thus become industry standard. In the search for green roof species outside of the *Sedum* genus, native plant species have been suggested as a potential pool for expanding the green roof plant palette as native plants are already suited to the existing climate conditions (MacIvor and Lundholm 2011, Butler et al. 2012). *A. canadensis* and *S. heterolepis,* the test species in this experiment, are native to Ontario and performed well at the London green roof location. However, while these plant species were in the hardiness range of both Halifax and Calgary, these species are not native to Alberta nor Nova Scotia. The Calgary green roof experienced plant death, to varying degrees, of both *A. canadensis* and *S. heterolepis*. The Halifax green roof also experienced plant death of *S. heterolepis*. The total lack of plant death at the London green roof supports arguments regarding native species suitability for green roof conditions.

Climate and microclimate conditions could also have had a role in plant performance differences across the green roof locations in survival and canopy density. Both Calgary and Halifax experience harsher, colder and longer winters than London and could have contributed to the plant death experienced. London has a milder winter and a longer growing season. With warm temperatures starting earlier in London, it is likely the London plants left dormancy earlier than the plants at Calgary and Halifax. Therefore, London plants would have had longer to develop biomass by first measurement in May, a head start which the other sites perhaps could not catch up to through the remainder of the season. The London roof may also have had a better microclimate due to the physical parameters of the roof. At the London green roof site, the third storey of the adjacent building was at the south end of the green roof site. This building structure could have blocked summer winds which predominantly come from the southwest, shielding the roof from winds that cause substrate desiccation, thereby allowing greater water availability to the plants. Calgary had an additional building structure to the north of the green roof, theoretically blocking some winter winds but leaving the green roof exposed to summer wind. Conversely, the Halifax green roof was highly exposed and subject to strong winds from all directions with only a small mechanical penthouse to the east. That Calgary had similar summer wind exposure to Halifax and receives more days with wind than Halifax, it is likely the extremely high rainfall profile of Halifax dampened Halifax plant performance. Halifax may have been too cold and/or too wet for *A. canadensis* and *S. heterolepis.* In Calgary, the lower precipitation levels than London could be the factor in poorer performance, with the test species finding conditions a little dry. Plant selection based not only on the climate conditions but also the microclimate may ensure optimal plant growth and performance.

Target module coverage was set at 80% for this study in accordance to FLL green roof guidelines (FLL 2002) developed in Germany and adopted worldwide. Calgary and London green roofs achieved the best coverage along with *S. spurium* and mixture modules. Halifax had poorer coverage and canopy density measures than both Calgary and London for most of the experimental period. It is possible that Halifax's poor coverage and overall lower canopy density can be attributed to, in addition to the climate conditions, the establishment methodology, being the only location where modules were plugs planted on site instead of at the nursery. The longer available time to set root and establish in Calgary and London due to the establishment methodology was reflected in the initial canopy density measurements. While London and

Calgary canopy densities were statistically similar at initial planting, Halifax initial canopy density was significantly lower than both. Ideally there would have equivalency between all sites at initial planting allowing all subsequent differences in plant performance to be attributed to plant species or climate. Coverage differences could have also been impacted by differences in growth forms and planting densities. Better coverage by *S. spurium* in this study, already planted at a higher density, could have been additionally augmented by its creeping mat growth form that is suited to creating coverage. Both *S. spurium* monocultures and mixture modules contained 5 plugs per module and for the most part achieved 80% coverage whereas *A. canadensis* and *S. heterolepis* modules were planted at three and one plug(s) per module respectively and these species held lower percent coverage. Mixture modules coverage could also have been enhanced, as Naeem et al. (1994) reported greater coverage is achieved through diverse community architectures.

In this study, mixture plantings canopy density performance varied little throughout the growing seasons, were able to achieve better coverage than both *A. canadensis* and *S. heterolepis* monocultures and held taller heights through a season. Mixtures for the most part performed significantly better than the best performing monoculture, *S. spurium*. However, mixture results in Halifax were dampened, statistically similar to the monoculture planting, again possibly due to the wet and/or cold climate. Across sites, mixture planting potentially helped buffer against plant death. No plugs/plantings of any species died when incorporated in a mixture module, even in locations where plant death had occurred in test and non-test monoculture modules. Mixtures have been shown to aid in survival and visual interest under green roof drought conditions (Nagase and Dunnett 2010, Butler and Orians 2011). Naeem et al. (1994) and Spehn et al. (2000) conclude that diverse plant species/community architecture allows for complimentary resource use.

By combining best performing species of target green roof benefits, Lundholm et al.

(2010) suggests mixtures incorporating the best performers are capable of outperforming a best monoculture species in meeting multiple green roof functions. Lundhom et al.'s (2010) multifunctional approach showed mixtures of forb, grass and *Sedum* to best perform stormwater capture and thermal cooling. In this study, the mixture planting capitalized on the best performing plant species with regard to height. *S. heterolepis* monoculture planting heights were greater than those of *A. canadensis* and *S. spurium* monocultures, due to its growth form. Plant height is a potential indicator of green roof thermal cooling and stormwater capture performance (Nagase and Dunnett 2012, Theodosiou 2003) and mixtures could increase service provision by incorporating taller plant species.

Plants were generally taller in 15 cm deep modules compared with the 10 cm modules. This was not the case for Halifax, where the two depths had similar heights. Halifax's plant heights were shortest from the three sites, potentially a stress response to the climate conditions. Interestingly, peak plant heights did not occur at the same sampling time point as peak canopy density by city or by species.

Timing of peak canopy density varied from year to year, and by species. In year 3, where data existed through the growing season for all sites, peak overall canopy density occurred in May for London and in June for Halifax and Calgary. These peaks did not correspond to any one monoculture species. Each plant species peak densities differed between sites. In year 3, London saw *A. canadensis* peak in May, *S. spurium* peak in June, *S. heterolepis* in July. Calgary had *S. heterolepis* peak in May, *A. canadensis* in July, *S. spurium* in August. Halifax peaks were *S. spurium* in June, *S. heterolepis* and *A. canadensis* in August. With measurement taking place in the third week of the month, it is possible I missed the true peaks of each green roof and plant species. More differentiation and effect from climate would have been seen with a finer measurement scale. However, the overall shifts and differences indicate an influence from climate upon peak overall green roof growth performance as well as an effect on individual plant species.

Within each plant phenology, I noted that plants looked less vigorous following flowering, especially in *S. spurium* modules. In *S. spurium* monocultures, canopy density measures dropped and leaves were smaller in size (researcher observation) in the month after flowering. The most drastic drop in *S. spurium* canopy density occurred year 2 in Halifax where canopy density went from 80.0±5.6 in June during flowering to 27.5±1.6 in July, post-flowering. While *S. spurium* canopy density measures were generally high and consistent, with less than two-fold difference in measures, modules of *A. canadensis* and *S. heterolepis* canopy density ranged greatly, measuring almost a four-fold range in canopy densities. In monoculture plantings, periods of low canopy density due to die back and dormancy are visually evident. Getter and Rowe (2006) suggested that diverse plantings can be utilized to visually buffer against dormancy periods. In this study, mixture modules had a two-fold range in canopy density, remaining relatively consistent throughout the growing season. I propose that the consistency in mixture planting canopy density is due in part to differing phenologies of the species incorporated. With staggered phenologies between species in mixture modules, a post-flowering drop in canopy density in one species would be buffered by canopy density by species in active growth periods.

S. heterolepis and *A. canadensis* both had greater year 1 to 2 growth rates than *S. spurium* monocultures and mixture plantings. As *Sedums* are valued by the industry for their ability to quickly cover and establish on green roofs, the greater year 1-2 growth rate by *S. heterolepis* and *A. canadensis* may have been impacted by the planting densities in this project. While *S. spurium* monoculture modules were planted with five plugs, *A. canadensis* and *S. heterolepis* were planted with three and one plug respectively. The greater available root and canopy space in the modules of lower planting density may have allowed the plants to spread more quickly from initial planting.

Year 2 to 3 growth rates were negative in both Halifax and London. This marks the variability that can occur year to year, most likely due to climate conditions. Mixtures held significantly higher year 2 to 3 gorwth rates than *S. heterolepis* whose rate was negative. *S. heterolepis* may simply have been unsuitable to the climates at the Calgary and Halifax locations.

Consistent with other studies, deeper substrate in this experiment generated greater canopy density in monoculture modules of all locations. However, I note that depth was not a significant factor in canopy density of mixture modules. The overall survival and better performance of mixtures in shallow modules over other species with high persistence rates supports mixtures as being advantageous over monoculture plantings. Aside from greater visual interest over *Sedum* or turf fields (Nagaoka et al. 2003), this study showed that higher canopy densities of mixtures are reliable across different climates and green roof conditions.

Conclusion

This study evaluated green roof plant performance of three species and a mixture planting in an identical green roof system across three cities of Canada. Overall performance was best in London, Ontario, followed by Calgary, Alberta and lastly Halifax, Nova Scotia. *Sedums* performed best out of the monoculture species while plant performance of *A. canadensis* and *S. heterolepis* was variable through the growing seasons and by location. Mixture plantings performed well in plant survival, canopy density, plant height and persistence rate in all locations and outperformed *Sedum* monocultures. The findings from this study suggests diverse plantings are suitable across different climates and has potential to allow incorporating species perhaps not perfectly suited to the climate. Another avenue for optimizing plant performance would be fitting plant selection to microclimate conditions of the local green roof.

References

Berndtsson, J.C. 2010. Green roof performance towards management of runoff water quantity and quality: a review. Ecological Engineering, 36: 351 – 360.

Bovin, M., Lamy, M., Gosselin, A., Dansereau, B. 2001. Effect of artificial substrate depth on freezing injury of six herbaceous perennials grown in a green roof system. HortTechnology, 11: 409 – 412.

Butler, C., Orians, C.M., 2011. Sedum cools soil and can improve neighboring plant performance during water deficit on a green roof. Ecological Engineering, 37: 1796-1803.

Butler, C., Butler, E., Orians, C.M. (2012). Native plant enthusiasm reaches new heights: perceptions, evidence, and the future of green roofs. Urban Forestry & Urban Greening, 11: 1-10.

Cook-Patton, S.C., Bauerle, T.L. 2012. Potential benefits of plant diversity on vegetated roofs: a literature review. Journal of Environmental Management, 106: 85 – 92.

DeNardo, J.C., Jarrett, A.R., Manbeck, H.B., Beattie, D.J., Berghage, R.D., 2005. Stormwater mitigation and surface temperature reduction by green roofs. Transactions of the ASAE, 48: 1491-1496.

Dunnett, N., Nagase, A., Hallman, A. 2008. The dynamics of planted and colonizing species on a green roof over six growing seasons 2001-2006: influence of substrate depth. Urban Ecosystems, 11:373-384.

Dunnet, N., Kingsbury, N. 2010. Planting Green Roofs and Living Walls, 2nd Ed. Timber Press, Portland.

Durhman, A.K., Rowe, D.B., Rugh, C.L. 2006. Effect of watering regimen on chlorophyll fluorescence and growth of selected green roof plant taxa. HortScience, 41: 1623-1628.

Dvorak, B., Volder, A. 2010. Green roof vegetation for North American ecoregions: a literature review. Landscape and Urban Planning, 96: 197 – 213.

Farrell, C., Szota, C., Williams, N.S.G., Arndt, S.K. 2013. High water users can be drought tolerant: using physiological traits for green roof plant selection. Plant Soil, 372(1): 177-193.

FLL, 2002. Richtlinie für die Planung, Ausführung und Pflege von Dachbegrünungen (in German) (Guidelines for planning execution and upkeep of Green roof sites). Bonn, Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau E.V.

Gazol, A., Camarero, J. 2012. The performance of Mediterranean subshrubs depends more on microsite than on regional climate conditions. Journal of Vegetation Science, 23: 1062-1070.

Gebert, L. 2015. Empirical and numerical approaches to predicting the thermal performance of green roofs. Master's thesis, Saint Mary's University, Halifax, Nova Scotia.

Getter, K.L., Rowe, D.B., 2006. The role of extensive green roofs in sustainable development. HortScience, 41: 1276-1285.

Getter, K.L., Rowe, D.B., Cregg, B.M. 2009. Solar radiation intensity influences extensive green roof plant communities. Urban Forestry and Urban Greening, 8: 269-281.

GRHC, 2013. Annual green roof industry survey for 2012. In: Green roofs for healthy cities. http://www.greenroofs.org/resources/SurveyReport2012FINAL.pdf

Jonasson, S. (1988). Evaluation of the point intercept method for the estimation of plant biomass. Oikos, 52: 101-106.

Jim, C.Y., Tsang, S.W., 2011. Biophysical properties and thermal performance of an intensive green roof. Building and Environment, 46: 1263-1274.

Kolb, W., Schwarz, T. 1986. Zum Klimatisierungseffekt von Pflanzbeständen auf Dächern, Teil I. Zeitschrift für Vegetationstechnick 9. Republished in Veitshoechheimer Berichte, Heft 39, Dachbegrünung. (cf. Dunnett and Kingsbury 2004).

Livingston, E.H., Miller, C., Lohr, M. 2004. Green roof design and implementation in Florida. In: Proceedings of the 2nd North American Green Roof Conference: Greening rooftops for sustainable communities, Portland, OR, The Cardinal Group, Toronto.

Lundholm, J., MacIvor, J.S., MacDougall, Z., Ranalli, M. 2010. Plant species and functional group combinations affect green roof ecosystem functions. PLoS ONE, 5: e9677.

Lundholm, J.T., Williams, N.S.G. "Effects of vegetation on green roof ecosystem services." In *Green Roof Ecocystems*, edited by R. Sutton, 211-232. Springer International Publishing Switzerland, 2015.

MacIvor, J.S., Lundholm, J. 2011. Performance evaluation of native plants suited to extensive green roof conditions in a maritime climate. Ecological Engineering, 37: 407 – 417.

Monterusso, M.A., Rowe, D.B., Rugh, C.L. 2005. Establishment and persistence of *Sedum* spp. and native taxa for green roof applications. HortScience, 40:391 – 396.

Nagaoka, N., Okada, N., Shimomura, T. 2003. Study on landscape evaluation structure of green roof with the video images. Journal of the Japanese Society of Revegetation Technology, 29(1): 113-118.

Naeem, S., Thompson, L.J., Lawler, S.P., Lawton, J.H., Woodfin, R.M. 1994. Declining biodiversity can alter the performance of ecosystems. Nature, 368: 734-737.

Nagase, A., Dunnett, N. 2010. Drought tolerance in different vegetation types for extensive green roofs: effects of watering and diversity. Landscape and Urban Planning, 97: 318-327.

Nagase, A., Dunnett, N., 2012. Amount of water runoff from different vegetation types on extensive green roofs: effects of plant species, diversity and plant structure. Landscape and Urban Planning, 104: 356-363.

Oberndorfer, E., Lundholm, J., Bass, B., Coffman, R.R., Doshi, H., Dunnett, N., Gaffin, S., Köhler, M., Liu, K.K.Y, Rowe, B., 2007. Green roofs as urban ecosystems: ecological structures, functions and services. BioScience, 57: 823 – 833.

Sailor, D.J., 2008. A green roof model for building energy simulation programs. Energy and Buildings, 40: 1466-1478.

Santamouris, M. 2012. Cooling the cities - a review of reflective and green roof mitigation technologies to fight heat island and improve comfort in urban environments. Solar

Energy, 103: 682-703.

Sims, A.W., Robinson, C.E., Smart, C.C., Voogt, J.A., Hay, G.J., Lundholm, J.T., Powers, B., O'Carroll, D.M. 2016. Retention performance of green roofs in three different climate regions. Journal of Hydrology, 542:115-124.

Spehn, E.M., Joshi, J., Schmid, B., Alphei, J., Körner, C. 2000. Plant diversity effects on soil heterotrophic activity in experimental grassland ecosystems. Plant and Soil, 224: 217-230.

Stovin, V. 2010. The potential of green roofs to manage urban stormwater. Water and Environment Journal, 24: 192-199.

Theodosiou, T.G. 2003. Summer period analysis of the performance of a planted roof as a passive cooling technique. Energy and Buildings, 35: 909 – 917.

VanWoert, N.D., Rowe, D.B., Andresen, J.A., Rugh, C.L., Fernandez, R.T., Xiao, L. 2005. Green roof stormwater retention: effects of roof surface, slope and media depth. Journal of Environmental Quality, 34: 1036 – 1044.

Wolf, D., Lundholm, J.T. 2008. Water uptake in green roof microcosms: effects of plant species and water availability. Ecological Engineering, 33: 179 – 186.

APPENDIX

Appendix A. Repeated measures ANOVA for monoculture plantings.

	Df	Sum Sq	Mean Sq	F value	Pr (>F)
Between-subject factors					
Site	2	58634	29317	135.353	< 2E-16
Species	2	161480	80740	372.770	< 2E-16
Depth	1	1076	1076	4.970	0.028338
Residuals	88	19060	217		
Within-subject factors					
Month	4	13850	3463	43.830	< 2E-16
Month x Site	8	15661	1958	24.781	< 2E-16
Month x Species	8	23073	2884	36.507	< 2E-16
Month x Depth	4	235	59	0.744	0.56242
Residuals	367	28993	79		
Year					
Year x Site	4	24574	6144	50.340	< 2E-16
Year x Species	4	2973	743	6.089	0.000128
Year x Depth	2	47	24	0.194	0.823554
Residuals	180	21967	122		
Month x Year	3	8043	2680.9	23.977	7.22E-13
Month x Year x Site	4	10615	2653.8	23.735	2.01E-15
Month x Year x Species	6	7829	1304.8	11.670	7.96E-11
Month x Year x Depth	3	114	38.1	0.340	0.7962
Residuals	160	17889	111.8		

Appendix B. ANOVA results of monoculture plantings monthly canopy density measures.

	Df	Sum sq	Mean Sq	F value	Pr(>F)
August year 1					
site	2	1588	794	11.836	2.27E-05
species	2	20685	10342	154.177	< 2E-16
depth	1	27	27	0.406	0.525
site x species	4	250	63	0.932	0.448
site x depth	2	251	126	1.873	0.159
species x depth	2	61	31	0.456	0.635
site x species x depth	4	487	122	1.815	0.131
Residuals	107	7178	67		
October year 1					
site	2	1799	900	17.580	2.87E-07
species	2	7307	3653	71.382	< 2E-16
depth	1	279	279	5.444	0.0216
site x species	4	493	123	2.408	0.0543
site x depth	2	8	4	0.074	0.9290
species x depth	2	197	98	1.922	0.1516
site x species x depth	4	111	28	0.541	0.7057
Residuals	100	5118	51		

	Df	Sum sq	Mean sq	F value	Pr(>F)
May year 2					
site	2	7922	3961	25.291	1.45E-09
species	2	44882	22441	143.283	< 2E-16
depth	1	2	2	0.012	0.914767
site x species	4	3841	960	6.131	0.000193
site x depth	2	33	17	0.107	0.899024
species x depth	2	859	429	2.742	0.069468
site x species x depth	3	362	121	0.770	0.513675
Residuals	97	15192	157		
June year 2					
site	1	6699	6699	22.299	1.35E-05
species	2	47793	23896	79.540	< 2E-16
depth	1	2197	2197	7.311	0.008799
site x species	2	4504	2252	7.495	0.001202
site x depth	1	3898	3898	12.974	0.000623
species x depth	2	1347	673	2.241	0.114750
site x species x depth	1	1936	1936	6.443	0.013623
Residuals	63	18927	300		
July year 2					
site	1	10013	10013	48.350	2.59E-09
species	2	6070	3035	14.656	6.14E-06
depth	1	670	670	3.238	0.0768
site x species	2	1795	897	4.333	0.0173
site x depth	1	34	34	0.164	0.6865
species x depth	2	1478	739	3.568	0.0341
site x species x depth	1	5	5	0.022	0.8821
Residuals	62	12840	207		
August year 2					
site	2	12311	6156	22.341	8.24E-09
species	2	4153	2076	7.535	0.000875
depth	1	88	88	0.321	0.572119
site x species	4	2351	588	2.133	0.081798
site x depth	2	321	161	0.583	0.560190
species x depth	2	184	92	0.334	0.716769
site x species x depth	3	1088	363	1.316	0.273195
Residuals	105	28931	276		

	Df	Sum sq	Mean sq	F value	Pr(>F)
May year 3					
site	2	39102	19551	696.955	< 2E-16
species	2	17402	8701	310.176	< 2E-16
depth	1	249	249	8.886	0.00369
site x species	4	2138	535	19.054	2.06E-11
site x depth	2	220	110	3.919	0.02330
species x depth	2	59	30	1.053	0.35304
site x species x depth	3	162	54	1.927	0.13079
Residuals	91	2253	28		
June year 3					
site	2	19017	9509	268.760	< 2E-16
species	2	39796	19898	562.411	< 2E-16
depth	1	370	370	10.454	0.00171
site x species	4	1664	416	11.756	9.68E-08
site x depth	2	329	165	4.652	0.01193
species x depth	2	123	62	1.742	0.18098
site x species x depth	3	239	80	2.256	0.08716
Residuals	91	3220	35		
July year 3					
site	2	18622	9311	208.270	< 2E-16
species	2	24948	12474	279.026	< 2E-16
depth	1	57	57	1.283	0.26
site x species	4	2711	678	15.161	1.56E-09
site x depth	2	48	24	0.535	0.588
species x depth	2	64	32	0.717	0.491
site x species x depth	3	121	40	0.901	0.444
Residuals	91	4068	45		
August year 3					
site	2	22258	11129	204.933	< 2E-16
species	2	25779	12890	237.356	< 2E-16
depth	1	0	0	0.004	0.950
site x species	4	5279	1320	24.304	1.07E-13
site x depth	2	81	40	0.745	0.478
species x depth	2	23	11	0.211	0.810
site x species x depth	3	153	51	0.937	0.426
Residuals	91	4942	54		

Appendix C. Repeated Measures ANOVA results of mixture and *Sedum spurium* monoculture planting treatments.

	Df	Sum Sq	Mean Sq	F value	Pr (>F)
Between-subject factors					
Site	2	62035	31018	127.890	< 2E-16
Species	1	7080	7080	29.192	6.28E-07
Depth	1	1132	1132	4.668	0.033655
Residuals	82	19888	243		
Within-subject factors					
Month	1	12040	12040	103.636	3.29E-16
Month x Site	2	4431	2216	19.071	1.58E-07
Month x Species	1	1	1	0.011	0.91817
Month x Depth	1	11	11	0.093	0.76076
Residuals	81	9526	116		
Year					
Year x Site	4	50518	12630	92.435	< 2E-16
Year x Species	2	1243	621	4.548	0.01202
Year x Depth	2	356	178	1.304	0.27447
Residuals	157	21451	137		
Month x Year	2	14680	7340	68.909	< 2E-16
Month x Year x Site	4	10181	2545	23.895	1.98E-15
Month x Year x Species	2	177	88	0.830	0.4382
Month x Year x Depth	2	96	48	0.450	0.6387
Residuals	156	16616	107		

Appendix D. ANOVA results of mixture and *Sedum spurium* plantings monthly canopy density measures.

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
August year 1					
site	2	1066	532.8	6.016	0.00354
species	1	6	6.4	0.072	0.78938
depth	1	0	0	0.000	0.99103
site x species	2	430	215.1	2.429	0.09392
site x depth	2	535	267.7	3.023	0.05370
species x depth	1	35	34.7	0.392	0.53300
site x species x depth	2	250	125.2	1.414	0.24869
Residuals	89	7882	88.6		
October year 1					
site	2	2357	1178.4	17.827	3.73E-07
species	1	327	326.8	4.944	0.0289
depth	1	104	104.4	1.579	0.2125
site x species	2	194	97.1	1.468	0.2363
site x depth	2	221	110.5	1.671	0.1943
species x depth	1	117	116.8	1.767	0.1874
site x species x depth	2	113	56.3	0.852	0.4305
Residuals	82	5420	66.1		

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
May year 2					
site	2	3152	1576.1	8.177	0.000592
species	1	319	318.7	1.654	0.202221
depth	1	25	24.9	0.129	0.720480
site x species	2	116	58.1	0.302	0.740458
site x depth	2	389	194.3	1.008	0.369590
species x depth	1	697	696.6	3.614	0.060932
site x species x depth	2	14	7.0	0.036	0.964440
Residuals	79	15226	192.7		
June year 2					
site	1	13890	13890	38.371	8.3E-08
species	1	212	212	0.585	0.44774
depth	1	2689	2689	7.429	0.00863
site x species	1	1	1	0.002	0.96770
site x depth	1	3415	3415	9.435	0.00333
species x depth	1	306	306	0.846	0.36164
site x species x depth	1	2913	2913	8.047	0.00640
Residuals	54	19548	362		
July year 2					
site	1	10846	10846	127.175	6.33E-16
species	1	288	288	3.381	0.0714
depth	1	186	186	2.179	0.1456
site x species	1	58	58	0.683	0.4120
site x depth	1	572	572	6.712	0.0122
species x depth	1	1	1	0.016	0.8989
site x species x depth	1	47	47	0.552	0.4606
Residuals	55	4691	85		
August year 2					
site	2	5119	2559.4	10.024	0.000119
species	1	306	305.9	1.198	0.276646
depth	1	132	131.5	0.515	0.474789
site x species	2	489	244.6	0.958	0.387554
site x depth	2	529	264.4	1.036	0.359262
species x depth	1	141	141.0	0.552	0.459399
site x species x depth	2	1706	853.0	3.341	0.039910
Residuals	89	22725	255.3		

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
May year 3					
site	2	46583	23291	559.823	< 2E-16
species	1	374	374	8.997	0.00367
depth	1	405	405	9.736	0.00256
site x species	2	348	174	4.177	0.01906
site x depth	2	272	136	3.266	0.04366
species x depth	1	132	132	3.176	0.07878
site x species x depth	2	119	60	1.431	0.24561
Residuals	75	3120	42		
June year 3					
site	2	27477	13738	320.836	< 2E-16
species	1	1003	1003	23.417	6.81E-06
depth	1	438	438	10.227	0.002028
site x species	2	820	410	9.574	0.000198
site x depth	2	168	84	1.966	0.147164
species x depth	1	176	176	4.116	0.046017
site x species x depth	2	63	32	0.740	0.480536
Residuals	75	3212	43		
July year 3					
site	2	24001	12000	185.172	< 2E-16
species	1	4106	4106	63.364	1.42E-11
depth	1	754	754	11.629	0.00105
site x species	2	4662	2331	35.968	1.12E-11
site x depth	2	492	246	3.798	0.02685
species x depth	1	754	754	11.632	0.00105
site x species x depth	2	752	376	5.805	0.00453
Residuals	75	4860	65		
August year 3					
site	2	31450	15725	249.470	< 2E-16
species	1	1289	1289	20.448	2.25E-05
depth	1	74	74	1.167	0.2835
site x species	2	96	48	0.758	0.4719
site x depth	2	363	181	2.877	0.0625
species x depth	1	83	83	1.321	0.2541
site x species x depth	2	81	41	0.643	0.5286
Residuals	75	4728	63		

Appendix E. Repeated measures ANOVA table for plant height by month.

Between-subject factors					
	Df	Sum Sq	Mean Sq	F value	Pr (>F)
Site	2	11440	5720	1061.717	< 2E-16
Species	3	673	224	41.631	< 2E-16
Depth	1	164	164	30.368	2.57E-07
Residuals	105	566	5		
Within-subject factors					
Month	1	3012.2	3012.2	1172.373	< 2E-16
Month x Site	2	195.5	97.8	38.045	2.77E-13
Month x Species	3	333.2	111.1	43.222	< 2E-16
Month x Depth	1	6.5	6.5	2.546	0.1134
Residuals	110	282.6	2.6		

Appendix F. ANOVA results for plant height by sampling month.

	Df	Sum sq	Mean Sq	F value	Pr(>F)
May year 3					
site	2	2288.9	1144.5	704.624	< 2E-16
depth	1	5.7	5.7	3.497	0.06420
species	3	527.6	175.9	108.283	< 2E-16
site x depth	2	16.0	8.0	4.913	0.00909
site x species	6	475.1	79.2	48.752	< 2E-16
depth x species	3	12.7	4.2	2.608	0.05540
site x depth x species	6	6.5	1.1	0.665	0.67841
Residuals	107	173.8	1.6		
June year 3					
site	2	4842	2420.8	1142.665	< 2E-16
depth	1	1	1.4	0.675	0.413083
species	3	222	74.0	34.909	8.2E-16
site x depth	2	34	17.2	8.130	0.000516
site x species	6	673	112.1	52.918	< 2E-16
depth x species	3	37	12.3	5.798	0.001037
site x depth x species	6	45	7.4	3.511	3285
Residuals	107	227	2.1		
July year 3					
site	2	2945.7	1472.8	480.976	< 2E-16
depth	1	6.3	6.3	2.062	0.154
species	3	204.3	68.1	22.234	3.03E-11
site x depth	2	95.8	47.9	15.640	1.12E-06
site x species	6	1028.8	171.5	55.996	< 2E-16
depth x species	3	5.1	1.7	0.555	0.646
site x depth x species	6	33.5	5.6	1.824	0.101
Residuals	106	324.6	3.1		
August year 3					
site	2	2207.0	1103.5	372.218	< 2E-16
depth	1	18.9	18.9	6.366	0.013179
species	3	532.8	177.6	59.911	< 2E-16
site x depth	2	44.2	22.1	7.447	0.000957
site x species	6	393.6	65.6	22.125	< 2E-16
depth x species	3	29.6	9.9	3.328	0.022596
site x depth x species	5	19.4	3.9	1.307	0.266717
Residuals	102	302.4	3.0		

Appendix G. ANOVA tables for year 1 to 2 and year 2 to 3 growth rates.

	Df	Sum sq	Mean Sq	F value	Pr(>F)
Year 1 to 2 Growth Rate					
site	2	6430	3215	10.189	8E-05
depth	1	90	90	0.286	0.59399
species	3	4205	1402	4.442	0.00531
site x depth	2	407	203	0.645	0.52649
site x species	6	5344	891	2.823	0.01309
depth x species	3	37	12	0.039	0.98983
site x depth x species	6	4164	694	2.200	0.04733
Residuals	124	39126	316		
Year 2 to 3 Growth Rate					
site	2	694	346.9	0.456	0.635
depth	1	522	522.4	0.687	0.409
species	3	8270	2756.8	3.626	0.015
site x depth	2	840	420.1	0.553	0.577
site x species	6	7861	1310.2	1.723	0.121
depth x species	3	2138	712.8	0.938	0.425
site x depth x species	6	4217	702.8	0.924	0.480
Residuals	124	94267	760.2		

Chapter 3:

Predictors of green roof performance by plant traits via vegetation characteristics

Abstract

Green roof services of thermal cooling and stormwater capture reduce building energy consumption and reduce strain on downstream hydrological infrastructure. Service provision by green rooftops can vary based on the plant species grown. In studies of ecosystem processes, plant traits are often used as predictors of services such as water purification and nutrient cycling. Here I investigated the use of plant traits as predictors of thermal cooling and stormwater capture on a green roof. To determine which traits might predict these green roof services, I analyzed correlations between plant and leaf traits, vegetation characteristics and service provision in 21 monoculture species grown in green roof modules.

Lower green roof surface temperatures were associated with high canopy density and high albedo while stormwater capture was negatively correlated to albedo and positively correlated to plant height. Albedo was in turn predicted by canopy density while canopy density was predicted by plant and leaf-level traits of plant height and specific leaf area. The results indicate that easy to measure plant traits can be utilized to select plant species to maximize stormwater capture and/or thermal cooling services on green roof systems.

Keywords: Extensive green roofs, plant traits, stormwater retention, thermal cooling

Introduction

Green rooftops are artificial ecosystems consisting of various engineered layers and vegetation. They provide services of stormwater management, summer cooling, mitigation of the urban heat island and habitat provision (Oberndorfer et al. 2007) with the ability to provide energy savings at the building level and changes to microclimates at larger urban scales. Green roof services derive from structural and functional attributes of both the living and engineered components. For example, green rooftops perform stormwater capture by retaining precipitation in the substrate and through uptake by the vegetation. This retention and uptake reduces the rate and volume of runoff from the building that then enters urban waterways. Stormwater runoff reduction by green rooftops is influenced by physical factors such as roof slope (VanWoert et al. 2005, Getter et al. 2007), substrate depth (Mentens et al. 2006, Berndtsson 2010), and climatic factors such as rainfall intensity and duration (Berndtsson 2010). While performance of stormwater retention is largely determined by substrate composition and depth, capture amount is also influenced by green roof vegetation (Dunnett et al. 2008, Wolf and Lundholm 2008, Lundholm et al. 2010, MacIvor and Lundholm 2011, MacIvor et al. 2011). Thermal services are provided through increased insulation, a higher thermal mass and plant canopy shading of the roof surface (Del Barrio 1998, Liu and Baskaran 2003, Getter and Rowe 2006). Heat flux through the roof is reduced by green rooftops through factors involving substrate depth, moisture content, and vegetation canopy and leaf area index (Del Barrio 1998). The role of vegetation in thermal cooling is through shading the substrate surface (DeNardo et al. 2005), increasing albedo (Gaffin et al. 2005), and transpirative cooling processes (Jim and Tsang 2011).

As vegetation has an effect on green roof services, the choice of green roof plants is important. The green roof industry has relied upon *Sedum* species for their drought tolerance and ability to withstand extensive green roof conditions, however, *Sedums* do not necessarily provide the best service provision. Dvorak and Volder (2010) found herbaceous plants to better capture stormwater than *Sedums* while Blanusa et al. (2013) found an herbaceous plant species to better perform thermal cooling. Some push has been made to include native species on green rooftops to varying success (Butler et al. 2012) while Lundholm (2006) suggested potential green roof plant species could be found in habitats with similar growing conditions as green rooftops and has seen success with some such species (Lundholm et al. 2010, MacIvor and Lundholm 2011). An approach by Farrell et al. (2013) looked to physiological traits to identify plant species which could optimize green roof hydrological functions and found that the best plants for water capture had high plasticity between high water use and drought tolerance and some form of root, leaf or stem succulence. Rayner et al. (2016) identified leaf succulence as a key trait for survival in extreme hot and dry green roof conditions. Plant traits are a way of understanding and organizing plant species, based not on taxonomy but rather on functional grounds of plant morphology, physiology and phenology. Traits are averaged measurements from multiple specimens of a species and therefore characterize the entire plant species. Two paradigms through which to view plant traits is either how they impact ecosystem function at the community level and/or how they respond to environmental conditions. Ecologists use these plant traits to probe biodiversity and ecosystem function (Gross et al. 2008, Lavorel and Grigulis 2012), with trait distributions providing clues to the relationship between trait and ecosystem function (Fry et al. 2013). While traits are useful in probing the trait-function relationship, I propose there exists a step between the trait at the leaf or plant level and ecosystem function. The mediating step arises when a plant species is aggregated in a stand and traits with similar or related processes occur concurrently and the overall impact can be measured. With regards to green rooftops, Cook-Patton and Bauerle (2012) define functional plant traits as "traits that contribute to a green roof's ability to provide services to an urban area." In this chapter, I investigate the potential to use plant traits as predictors of green roof thermal cooling and stormwater retention services.

Cornelissen et al. (2003) suggest a number of functional traits which are relatively easy to measure and strongly predict or are influential in ecosystem processes. Some traits are already suggested to have linkages to green roof services. Plant height is a trait found to be positively correlated with higher stormwater capture in empirical studies (e.g. Nagase and Dunnett 2012) and modeled to be negatively correlated with substrate temperatures (Sailor 2008). It is reasoned that taller plants have higher overall transpiration rates and provide greater shading of the soil surface, thereby reducing surface temperatures (Theodosiou 2003, Wong et al. 2003). Plant height also affects rainfall interception (Crockford and Richardson 2000) with taller plants capturing greater stormwater amounts (Nagase and Dunnett 2012). It is proposed here that leaf area (LA) may act in a similar fashion as plant height, with larger LAs better intercepting rainfall and providing greater shading benefits. Specific leaf area (SLA), calculated as one-sided leaf area divided by leaf dry weight (mm^2/mg), is a measure that often acts as a marker of plant strategy in the leaf economics spectrum (Vendramini et al. 2002). Both SLA and LA show strong positive correlations with evapotranspiration rates (Reich et al. 1999, Westoby et al. 2002) which would theoretically impact green roof service provision since removal of soil moisture results in greater retention capacity (Wolf and Lundholm 2008, Lundholm et al. 2010). Leaf dry matter content (LDMC) is a measure of leaf dry weight over leaf fresh weight (mg/g) and is also a marker of plant strategy along the leaf economics spectrum resource axis which spans from quick to slow return on nutrient investment (Wilson et al. 1999, Wright et al. 2004). Lower LDMC values are typically found in productive and/or disturbed environments, and correspond with a quicker return on investment.

I considered vegetation characteristics of albedo, canopy density, water loss and canopy growth rate. While plant traits are measured from specimens growing in their natural environment and generalized to characterize a whole species, vegetation characteristics are measured on the green roof system and are indicative of that system only. Vegetation characteristics are measured on the same system as ecosystem services. Albedo, as a vegetation characteristic is involved in green roof thermal cooling by increasing reflectance of solar radiation thereby reducing heat absorption (Sailor 2008). Canopy density may play an additional role in thermal cooling through shading and influence stormwater capture as stormwater capture may increase with canopy architecture complexity (Rixen and Mulder 2005). Evapotranspiration is linked to stormwater capture as the rate at which water is removed from the substrate will dictate how much pore space is available to capture water when it rains (Berndtsson 2010). Canopy growth rate is similar to relative growth rate (RGR), with which SLA scales (Poorter et al. 2009). Related to other traits, canopy growth rate may be related to canopy features that play a role in stormwater and thermal benefits.

Since ecosystem functions are influenced by the functional traits of plants, I propose that traits can be utilized to model green rooftop ecosystem service provision. The purpose of this study was to identify which traits, if any, can be used to explain the processes of, and later predict, green roof services of stormwater capture and thermal cooling.

To determine whether traits can be utilized to model green roof thermal cooling and stormwater capture, I measured plant traits of 21 plant species and measured their corresponding green roof performance of these services. For each test species, plant traits were obtained from specimens growing in natural habitats. The test species were grown in a modular green roof system in monoculture plantings. From these modules, green roof services of stormwater capture and thermal cooling were measured, along with vegetation characteristics of albedo, canopy density, water loss and canopy growth rate. Correlations between traits and service provision via vegetation characteristics were evaluated by multiple linear regression. From the significant relationships, a path diagram was generated to explain and visualize the linkage between traits to service provision.

Methods

Green Roof Site

The green roof testing facility was located atop the Patrick Power Library of Saint Mary's University in Halifax, Nova Scotia, Canada. Halifax, NS experiences a cold, humid climate and receives high precipitation amounts (Table 1) (Environment Canada, 2015). The green roof site is approximately five meters above ground level and circumscribed by buildings one to three stories higher on all sides. The Patrick Power Library rooftop had an in-ground green roof system installed circa 1972. The in-ground green roof consists of lawn grass and wildflowers over 45 – 60 cm of clay soil. The soil is separated from underlying concrete slabs by a waterproofing membrane. Experimental modules were placed atop the in-ground green roof separated by a weed barrier fabric (Quest Plastics Ltd., Mississauga, ON, Canada). The weed barrier fabric acted to prevent any interaction between the experimental module's plant roots and the pre-existing green roof.

Table 1. Climate measures of Halifax, Nova Scotia from May to October, 2008 to 2010.

	2008	2009	2010
Daily maximum temperature range (°C)	13.1 - 25.8	11.5 - 25.1	13.3 - 25.1
Daily minimum temperature range (°C)	4.7 - 15.3	2.3 - 14.6	5.0 - 15.0
Monthly precipitation range (mm)	69.1 - 299.4	71.0 - 179.6	48.0 - 153.6

Green Roof Modules

Modules (Botanical Nursery LLC, Wayland, MA, USA) measured 40 cm x 40 cm along the interior edge. Each module contained, from the bottom upwards, a geocomposite nonwoven water retention layer (Huesker Inc., Charlotte, NC, USA), a filter layer, an Enkamat drainage layer (Colbond Inc., Enka, NC, USA), and 6 cm of substrate.

The substrate for green roof modules planted in 2007 was Sopraflor X green roof substrate (Soprema Inc., Drummondville, QC, Canada). Sopraflor X is comprised of crushed brick, blond peat, perlite, sand and vegetable compost. Its pH measured 7.6 and has physical properties of 60-70% total porosity, bulk density 1150 – 1250 kg/m^3 and 5-10% organic matter (dry content). Modules planted in 2009 were comprised of a 1:4 mix of Pro-Mix potting soil (Premier Tech, Rivière-du-Loup QC, Canada) and Sopraflor X growing medium (Soprema Inc., Drummondville, QC, Canada).

Green Roof Monoculture Modules

Twenty-one plant species were propagated as plugs from seeds and cuttings in the Saint Mary's University greenhouse in Pro-Mix potting soil (Premier Horticulture, Rivière-du-Loup, QC, Canada). Some plants were collected and propagated starting from summer 2006 and planted in spring 2007 while the rest were propagated starting fall 2008 and planted in spring 2009 (Table 2). Four plant species were propagated over both periods.

Seeds and cuttings used for propagation were collected from around Halifax and Chebucto Head, a coastal barrens environment approximately 25 km outside Halifax, NS. One special case in propagation was *Arctostaphylos uva-ursi*, collected in 2009 as cuttings from Chebucto Head. The cuttings were passed to M2 Horticulture in Truro, Nova Scotia who used a misting system to stimulate root growth. Due to poor propagation success in 2006 – 2007 of *Gaultheria procumbens*, *Vaccinium vitis-idaea* and *Poa compressa*, extra plants of these species were collected from Chebucto Head and Polly's Cove (approximately 45 km southwest of Halifax). These plants were potted into plugs using the same Pro-Mix potting soil used for propagation and allowed to establish for two weeks prior to planting into modules.

The 21 test plant species included three non-native, proven green roof suitable plants

(*Sedum acre*, *Sedum spurium*, and *P. compressa*) and 19 indigenous species selected by the habitat template approach proposed by Lundhom (2006). The 21 plant species belong to five life-form groups: graminoids, subshrub/creeping shrubs, tall forbs, ground-covering forbs, and succulents (Table 2). Of the 13 species propagated in 2006-07, Lundholm et al. (2010) found that green roof performance differed within each life-form group.

Table 2. List of native and non-native plant species grown in modules in monoculture. Non-native plant species are indicated by an asterisk (*).

Plant Species	Common Name	Life Form	2007	2008
Arctostaphylos uva-urvi	Bearberry	Creeping shrub		x
Aster novae-belgii	New York aster	Tall forb		x
Campanula rotundifolia	Harebell	Tall forb	x	
Carex argyranthra	Hay sedge	Graminoid		x
Carex nigra	Black sedge	Graminoid	x	x
Danthonia spicata	Wire grass	Graminoid	x	x
Deschampsia flexuosa	Crinkled hair grass	Graminoid	x	x
Empetrum nigrum	Black crowberry	Creeping shrub	x	x
Festuca Rubra	Red fescue	Graminoid		x
Gaultheria procumbens	Wintergreen	Subshrub	x	
Plantago maritima	Seaside plantain	Tall forb	x	
*Poa compressa**	Canada bluegrass	Graminoid	x	
Sagina procumbens	Birdseye	Ground-covering forb	x	
*Sedum acre**	Mossy stonecrop	Succulent	x	
Sedum rosea	Roseroot	Succulent	x	
*Sedum spurium**	Garden stonecrop	Succulent	x	
Sibbaldiopsis tridentata	Three-toothed cinquefoil	Creeping shrub		x
Solidago bicolor	White goldenrod	Tall forb	x	x
Solidago puberula	Downy goldenrod	Tall forb		x
Vaccinium macrocarpon	Large cranberry	Creeping shrub		x
Vaccinium vitis-idaea	Mountain cranberry	Subshrub	x	

Plugs were planted as monocultures in modules, comprised as a mix of larger and smaller plugs. Plants started in 2006 were planted into green roof modules in spring 2007 at a planting density of 21 plugs per module. Plants propagated in 2008 were planted into modules spring 2009. The number of plugs planted in 2009 varied per species, aiming to achieve 100% coverage of the module upon maturation. Maximum planting density was 21 plugs per module but varied based on growth form predictions of mature plant canopy size. *Aster novae-belgii* received the lowest density planting at 8 plugs per module.

Following planting, modules received water only from natural precipitation events and the once monthly artificial rain events created to measure stormwater capture. To retain monocultures, modules were weeded once to twice a month to remove any non-target species that arrived or germinated. Plantings of both 2007 and 2009 were considered to have reached maturity and maximum size by the end of the 2010 growing season.

Green Roof Performance

Stormwater capture and substrate temperatures were measured once monthly from June to August 2010. Gravimetric soil moisture was measured utilizing a PX-Series Checkweighing bench scale (ATRON Systems Inc., West Caldwell, NJ, USA). Modules were tested for stormwater capture once a month during the second week of each month within one hour of solar noon on a sunny day. Modules were weighed and then watered with 1.3 kg of water, simulating an intermediate rain event for Halifax, NS. The artificial rain event size was based on the per day average rainfall for Halifax between May and October 2008, amounting to a 10 mm rain event (Fogarty 2009). The modules were then reweighed ten minutes, 24 hours, and 48 hours after the simulated rain event. If a natural rain event occurred over the 48 hour weighing period, the data were discarded. Stormwater capture was defined as the difference in module weight before watering and the weight 10 minutes after watering (Lundholm et al. 2010, MacIvor and Lundholm 2011). For use in analysis, a stormwater capture index was created by dividing the capture amount of a module by the average capture of the unplanted control modules of the corresponding period. Measurements were averaged across all dates by plant species.

Substrate surface temperatures were measured once per month between June and August within one hour of solar noon on a sunny day using a Taylor 9878 Slim-Line Pocket Digital Thermometer (Commercial Solutions Inc., Edmonton, AB, Canada). Taking measurements around solar noon should capture maximal differences across plant species in substrate cooling. Measurements were made at the centre of each module within the top 1 cm of substrate media. An index of surface temperature was generated by dividing each module temperature measurement by the average temperature of the unplanted control modules on the corresponding date. Measurements were then averaged over each sampling date. The temperature index was multiplied by -1 to generate a cooling index whereby higher index values indicate a lower temperature relative to the control.

Vegetation Characteristics

To measure canopy albedo, modules were taken and isolated on a grey-coloured weed barrier fabric (Quest Plastics Ltd., Mississauga, ON, Canada). A single LI-COR pyranometer sensor and LI-250A light meter (LI-COR Biosciences, Lincoln, NE, USA) was affixed to a retort stand with the sensor and light meter 35 cm above the module (MacIvor and Lundholm 2011). Under clear sky conditions and within one hour of solar noon, when incoming solar radiation is most constant, incoming and reflected solar radiation was measured for each module. Incoming radiation (W/m^2) was measured by directing the pyranometer sensor towards the sky (180° away from the module), and reflected solar radiation was measured by rotating the sensor toward the module. Measurements were taken once a month between June and August 2010. Measurements made in July had the greatest spread of albedo among species and only these measures were used for statistical analysis.

Canopy density, an estimate of above-ground biomass by the point-interception method (Floyd and Anderson 1987) was determined using the Ranalli box (Domenico Ranalli, Regina, SK, Canada). The Ranalli box is a 36 cm three-dimensional cube with 16 equally spaced, 6 mm diameter rods (or points). The box was placed above each module and the number of contacts made between the plant structure and the rods was counted. Measurements began at initial planting and continued monthly over the following growing seasons (May to September). Among an evenly spaced grid pattern, biomass is strongly correlated to total number of contacts between points and plant matter (Jonasson 1988). For use in statistical analysis, canopy density measurements from August 2010 were used.

Canopy growth rate was calculated as the change in canopy density over the first year of growth. Canopy density measurements used to determine canopy growth rate were from August of the first year after planting and the following August. Growth rate was calculated as ln(density at t_2) - ln(density at t_1) / number of days between t_1 and t_2. Therefore, for plants started in 2007, canopy growth rate was determined from canopy density measures in August 2007 and August 2008. Similarly, for plants started in 2008, canopy growth rate was determined from measurements August 2008 and August 2009. These growth rates provide general estimates of early growth rates in the green roof environment.

Net water loss was designated as the difference in module weight between 10 minutes and 24 hours after the simulated rain events made June - August 2010. Similar to measurements of stormwater capture, monthly measurements were averaged together and an index created by dividing by the averaged control modules stormwater capture performance.

Plant Traits

Plant traits of plant height, leaf area (LA), specific leaf area (SLA), and leaf dry matter content (LDMC) were determined for all test 21 species.

The traits of plant height, LA, SLA, LDMC were determined using measurements taken from five specimens of each test species. Leaf samples were obtained from different individuals found growing in their natural environments at Chebucto Head, Point Pleasant Park, and around Saint Mary's University, NS, Canada. Healthy leaves from well developed plants were selected whereas damaged or senescent leaves were omitted from collection and measurement.

Leaf length, width and thickness were obtained at the collection site using a ruler and an ABSOLUTE Digimatic caliper (Mitutoyo, Cole Harbour, NS, Canada). Corresponding plant height was recorded. Leaf fresh weight was measured using a Mettler Toledo analytical balance (Mettler Toledo, Mississauga, ON, Canada) and the leaf scanned. Leaves were then dried at 50°C for 48 hours and dry weight measured. Measurements for plant traits were averaged over the samples (Cornelissen et al. 2003).

Plant height was considered the height in cm from the base of the plant to the top vegetative height. LA measured the one-sided surface area in mm^2 of a single leaf was calculated using Image J software (Image Processing and Analysis in Java, NIH, USA). SLA was calculated as one-sided leaf area divided by its oven-dried leaf mass, mm^2/mg. Lower SLA values are generated from denser leaf tissues as more biomass is invested in an area unit. LDMC is the measure of dry leaf weight (mg) divided by fresh leaf weight (g). High LDMC values correspond to leaves with lower water content when fresh.

Statistical Analysis

Prior to analysis, I averaged measurements for each ecosystem service, vegetation characteristic and plant trait by the plant species to generate one indicator value per service/characteristic/trait per species. Stormwater capture and thermal cooling were indexed by the corresponding performance by the control, substrate only, modules. Variables were transformed to improve homogeneity of variance where necessary (Table 3) and standardized to Z-scores prior to analysis.

Table 3. Transformations applied to leaf traits, plant traits and vegetation characteristics.

Variable	Transformation
Canopy Density	$x^{1/2}$
Canopy Growth Rate	ln(x+0.1)
Net Water Loss	none
Albedo	none
Plant Height	$x^{1/2}$
Leaf Area	ln(x)
Specific Leaf Area	ln(x+1)
Leaf Dry Matter Content	none

A hypothetical model of traits (Figure 1), via vegetation characteristics, driving green roof services of stormwater capture and thermal cooling was generated based on existing knowledge. These predicted relationships were tested using Akaike Information Criterion (AIC) to indentify the best model. In instances where no vegetation characteristics were found to drive the green roof service, new models were generated to test for direct influence by plant traits.

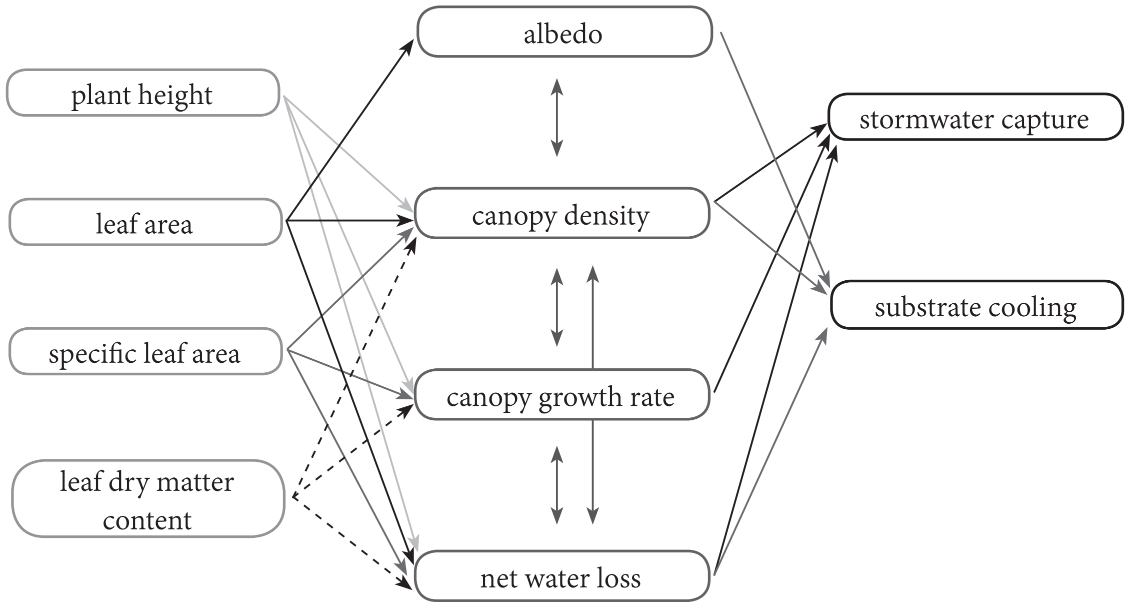

Figure 1: Hypothetical model linking traits to green roof services via vegetation characteristics. Dashed line indicates a predicted inverse relationship.

From AIC, the best models were considered those with low delta weights (≤7). When multiple models had delta weights below 7, it was determined that no one best model existed. As no best model was found, model averaging was used to generate standardized regression coefficients, with the β coefficient indicating the strength of the relationship. The models generated from AIC are identified in Table 4, along with the results from model averaging. Three models from AIC analysis for stormwater capture, with delta weight ≤7, had 95% confidence intervals that did not include 0 when model averaging was applied (Table 4). From model averaging, predictors whose 95% confidence interval did not overlap zero were considered significant. A path diagram (Figure 2) was constructed including only these predictors. Model selection and model averaging was conducted using the MuMIn R-package (Bartoń 2015).

Table 4. Linear regression model results from model averaging. Predictors in bold indicate those whose confidence interval (CI) does not overlap zero.

Variable	Predictor	Model Averaged β coefficient	95% CI lower bound	95% CI upper bound
Stormwater Capture				
model 1	**Albedo**	**-0.53**	**-0.92**	**-0.17**
	Canopy Density	0.27	-0.17	0.72
	Canopy Growth Rate	0.32	-0.08	0.73
	Net Water Loss	0.04	-0.35	0.41
model 2	**Plant Height**	**0.40**	**0.02**	**0.78**
	Specific Leaf Area	-0.21	-0.61	0.17
	Leaf Area	0.14	-0.31	0.60
	Leaf Dry Matter Content	0.37	-0.01	0.75
model 3	**Albedo**	**-0.53**	**-0.86**	**-0.20**
	Plant Height	**0.50**	**0.17**	**0.83**
	Canopy Density	-0.05	-0.51	0.54
	Canopy Growth Rate	0.01	-0.34	0.61
	Net Water Loss	0.14	-0.37	0.26
Substrate Cooling	**Albedo**	**0.40**	**0.17**	**0.63**
	Canopy Density	**0.60**	**0.36**	**0.85**
	Canopy Growth Rate	-0.08	-0.32	0.17
	Net Water Loss	0.06	-0.15	0.26

Table 4 continued. Linear regression model results from model averaging. Predictors in bold indicate those whose confidence interval (CI) does not overlap zero.

Variable	Predictor	Model Averaged β coefficient	95% CI lower bound	95% CI upper bound
Albedo	**Canopy Density**	**0.48**	**0.06**	**0.91**
	Plant Height	-0.19	-0.67	0.29
	Specific Leaf Area	0.36	-0.03	0.76
	Leaf Area	0.01	-0.39	0.41
	Leaf Dry Matter Content	-0.10	-0.49	0.27
	Canopy Growth Rate	0.36	-0.04	0.78
Canopy Density	**Plant Height**	**0.50**	**0.17**	**0.83**
	Specific Leaf Area	**0.51**	**0.22**	**0.79**
	Leaf Area	-0.02	-0.39	0.35
	Leaf Dry Matter Content	-0.06	-0.41	0.28
	Canopy Growth Rate	0.35	-0.01	0.72
Canopy Growth Rate	Plant Height	0.61	0.26	0.96
	Specific Leaf Area	0.15	-0.19	0.50
	Leaf Area	0.04	-0.41	0.49
	Leaf Dry Matter Content	-0.28	-0.61	0.06
Net Water Loss	Canopy Density	-0.08	-0.56	0.31
	Canopy Growth Rate	-0.13	-0.58	0.40
	Plant Height	0.21	-0.25	0.68
	Specific Leaf Area	0.19	-0.24	0.62
	Leaf Area	0.24	-0.17	0.65

Results

Path Diagram

From our AICc analysis to predict drivers of green roof services and vegetation characteristics, no one model was demonstrably stronger than another. As such, model averaging was used in all cases. From model averaging, green roof service of stormwater capture waas positively predicted by plant height and negatively correlated to albedo (Table 4). Thermal cooling was positively correlated to both canopy density and albedo. Vegetation characteristic albedo was positively predicted by canopy density while canopy density was positively correlated to traits plant height and specific leaf area measures (Figure 2).

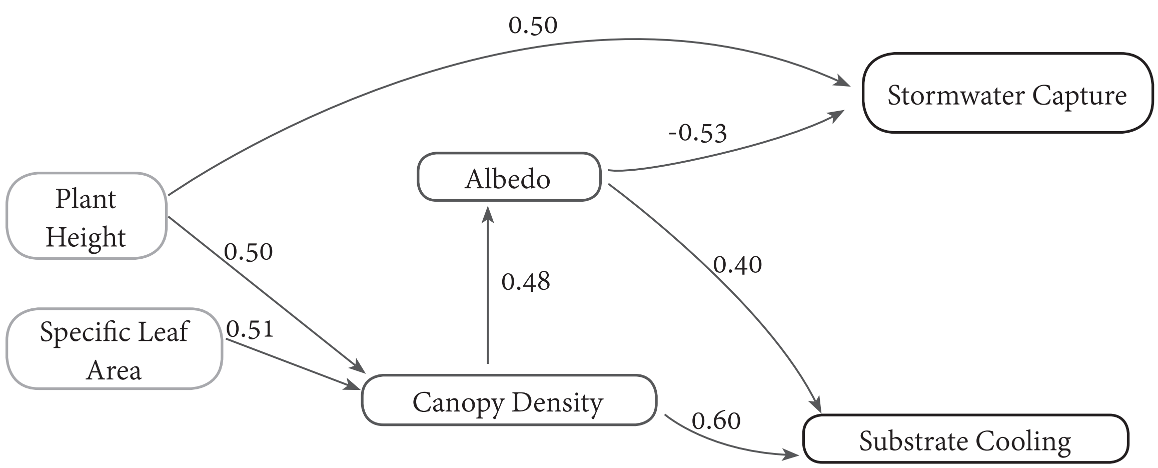

Figure 2: Path diagram linking whole plant and leaf level traits to green roof performance measures via vegetation characteristics.

Plant and Leaf Traits

Average plant height measured in the field ranged from under 2 cm to 66 cm. Graminoid life forms dominated the tallest plant heights, but were variable in their average heights. Creeping forbs and shrubs were consistently short, while succulents were relatively short but highly variable. Two of the shortest plant species were succulents *Sedum acre* and *Sedum spurium*. Tall forb species were similar to graminoids with relatively tall yet variable heights.

Leaf area (LA) measurement ranged from 4.6±0.36 mm^2 to 1662.0±465.03 mm^2, spanning three orders of magnitude (Table 5). The largest LA values were possessed by graminoid life forms, highest in sod-forming graminoids but variable. Forb and succulent growth forms held the smallest leaf areas but were also variable in their range.

Specific leaf area (SLA) generally showed no trends with respect to growth form, being highly variable within a group. The highest SLA belonged to *Sagina procumbens*, a creeping forb, while the lowest SLA value belonged to *Arctostaphylos uva-ursi*, a creeping shrub. SLA ranged from 5.9±0.5 to 92.4±23.3 mm^2/g.

Leaf dry matter content (LDMC) ranged from 85.4±4.88 mg/g to 582.6±17.15 mg/g, a seven-fold difference (Table 5). A succulent, *Sedum rosea*, held the lowest value while *Vaccinium macrocarpon*, a creeping shrub, held the greatest value. Succulents all held low LDMC values, along with *Empetrum nigrum*, *Plantago maritima*, and *S. procumbens*, all from distinct growth form groups.

Vegetation Characteristics

Albedo values for succulents were highly varied, with succulent growth forms exhibiting both the highest and lowest values. *S. acre* had the highest reflectivity at 26% while *S. rosea*

Table 5. Summary of plant trait values, vegetation characteristics and green roof services.

Plant Species	Growth Form	Plant Traits				Vegetation Traits				Green Roof Services	
		height (cm)	leaf area (mm^2)	specific leaf area (mm^2/mg)	leaf dry matter content (mg/$g_{fresh\ weight}$)	canopy growth rate	canopy density	albedo	net water loss index	stormwater capture index	thermal cooling index
Arctostaphylos uva-urvi	creeping shrub	6.0 ± 1.14	128.5 ± 16.6	5.9 ± 0.5	444.7 ± 7.3	$6.5 \times 10^{-4} \pm 1.1 \times 10^{-4}$	22.0 ± 11.7	0.17 ± 0	0.95 ± 0.0	1.03 ± 0.0	-1.02 ± 0.0
Aster novae-belgii	tall forb	53.6 ± 5.4	1062.5 ± 220.8	23.0 ± 1.4	195.6 ± 6.0	$3.8 \times 10^{-3} \pm 4.4 \times 10^{-4}$	55.4 ± 8.8	0.2 ± 0.0	1.22 ± 0.1	1.04 ± 0.0	-0.88 ± 0.0
Campanula rotun-difolia	tall forb	16.4 ± 2.8	102.2 ± 23.9	16.3 ± 1.8	262.0 ± 22.1	$3.3 \times 10^{-3} \pm 1.3 \times 10^{-3}$	109.7 ± 5.0	0.19 ± 0	1.04 ± 0.1	0.96 ± 0.0	-0.8 ± 0.0
Carex argyranthra	graminoid	63.0 ± 0	1451.1 ± 137.0	35.3 ± 4.8	580.8 ± 27.4	$8.2 \times 10^{-4} \pm 8.7 \times 10^{-7}$	162.8 ± 24.7	0.2 ± 0.0	1.14 ± 0.0	1.04 ± 0.0	-0.8 ± 0.0
Carex nigra	graminoid	66.6 ± 3.4	1116.1 ± 141.4	10.5 ± 0.9	401.2 ± 23.5	$9.4 \times 10^{-4} \pm 1.4 \times 10^{-4}$	154.1 ± 20.5	0.2 ± 0.0	1.10 ± 0.0	1 ± 0.0	-0.82 ± 0.0
Danthonia spicata	graminoid	36.0 ± 1.7	90.2 ± 10.8	9.5 ± 1.0	402.8 ± 46.6	$1.1 \times 10^{-3} \pm 3.8 \times 10^{-4}$	121.5 ± 13.1	0.18 ± 0	0.87 ± 0.0	0.99 ± 0.0	-0.85 ± 0.0
Deschampsia flexuosa	graminoid	56.8 ± 2.1	81.8 ± 13.2	13.3 ± 2.2	368.8 ± 45.9	$1.7 \times 10^{-3} \pm 4.4 \times 10^{-4}$	97.8 ± 14.6	0.17 ± 0	0.95 ± 0.0	1.01 ± 0.0	-0.9 ± 0.0
Empetrum nigrum	creeping shrub	8.4 ± 1.3	4.6 ± 0.4	40.1 ± 3.1	90.2 ± 20.8	$1.7 \times 10^{-4} \pm 4.5 \times 10^{-4}$	55.5 ± 9.8	0.17 ± 0.0	0.91 ± 0.0	1.07 ± 0.0	-0.94 ± 0.0
Festuca Rubra	graminoid	55.0 ± 6.4	141.1 ± 26.6	16.1 ± 4.0	303.5 ± 38.8	$1.3 \times 10^{-3} \pm 1.5 \times 10^{-3}$	242.5 ± 38.3	0.18 ± 0.0	1.02 ± 0.0	1.11 ± 0.0	-0.85 ± 0.0
Gaultheria procumbens	subshrub	9.8 ± 1.3	357.8 ± 38.4	7.3 ± 0.5	382.9 ± 10.1	$-2.7 \times 10^{-3} \pm 1.3 \times 10^{-3}$	5.0 ± 3.6	0.16 ± 0	1.11 ± 0.1	1.04 ± 0.0	-0.95 ± 0.0
Plantago maritima	tall forb	14.0 ± 2.5	228.7 ± 81.2	7.3 ± 0.6	112.6 ± 6.5	$1.3 \times 10^{-3} \pm 4.3 \times 10^{-4}$	46.7 ± 6.9	0.17 ± 0	0.87 ± 0.1	1.01 ± 0.0	-0.88 ± 0.0
*Poa compressa**	graminoid	26.2 ± 5.6	1662.0 ± 465.0	41.8 ± 6.9	244.8 ± 57.3	$3.4 \times 10^{-3} \pm 6.8 \times 10^{-4}$	208.7 ± 60.2	0.19 ± 0	0.92 ± 0.1	1.01 ± 0.0	-0.74 ± 0.0
Sagina procumbens	ground-covering forb	1.5 ± 0.3	16.5 ± 4.0	92.4 ± 23.3	167.0 ± 19.5	$-2.7 \times 10^{-3} \pm 5.1 \times 10^{-4}$	101.3 ± 7.7	0.18 ± 0	1.10 ± 0.1	0.95 ± 0.0	-0.86 ± 0.1
*Sedum acre**	succulent	3.8 ± 0.3	18.5 ± 2.8	37.0 ± 8.4	124.7 ± 13.6	$1.4 \times 10^{-3} \pm 5.1 \times 10^{-4}$	124.0 ± 29.5	0.26 ± 0.0	1.07 ± 0.1	0.87 ± 0.0	-0.74 ± 0.0
Sedum rosea	succulent	17.6 ± 5.0	152.8 ± 36.0	16.9 ± 1.1	85.4 ± 4.9	$-2.7 \times 10^{-3} \pm 1.0 \times 10^{-3}$	22.3 ± 6.3	0.16 ± 0	0.96 ± 0.0	0.96 ± 0.0	-0.94 ± 0.0
*Sedum spurium**	succulent	5.2 ± 1.2	162.9 ± 11.8	30.0 ± 3.2	86.7 ± 5.5	$-8.5 \times 10^{-4} \pm 1.5 \times 10^{-3}$	86.5 ± 38.5	0.21 ± 0	0.84 ± 0.1	0.93 ± 0.0	-0.8 ± 0.0
Sibbaldiopsis tridentata	creeping shrub	9.2 ± 2.8	395.6 ± 108.3	8.1 ± 0.3	380.9 ± 6.8	$-3.4 \times 10^{-3} \pm 1.8 \times 10^{-3}$	39.7 ± 14.7	0.17 ± 0.0	1.02 ± 0.0	1.07 ± 0.0	-0.92 ± 0.0
Solidago bicolor	tall forb	29.1 ± 2.9	653.8 ± 222.2	8.0 ± 0.6	267.8 ± 12.9	$2.5 \times 10^{-3} \pm 5.7 \times 10^{-4}$	57.9 ± 18.1	0.2 ± 0.0	0.95 ± 0.0	1.03 ± 0.0	-0.89 ± 0.0
Solidago puberula	tall forb	41.1 ± 3.5	705.5 ± 75.1	28.4 ± 2.9	448.4 ± 24.5	$2.2 \times 10^{-3} \pm 7.1 \times 10^{-4}$	55.1 ± 15.4	0.2 ± 0.0	0.94 ± 0.0	1.06 ± 0.0	-0.93 ± 0.0
Vaccinium macro-carpon	creeping shrub	8.0 ± 1.1	26.0 ± 2.3	7.3 ± 0.6	582.6 ± 17.2	$-1.4 \times 10^{-3} \pm 8.5 \times 10^{-4}$	13.7 ± 3.9	0.18 ± 0.0	0.9 ± 0.0	1.04 ± 0.0	-0.99 ± 0.0
Vaccinium vitis-idaea	subshrub	3.6 ± 0.5	56.2 ± 7.6	6.2 ± 0.4	465.4 ± 9.1	$-3.1 \times 10^{-3} \pm 8.9 \times 10^{-4}$	0.0 ± 0.0	0.16 ± 0.0	1.11 ± 0.1	0.97 ± 0.0	-0.97 ± 0.0

measured 16% reflectivity. Variability in albedo was lower for all other growth forms, ranging between 16% and 19% reflectivity (Table 5).

Canopy density ranged from zero to 243 contacts/0.07 m^3. Graminoids tended to have relatively high canopy densities with *Festuca rubra* exhibiting the highest canopy density of all species tested. Creeping shrubs all had low canopy density values while tall forbs were intermediate in canopy density. All growth form groups had moderate variation in their values.

Canopy growth rates were negative for seven species: *Gaultheria procumbens*, *S. procumbens*, *S. rosea*, *S. spurium, Sibbaldiopsis tridentata*, *V. macrocarpon* and *Vaccinium vitis-idaea*. These species belong to creeping shrub and forbs, and succulent growth forms. However, succulent *S. acre* had a relatively high growth rate. Graminoids and tall forbs both held consistently high canopy growth rates.

Water loss amounts did not follow any trends related to growth forms and ranged from 16% less to 22% more water loss than unplanted control modules (Table 5). *S. spurium* modules lost the least amount of water and *Symphotrichum novi-belgii* the most.

Green Roof Services

Stormwater capture was affected by vegetation with *F. rubra* capturing 11% more than unplanted control modules. Several species captured less than the unplanted controls with all succulents performing stormwater capture poorly. *S. acre* absorbed the least, retaining 87% of the unplanted control capture amount. Tall forbs generally performed stormwater capture well while creeping forb species exhibited both high and low water use.

Thermal cooling was best performed by *P. compressa* and *S. acre*, lowering substrate temperatures by 26% below unplanted controls (Table 5). While *S. acre* was one of the best performers, succulents were highly variable in thermal cooling. Creeping shrubs tended to cool the substrate the least, with *A. uva-ursi*, *V. macrocarpon* and *V. vitis-idaea* performance similar to control modules. Tall forbs were also poor performers while graminoids were variable in their cooling ability.

Discussion

Plant traits are generalized measures for a species and affect ecosystem processes through vegetation characteristics (Guha and Reddy 2012, Yan et al. 2012, Fry et al. 2013). In this study, I found predictors of green roof services in plant traits. Traits measured from specimens found in naturally occurring populations were found to drive green roof vegetation characteristics which in turn were related to ecosystem services.

Thermal cooling was related to vegetation characteristics of canopy density and albedo, replicating findings from others studies (Takebayashi and Moriyama 2007, Lundholm 2010). Canopy density in this study reflected the living leaf and stem biomass in a green roof module. Canopy density may have reduced surface temperatures by shading the substrate surface (Theodosiou 2003) or by containing a cooler air pocket above the surface layer (Dimoudi and Nikolopoulou 2003). Greater canopy density covers and shields more substrate from solar radiation and better traps air. Highest canopy density in this study was found in sod-forming graminoids yet substrate temperatures were best reduced by *Sedum acre*, which did not exhibit the highest canopy density. Likewise, succulent *Sedum spurium* lowered temperatures more than some sod-forming graminoids that had greater canopy density. This suggests that another process aside from canopy shading is involved in substrate cooling. This study found surface cooling also positively correlated to albedo. Albedo acts in the process of cooling by reflecting more solar radiation. Consequently, less solar radiation is absorbed and translated into heat energy on the roof (Taha 1997). *S. acre* exhibited the greatest albedo out of the species tested and reduced surface temperature by 26%.

In this study, albedo was predicted only by canopy density. Albedo values are raised by greater canopy density through a greater provided area for reflection and by the higher albedo of vegetation over substrate albedo (Oke 1978). No plant trait measured in this study was predictive of albedo values although Ollinger (2011) identified traits of leaf nitrogen content, leaf and canopy water content and lateral spread as some of the traits to drive optical reflectivity. Albedo and reflectance characteristics are also influenced by canopy density factors including leaf architecture, branching intensity, leaf orientation and lateral spread (Sandmeier et al. 1998, Kumar et al. 2001, Ollinger 2011). In this study, creeping shrubs had low canopy density and low albedo values and performed thermal cooling the poorest. No growth form group held simultaneously high albedo and canopy density values although sod-forming graminoids and succulents made up the best performers of thermal cooling.

In accordance with other studies, I found stormwater capture to be little improved by vegetation. Others studies have concluded that increasing substrate depth is the easiest and most effective way to increase stormwater retention (VanWoert et al. 2005). However, this study found plant species type to be able to alter the capture amount, with sod-forming graminoid *Festuca rubra* retaining 10% more than control modules. Stormwater capture was negatively correlated to albedo and positively related to plant height. *F. rubra* was one of the taller specimens, with the highest canopy density. Sailor (2008) found a relationship between albedo and green roof substrate moisture levels where saturated green roof substrate was less reflective and drier substrate more reflective. From Sailor's findings, the logical conclusion would be that with increased albedo indicative of a drier substrate, a greater albedo green roof system would be more capable of water uptake as drier antecedent substrate conditions retain more. I believe that the negative relationship generated in this study between albedo and stormwater capture was influenced by the performance of succulents *S. acre* and *S. spurium*. These species were the most reflective out of the test species and captured the least amount of water. *Sedums* are known to be drought-tolerant, having low water requirements, and poor performers of water capture (VanWoert et al. 2005, Dunnett et al. 2008). Low capture in these species may be a function of both reduced transpiration from the plants and reduced evaporation from the substrate. It is also possible that albedo influences direct evaporation from the soil surface. With more shade from higher albedo, in part influenced by canopy density, less evaporation from the soil surface is possible leading to wetter antecedent conditions which reduces future possible capture.

Plant species that are relatively tall in their natural environments predicted greater stormwater capture, corroborating findings by Nagase and Dunnett (2012). Ecologically, greater plant height is typically an indicator of high resource users from resource rich environments where high growth rates and tall plant heights are competitive factors in reaching resources. Conversely, short heights are often considered a drought tolerance feature, a condition often found in resource-poor environments (Gross et al. 2008). While I found tall plants to better perform water capture, it is important to note that the species in this study all originate from low resource habitats. Plants adapted to low resource environments are relatively shorter than plants of resource rich environments (Gross et al. 2008). As the plants in this study were from low resource environments, tall plants in the study were the tallest of a short group. In this light, the tall plants performed well in terms of survival and storm water capture. It is necessary to note that tall plants from richer environments would have higher water needs and therefore be more susceptible to drought in green roof systems. Tall plants may have other resource requirements for long-term success that may demand additional fertilization, maintenance or irrigation which may limit incorporation of truly tall species on green roofs.

Plant height was also correlated with greater canopy density in this study. This agrees with findings by Axmanová et al. (2012) where biomass was best modelled by canopy coverage and median height. Again, as taller plants are indicative of a life strategy of high resource use and quick return on resources, it follows that resource allocation into biomass would include canopy density serving as light capturing structures.

Canopy density was positively correlated with specific leaf area (SLA). SLA is another indicator of plant strategy (Wilson et al. 1999) where plants with higher SLA exhibit quick growth and return on resources (Wright and Sutton-Grier 2012). Typically plants with higher SLA values are found in resource-rich environments, thus high SLA values indicate a plant strategy that allows quicker formation of biomass and light intercepting structures. Similar to plant height, these traits are necessary in environments where fast growth and resource uptake are competitive strategies. Again, the test species are naturally found in coastal barrens and rock outcrops, harsh environments with relatively low resource availability. As such, high SLA species of this study would be found in the most fertile spaces of these harsh environments. SLA is also strongly positively correlated to photosynthesis and transpiration rates (Reich et al. 1999, Westoby et al. 2002), processes that translate to development of canopy structures.

There were a number of measured traits at all scales that were not predicted or predictive in my analysis. I expected stormwater capture to be driven by water loss measures as other studies find water loss and antecedent moisture conditions predictors of storm water capture performance (Berndtsson 2010, Jim and Peng 2012). In this study, water loss reflected water lost from the module between 10 minutes and 24 hours after the simulated rain event. These water loss measurements register the total change in weight from both evaporation from the substrate and transpiration by the plants, but only in the first 24 hours. A link between water loss and stormwater capture may have been found along with species differentiation in performance had the measurement period been longer, lasting from rain event to rain event. I also expected water loss to be linked to thermal cooling as Takakura et al. (2000) estimated transpiration to contribute up to 30% of cooling benefits. Plant transpiration works to create a green roof microclimate by cooling the air boundary layer over the substrate surface (Kolb and Schwarz 1986, Theodosiou 2013). Meng and Hu (2005) attributed surface temperature reductions of 25°C to evaporative cooling and Takebayashi and Moriyama (2007) noted that in summer months, vegetated green rooftops were significantly cooler due to plant transpiration. Conversely, in winter when plants were not active, green roofs exhibited similar temperatures as control unplanted green roofs.

The lack of a relationship between canopy density and water loss may also be due to the measurement method. Water loss partly consists of consumption by plants and this water loss should be correlated with canopy biomass (Lawlor 2002, Morgan et al. 2004, Knapp et al. 2008). However, uptake amounts by biomass is also counteracted by canopy shading of the surface. Shading of the soil surface through canopy coverage and creation of a larger air boundary layer size reduces evaporation and evapotranspiration (van Bavel and Hillel 1976, Lohr and Pearson-Mims 2001, Wolf and Lundholm 2008, Butler and Orians 2011, Tabares-Velasco and Srebric 2012). I note that in this study, *Gaultheria procumbens* and *Vaccinium vitis-idaea* had canopy densities of zero, due to extremely low growth forms such that their leaves did not reach the sampling frame, yet exhibited high water loss rates. I suspect that due to the lack of canopy biomass, evaporation from the soil surface was unhindered, however when these species were omitted from analysis, a relationship between canopy density and water loss still failed to emerge.

Canopy growth rate wasn't predictive of either green roof ecosystem function measured. I supposed that canopy growth rate would have predicted green roof services as plant growth, and therefore a non-zero or non-negative growth rate, would have water requirements that would be reflected in its stormwater capture ability. Growth would involve evapotranspiration that would influence surface cooling. Canopy growth rate could have been interpreted as a possible indicator of plant strategy, with close to 0 or negative rates indicating plants that respond to environmental stress or drought by growing little after initial planting or losing biomass. However, interpretation of these poor canopy growth rate values may be problematic as plants with 0 or negative rates could either simply be unsuited to green roof conditions, or conversely, highly stress tolerant. An alternative way to probe canopy growth rate could have been to measure carbon assimilation rates, or nutrient uptake rates, however these measurements are less easy to obtain.

Traits of leaf area (LA) and leaf dry matter content (LDMC) were not predictive of any vegetation characteristic. While LDMC is another indicator of plant strategy along the resource-axis, although most studies have coalesced around SLA as the key trait to consider (Westoby 1998, Wilson et al. 1999). Leaf area could have been related as high stress environments (drought, extreme cold or heat, high-radiation) select for smaller leaf areas (Cornelissen et al. 2003). As such, high water capture may have been predicted by larger leaf areas.

While I measured traits from naturally occurring populations, it may be satisfactory to measure traits from plants grown in a green roof system. Mokany and Ash (2008) found that some traits are consistent between natural populations and pot-grown species grown in controlled conditions. SLA is one trait which transfers well whereas whole plant traits weren't as consistent, perhaps requiring more time to resemble natural communities. However, when trait measurements were different in Monkany and Ash (2008), species rankings still held between field and pot-grown plants. This could expand the ability to measure traits if flora trait databases are lacking and using rankings to select green roof plant species.

Conclusion

This study used whole-plant and leaf traits measured from an average of five specimens found growing in naturally occurring populations. Green roof ecosystem services and vegetation characteristics were measured on the roof, averaged from replicate modules of the same species. Some traits were highly variable within a species, but a predictive model was constructed.

This study demonstrates that easy to measure leaf traits and canopy traits can predict green roof service provision. Greater service provision of stormwater capture and surface cooling were provided by plants with tall plant heights and greater specific leaf area. While the indices generated are relevant to this green roof study alone, traits can be used to screen potential plants for maximizing green roof service provision. From using traits available in flora databases, researchers and industry could vastly expand the plant palette for green rooftops while maximizing functional requirements.

References

Axmanová, I., Tichy, L., Fajmanová, Z., Hájková, P., Hettenbergerová, E., Li, C., Merunková, K., Nejezchlebová, M., Otypková, Z., Vymazalová, M., Zeleny, D. 2012. Estimation of herbaceous biomass from species composition and cover. Applied Vegetation Science, 15: 580-589.

Bartoń, Kamil. 2015. MuMIn: Multi-Model Inference. R package version 1.15.1. http://CRAN.R-project.org/package=MuMIn

Berndtsson, J.C. 2010. Green roof performance towards management of runoff water quantity and quality: a review. Ecological Engineering, 36: 351-360.

Blanusa, T., Vaz Monteiro, M.M., Fantozzi, F., Vysini, E., Li, Y., Cameron, R.W.F. 2013. Alternatives to *Sedum* on green roofs: can broad leaf perennial plants offer better 'cooling service'? Building and Environment, 59: 99-106.

Butler, C., Orians, C.M., 2011. Sedum cools soil and can improve neighboring plant performance during water deficit on a green roof. Ecological Engineering, 37: 1796-1803.

Butler, C., Butler, E., Orians, C.M. (2012). Native plant enthusiasm reaches new heights: perceptions, evidence, and the future of green roofs. Urban Forestry & Urban Greening, 11: 1-10.

Cook-Patton, S.C., Bauerle, T.L. 2012. Potential benefits of plant diversity on vegetated roofs: a literature review. Journal of Environmental Management, 106: 85-92.

Cornelissen, J.H.C., Lavorel, S., Garnier, E., Díaz, S., Buchmann, N., Gurvich, D.E., Reich, P.B., ter Steege, H., Morgan, H.D., van der Heijden, M.G.A., Pausas, J.G., Poorter, H. 2003. A handbook of protocols for standardised and easy measurement of plant functional traits worldwide. Australian Journal of Botany, 51: 335-380.

Crockford, R.H., Richardson, D.P., 2000. Partitioning of rainfall into throughfall. Stemflow and interception: Effect of forest type, ground coer and climate. Hydrological Processes, 14: 2903-2920.

Del Barrio, E.P., 1998. Analysis of the green roofs cooling potential in buildings. Energy and Building, 27: 179-193.

DeNardo, J.C., Jarrett, A.R., Manbeck, H.B., Beattie, D.J., Berghage, R.D., 2005. Stormwater mitigation and surface temperature reduction by green roofs. Transactions of the ASAE, 48: 1491-1496.

Dimoudi, A., Nikolopoulou, M., 2003. Vegetation in the urban environment: microclimatic analysis and benefits. Energy and Buildings, 35: 69-76.

Dunnett, N., Kingsbury, N. 2004. Planting options for extensive and semi-extensive green roofs. Greeing Rooftops for Sustainable Communities Conference, Portland, OR.

Dunnett, N., Nagase, A., Booth, R., Grime, P., 2008. Influence of vegetation composition on runoff in two simulated green roof experiments. Urban Ecosystems, 11: 385-398.

Dvorak, B., Volder, A. 2010. Green roof vegetation for North American ecoregions: a literature review. Landscape and Urban Planning, 96: 197 – 213.

Environment Canada (accessed August 28, 2015). National Climate Data and Information Archive: Canadian Climate Normals and Averages 1971-2010. Available at: http://climate.weather.gc.ca/climate_normals/index_e.html.

Farrell, C., Szota, C., Williams, N.S.G., Arndt, S.K. 2013. High water users can be drought tolerant: using physiological traits for green roof plant selection. Plant Soil, 372(1): 177-193.

Fogarty, C. (2009). Halifax monthly climate averages. Nova Weather. Accessed 19 February 2010 (available at http://www.novaweather.net/).

Fry, E.L., Power, S.A., Manning, P. 2013. Trait-based classification and manipulation of plant functional groups for biodiversity-ecosystem function experiments. Journal of Vegetation Science, 25: 248-261.

Gaffin, S.R., Rosenzweig, C., Parshall, L., Beattie, D., Berghage, R., O'Keeffe, G., Braman, D. 2005. Energy balance modeling applied to a comparison of green and white roof cooling efficiency. In: Proceedings of the 3rd North American Green Roof Conference: Greeing rooftops for sustainable communities, Washington, DC, The Cardinal Group, Toronto.

Getter, K.L., Rowe, D.B., 2006. The role of extensive green roofs in sustainable development. HortScience, 41: 1276-1285.

Getter, K.L., Rowe, D.B., Andresen, J.A., 2007. Quantifying the effect of slope on extensive green roof stormwater retention. Ecological Engineering, 31: 225-231.

Gross, N., Robson, T.M., Lavorel, S., Albert, C., Le Bagousse-Pinguet, Y., Guillemin, R., 2008. Plant response traits mediate the effects of subalpine grasslands on soil moisture. New Phytologist, 180: 652-662.

Guha, A., Reddy, A.R. 2013. Leaf functional traits and stem wood characteristics influencing biomass production of mulberry (*Morus* spp. L) genotypes grown in short-rotation coppice system. BioEnergy Research, 6: 547-563.

Jim, C.Y., Peng, L.H. 2012. Substrate moisture effect on water balance and thermal regime on a tropical extensive green roof. Ecological Engineering, 47: 9-23.

Jim, C.Y., Tsang, S.W., 2011. Biophysical properties and thermal performance of an intensive green roof. Building and Environment, 46: 1263-1274.

Jonasson, S. (1988). Evaluation of the point intercept method for the estimation of plant biomass. Oikos, 52: 101-106.

Knapp, A.K., Briggs, J.M., Collins, S.L., Archer, S.R., Bret-Harte, M.S., Ewers, B.E., Peters, D.B., Young, D.R., Shaver, G.R., Pendall, E., Cleary, M.B., 2008. Shrub encroachment in North America grasslands: shifts in growth form dominance rapidly alters control of ecosystem carbon inputs. Global Change Biology, 14: 615-623.

Kolb, W., Schwarz, T. 1986. Zum Klimatisierungseffekt von Pflanzbeständen auf Dächern, Teil I. Zeitschrift für Vegetationstechnick 9. Republished in Veitshoechheimer Berichte, Heft 39, Dachbegrünung. (cf. Dunnett and Kingsbury 2004).

Kumar, L., Schmidt, K.S., Dury, S., Skidmore, A.K., 2001. Imaging spectroscopy and vegetation science. In: Meer, F.D.v.d. & Jong, S.M. (eds.). Imaging spectrometry: basic principles and prospective applications. pp. 111-155. Kluwer Academic, Dordrecht, NL.

Lavorel, S., Grigulis, K., 2012. How fundamental plant function trait relationships scale-up to trade-offs and synergies in ecosystem services. Journal of Ecology, 100: 128-140.

Lawlor, D.W., 2002. Limitation of photosynthesis in water-stressed leaves: stomata vs. metabolism and the role of ATP. Annals of Botany, 89: 871-885.

Liu, K., Baskaran, B., 2003. Thermal performance of green roofs through field evaluation. In: Proceedings of 1st North American Green Roof Conference: Greening Rooftops for Sustainable Communities, Chicago, May 29-30. The Cardinal Group, Toronto.

Lohr, V.I., Pearson-Mims, C., 2001. Mulching reduces water use of containerized plants. HortTechnology, 11: 277-278.

Lundholm, J.T., 2006. Green roofs and facades: a habitat template approach. Urban Habitats, 4: 87-101.

Lundholm, J., MacIvor, J.S., MacDougall, Z., Ranalli, M., 2010. Plant species and functional group combinations affect green roof ecosystem functions. PLoS ONE, 5: E9677.

MacIvor, J.S., Lundholm, J., 2011. Performance evaluation of native plants suited to extensive green roof conditions in a maritime climate. Ecological Engineering, 37: 407-417.

MacIvor, J.S., Ranalli, M.A., Lundholm, J.T. 2011. Performance of dryland and wetland plant species on extensive green roofs. Annals of Botany, 107: 671-679.

Meng, Q., Hu, W., 2005. Roof cooling effect with humid porous medium. Energy and Buildings, 37: 1-9.

Mentens, J., Raes, D., Hermy, M., 2006. Green roofs as a tool for solving the rainwater runoff problem in the urbanized 21st century? Landscape and Urban Planning, 77: 217-226.

Mokany, K., Ash, J. 2008. Are traits measured on pot grown plants representative of those in natural communities? Journal of Vegetation Science, 19: 119-126.

Morgan, J.A., Pataki, D.E., Körner, C., Clark, H., Del Grosso, S.J., Grünzweig, J.M., Knapp, A.K., Mosier, A.R., Newton, P.C.D., Niklaus, P.A., Nippert, J.B., Nowak, R.S., Parton, W.J., Polley, H.W., Shaw, M.R., 2004. Water relations in grassland and desert ecosystems exposed to elevated atmospheric CO_2. Oecologica, 140: 11-25.

Nagase, A., Dunnett, N., 2012. Amount of water runoff from different vegetation types on extensive green roofs: effects of plant species, diversity and plant structure. Landscape and Urban Planning, 104: 356-363.

Oberndorfer, E., Lundholm, J., Bass, B., Coffman, R.R., Doshi, H., Dunnett, N., Gaffin, S., Köhler, M., Liu, K.K.Y, Rowe, B., 2007. Green roofs as urban ecosystems: ecological structures, functions and services. BioScience, 57: 823 – 833.

Oke, T.R., 1978. Boundary Layer Climates. Methuen & Co. Ltd., London.

Ollinger, S.V., 2011. Sources of variability in canopy reflectance and the convergent properties of plants. New Phytologist, 189: 375-394.

Poorter, H., Niinemets, Ü., Poorter, L., Wright, I.J., Villar, R., 2009. Causes and consequences of variation in leaf mass per area (LMA): a meta-analysis. New Phytologist, 182: 565-588.

Rayner, J.P., Farrell, C., Raynor, K.J., Murphy, S.M., Williams, N.S.G., 2016. Plant establishment on a green roof under extreme hot and dry conditions: The importance of leaf succulence in plant selection. Urban Forestry & Urban Greening, 15: 6-14.

Reich, P.B., Ellsworth, D.S., Walters, M.B., Vose, M.J., Gresham, C., Volin, J.C., Bowman, W.D., 1999. Generality of leaf trait relationships: a test across six biomes. Ecology, 80: 1955-1969.

Rixen, C., Mulder, C.P.H., 2005. Improved the water retention links high species richness with increased productivity in arctic tundra moss communiites. Oecologia 146: 287-299.

Sailor, D.J., 2008. A green roof model for building energy simulation programs. Energy and Buildings, 40: 1466-1478.

Sailor, D.J., 2008. A green roof model for building energy simulation programs. Energy and Buildings, 40: 1466-1478.

Sandmeier, S., Müller, C., Hosgood, B., Andreoli, G., 1998. Physical mechanisms in hyperspectral BRDF data of grass and watercress. Remote Sensing of Environment, 66: 222-233.

Tabares-Velasco, P.C., Srebric, J., 2012. A heat transfer model for assessment of plant based roofing systems in summer conditions. Building and Environment, 49: 310-323.

Taha, H., 1997. Urban climate and heat islands: albedo, evapotranspiration and anthropogenic heat. Energy and Buildings, 25: 99-103.

Takakura, T., Kitade, S., Goto, E., 2000. Cooling effect of greenery cover over a building. Energy and Buildings, 31: 1-6.

Takebayashi, H., Moriyama, M., 2007. Surface heat budget on green roof and high reflection roof for mitigation of urban heat island. Building and Environment, 42: 2971-2979.

Theodosiou, T.G., 2003. Summer period analysis of the performance of a planted roof as a passive cooling technique. Energy and Buildings, 35: 909-917.

Theodosiou, T., Aravantinos, D., Tsikaloudaki, K. 2013. Thermal behaviour of a green vs. a conventional roof under Mediterranean climate conditions. International Journal of Sustainable Energy, 33: 227-241.

Van Bavel, C.H.M., Hillel, D.I., 1976. Calculating potential and actual evaporation from a bare soil surface by simulation of concurrent flow of water and heat. Agricultural Meterology, 17: 453-476.

VanWoert, N.D., Rowe, D.B., Andresen, J.A., Rugh, C.L., Fernandez, R.T., Xiao, L., 2005. Green roof stormwater retention: effects of roof surface, slope and media depth. Journal of Environmental Quality, 34: 1036-1044.

Vendramini, F., Díaz, S., Gurvich, D.E., Wilson, P.J., Thompson, K., Hodgson, J.G., 2002. Leaf traits as indicators of resource-use strategy in floras with succulent species. New Phytologist, 154: 147-157.

Westoby, M. 1998. A leaf-height-seed (LHS) plant ecology strategy scheme. Plant and Soil 199: 213-227.

Westoby, M., Falster, D.S., Moles, A.T., Vesk, P.A., Wright, I.J., 2002. Plant ecological strategies: some leading dimensions of variation between species. Annual Review of Ecology and Systematics, 33: 125-159.

Wilson, P.J., Thompson, K., Hodgson, J.G. 1999. Specific leaf area and leaf dry matter content as alternative predictors of plant strategies. New Phytologist, 143: 155-162.

Wolf, D., Lundholm, J.T. (2008). Water uptake in green roof microcosms: effects of species and water availability. Ecological Engineering, 33: 179-186.

Wong, N.H., Chen, Y., Ong, C.L., Sia, A., 2003. Investigation of thermal benefits of rooftop garden in the tropical environment. Building and Environment, 38: 261-270.

Wright, I.J., Reich, P.B., Westoby, M., Ackerly, D.D., Baruch, Z., Bongers, F., Cavender-Bares, J., Chapin, T., Cornelissen, J.H.C., Diemer, M., Flexas, J., Garnier, E., Groom, P.K., Gullas, J., Hikosaka, K., Lamont, B.B., Lee, T., Lee, W., Lusk, C., Midgley, J.J., Navas, M., Niinemets, Ü., Oleksyn, J., Osada, N., Poorter, H., Poot, P., Prior, L., Pyankov, V.I., Roumet, C., Thomas, S.C., Tjoelker, M.G., Veneklaas, E.J., Villar, R., 2004. The worldwide leaf economics spectrum. Nature, 428:821-827.

Wright, J.P., Sutton-Grier, A. 2012. Does the leaf economic spectrum hold within local species pools across varying environmental conditions? Functional Ecology, 26: 1390-1398.

Yan, E., Milla, R., Aarssen, L.W., Wang, X., 2012. Functional relationships of leafing intensity to plant height, growth form and leaf habit. Acta Oecologica, 41: 20-29.

Chapter 4

Synthesis: Climate and plant traits as influences on green roof performance

The goals of this thesis were twofold: first to quantify the growth performance of monoculture and mixture plantings in different climates of Canada; second to elucidate the relationship between plant traits and green roof services through vegetation characteristics. In chapter two, there were significant differences in plant survival and performance across sites with identical green roof systems. In chapter three, green roof services of stormwater capture and thermal cooling were linked to two vegetation characteristics, with stormwater capture also directly linked to plant height. The path analysis we generated describes the functional relationship from plant traits to green roof services.

While each chapter probes different aspects of green roof performance, the results indicate how plant species and trait value can impact green roof function. Results from this study furthers understanding of green roof performance and present additional methodology for optimization.

Green Roof Plant Performance Across Three Climate Contexts of Canada

Overall plant performance was best at the London, Ontario green roof site. The London green roof experienced no plant death, had stable coverage and the largest canopy density. The better plant performance at the London green roof could be linked to the climate and/or the better suitability of the plant species to the London climate. London experiences more temperate conditions than both Calgary and Halifax, and our non-*Sedum* plant species, *Aquilegia canadensis* and *Sporobolus heterolepis,* are both native to Ontario and therefore adapted to the local conditions in London. The confluence of these two factors was clearly exhibited in better plant survival and greater canopy density. Plant death of *A. canadensis* and *S. heterolepis* occurred in Calgary, while only *S. heterolepis* died on the Halifax roof. As both Calgary and Halifax undergo longer and colder winters than London, and the plant deaths were observed following the first overwintering, we observe the effect of climate on plant survival. Regarding native species, even London's worst performing modules had equivalent or greater canopy density than the best modules in Calgary and Halifax, which lends support to the habitat template approach (Lundholm 2006). Even while shallow modules generated less canopy density, London's shallow modules performed as well as, or better than, the deep modules in Calgary and Halifax.

Although *Sedum spurium* is not native to any of our green roof locations, *S. spurium* was included in this study to provide a marker of industry requirements in terms of coverage and overall performance. No death of *S. spurium* occurred, while the other species did at some locations, and *S. spurium* outperformed *A. canadensis* and *S. heterolepis* in all performance measures. *Sedums* are considered to be a reliable green roof plant due to their drought-tolerance and wide climate suitability. Although *Sedums* have done well in many climates, they too are susceptible, like our test species, to climate conditions, having been shown to perform poorly in extreme hot and extreme cold conditions (Boivin 2001, Livingston et al. 2004).

Overall, our mixture planting treatment outperformed the best monoculture, *S. spurium*. Similar to other studies that showed better survival in mixture plantings (Nagase and Dunnet 2010, Butler and Orians 2011), no *S. heterolepis* or *A. canadensis* plugs died within a mixture module at any location. Mixture plantings were able to resource share and capitalize upon the best aspects of each species to generate greater canopy density and height.

From the finding that climate influences canopy density and plant survival, it follows that it would be beneficial to have tactics that maximize plant survival and best create canopy density within a climate condition. As canopy density influences green roof services of stormwater capture and thermal cooling. From my investigations, plant and leaf traits can serve as indicators of canopy density, generating a methodology for identifying potential strong service performers without needing to trial in-situ each and every plant species.

Predictors of Green Roof Performance by Plant Traits via Vegetation Characteristics

Green roof service provision of stormwater capture and thermal cooling were predicted by plant traits via vegetation characteristics. Our predictive traits were plant height and specific leaf area (SLA). Taller plants are typically found in resource-rich environments and are an indicator of competitive growth strategy. Environments with high water availability tend to have plants with tall canopies and deep roots with short root lengths. Specific leaf area is a marker of the rate of resource uptake and transformation into light-capturing structures. In my path analysis, these two traits were linked to storm water capture and thermal cooling, either directly or indirectly. Both traits were positively related to canopy density measures, where greater ability to quickly utilize resources into sunlight capturing structures manifested in above-ground biomass. In turn, canopy density was related to albedo measures, with higher reflectivity arising from greater canopy biomass. Oke (1978) found that plant biomass generally has higher reflectivity than soil, so with more above-ground biomass, more of the lower reflectivity substrate was covered and therefore overall reflectivity heightened. Canopy density also drove thermal cooling whereby greater canopy density better reduced/lowered substrate temperatures. It is reasoned that canopy reduces substrate temperatures through shading the surface and evaporative cooling processes. Albedo also reduced substrate temperatures, by reflecting solar radiation and preventing it from being absorbed by the substrate. Albedo was also negatively correlated with stormwater capture.

Surprisingly, not more traits were predictive in this study. I had predicted that LDMC would be linked to measures of water loss and stormwater capture as LDMC indicates how much water is being stored in the plant leaf. Wilson et al. (1999) advocated for LDMC as a useful plant measure and good substitute for SLA, arguing that LDMC is an indicator of the same resource-axis as SLA, tending to scale with 1/SLA, and has less inherent variability in its measurement. Cornelissen et al. (2003), however, only suggests LDMC as a viable substitute for SLA when leaf area is difficult to measure. I also predicted that leaf area, as it is related to leaf energy and water balance, would be related to green roof services, however SLA is a better indicator of the resource allocation and most research tends to coalesce around SLA as the key trait, showing stronger relationships than other traits to ecosystem function.

While we found that plant traits did not necessarily link to life form groups, traits rooted in morphology did tend to cluster more by growth form than leaf dry matter content (LDMC) or specific leaf area (SLA) which are not based on morphology. However, some growth forms showed some generalities and could, if needed, be used in lieu of traits for plant selection. Graminoid growth forms overall exhibited taller heights and greater leaf areas. Tall forms were generally tall as their name suggests, while creeping shrubs and creeping forms were consistently short. Forbs were generally small in leaf area. LDMC values were low in succulents, while SLA did not trend with any growth form.

Synthesis

From the findings of this research, we could adjust the path analysis linking leaf and whole-plant traits to green roof services with another layer of relationship where each of the traits driving green roof ecosystem services are in turn determined by a climate trait. While climate is a composite of factors and events and can not be assigned a single value, we know that climate impacts each of our trait drivers. From our chapter 2 work, we showed that climate influences canopy density growth within a growing season and from year to year. In chapter 3, that canopy density was shown to influence green roof albedo, stormwater capture and substrate cooling. Similarly, plant growth is significantly impacted by the amount, and also the timing, of precipitation (Knapp et al. 2002, Heisler and Weltzin, 2006, Heisler-White et al. 2009), and SLA affected by the soil water content (Albert et al. 2012). Thereby our canopy density, plant height and SLA traits were all influenced by the precipitation characteristics, and even more so influenced by temperature (Moles et al. 2014). So while traits provide a useful framework through which we can study ecosystem function/green roof services, it is insufficient to consider traits without considering the context of the green roof system inclusive of climate.

From the results of this work, our suggestion is to overlay plant trait information over existing approaches to green roof planting. From a successful green roof, trait values could be obtained and with the habitat template approach, applied to select native plant species of another location. Those plant species would be climate adapted, and the similar trait values could potentially drive services as well as the original roof. This approach could better guide plant choices among untested species, as well as allow plants declared unsuccessful in other locations to be reconsidered, for a climate where the species may be better suited. Trait information could also be used to guide mixture planting to ensure niche differentiation. Catalano et al. (2016) found green roof plant composition to drastically change over time in life growth forms and life strategies due to empty niches in the original plant composition. Even in a green roof with a phylogenetic approach of having plant species with greater shared evolution to ensure one goal or service (MacIvor et al. 2016), plants could be selected within those parameters for as much trait variability as possible to best provide niche differentiation, resource sharing and performance of other green roof services. Through niche differentiation, plant communities could remain more stable over time, potentially lowering maintence cost related to upkeep and removing volunteer plant species.

Suggested future research would involve more test species and an extended list of traits and services. A fuller exploration into traits driving canopy density could be investigated, as canopy density is related to aesthetic as well as functional services and what provides the green portion of the name. Green roof water uptake could be influenced by the photosynthetic pathways and specific root length of a plant species. Flammability (a liability on green roofs) could be investigated in traits of twig dry matter content and bark thickness and quality.

Extending this methodology of linking plant traits to green roof services could help identify the best performers and aid in optimizing desired green roof function. Green roof services could become more tailored to the needs of each location - be it storm water capture in cities with large rainfall amounts or limited sewer capacity, or thermal cooling in hot climates.

Conclusion

With incentive programs or bylaw requirements for green roof installation in urban centres, green rooftops are often created with the lowest input of cost and/or maintenance. This has encouraged the ubiquitous use of *Sedum* on green rooftops, often in monoculture planting. However, visual preference is for diverse plantings, which studies show also functionally perform better. This study showed mixtures to perform better than monocultures in terms of plant survival and canopy density across different climates. This study also found plant traits of plant height and specific leaf area markers of canopy density, and through canopy density, predictive of green roofs services of stormwater capture and thermal cooling. This research contributes to knowledge aiming to optimize green roof function through plant selection and highlights the impact climate has upon each factor of green roof performance. Climate determined traits can be used to guide green roof plant selection for desired green roof services.

References

Albert, K.R., Kongstad, J., Schmidt, I.K., Ro-Poulsen, H., Mikkelsen, T.N., Michelsen, A., van der Linden, L., Beier, C., 2012. Temperate heath plant response to dry conditions depends on growth strategy and less on physiology. Acta Oecologica, 45: 79-87.

Bovin, M., Lamy, M., Gosselin, A., Dansereau, B. 2001. Effect of artificial substrate depth on freezing injury of six herbaceous perennials grown in a green roof system. HortTechnology, 11: 409 – 412.

Butler, C., Orians, C.M., 2011. Sedum cools soil and can improve neighboring plant performance during water deficit on a green roof. Ecological Engineering, 37: 1796-1803.

Catalano, C., Marcenò, C., Laudicina, V.A., Guarino, R., 2016. Thirty years unmanaged green roofs: Ecological research and design implications. Landscape and Urban Planning, 149: 11-19.

Cornelissen, J.H.C., Lavorel, S., Garnier, E., Díaz, S., Buchmann, N., Gurvich, D.E., Reich, P.B., ter Steege, H., Morgan, H.D., van der Heijden, M.G.A., Pausas, J.G., Poorter, H. 2003. A handbook of protocols for standardised and easy measurement of plant functional traits worldwide. Australian Journal of Botany, 51: 335-380.

Heisler, J.A., Weltzin, J.F., 2006. Variability matters: towards a perspective on the influence of precipitation on terrestrial ecosystems. New Phytologist, 172: 189-192.

Heisler-White, J.L., Blair, J.M., Kelly, E.F., Harony, K., Knapp, A.K., 2009. Contingent productivity responses to more extreme rainfall regimes across a grassland biome. Global Change Biology, 15: 2894-2904.

Knapp, A.K., Fay, P.A., Blair, J.M., Collins, S.L., Smidth, M.D., Carlistre, J.D., Harper, C.W., Danner, B.T., Lett, M.S., McCarron, J.K., 2002. Rainfall variability, carbon cycling, and plant species diversity in a mesic grassland. Science, 298: 2202-2205.

Livingston, E.H., Miller, C., Lohr, M. 2004. Green roof design and implementation in Florida. In: Proceedings of the 2nd North American Green Roof Conference: Greening rooftops for sustainable communities, Portland, OR, The Cardinal Group, Toronto.

Lundholm, J.T., 2006. Green roofs and facades: a habitat template approach. Urban Habitats, 4: 87-101.

MacIvor, J.S., Cadotte, M.W., Livingstone, S.W., Lundholm, J.T., Yasui, S.E., 2016. Phylogenetic ecology and the greening of cities. Journal of Applied Ecology, 53: 1470-1476.

Moles, A.T., Perkins, S.E., Laffan, S.W., Flores-Moreno, H., Awasthy, M., Tindall, M.L., Sack, L., Pitman, A., Kattge, J., Aarssen, L.W., Anand, M., Bahn, M., Blonder, B., Cavender-Bares, J., Cornelissen, J.H.C., Cornwell, W.K., Díaz, S., Dickie, J.B., Freschet, G.T., Griffiths, J.G., Gutierrez, A.G., Hemmings, F.A., Hickler, T., Hitchcock, T.D., Keighery, M., Kleyer, M., Kurokawa, H., Leishman, M.R., Liu, K., Niinemets, Ü., Onipchenko, V., Onoda, Y., Penuelas, J., Pillar, V.D., Reich, P.B., Shiodera, S., Siefert, A., Sosinki Jr., E.E., Soudzilovskaia, N.A., Swaine, E.K., Swendon, N.G., van Bodegom, P.M., Warman, L., Weiher, E., Wright, I.J., Zhang, H., Zobel, M., Bonser, S.P., 2014. Which is a better predictor of plant traits: temperature or precipitation? Journal of Vegetation Science, 25: 1167-1180.

Nagase, A., Dunnett, N. 2010. Drought tolerance in different vegetation types for extensive green roofs: effects of watering and diversity. Landscape and Urban Planning, 97: 318-327.

Oke, T.R., 1978. Boundary Layer Climates. Methuen & Co. Ltd., London.

Wilson, P.J., Thompson, K., Hodgson, J.G. 1999. Specific leaf area and leaf dry matter content as alternative predictors of plant strategies. New Phytologist, 143: 155-162.