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GREEN ROOFS AS CONSTRUCTED ECOSYSTEMS: NATIVE PLANT PERFORMANCE AND INSECT DIVERSITY

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ABSTRACT

GREEN ROOFS AS CONSTRUCTED ECOSYSTEMS: NATIVE PLANT PERFORMANCE AND INSECT DIVERSITY

J. Scott MacIvor

Green roofs are increasing substantially in urban areas because they contribute to numerous environmental, social and economic benefits while occupying unused city space. This study has two objectives: to quantify the performance of native plants on extensive green roofs so to improve plant selection and design; and to compare insect diversity and composition of green roofs with that of adjacent ground level urban habitat which is critical in understanding green roof ecology. Several plant species had optimal survival and cover, as well as improved performance over growing medium only controls, although sizable differences existed within and between life form groups. Green roof insect diversity was similar to that of ground level urban habitat and many unique species were identified. Interestingly, plant richness had a sizable effect on insect richness. Taken together, these experiments demonstrate that plant selection is important in both improving green roof technical performance and creating urban habitat.

August 10th 2010

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CHAPTER 1

INTRODUCTION: "GREEN ROOFS AS CONSTRUCTED ECOSYSTEMS: NATIVE PLANT PERFORMANCE AND INSECT DIVERSITY"

Introduction

The conversion of green space into impervious surfaces in urban areas is intimately linked with human health and local ecosystem functioning (Collinge 1996; Alberti 2005; Foley et al. 2005). As urban populations continue to expand (Creasey 2007), these surfaces come to dominate the landscape, exacerbating the effects of environmental degradation, climate change and biodiversity loss on urban areas (De Groot et al. 2002; Fraser 2005). Whereas roads, sidewalks and parking lots are associated with the mobility and activity of pedestrian and vehicular traffic, building rooftops, which many would consider unexploited city space occupy up to 20-30% of total urban impervious surface within a city (Banting 2005; Carter and Jackson 2007). Rooftops not only divert up to 100% of stormwater and increase downstream erosion, but also account for up to 60% of building cooling load, contributing a significant source of building energy consumption (Maneewan et al. 2005). To address these urban land-use and energy issues, numerous cities across North America are covering their rooftops with growing medium and vegetation, creating green roofs.

Green roofs are contained vegetated spaces on top of flat or pitched roofs, and almost always consist of plants and growing medium, a waterproofing membrane, root barrier and a drainage layer (Oberndorfer et al. 2007). These constructed ecosystems are often categorized into two types: intensive and extensive, although hybrid roofs that have features of both are also common. Intensive green roofs are characterized by deeper growing medium and thus a more diverse plant community, but also higher cost, weight and material usage (Dunnett and Kingsbury 2010). Intensive roofs need regular maintenance and irrigation because of their size, whereas extensive green roofs are

designed to require very little upkeep. Extensive green roofs are characterized by shallow growing medium and are lightweight. Plants on extensive green roofs must be drought-tolerant because the shallow growing medium results in periodic drought and rapid fluctuations in soil moisture (Wolf and Lundholm 2008).

The vegetation and growing medium of green roofs contribute to numerous public (community-wide) and private (home-, building-owner) benefits. Two of the most valued benefits are stormwater retention and roof cooling during hot weather. Green roofs can capture up to 100% of the stormwater that falls on a green roof surface (Mentens et al. 2006), effectively reducing pollution dispersal and erosion, as well as (to a lesser extent) natural waterway degradation and the volume of stormwater diverted to water treatment facilities (Getter and Rowe 2006; Oberndorfer et al. 2007). During a rain event, water that falls on a green roof is temporarily stored in the growing medium, reducing its peak flow and runoff (DeNardo et al. 2005; Berndtsson et al. 2006). Plant water uptake and transpiration further increases the ability of a green roof to hold water after repeated rain events (Wolf and Lundholm 2008; Lundholm et al. 2010), also contributing to roof cooling.

Reducing the roof surface temperature during warm seasons results in decreasing energy costs to cool the interior space of a building (Del Barrio 1998; Liu and Minor 2005). Unlike conventional asphalt rooftops that absorb solar radiation and re-radiate it as heat (Oke 1978), vegetated surfaces have higher albedo and thus reflect a much greater percentage of incoming solar radiation. Green roof growing medium and vegetation also act as a thermal mass, dampening thermal fluctuations year round (Liu and Baskaran 2003; Del Barrio 1998). Not only are the optical properties of the green roof vegetation

important for roof cooling, aboveground biomass and cover increase evapotranspiration, decreasing roof surface temperature. For example, Takakura et al. (2000) showed that water evaporated from vegetative surfaces contributes up to 30% of total green roof cooling. Shading the roof surface (Niachou et al. 2001), and the trapping of low temperature air masses within pockets formed by dense vegetation (Dimoudi and Nikolopolou 2003) also contribute to roof cooling.

Many other tangible and intangible benefits of green roofs have been empirically examined or modeled to illustrate their contribution to environmental, economic and social wellbeing in cities. Green roofs mitigate the urban heat island effect, a consequence of solar radiation being absorbed by impervious surfaces that leads to human and environmental health issues as a result of increased ambient air temperatures compared to surrounding natural areas (Niachou et al. 2001; Getter and Rowe 2006). Green roofs also contribute to a reduction in CO_2 emissions and other airborne particulates, which adhere to leaf surfaces or are absorbed if particulate size is sufficiently small (Currie and Bass 2008). The vegetation and growing medium protects the roof membrane from extreme climate and the damaging effects of solar radiation, decreasing the frequency of replacing the roofing membrane – a significant expense (Dunnett and Kingsbury 2010). The physical impact of vegetation on the roof surface also increases sound insulation (Connelly and Hodgson, 2008). Intuitively, green roofs also increase green space in cities, which is often lacking in highly developed areas, making cities more livable (Oberndorfer et al. 2007). Finally, with sensible plant selection, green roofs can provide habitat for a wide range of locally occurring flora and fauna (Brenneisen 2006), potentially decreasing fragmentation of urban green spaces for highly mobile species such as insects and birds.

Plant Selection

Despite the considerable contribution of the vegetation layer to the performance of a green roof, research has generally ignored the influence of plant species and life-form composition in green roof functioning (Dunnett and Kingsbury 2010; Lundholm et al. 2010). Careful plant selection is essential to the success and performance of a green roof with respect to roof cooling and stormwater retention benefits, but also green roof aesthetics, in that, survival, cover and plant phenology may affect visual appeal and habitat value. A major hurdle in selecting plant species for a green roof is that the green roof microclimatic conditions greatly influence plant growth and survival, and thus, their contribution to various roof functions (Koehler 2003; Lundholm 2006). Extensive green roof microclimate conditions in particular are especially difficult and include shallow growing medium depth, drought conditions, and full exposure to sun and wind (Dunnett and Kingsbury 2010). At a smaller scale, roof inclination, shade from roof structures such as chimneys, reflective surfaces, exhaust pipes, and air conditioning units can also influence plant growth on green roofs (Koehler 2003). In temperate North American climates, green roof growing media must be able to withstand erosion from extreme wind, rain, ice, and snow. Moreover, the plants must survive long-term in a low organic, porous growing medium, which is used to reduce weed proliferation, soil erosion, weight, and to increase the water holding capacity (Oberndorfer et al. 2007). The growing medium is typically made up of mineral based mix of sand, gravel, recycled crushed brick, leica, peat, some organic matter and soil (Peck and Kuhn 2004).

Long-term research and industry experience have led experts to recommend extensive green roof plants be fast-establishing and low-growing, mat-forming or

cushion-forming species with succulent leaves or the ability to store water, shallow spreading roots, and efficient reproduction (White and Snodgrass 2003; Snodgrass and Snodgrass 2006; Dunnett and Kingsbury 2010). Mixing species with short and long life-cycles and those with only some or all of the traits mentioned is expected to be the best approach to ensure establishment, long-term viability and complementarity (Lundholm et al. 2010). That said, most green roofs in North America are modeled so closely after the modern European designs that many of the same species of plants are used (Natvik 2008). These industry standard species are typically *Sedums* (Family: Crassulaceae), which are almost always planted in monoculture (Rowe et al. 2003; VanWoert et al. 2005; Getter and Rowe 2008) and are extremely hardy (Snodgrass and Snodgrass 2006). Some (Hauth and Liptan 2003; Dewey et al. 2004; Monterusso et al. 2005; Thuring 2007; Sutton 2008; Lundholm et al. 2010) have described or measured the performance of locally occurring species on green roofs in North America. Whereas these studies have produced mixed results, numerous species have been shown to perform equal to or better than the industry standards. One study in particular, Lundholm et al. (2010) documents many successful species on extensive green roofs that occur along the coastal barrens of Nova Scotia. Designing green roofs as habitat for locally occurring plant communities, and more generally, combining conservation biology with architecture, planning and engineering are steps in an interdisciplinary process necessary to lessen the impacts of constructed impervious surfaces on biodiversity and ecosystem health.

Green Roof Habitat Value

Research on green roofs is dominated by studies of energy and stormwater performance and their potential role in providing habitat in cities is greatly understated.

Supporting biodiversity, particularly that of insects and plants in cities is critical to sustain essential ecosystem services such as pollination, pest control, and decomposition (Foley et al. 2005; Strauss and Biedermann 2006). Green roofs have been reported to provide habitat for numerous species, primarily insects and other invertebrates (Coffman and Davis 2005; Shrader and Boening2006; Kadas 2006; Lundholm et al. 2009; Colla et al. 2009), but also birds (Gedge 2003; Baumann 2006). Interestingly, Brenneisen (2006) showed that beetle and spider richness was highest on green roofs with the most diverse plant communities, and that the number of species increased over a period over time on green roofs specifically designed for biodiversity. Few studies have examined whether the diversity of invertebrates on green roofs differs from that of adjacent ground-level urban habitat, which would provide great insight into how best to manage these constructed ecosystems, and a first step in understanding green roof ecology. One such study in Germany, found that of thirty-eight Collembolan species inhabiting urban ground level soils, thirty of them were found inhabiting green roofs (Schrader and Boening 2006). Collembolans are decomposers, and thus promote soil development on green roofs and also reduce soil erosion by catalyzing microbial activity. Many other invertebrates are also active in decomposition and nutrient cycling processes within cities and increasing their presence with green roofs will only improve upon the numerous benefits already appreciated.

In cities, the greatest diversity of beneficial insect species is often supported in green spaces that have high floral richness (Savard et al. 2000; Smith et al. 2005) and that are completely exposed to sunlight (Matteson and Langellotto 2010). When planning ground-level urban habitat in a manner conducive to sustaining biodiversity, it is difficult

to increase sunlight without disturbing the surrounding buildings or large trees that are characteristic of most urban green spaces. Many green roofs, however, experience almost 100% exposure to sunlight, and thus may represent new and better opportunities to provide resources for pollinators compared with level-ground urban habitats. With research on plant survival and selection, these unused city spaces could be purposefully planted with species designed to attract pollinators and other beneficial insects, reconciling human needs with those of wild species (Rosenzweig, 2003).

Thesis objectives

In this study, three primary green roof functions were quantified: roof cooling, stormwater retention and habitat value for insects. Two functions, roof cooling and stormwater retention were evaluated (in chapter two) using experimental extensive green roof modules with 6 cm growing medium depth upon on a single rooftop, whereas habitat value was evaluated (in chapter three) on existing intensive green roofs with growing medium depths greater than 12" and adjacent ground level urban habitat found within the downtown area of Halifax, Nova Scotia. In chapter two, the objectives were to identify locally occurring plant species capable of surviving on extensive green roofs and to evaluate and compare the individual contribution of each species to extensive green roof cooling and stormwater retention benefits. Individual plant species and life-form group performance was quantified in the modular extensive green roof system to increase sample size and because the opportunity to retrofit existing buildings with lightweight extensive green roofs is greater than with heavier intensive green roofs.

The habitat value of green roofs, quantified as insect diversity and species composition, was compared between intensive green roofs and adjacent ground-level

green space because intensive green roofs comprise the majority of green roofs in Halifax (> 70%). Moreover, the extensive green roofs in the city are small and most are situated on single-family residential homes. The objectives in chapter three were to quantify the similarity of insect diversity between intensive green roofs and adjacent ground-level habitat patches by comparing species richness, composition and abundance of insect assemblages. Previous studies have tended to focus on the diversity of single green roofs (e.g. Coffman and Davis 2005; Lundholm et al. 2009), whereas here multiple sampling sites were necessary for statistical comparison. Although not compared in this study, intensive green roofs are expected to provide greater habitat value than extensive green roofs because although highly mobile species (e.g. bees, butterflies) will be able to access floral resources at both equally, the characteristically shallow growing mediums of extensive green roofs may dry out in the summer, or freeze over in the winter, which would be detrimental to soil-dwelling insects and larval development.

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CHAPTER 2

PERFORMANCE EVALUATION OF NATIVE PLANTS SUITED TO EXTENSIVE GREEN ROOF CONDITIONS IN A MARITIME CLIMATE

Abstract

Assessing plant species performance on extensive green roofs can improve green roof functioning, aesthetics, longevity and diversity of plant palettes available for the green roof industry. In this study, we evaluate not only survival and cover, but also roof cooling and stormwater retention properties of fifteen plant species native to the coastal barrens of Atlantic Canada in extensive green roof monocultures. After a complete growing season (May- October 2009), all but one species had greater than 80% survival, and ten species reached greater than 90% groundcover. Over the growing season, the top performing species reduced roof surface temperature by an average of 3.44°C and increased solar reflectivity by 3% over the growing-medium only controls. Moreover, the best species retained 75.3% of experimentally added stormwater. In general, graminoids performed better than creeping shrubs and forbs for most functions, although significant variation existed within life-form groups.

Keywords: Extensive green roofs, Native plants, Green roof design, roof cooling, stormwater retention

Introduction

Impervious surfaces are dominant features of the urban landscape and include roads, parking lots, building walls and rooftops. These surfaces absorb solar radiation and have an infiltration capacity close to zero (Booth and Jackson 1997), in contrast to the original vegetated habitat (Lundholm 2006), thereby intensifying several urban environmental issues such as increasing volume and decreasing quality of stormwater runoff (Bolund and Hunhammar 1999; Mentens et al. 2006), loss of floral and faunal diversity, and the urban heat island effect (Fraser 2005).

One solution to mitigate the impacts of conventional building rooftops in cities is to convert them into green roofs. Green roofing involves adding vegetation and growing medium to the roof surface of buildings over a series of root barrier and waterproofing membranes (Oberndorfer et al. 2007). Green roofs are categorized into two types: intensive and extensive. Intensive roofs have deep growing media and often a more diverse plant community, but structural load and costs are often high (Dunnett and Kingsbury 2010). Extensive green roofs are characterized by shallow growing medium, usually much less than 15cm, and are lightweight. Plants on extensive green roofs must also be drought tolerant and capable of surviving difficult growing conditions because the shallow substrate and full exposure to the environment permits periodic drought and rapid fluctuations in soil moisture (Wolf and Lundholm 2008; Dunnett and Kingsbury 2010). Extensive green roofs are less expensive and the focus of most research studies because quantifying their benefits improves the likelihood of widespread retrofitting of existing buildings in cities.

The public and private benefits of green roofs are well known, but vary

considerably according to geographic location, climate, building type, construction detail, and the vegetation selected (Oberndorfer et al. 2007; Spolek 2008). Whereas green roofs contribute aesthetic value (Peck et al. 1999), habitat for organisms in addition to plants (Brennisen 2006), mitigation of the urban heat island (Banting et al. 2005), CO_2 sequestration (Currie and Bass 2008), and protection of the roofing membrane (Clark et al. 2008), the two most intensely researched green roof functions are roof cooling (Liu and Minor 2005), and stormwater retention (Berndtsson et al. 2006; Getter and Rowe 2006). Although these benefits were identified long ago, research quantifying them with respect to plant selection on extensive green roofs is lacking (Rowe et al. 2005).

Roof cooling

Roofs account for up to 60% of a building's cooling load (Maneewan et al. 2005), and thus represent a potentially significant source of energy to maintain interior space at desirable temperatures. Unlike conventional roof surfaces that have low reflectivity and absorb solar radiation, vegetative surfaces reflect solar radiation. Vegetation canopy cover also improves shading (Niachou et al. 2001) and the trapping of low temperature air masses by above ground vegetative parts (Dimoudi and Nikolopolou 2003). In combination with evapotranspiration (Takakura et al. 2000) these plant properties cool the boundary layer immediately over the roof surface. Many studies have reliably shown that heat transfer is significantly greater on conventional roofs compared to green roofs (Clark et al. 2008) and although many studies conclude that plant selection influences roof cooling (e.g. Spolek 2008), few have examined the effect of plant selection beyond that of the industry-standard *Sedum* species. One exception is Lundholm et al. (2010) who found the best plant mixtures, which contained sedums, grasses and tall forbs, kept the surface

of an extensive green roof module ~2°C cooler than the best sedum monoculture, and ~11.5°C cooler than growing-medium only controls over three growing seasons.

Stormwater retention

Water uptake and transpiration by plants, in combination with evaporation and the soil moisture content of the growing medium, all influence an extensive green roof's ability to hold water after a rain event (Villarreal and Bengtsson 2005; Spolek 2008; Wolf and Lundholm 2008; Dunnett and Kingsbury 2010). In Toronto, Liu and Minor (2005) found that extensive green roofs were capable of retaining 57% of the annual rainfall, and in Vancouver, Connelly et al. (2006) found that extensive green roofs are capable of retaining up to 94% in the warm seasons. Large-scale modeling studies have also corroborated evidence in support of green roof stormwater retention. For example, Mentens et al. (2006) found that in a predicted scenario of 10% green roof coverage in Brussels, Belgium, regional stormwater runoff would be reduced up to 2.7%.

Whereas the bulk of stormwater captured is held in the growing medium, recent studies examining how plant selection influences water capture and loss over time have begun to identify locally occurring species that perform as well or better than the green roof industry standards in North America. In New York, Compton and Whitlow (2006) found that two natives, *Spartina alterniflora* and *Solidago canadensis*, had evapotranspiration rates 4-8 times greater than *Sedum* species grown in a greenhouse, suggesting building cooling potential might be enhanced using species other than *Sedums*. In Halifax, Wolf and Lundholm (2008) demonstrated that water holding capacity varies considerably between a number of native and industry-standard plants with respect to species type, growth form, and water availability. A more comprehensive examination in

Lundholm et al. (2010), in which different numbers and combinations of species were compared to examine the influence of diversity on roof performance, provided direct evidence that species with high water loss have greater potential for stormwater capture. Furthermore, that several native species performed this function equal to or better than *Sedums*.

Plant evaluation

Careful plant selection is essential to not only the success and performance of a green roof cooling and stormwater retention benefits, but also aesthetics, in that survival, cover and plant phenology may affect visual appeal. Long-term research and industry experience have led experts to recommend extensive green roof plants be fast-establishing and low-growing, mat-forming or cushion-forming species with succulent leaves or the ability to store water, shallow spreading roots, and efficient reproduction (White and Snodgrass 2003; Snodgrass and Snodgrass 2006; Dunnett and Kingsbury 2010). Mixing species with short and long life-cycles and those with only some or all of the traits mentioned is expected to be the best approach to ensure establishment, long-term viability and complementarity.

As mentioned, the most commonly used extensive green roof plants are succulents of the genus *Sedum*, followed by stress-tolerant grasses and herbs. *Sedum* species (Family: Crassulaceae) are widely used on extensive green roofs, often in monocultures and even on pre-grown mats, because they are extremely hardy, form relatively shallow roots, store water, and exhibit CAM photosynthesis which minimizes water loss (Durhman et al. 2006; Dunnett and Kingsbury 2010). Most *Sedums* used on green roofs in North America are native to Europe and Asia, but several are native to North America;

for example, *Sedum spathifolium*, *Sedum ternatum*, and *Sedum oreganum*, all of which have been incorporated into their regional green roof industry. Due to their tolerance of extensive green roof conditions, the industry-standard *Sedums* are often the first choice for installers in North America. This is also because they dominate the plant lists that must be borrowed from European regions were plant selection has been extensively studied (Thuring 2007). While employing *Sedums* in North America poses few problems, Sutton (2008) stated that the overuse of non-native *Sedums* on extensive green roofs could become problematic in the future, because they may acquire molds, fungus, and insect pests in the North American climate, which is drier than Europe with more extreme summers and winters.

Whereas one would expect that green roofs that incorporate locally occurring vegetation would provide greater biodiversity than a typical non-native *Sedum* roof, within certain regions there may not be native vegetation able to withstand the stresses encountered on an extensive green roof (Getter and Rowe 2006). Furthermore, because many native species have evolved in deep soils of particular microbial communities and nutrient regimes that are difficult to replicate on roofs, the extensive green roof environment is often a poor match for locally occurring plant species (White and Snodgrass 2003; Brenneisen 2006; Dunnett and Kingsbury 2010). For example, Monterusso et al. (2005) tested native grassland perennials on non-irrigated extensive green roofs in Michigan using 10cm of growing medium and only 4 out of 18 survived after three growing seasons. In another study on an irrigated intensive green roof, Dewey et al. (2004) evaluated 35 native grasses and wildflowers and found that 21 species were suitable for a meadow mixture with a 1.0 m media depth. Employing native plant species

on extensive green roofs is often further limited by a lack of availability and experience at nurseries. Moreover, seeds do not easily germinate on rooftops (White and Snodgrass 2003) and so greenhouse trials and experimentation become necessary to reduce cost and potential error. On the other hand, it is known that native plants have evolved to optimally grow and survive in their regional microclimatic conditions, pests and diseases (White and Snodgrass 2003; Dewey et al. 2004) and in Canada, this includes extreme winter weather. For example, Lundholm et al. (2010) describes ten native and three industry-standard species that all achieved close to 100% survival after three growing seasons on non-irrigated extensive green roof modules (2007-2009) in Halifax, Nova Scotia.

The first step in selecting plants suitable to an extensive green roof environment is to understand the characteristics of the habitat in which the species naturally occurs. Lundholm (2006) describes how selecting plants from habitats that exhibit microclimatic characteristics similar to extensive green roofs (shallow growing medium, high winds, intermittent flooding and drought as well as absence of tree cover) increases the chance of discovering suitable plant species. The habitat examples he gives include permanently open spaces such as rocky outcrops, cliffs and dunes, as well as alpine, heathland, and alvar habitats (Lundholm 2006). Experimentation with species from these habitat types on extensive green roofs is being carried out across Canada and the U.S. with a number of successful species coming from the coastal barrens of Atlantic Canada (Lundholm et al. 2009), the escarpment and alvar regions of Southern Ontario (Natvik 2008), and the coastal bluffs of British Columbia (Sharp 2003; Thuring 2007).

Developing lists of suitable green roof plant species for different regions in North America is not only valuable to optimize the functioning and longevity of the green roof

(Getter and Rowe 2006), but also to maximize the number of species available for installations as they becoming increasingly common in many cities. Designing green roofs with local plant communities whenever possible may not only require less irrigation and maintenance but may also augment pollination, food and habitat resources for native birds and insects (Brenneisen 2006; Lundholm 2006). In addition, policies or incentives for biodiversity and nature conservation may favor green roofs with locally distinctive and/or culturally representative plant communities (Oberndorfer et al. 2007). In this study, the objectives were to identify locally occurring plant species capable of surviving on extensive green roofs and to evaluate and compare the individual contribution of each species to green roof cooling and stormwater retention benefits. Furthermore, groundcover, aboveground biomass and growth rate were compared between species as these plant properties are thought to influence green roof performance (e.g. Wolf and Lundholm 2008; Ranalli et al. 2008; Lundholm et al. 2010). As mentioned, numerous extensive green roof candidate species inhabit the coastal barrens of Atlantic Canada, and it is from this habitat that plants were selected based on their growth habit, previous use on green roofs, and our ability to propagate them successfully.

Methods

Site

This study was conducted at the green roof testing facility located on top of a pre-existing green roof on the one-story, north section of the Patrick Power Library at Saint Mary's University in Halifax, Nova Scotia, Canada (44°39'N, 63°35'W). The green roof testing facility is approximately 5m from ground level and is sheltered from buildings 1 - 3 stories higher on all four sides. The pre-existing green roof was constructed

approximately 35 years ago, and consists mainly of grasses and wildflowers, 12" of clay soil, and a waterproofing membrane that covers concrete slabs. During the study period (May – October 2009), weather station data at the green roof testing facility showed that the monthly minimum mean temperature on the roof ranged from -0.4 - 10.1°C and the monthly maximum temperature ranged from 20.4 – 33.4°C. The monthly precipitation values for Halifax ranged from 98.3 - 135.4 mm (Fogerty 2009).

At the green roof testing facility, 160 modules (Botanical Nursery LLC, Wayland, MA, USA) were planted in monocultures (Fig. 1). Each module represents a single sampling unit and consists of a square plastic free-draining tray 36cm x 36cm along the inside perimeter. The modules were lined with a composite non-woven water-retention layer (Huesker Inc., Charollte, NC, USA), an Enkamat drainage layer, a site of attachment for plant roots and a filter layer (Colbond Inc., Enka, NC, USA). The substrate layer consisted of a (1:4) mix of Pro-mix potting soil (Premier Tech, Riviere-du-Loup, QC, Canada) and Sopraflor X growing medium (Soprema Inc., Drummondville, QC, Canada). Sopraflor X consists of crushed brick, blond peat, perlite, sand and vegetable compost. The Sopraflor X growing medium has a pH of 6.0-7.0, a total porosity of 60-70%, a bulk density of 1150-1250 kg/m^3 and an organic matter content (by dry weight) of 5-10%. The substrate layer was approximately 6 cm deep, and all modules were placed overtop of a weed barrier fabric (Quest Plastics, Ltd., Mississauga, ON, Canada) to prevent plants from rooting into the pre-existing green roof, and to reduce any influence the grasses might have on the monocultures.

Plants

Monocultures of fifteen species indigenous to Nova Scotia and a growing medium

only control were planted in 10 modules each. Life-form groups and plant species included were: graminoids (*Carex argyrantha* Tuck., *Carex nigra* (L.) Reichard, *Danthonia spicata* (L.) P. Beauv. Ex Roem & Schult., *Deschampsia flexuosa* (L.) Trin., *Festuca rubra* L. and *Luzula multiflora* (Ehrh.) Lej.); creeping forbs (*Fragaria virginiana* Duchesne); tall forbs (*Aster novae-belgii* L., *Solidago bicolor* L. and *Solidago puberula* Nutt.); and creeping shrubs (*Sibbaldiopsis tridentata* (Aiton) Rydb., *Empetrum nigrum* L., *Arctostaphylos uva-ursi* (L.) Spreng., *Vaccinium angustifolium* Aiton and *Vaccinium macrocarpon* Aiton) (Table 1). Six of these species performed well in previous studies with less replication: *D. spicata*, *D. flexuosa*, *S. tridentata, S. bicolor*, *E. nigrum* and *V. macrocarpon* (see Ranalli et al. 2008; Lundholm et al. 2010), and thus were included in this study to better elucidate their individual performance on extensive green roofs. Moreover, Snodgrass and Snodgrass (2006) identify graminoids from the genera *Carex*, *Festuca* and *Deschampsia* as groups in which shallow rooting species suited to extensive green roofs might exist. All species in this study were collected as seeds and cuttings from the coastal barrens at Chebucto Head, Nova Scotia (~25km southeast of Halifax). There were two exceptions: *F. virginiana* was collected as cuttings with rooting material from underneath the MacDonald Bridge in Dartmouth, Nova Scotia, and planted directly into the modules within 24 hours; *A. uva-ursi* was collected as 15 cm rootless cuttings of the terminal bud from large mature plants at Chebucto Head which were grown at M2 Horticulture in Truro, Nova Scotia using a misting system to promote root growth. Several other native plant species collected from the same location were germinated for this study, but weren't included due to insufficient numbers: *Carex scoparia*, *Rhododendron canadensis*, *Cornus canadensis*, *Juniperus horizontalis*, *Corema conradii*,

and *Hudsonia ericoides*.

All seeds and cuttings were propagated as plugs in the Saint Mary's University greenhouse and at the green roof testing facility between October 2008 and April 2009. Pro-Mix potting soil (Premier Horticulture, Riviere-du-Loup, QC, Canada) was used in the plugs and during seed germination. At time of planting, each of the plants selected differed in size both within and between species. To control for these differences within species, we planted a mix of both relatively large and small plants (of the same species) in all of the monoculture treatments. To control for differences between species, each species was planted with a maximum of 21 individual plants per module. The number of plants in each module was determined based on the plant species size and proximity to which 100% cover was to be expected by the end of the growing season. Planting began in mid-April, and data were collected between May and October 2009. To maintain species composition, any plants not planted that germinated in the module were removed by hand once or twice a month during the study period. The plants only received water through precipitation and artificial watering events necessary for the water capture and water loss experiments.

Green roof functions

Survival, cover, above ground biomass and growth rate

Survival, cover and an index of above ground biomass were recorded in all modules during the fourth week of each month in the study period (May – October 2009). Plant survival was assessed visually. Each plant was given a rating of 1 or 0, representing alive or dead, and these values were summed and divided by the total to get a percent survival. Cover was assessed with a three-dimensional pin-frame (Domenicio Ranalli, Regina,

Sask., Canada) using the point interception method (Floyd and Anderson 1987). The frame was as long and wide as one of the extensive green roof modules used in this study, 30 cm high and contained 16 equally spaced rods (6 mm diameter) (Fig. 2A). Percent cover (%) was recorded as the number of rods touched by any above ground portions of the planted monoculture divided by 16. To obtain a rough index of aboveground biomass for each monoculture, the number of times any portion of above ground plant material touched any of the pins was recorded. Only living and green portions of plants touching a pin were recorded. In May, August and October each pin was divided by height into three equal 11 cm sections: bottom (0-10 cm); middle (11-20 cm); top (21-30cm), and the number of touches at each level were recorded to obtain separate indexes of above ground biomass at each canopy level (Fig. 2B). Growth rate was recorded as the difference between the number of times a plant hit one of the pins in the frame at the final (or peak) measurement minus the number of hits recorded during the first measurement.

Surface and bottom temperature

Surface and bottom temperature (in °C) of each module were recorded using a Taylor 9878 Slim-Line Pocket Thermometer probe (Commercial Solutions Inc., Edmonton, AB, Canada) in the third week of May, July, August, September and October 2009. Temperature readings were taken at the center of modules when fully exposed to the sun (between 10:30 am and 1:30 pm AST) within the block design. Surface temperature was taken from the top 1cm of the module growing medium surface and bottom temperature was taken by inserting the probe through the growing medium at the base of the module (~5 cm).

Albedo

To characterize the albedo of the canopy created by each plant species, the incoming and reflected solar radiation was measured using a single LI-COR pyranometer sensor and LI-250A light meter (LI-COR Biosciences, Lincoln, NE, USA) attached to a retort stand at a fixed position (35cm) above each module. Incoming solar radiation (in W/m^2) was measured first by pointing the sensor at a 90° angle from the green roof module surface, then rotating the sensor 180° so that it faced the module to collect the reflected radiation. Measurements were made under clear sky conditions prior to solar noon (between 10:00 am and 1:00 pm), when incoming solar radiation is relatively constant. At the time of measurement, each module was removed from the remaining modules, and placed on top of a grey colored weed barrier fabric (Quest Plastics Ltd., Mississauga, ON, Canada) to ensure that reflected radiation values are representative only of the module being measured.

Stormwater capture and loss

A PX-Series Checkweighing bench scale (ATRON Systems Inc., West Caldwell, NJ, USA) was used to weigh each module to determine the gravimetric substrate moisture content in the second week of May, June, July, August and September. Each module was weighed, and then 1.30 kg of water was added to the centre using a watering can to signify a 10mm rain event, which was considered an intermediately sized rain event based on observations of daily rainfall from May - October 2008 (Fogerty 2009). Water was added slowly to the surface of the growing medium, to ensure than the entire volume of water made it into the module. Ten minutes after watering, each module was weighed a second time. Some water passed through the module within the first ten minutes, and any remaining was considered to represent the amount retained. After 24 hours, each module

was weighed a third time, and then a fourth and final time after 48 hours. If a natural rain event occurred within the 48 hour time period, the data were discarded.

The amount of water captured by each module during a rain event was calculated as the difference between the first weighing after watering, and the initial weight prior to watering. Total water capture represented the sum of the weights of water capture across all experimental rain events. Water loss is an indirect estimate of evapotranspiration and was calculated for each module as the difference between the second weighing of each module (10 minutes after watering) and the fourth weighing (48 hours following experimental addition of water). At each weighing, all modules were weighed within 1.5 hours of each other, and in the same order, from block 1 to 5 to reduce the possible differences in weight due to differences in the time of weighing. Temperature change, recorded as the difference between the surface and bottom temperature was plotted against water loss to determine whether these variables were correlated.

Experimental design

The modules were set within a randomized block design consisting of five blocks with two replicates of each species (and control) per block. Included in the block design was a second experiment employing the same modular system described above, but separate from this study and so not described here. Each of the five blocks consisted of two rows arranged with the other experiment such that each block was between three to four modules wide and up to twenty blocks long. Blocks were oriented approximately north to south since the dominant sunlight and shadow gradient (from surrounding buildings) occurred along a west to east orientation across the site. The modules were lined up touching each other, with walkways between each block. To compensate for

environmental variation within blocks, the modules were rotated such that the last three modules in the last row of each block were moved to the beginning of the first row, and all the other modules were moved back three spaces once a month during the watering experiments.

Initially there were differences in plant size among species that diminished over time, so rather than combining data from the entire study period, statistical analysis was performed only on data collected in August to ensure that those species in their first growing season had sufficient time to grow and mature outdoors. August was also the warmest month during the study period (see Lundholm et al. 2010). Prior to analysis, surface and bottom temperature were plotted and found to be correlated (R^2=0.74), thus only surface temperature was used because it better reflected the effect of the vegetation cover and above ground biomass (Fig. 3). A Levene's test in SPSS (v17.0) revealed that the variance in surface and bottom temperature, albedo, water capture and water loss (after 48 hours) data for August was homogeneous and so separate general linear models (GLM) ($\alpha = 0.05$) with block as a random factor were fit to each of the roof functions to determine if there was any significant difference. Separate GLMs for each roof function were repeated with plant cover (%) as a co-variable because cover varied considerably between species, and decreased by the end of the study period. As well, albedo and surface temperature were strongly linked to vegetative cover in another study using similar modules conducted during the same growing season (Lundholm et al. 2010) and so by including cover as a co-variable, the species-specific albedo values representing optical properties of the vegetation independent of cover could be assessed. After all GLM (with and without cover as co-variable), post-hoc analysis using a Tukey-HSD

adjustment for multiple comparisons ($\alpha = 0.05$) was employed to test for pairwise differences between all species and the growing medium only controls.

Results

Survival, cover, above ground biomass and growth rate

At the end of the growing season, 12 of the 15 species planted had close to 100% survival, two species (*A. uva-ursi* and *A. novae-belgii*) had greater than 80% survival and one species died altogether (*V. angustifolium*) (Table 1). The two species collected from cutting or dividing plants from off site, *F. virginiana* and *A. uva-ursi* had 99.44% and 80% survival respectively.

Ten of the species planted reached greater than 90% cover by October, and of these, seven were in their first growing season (Fig. 4). Of the species taken from cuttings of specimens that had already been planted on the green roof for three growing seasons, only *D. spicata* and *S. tridentata* had greater than 99% cover, while *E. nigrum* and *V. macrocarpon* reached 87% and 78% respectively.

As in Lundholm et al. (2010), graminoids had high aboveground biomass (Fig. 5) at the end of the study period; only 6 species total (4 grasses, *A. novae-belgii* and *S. tridentata*) reached the middle of the pins on the frame. These same species (except *S. tridentata*) also reached the top portion of the pin frame. *Carex argyrantha* had the highest recorded aboveground biomass in the middle and top canopy levels even though much of its canopy consisted of dead leaves (Fig. 5). Interestingly, even though *F. virginiana* reached almost 100% cover at the end of the study period, the aboveground biomass index (which is based on the total number of hits, rather than the number of pins hit) was relatively low. *Fragaria virginiana* grew extremely close to the growing medium

and thus their leaves hit each pin only once or twice. Similarly, species growth form seemed to influence their positioning of above ground biomass within each module, thereby affecting cover measurements. For example, some *A. novae-belgii* plants grew up and over the height of the pin-frame by September, thus those upper portions of the plant weren't quantified, and so a peak cover of only 71% was reported. Another species, *A. uva-ursi*, reached a peak cover of only 58%, likely because it grows upward, then bends over, such that the terminal bud grows along the surface of the growing medium, then up and over the edge of the module. In general, growth rates tended to increase over time (with the exception of *V. angustifolium*) and varied considerably more between life-form groups than within (Fig. 6).

The most prolific "invaders" were species planted in modules within the same block design, but not included in this study such as *Poa compressa*, *Sedum acre* and *Plantago maritima*. Other "invading" species included species planted in this study, such as *D. spicata* and *S. bicolor*, as well as some not intentionally planted in any of the modules or on the green roof testing facility including *Cerastium fontanum, Leontodon taraxacoides, Oxalis stricta, Poa pratensis, Taraxacum officianale*, and *Trifolium repens.*

Surface temperature

In general, surface temperature increased until July, and then decreased over the remainder of the study period for all species and growing medium only controls (Fig. 7). Vegetated module mean (±Std. error) surface temperature ranged from 21.5±0.67°C (*S. tridentata*) to 24.6±0.87°C (*A. uva-ursi*), whereas the growing medium only control surface temperature was 24.5±0.85°C (Table 2). The treatment with the highest recorded mean surface temperature (24.7±0.94°C) was *V. angustifolium,* which during the study

period had all died. In Lundholm et al. (2010) a conventional roof surface had an average surface temperature of 38.03±0.75°C during the same period. Thus the effect of vegetation in the highest performing species in this study resulted in an average surface temperature reduction of more than 3°C over growing medium only controls and more than 16°C over conventional roof surfaces over the entire study period. For the month of August when outdoor temperatures were highest, the module surface of *C. argyrantha* was an average of 3.44°C cooler than the growing medium only control. The lowest observed mean surface temperature was 14.33±0.23°C in *C. argyrantha* in October and the highest was 32.2±1.96°C for *V. angustifolium* in July.

When the effect of cover was included as a co-variable, neither cover [$F(1, 15) = 1.491$, $p = 0.226$], nor species effects [$F(15,144) = 1.054$, $p = 0.413$] significantly influenced surface temperature (Fig. 8). However, when the effect of cover was ignored, the species effect was significant [$F(15,144) = 2.061$, $p = 0.025$],even though post-hoc analysis revealed that only one species, *C. argyrantha*, was significantly different from the control.

Interestingly, there was a block effect where surface temperature in blocks 1-4 were significantly greater than that of block 5, both when cover was included as a co-variable [$F(4,60) = 14.282$, $p < 0.05$] and when it was removed [$F(4,60) = 14.980$, $p < 0.05$] (Fig. 9). These results suggest the effect of location significantly influences surface temperature above and beyond the effect of species or cover.

Albedo

For all species and the growing medium only control, albedo increased over the growing season and was greatest at the end of the study period (Fig. 10). The lowest mean

albedo observed was 0.15±0.013 in May for *V. angustifolium* and the highest was 0.32±0.006 for *C. argyrantha* in October. Over the entire study period, planted modules reflected on average 0.18±0.003 (*A. uva-ursi*) to 0.22±0.007 (*C. argyrantha*) of incoming solar radiation whereas growing medium only controls and the *V. angustifolium* modules reflected only 0.17±0.002 and 0.17±0.003 respectively (Table 2). Lundholm et al. (2010) reported the temporal mean albedo of a conventional roof control at the same research facilities over the same period as this study as 0.066±0.006. Thus the best performing species in monoculture increased reflectivity of the green roof by 22.2% over the growing medium only control and more than 200% over a conventional roof surface.

In general, there is a lot of variation in albedo within life-form groups; for example, both the top and bottom two performing species contained both a graminoid and a creeping shrub. When cover was included as a co-variable in the general linear model, both cover [$F(1,15) = 7.563$, $p = 0.007$] and to a greater extent, species [$F(15,144) = 34.001$, $p < 0.05$] significantly influenced the measured albedo values (Fig. 11). When the effect of cover was ignored, the species effect almost doubled [$F(15,144) = 57.410$, $p < 0.05$]. Whether cover was included as a co-variable or not, post-hoc analysis using a Tukey-HSD revealed that the albedo of *C. argyrantha* was significantly greater than all species included in the study, as well as the growing medium only control. *Sibbaldiopsis tridentata* also had a high albedo, and although it occupies a lower canopy level (see. Fig. 2), it was still significantly greater than the growing medium only control and all species except *C. argyrathra.*

No block effect was detected for albedo measurements when the effect of cover was included as a co-variable [$F(4,60) = 0.992$, $p = 0.419$] or when it was ignored

[$F(4,60) = 0.965$, $p = 0.453$]. This wasn't surprising, as the protocol used to collect this data requires that each module be moved from the block design and placed on a uniformly grey landscaping mat, in full sunlight, on level ground, to minimize environmental variability, which if left in the block formation, might have influenced the pyranometer readings.

Water Capture

Modules received 1.30 kg of water at each event and, on average over the study period, vegetated modules retained between 0.84±0.02kg (*D. spicata*) and 0.98±0.02kg (*C. argyrantha*), whereas growing medium only controls retained 0.93±0.02kg (Table 2). Thus, the best species in monoculture retained 75.3%, approximately 4% greater than that of the growing medium only control. Water capture was highest in June for all species and control (Fig. 12), which was the month in which the modules were driest (pers. Obv.). June also received the least amount of rainfall, and so it is expected the water content of each module was low so capture potential would be high.

For the month of August, *C. argyrantha* captured significantly greater amounts of water than the growing medium only control and all species (except *C. nigra*) (Fig. 13). On the other hand, *D. spicata* captured significantly less water than all species and the growing medium only control, except *V. macrocarpon*. All other species were not significantly different from one another and the growing medium only control. The effect of cover alone did not significantly influence water capture [$F(1,15) = 0.255$, $p = 0.615$], whereas species type did with the effect of cover included [$F(15,144) = 4.201$, $p < 0.05$) or ignored ($F(15,144) = 4.201$, $p < 0.05$).

The block effect significantly influenced module water capture, regardless of whether cover was included as a co-variable [$F(4,60) = 10.714$, $p > 0.05$], or not [$F(4,60) = 10.804$, $p > 0.05$] (Fig. 14). The block effect was stronger than the species effect and interestingly, block 1-4 were no different from one another, but all captured significantly more water than block 5. Water capture was greatest in the westernmost block moving towards the easternmost, likely because the westernmost blocks are drier prior to watering because they endure longer periods of full sunlight (Ranalli, 2010), allowing them to capture and store more of the water added when conducting water capture and loss experiments.

Water loss

In the vegetated modules, water loss ranged from 0.76±0.02kg (*D. spicata*) to 0.96±0.04 (*C. argyrantha*). In the growing medium only controls, average water loss over the study period was 0.92±0.03kg.Water loss was highest in May, a month after first being planted in the modules when the area occupied by the roots in the growing medium was lowest. Water loss decreased over the growing season for all species and growing medium only control (Fig. 15).

Cover was not a significant effect in influencing water loss between species [$F(1,15) = 0.255$, $p = 0.589$), however the species effect was significant in influencing water loss when cover was included as a co-variable [$F(15,144) = 3.589$, $p < 0.05$], and when cover is ignored [$F(15,144) = 3.688$, $p < 0.05$] (Fig. 16).

For water loss, the block effect stronger than the species effect and was significant when cover was included as a co-variable [$F(4,60) = 22.345$, $p < 0.05$) and when it was ignored [$F(4,60) = 22.499$, $p <0.05$) (Fig. 17). Water loss also increased from the

westernmost block to the easternmost, with block 1-3 losing significantly more water through evapotranspiration than block 4, and block 4 losing significantly more than block 5. Similar to water capture, exposure to sunlight likely increased water loss through evapotranspiration in the westernmost blocks; even though all measurements were made on sunny days between 11:00am and 2:00pm, and sun passed over the site hitting the westernmost blocks first.

Discussion

Overall

In this study, many of the locally occurring species showed equivalent, or improved performance for some or all of the green roof function measured compared to the growing medium only control, and the conventional roof surface described in Lundholm et al. (2010) from the same green roof testing facility. Surprisingly, some of the locally occurring species also exhibited improved performance over the common green roof succulents and grass species tested in Lundholm et al. (2010), even though the plants in that study had been outdoors in identical modules for three growing seasons. Another trend observed in this study was that there was a lot of variation within life-form groups for each of the green roof functions (e.g. Wolf and Lundholm 2008); however, there were certain species that consistently outperformed all others, such that life-form groups were not necessarily equivalent to functional groups, which are groupings of the species by how similarly they perform the roof functions measured in this study. By and large, whereas plant selection, survival and growth clearly improve green roof functioning, as well as numerous other benefits not documented in this study, environmental conditions influence extensive green roof performance over and above that

of the plants. This was evident in the block design, in which exposure to the sun increases from the westernmost section of the study area (block 1) to the easternmost (block 5) throughout the day.

Fortunately, the conditions for growing plants on extensive green roofs throughout northeastern North America are typically favorable, because of the cool climate and an ideal precipitation rate (Snodgrass and Snodgrass 2006). However, Carter and Butler (2008) suggested that diverse extensive green roofs that incorporate locally occurring and non-*Sedum* species will require more water to survive based on their results in Massachusetts, echoing both Monterusso et al. (2005) and Dewey et al. (2004). In this study, most species performed exceptionally well considering the challenges of the extensive green roof environment; some species even flowered by the end of the first growing season. Of the graminoids, *L. multiflora*, and *C. argyrantha* flowered within the first season. *Danthonia spicata* also flowered, and although these specimens had already been outdoors for two growing seasons, they were grown from fragments of the original plants. As of May 2010, many of the *C. nigra* and *L. multiflora* have flowered en masse (MacIvor, pers. observ.). Similarly, the only creeping forb in the study, *F. virginiana* flowered and fruited in the first year (256 strawberries collected and consumed) and have started again as of May 2010. Of the tall forbs, all of *A. novae-belgii* flowered, whereas only a few *S. bicolor* specimens flowered, and none of the *S. puberula*. Similar to results in Ranalli et al. (2008), *S. bicolor* mostly did not flower in the first growing season, but did in the second and third, which greatly improved its performance in monoculture and in mixture (Lundholm et al. 2010). Of the creeping shrubs, only *S. tridentata* flowered. Flowering is not only a valuable characteristic because it adds aesthetics and valuable

resources for pollinating birds and insects (Smith et al. 2005; Dunnett and Kingsbury 2010), but potentially also the green roof functions measured in this study, as flowering is associated with increasing biomass, which is related to roof cooling. The optical properties of flowers might also increase reflectivity of solar radiation.

In general, graminoids performed best, however, *L. multiflora* and *D. spicata* ranked last for water capture and loss, while *C. argyrantha*, *C. nigra* and *D. flexuosa* were among the top four performers for both functions. The variation in water retention that existed among graminoid species might reflect age, evapotranspiration rates or the effects of rooting structure on growing medium porosity. Snodgrass and Snodgrass (2006) recommended that "thirsty" grasses should be avoided on green roofs; however, combining them with species that hold water longer in the growing medium (e.g. *Sedum* spp.) might result in optimal evapotranspiration and roof cooling achieved through interspecific facilitation (Butler and Orians 2009). Support for this idea is reported in Lundholm et al. (2010) in which mixtures of three or five plant life forms, for example sedums, grasses and tall forbs, rather than monocultures or plantings of a single life-form group led to optimal water retention and loss. The performance of creeping shrubs was just as variable as that of the graminoids in that *Sibbaldiopsis tridentata* was one of the top performing species while the remaining creeping shrubs ranked among the worst. Even though the *S. tridentata* treatment contained plants divided from plants previously grown outdoors for two growing seasons, so did both *V. macrocarpon* and *E. nigrum*. The leaves of *V. macrocarpon* and *E. nigrum* were varying shades of red rather than green for the latter half of the growing season. A possible explanation is that these species are less stress-tolerant to consistently higher temperatures; the extensive green roof environment

is a few degrees warmer than the coastal barrens (Ranalli 2010). Niachou et al. (2001) found that green roofs covered by dark green vegetation maintained cooler roof temperatures that those covered with red vegetation. This suggests that planning green roofs with species that have leaves that change colour throughout the season might reflect another opportunity to further improve roof cooling in the warmest parts of the season, while mitigating the effect, and retaining visual interest, in the cooler seasons. Lastly, only a few individual *V. angustifolium* specimens survived the growing season, likely because the plants were not healthy at time of planting as a result of propagation technique employed in the greenhouse. It is recommended that this species be only planted as larger, robust plants, which would increase cost per plant, but also survival and blueberry yields. To increase cranberry yields from *V. macrocarpon*, a similar strategy is recommended. The provisioning of food is a unique and appealing characteristic of any extensive green roof plant, and not only did *F. virginiana* provide copious flowers and strawberries, it was the top performing forb, ranking within the top species in the study for all green roof functions. The *Solidago* species performed reasonably for their first growing season, but both ranked lower than the growing medium only control, which was in contrast with Lundholm et al. (2010) where *S. bicolor* was the top performing species in monoculture. *Aster novae-belgii* was among the species with the highest growth rate and dominated the upper canopy level compared with the other species tested, thus on roofs that do not experience extreme wind, this species might be best planted with groundcover species that occupy lower levels of the canopy.

Surface temperature

Although the growing medium only controls experienced one of the highest surface temperatures over the study period, two species (aside from the *V. angustifolium* modules) had higher surface temperatures: *D. flexuosa* and *A. uva-ursi*. It was not surprising that due to low cover in *A. uva-ursi* (58% at the end of the season) that the surface temperature of the modules containing this species did not perform as well as the controls, but it was not clear why *D. flexuosa* performed so poorly, particularly with respect to the other graminoids. These two species also had significantly higher surface temperatures than the top three performing species: *C. argyrantha*, *S. tridentata*, and *D. spicata*, which were all within the best six species for peak cover and peak aboveground biomass. Whereas *D. flexuosa* had one of the highest surface temperatures and *D. spicata* one of the lowest, the reverse was true in Lundholm et al. (2010), in which *D. flexuosa* was much larger and had greater aboveground biomass and *D. spicata* had less dead leaves. In this study, dead leaves and stalks were not included in the aboveground biomass index, even though it could have influenced surface temperature by contributing to cover. To optimize green roof cooling, Del Barrio (1998) recommended choosing plants with a mainly horizontal leaf distribution and large foliage. In support, Theodosiou (2003) found that the more extensive the foliage density of a particular plant, the more the heat flux through the roof decreases. Moreover, the top performing species in Lundholm et al. (2010) for roof cooling in monocultures and mixtures was *Solidago bicolor*, in which all specimens had large broad basal leaves and a tall flower stalk.

Since including cover as a co-variable in the analysis did not significantly influence surface temperature by treatment, a combination of different morphological properties of the above ground portions of each species, such as canopy cover and leaf

optical properties, likely act in shading the module surface and reflecting solar radiation, thereby reducing surface temperature. This is further supported by the fact that those species with the greatest cover had the lowest surface temperature when cover was not included as a co-variable. For example, low surface temperatures were observed over the study period in two of the species obtained by dividing plants that had been growing for three seasons outdoors (*S. tridentata* and *D. spicata*), but also *C. argyrantha* and *C. nigra*, which both had high growth rates and aboveground biomass indexes. Moreover, Lundholm et al. (2010) found that the best plant mixtures, which were also among the top performers for cover and biomass, kept the surface of an extensive green roof module ~11.5°C cooler than growing-medium only controls.

Albedo

As vegetated surfaces almost always have greater albedo values than non-vegetated surfaces (Oke 1978), it was not surprising that the growing medium only control had the lowest recorded albedo over the study period. The *V. angustifolium* treatment had the same albedo as the control, although this was expected, as almost all of the specimens died before the end of the season. *Arctostaphylos uva-ursi* was the next lowest performing species, which coincidentally had the lowest peak ground cover. In general, albedo increased with increasing peak cover and biomass. Those species with the greatest albedo were also those with the lowest surface temperature. For instance, five of the top performing species: *C. argyrantha*, *C. nigra*, *D. spicata, S. tridentata*, and *F. virginiana* placed within the top performing species for albedo, surface temperature, peak aboveground biomass and cover. These observations agree with results in Lundholm et al. (2010) who found that albedo was related to biomass and canopy cover, where greater

biomass corresponded to overall greater reflection of solar radiation. Interestingly, although all five of these top performers reached close to 100%, they include three growth forms (graminoids, forbs, shrubs) and occupy different levels of the canopy.

The effect of cover significantly influenced the variation in albedo recorded for species and the growing medium only control; however, the species effect was so strong, to a point where the effect on albedo did not differ considerably whether cover was included as a co-variable or not. One exception was that both growing medium only controls and *V. angustifolium* modules had significantly higher albedo than *E. nigrum* and to a lesser extent *V. macrocarpon* when the variation attributed to cover was separated from the species effect. When the effect of cover is ignored, the opposite occurs and both *E. nigrum* and *V. macrocarpon* exhibit greater reflectance than the growing medium only control and *V. angustifolium*. Clearly, the growing medium used in the study had a higher reflectance than the foliage of some species used in the study, particularly those within the creeping shrub life-form group (e.g. Ranalli 2010). Thus, while plant cover influences albedo, the species effect suggests that plant properties such as leaf colour and seasonal growth periods might be mechanisms of plant performance worth examining to increase green roof solar reflectance, and the subsequent roof cooling and economic savings. Moreover, using a more reflective growing medium could increase the overall albedo of the green roof, thereby increasing its roof cooling potential. Another noteworthy effect of the growing medium on the reflectivity recorded in the study was that even though there was no vegetative growth in either the growing medium only control, or the *V. angustifolium* modules, both treatments experienced increasing albedo over the study period, but much less so than the planted treatments. We suspect that environmental

conditions influenced the positioning of growing medium particles of differential reflectivity in such a way that at planting, the light orange colored crushed brick was better dispersed throughout each module, then over time rain and wind pushed the smaller, darker growing medium particles lower into the module, making the crushed brick more pronounced on the module surface. Those treatments with less cover had more exposed brick, which when very dry is a light orange/brown, and lighter colors reflect solar radiation better than darker colors (Oke 1978).

Water capture

Although differing in plant species, growing medium and data collecting protocols, the vegetated extensive green roof modules in this study captured similar amounts of water as the modules described in Carter and Butler (2009) (average captured volume = 67%) and slightly less so than the extensive cells in Liu and Minor (2005) (average captured volume = 70-90%). In contrast with Lundholm et al. (2010) in which growing medium only controls captured more water than all other species in monoculture, the temporal means which reflect the average water captured over the study period for each species shows that three graminoids (*C. argyrantha*, *C. nigra*, and *D. flexuosa*) captured more than the control, and one creeping forb (*F. virginiana*) captured an equal amount (Table 2). Of these species only *D. flexuosa* was included in Lundholm et al. (2010), in which it was one of the worst performing species for this function, potentially because in that study it had been outdoors for three growing seasons, whereas it was only in its first growing season in this study.

As reported in other studies (e.g. VanWoert et al. 2005; Carter and Butler 2008; Lundholm et al. 2010), there was a minimal effect of vegetation on water capture over

and above that of the growing medium only controls. Lundholm et al. (2010) found that *D. spicata* captured the least amount of water overall, and in this study, another clump-forming grass, *L. multiflora* captured significantly less water than most species. Both of these species formed extremely dense fibrous roots in the modules to the point where it was difficult to insert the hand-held temperature probe by the end of the study period. It is thought that the low water capture and loss values recorded for these species is related to their rooting density, and the surface area it occupies within the module, which would reduce growing medium porosity and the overall volume of space in which water could be stored and captured. Since these species both share characteristics of a suitable extensive green roof grass (e.g. cushion-forming, shallow rooting systems), are found naturally occurring in characteristically similar habitats and performed comparably for all functions measured, it would likely be possible to substitute one for the other on an extensive green roof installation, depending on regional availability.

Water loss

In this study, the growing medium only control was one of the highest performers for water loss, whereas some planted monocultures with close to 100% (e.g. *Carex* spp., *F. rubra*) or much less cover (e.g. *A. uva-ursi*, *A. novae-belgii*, and *V. angustifolium*) performed as well or better in the August analysis and ranking of the temporal means (Table 2). As well as having the highest temperature and lowest albedo, it is likely that any water in the growing medium only control is being evaporated at a greater rate than in vegetated modules (Wolf and Lundholm 2008). Lundholm et al. (2010) suggested that low diversity canopies, such as in monocultures, which were the focus of this study, prevent evaporation (affecting water loss) by reducing the amount of water that can be

captured in subsequent rain events by shading the surface of the growing medium. However, some grasses and other species performed almost as well as the growing medium only control in losing water over the 48 hour period, likely because they have high transpiration rates, which in turn contribute to roof cooling (Snodgrass and Snodgrass 2006; Dunnett and Kingsbury 2010). This is evident in that some of the species with the highest water loss, *C. argyrantha*, *F. rubra*, and *S. tridentata* had low surface temperatures and high reflectance. Although the block effect significantly influenced both surface temperature and water loss more than species differences, in general, treatments that had low cover had greater surface temperatures, and thus greater differences in temperature that would lead to greater water loss through evaporation. Surface temperature varied more than bottom temperature because the amount of growing medium in each module was constant, whereas vegetative cover differed considerably and has a more direct influence on the more variable surface temperature. Interestingly, some species with little change in temperature from surface to bottom such as *C. argyrantha* and *C. nigra* had high water loss. For these species, having high aboveground biomass and cover may shade and reflect solar radiation, but also create more surface area for transpiration. Clearly, these species are effective at taking in copious amounts of water, which agrees with their ranking as top performers for water capture. Species that can increase water loss from the growing medium will not only improve roof cooling through evapotranspiration, but also create more space (e.g. reduce soil moisture content) for water capture in subsequent rain events.

Although cover as a co-variable did not significantly influence the mean water loss between species, the top three performing treatments in August analysis were also

within the top performers for cover and biomass (Fig. 14), agreeing with previous studies that have demonstrated the relationship between leaf area or biomass and evapotranspiration rates (Lundholm et al. 2010). Interestingly, it was the block effect (Fig. 15) that explained more of the variation than the species effect, suggesting environmental characteristics of green roofs such as wind, average sunlight and shading play an important role in the optimization of water loss in different species (Dunnett and Kingsbury 2010).

Comparison to industrial standard extensive green roof vegetation

In searching for alternative, and locally occurring species for consideration as suitable extensive green roof species, basic vegetative research on both the industry standards and alternative species is required in a particular region (Ranalli 2010). Despite some differences between the modular conditions in this study and Lundholm et al. (2010) (all plants were in their third growing season, each module was planted with 21 plants, and only 3 replicates per species in the latter study), there were surprising differences in performance between the species in this study and the industry standard green roof succulents (*Sedum acre* and *Sedum spurium*) and grass species (*Poa compressa*). In Lundholm et al. (2010), *S. acre* had excellent cover, likely resulting in its low roof surface temperature; however, water capture was also low. Overall, *S. acre* consistently performed worse than several species in my study, in particular, *C. argyrathra*, *C. nigra*, *F. virginiana*, and *S. tridentata*. The other species tested, *S. spurium*, had low cover, in part because it was severely infested by aphids, resulting in leafless stalks trailing over the growing medium surface, whose leaves returned in September and October. *Sedum spurium* also had very shallow roots, as well as high

water loss, comparable to that of the control. Again, several of the species in my study performed better than this species, even though only in the first growing season. Lastly, *P. compressa* had similar growth rate and water loss as *C. argyrantha*, but performed consistently lower for all functions measured. Clearly, *C. argyrantha*'s performance under such difficult conditions as presented in this study should warrant its use in place of other non-native, medium sized grasses, such as *P. compressa*, on extensive green roofs in northeastern North America, whenever possible.

Invasibility

A variable worth exploring in future experiments that quantify green roof performance is the invasibility of the green roof to species not initially planted. In this study, a number of cosmopolitan and native plant species invaded the modules, requiring monthly removal to reduce any effect they might have had on survival or performance of the intentionally planted species. A number of plant species invaded the planted modules over the study period and were removed monthly. Preventing weedy or unwanted species from persisting on green roofs requires maintenance, thereby increasing the overall cost. Studies that monitor the invasibility of extensive green roofs should examine how growth form of green roof plants might decrease the likelihood of weedy species persisting. Many green roof companies now offer pre-grown *Sedum* mats that provide close to 100% cover upon installation, thereby decreasing the growth of unwanted species while the desirable species establish. In this study, monocultures of certain species; for example, *S. tridentata*, *L. multiflora* and *D. spicata* tended to have less "invaders" in their replicates than species with less cover such as *V. macrocarpon* and *A. uva-ursi*.

Summary

If green roofs are properly designed and installed with a diverse plant community adapted to the local conditions, their contribution to mitigating the effects of impervious rooftops and restoring some of the ecology of highly developed urban areas could be substantial (Platt 2004). Many cities in North America recognize their potential and are now installing green roofs at an unprecedented rate with the help of incentive programs, by-laws, construction standards and support from the public, government and all levels of industry (Green Roofs for Healthy Cities 2009).This study demonstrates that there is value in comparing the performance of novel green roof species both locally-occurring and those shown to work well in other regions, because understanding their performance on extensive green roofs will improve roof function, diversity and habitat value. This type of research is also important ground-work in initiating local green roof activity, in that, understanding which plants survive and perform optimally increases confidence and support within regional and national green roof industries.

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Table 1. A list and description of species planted in the study. In the Seeds column, the dates refer to when they were germinated and in the Cuttings column the dates refer to when they were removed from the source plant. In the Collected column, RH = Residential house, Halifax, NS; CH = Coastal barrens at Chebucto Head, NS; SMU = the Saint Mary's University Green Roof Testing Facility, Halifax, NS; PP = Point Pleasant Park, Halifax, NS; and MB = MacDonald Bridge, Dartmouth, NS.

Latin name	Common name	Family	Growing seasons	Seeds	Cuttings	Collected	Planted per module	Foliage	Life-form group	Survival at end of study
Carex argyrantha	Hay Sedge	Cyperaceae	1	Sept. 08	-	RH	18	Perennial	Graminoid	99.4±0.6%
Carex nigra	Black Sedge	Cyperaceae	1	Sept. 08	-	CH	18	Perennial	Graminoid	100±0.0%
Danthonia spicata	Wire Grass	Poaceae	1 - 3	Sept. 08	Apr. 09	CH/ SMU	15	Perennial	Graminoid	100±0.0%
Deschampsia flexuosa	Wavy Hair Grass	Poaceae	1	Sept. 08	-	CH	14	Perennial	Graminoid	97.9±1.1%
Festuca rubra	Red Fescue	Poaceae	1	Sept. 08	-	CH	21	Perennial	Graminoid	100±0.0%
Luzula multiflora	Common Woodrush	Juncaceae	1	Sept. 08	-	CH	20	Evergreen	Graminoid	99.5±0.5%
Aster novae-belgii	New York aster	Asteraceae	1	Jan. 09	-	PP	8	Perennial	Tall forb	80.0±6.8%
Solidago bicolor	White Goldenrod	Asteraceae	1	Jan. 09	-	SMU	21	Perennial	Tall forb	99.0±1.0%
Solidago puberula	Downy Goldenrod	Asteraceae	1	Jan. 09	-	CH	15	Perennial	Tall forb	95.8±1.5%
Fragaria virginiana	Wild Strawberry	Rosaceae	Unknown	-	Apr. 09	MB	18	Perennial	Creeping forb	99.4±0.6%
Arctostapholos uva-ursi	Bearberry	Ericaceae	Unknown	-	Sept. 08	CH	10	Evergreen	Creeping shrub	85.1±1.9%
Empetrum nigrum	Black Crowberry	Empetraceae	1 - 3	Sept. 08	Apr. 09	CH/ SMU	18	Evergreen	Creeping shrub	99.4±0.6%
Sibbaldiopsis tridentata	Three-toothed Cinquefoil	Rosaceae	1 - 3	Sept. 08	Apr. 09	SMU	15	Evergreen	Creeping shrub	99.3±0.7%
Vaccinium angustifolium	Low-bush Blueberry	Ericaceae	1	Sept. 08		CH	13	Evergreen	Creeping shrub	2.7±1.9%
Vaccinium marcocarpon	Large Cranberry	Ericaceae	3	-	Apr. 09	SMU	16	Evergreen	Creeping shrub	99.4±0.6%

Table 2. Performance of each roof function ranked from best to worst by the temporal mean (mean±SE) of each species and the growing medium only control (except water capture and loss, which included only data from May-August because September data greatly decreased the mean performance over time). Peak biomass and cover values reflect only the final measurement (October).

	Rank	Albedo (%)	Temp. (°C)	Water Loss (kg)	Water Capture (kg)	Peak biomass index	Peak cover (%)
Best	1st	*C. argyrantha* (0.22±0.007)	*S. tridentata* (21.5±0.67)	*C. argyrantha* (0.96±0.04)	*C. argyrantha* (0.98±0.02)	*C. argyrantha* (126.3±5.02)	*C. argyrantha* (100±0.00%)
	2nd	*S. tridentata* (0.21±0.004)	*D. spicata* (22.1±0.68)	*A. uva-ursi* (0.92±0.03)	*D. flexuosa* (0.95±0.02)	*F. rubra* (114.9±4.71)	*C. nigra* (100±0.00%)
	3rd	*F. virginiana* (0.20±0.004)	*C. argyrantha* (22.2±0.73)	*C. nigra* (0.92±0.03)	*C. nigra* (0.94±0.02)	*C. nigra* (91.4±3.30)	*D. spicata* (100±0.00%)
	4th	*D. spicata* (0.20±0.004)	*C. nigra* (22.7±0.80)	*A. novae-belgii* (0.92±0.03)	*F. virginiana* (0.93±0.02)	*D. spicata* (75.5±3.00)	*F. rubra* (100±0.00%)
	5th	*L. multiflora* (0.19±0.004)	*F. virginiana* (22.9±0.79)	Control (0.92±0.03)	Control (0.93±0.02)	*L. multiflora* (59.2±2.77)	*L. multiflora* (100±0.00%)
	6th	*C. nigra* (0.19±0.004)	*L. multiflora* (23.0±0.75)	*V. angustifolium* (0.91±0.03)	*V. angustifolium* (0.92±0.02)	*S. tridentata* (50.7±2.42)	*S. tridentata* (99±0.63%)
	7th	*S. bicolor* (0.19±0.004)	*E. nigrum* (23.4±0.85)	*S. bicolor* (0.91±0.03)	*E. nigrum* (0.92±0.02)	*D. flexuosa* (44.0±3.09)	*S. bicolor* (96±1.00%)
	8th	*F. rubra* (0.19±0.005)	*S. puberula* (23.6±0.91)	*S. tridentata* (0.90±0.02)	*A. uva-ursi* (0.91±0.02)	*A. novae-belgii* (27.8±2.63)	*F. virginiana* (95±1.60%)
	9th	*A. novae-belgii* (0.19±0.005)	*V. macrocarpon* (23.6±0.87)	*F. virginiana* (0.90±0.03)	*F. rubra* (0.91±0.02)	*F. virginiana* (23.7±1.51)	*D. flexuosa* (93±2.04%)
	10th	*S. puberula* (0.18±0.004)	*S. bicolor* (23.8±0.90)	*F. rubra* (0.90±0.02)	*A. novae-belgii* (0.91±0.02)	*E. nigrum* (20.2±1.07)	*S. puberula* (90±2.67%)
	11th	*V. macrocarpon* (0.18±0.003)	*A. novae-belgii* (23.9±0.87)	*D. flexuosa* (0.88±0.03)	*L. multiflora* (0.91±0.02)	*S. bicolor* (19.6±1.07)	*E. nigrum* (87±1.97%)
	12th	*E. nigrum* (0.18±0.003)	*F. rubra* (23.9±0.90)	*S. puberula* (0.88±0.03)	*S. tridentata* (0.91±0.02)	*S. puberula* (19.5±0.95)	*V. macrocarpon* (78±2.20%)
	13th	*D. flexuosa* (0.18±0.003)	Control (24.5±0.85)	*E. nigrum* (0.88±0.03)	*S. puberula* (0.89±0.02)	*V. macrocarpon* (15.5±1.78)	*A. novae-belgii* (71±2.67%)
	14th	*A. uva-ursi* (0.18±0.003)	*D. flexuosa* (24.5±0.87)	*V. macrocarpon* (0.87±0.03)	*S. bicolor* (0.89±0.02)	*A. uva-ursi* (10.8±0.74)	*A. uva-ursi* (58±2.24%)
	15th	*V. angustifolium* (0.17±0.003)	*A. uva-ursi* (24.6±0.87)	*L. multiflora* (0.86±0.03)	*V. macrocarpon* (0.88±0.02)	*V. angustifolium* (0.0±0.00)	*V. angustifolium* (0±0.00%)
Worst	16th	Control (0.17±0.002)	*V. angustifolium* (24.7±0.94)	*D. spicata* (0.76±0.02)	*D. spicata* (0.84±0.02)	Control (0.0±0.00)	Control (0±0.00%)

Figures

Figure 1. The block design and modules employed in the study.

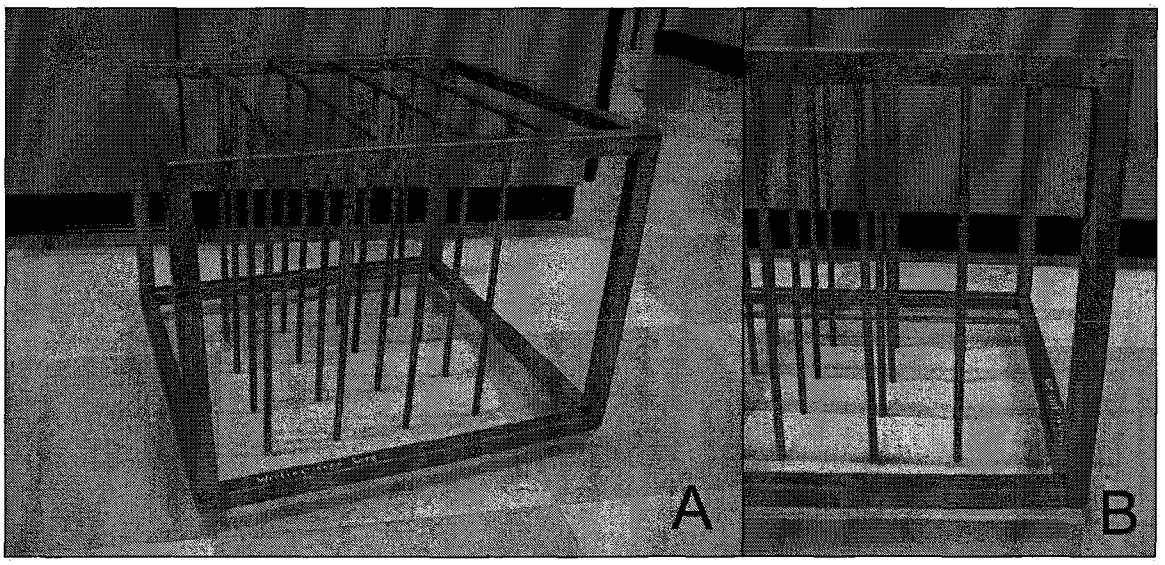

Figure 2. A. The pin frame used in the study. B. How each pin was divided into three equally spaced heights to record canopy changes in aboveground biomass.

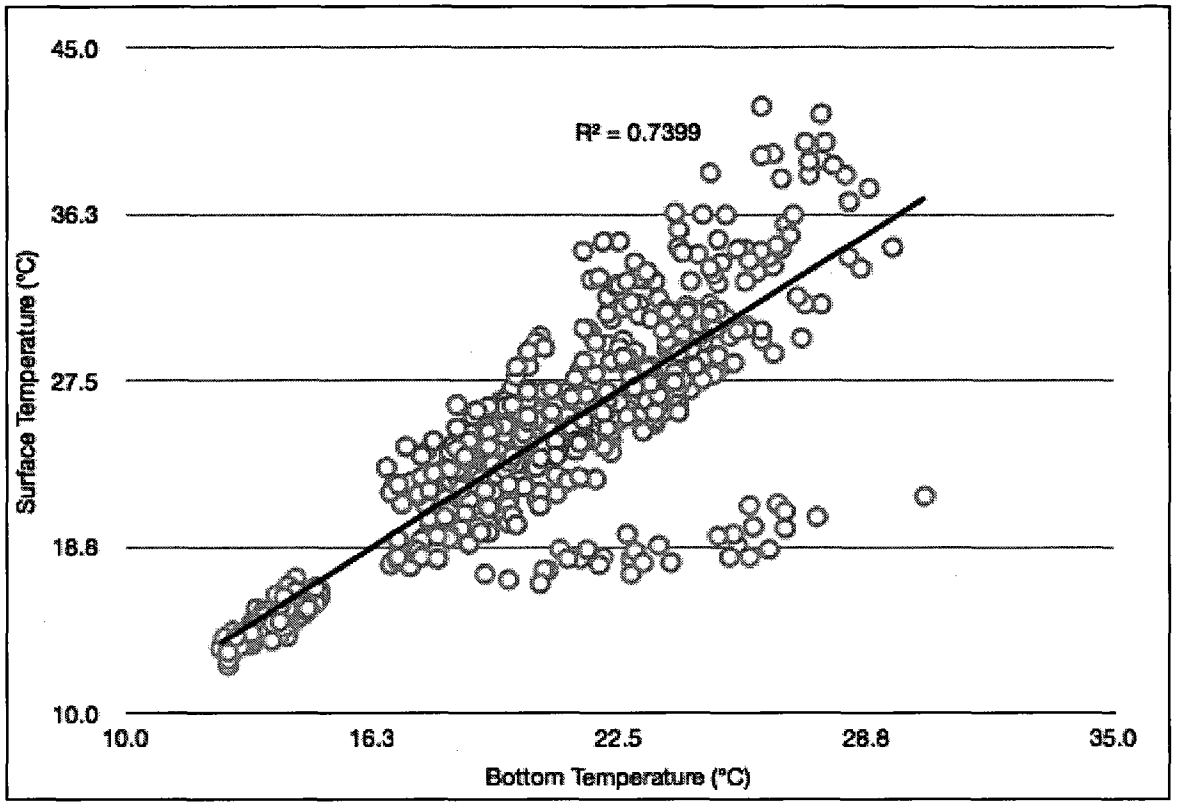

Figure 3. All surface and bottom temperatures of each module during the study period were plotted and correlated, and so only surface temperature was used in analyses. Surface temperature, rather than bottom temperature, more accurately reflects the effects of above ground canopy on roof cooling.

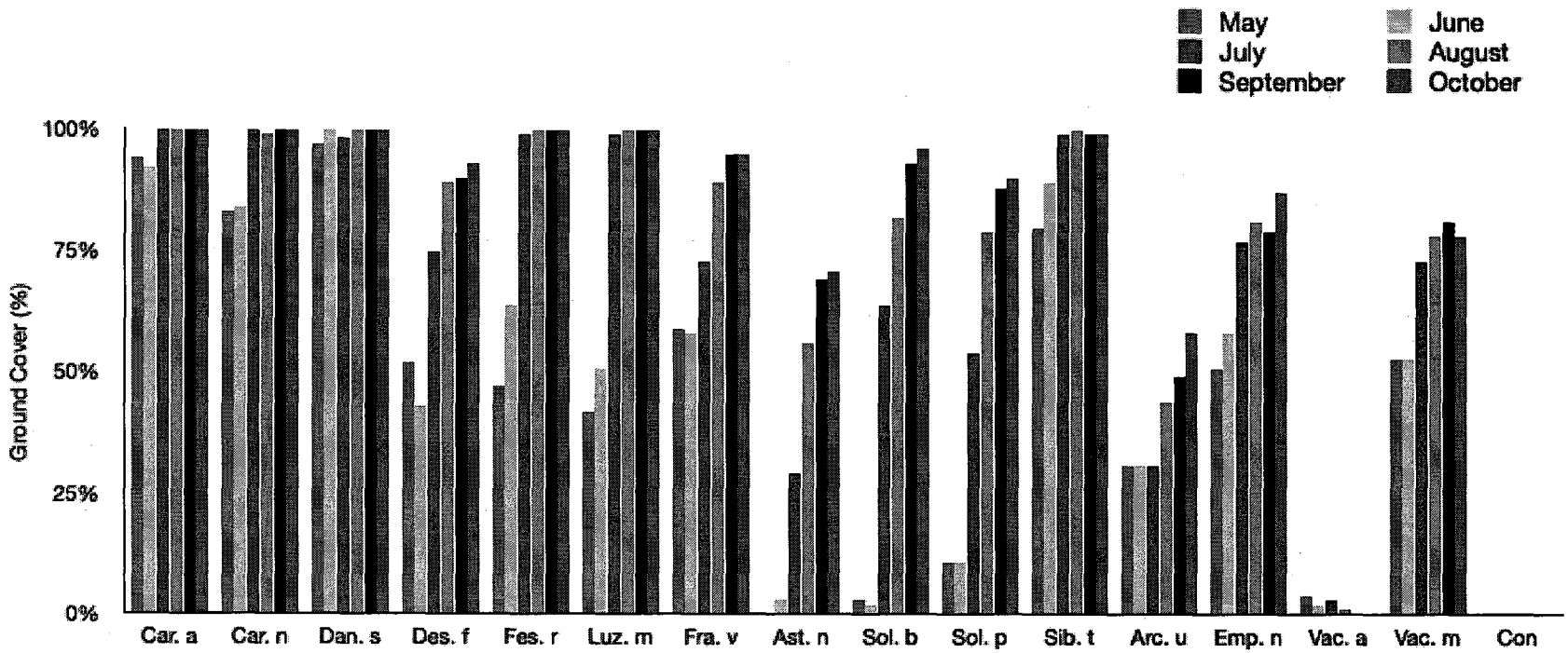

Figure 4. Monthly mean canopy cover (%) recorded as the number of rods touched by vegetation (out of 16) for each species between May and October 2009.

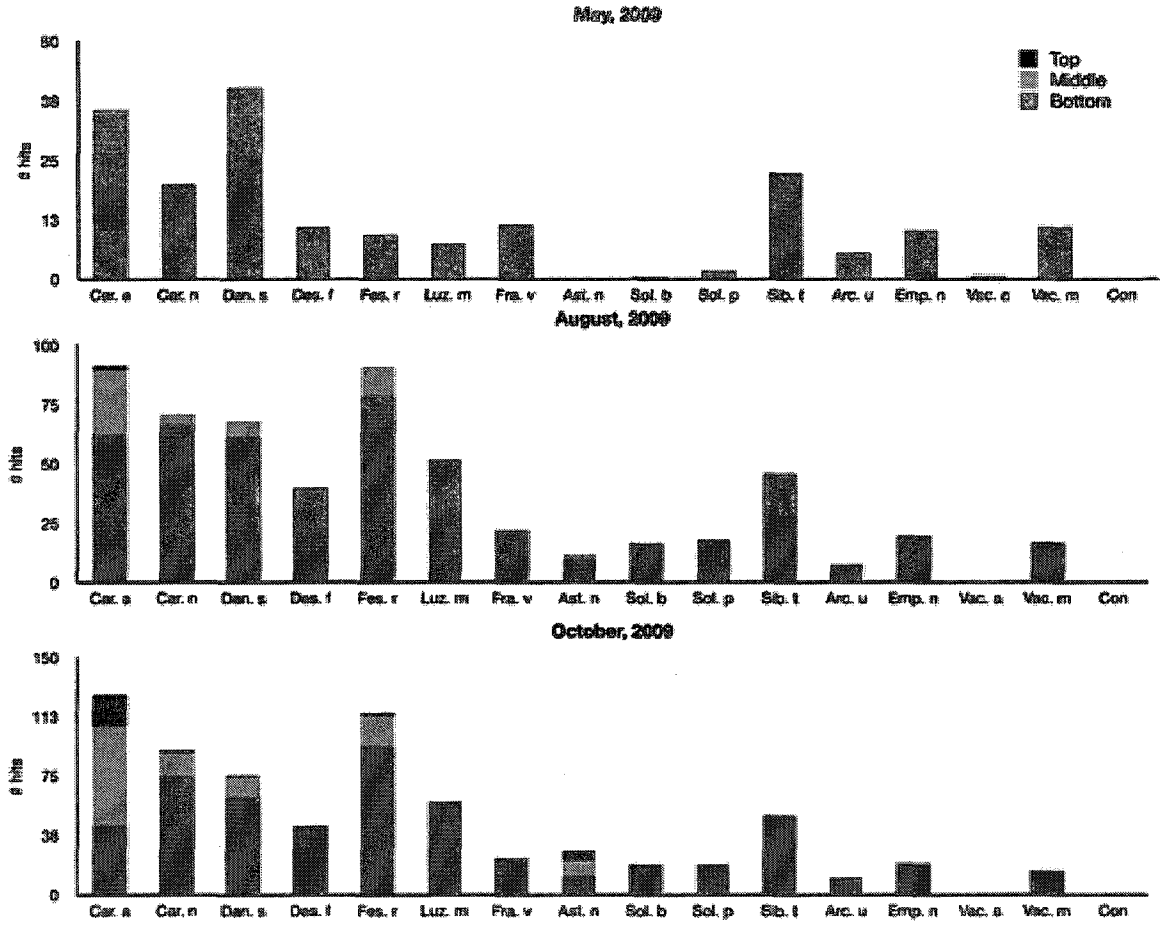

Figure 5. Mean index of above ground biomass for each species at each level of the pin frame: bottom (0-10cm); middle (11-20cm); top (21-30cm) recorded in May, August and October 2009. The index of above ground biomass represents the sum of total hits by vegetation on the 16-rod pin frame per module and averaged for each species.

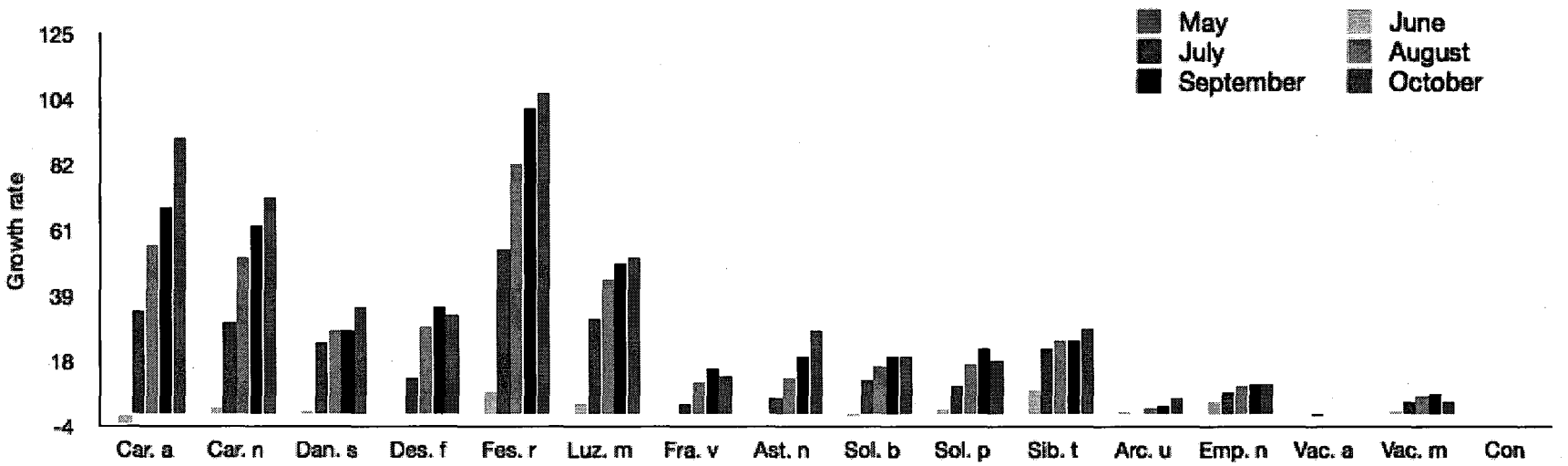

Figure 6. Monthly mean growth rates for each species between May and October 2009. Growth rates were measured as the above ground biomass index for the selected month subtracted by the previous month. The May growth rate for each species reflects the May above ground biomass index.

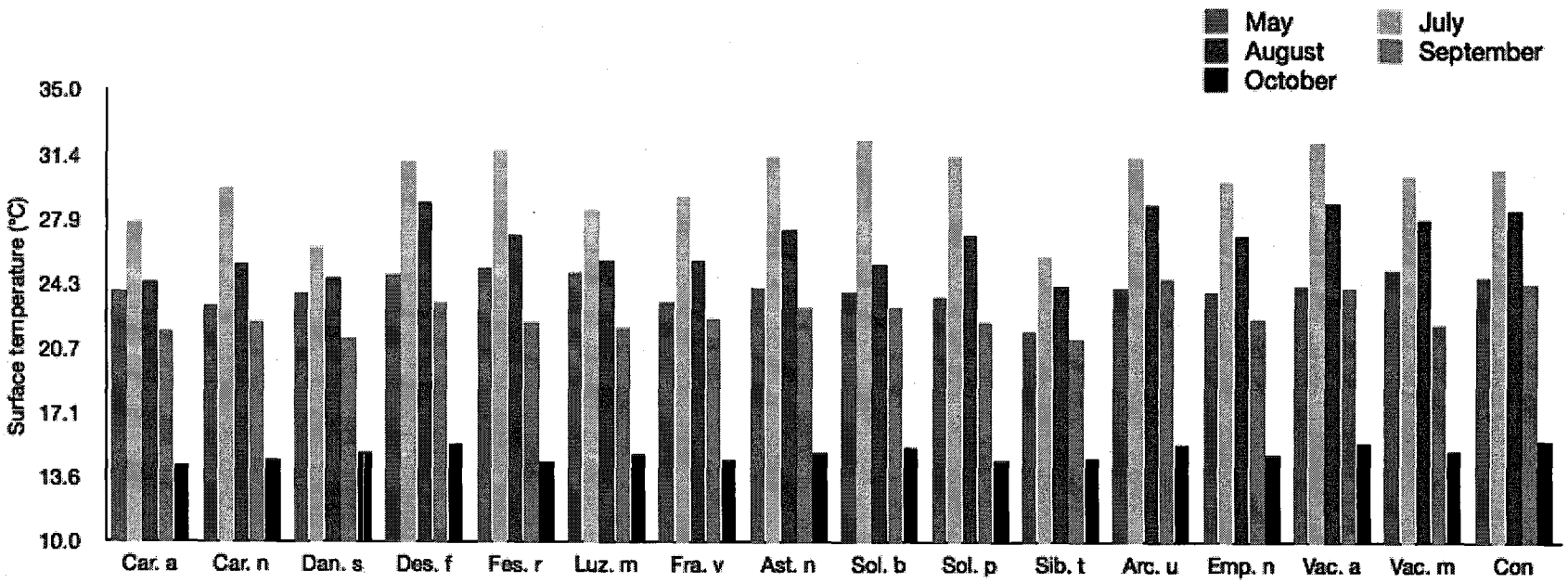

Figure 7. Monthly mean surface temperature for each species and growing medium only control between May and October 2009.

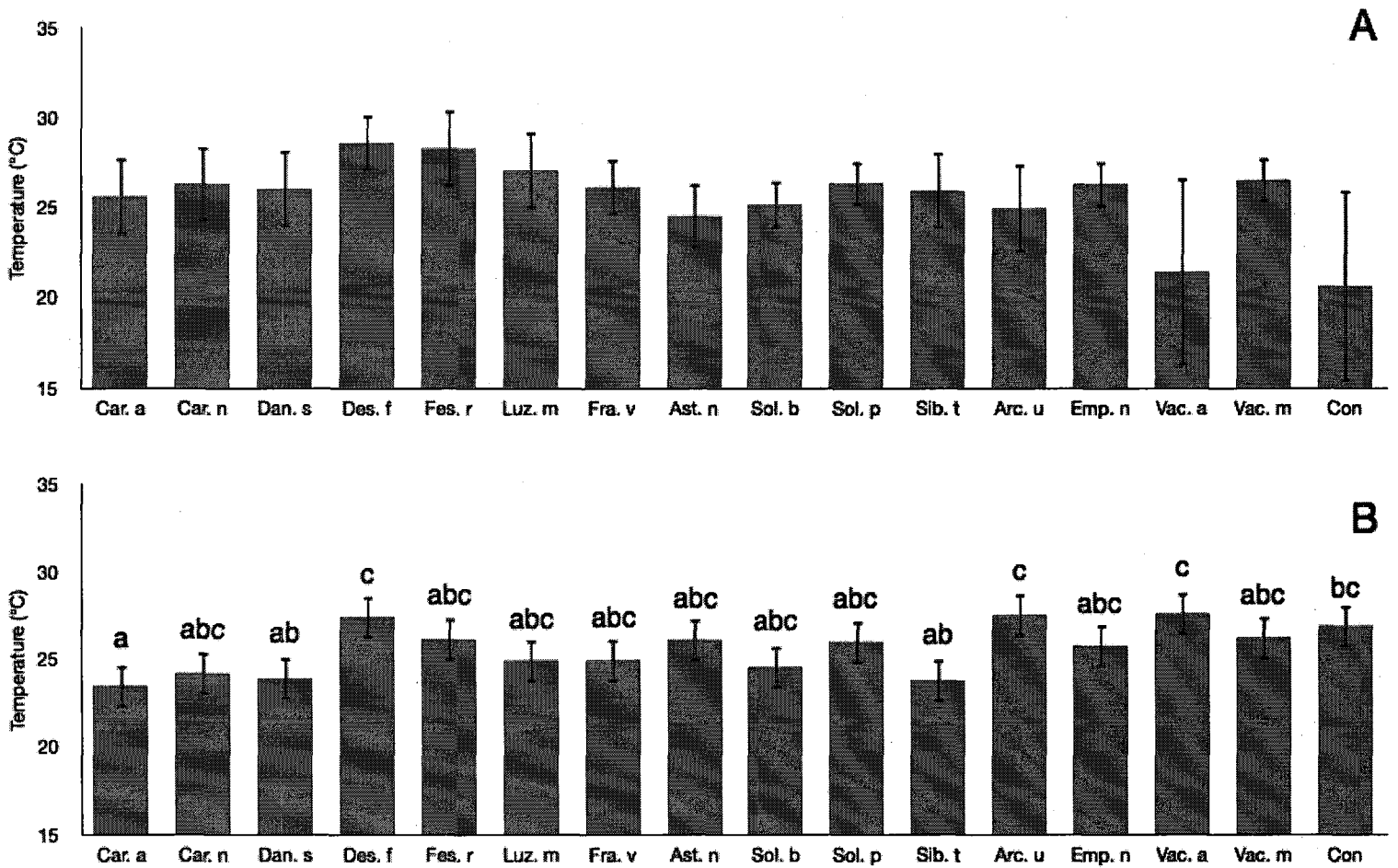

Figure 8. Differences in mean August surface temperature (mean±SE) for each species and growing medium only control. In bargraph A, the species effect is presented with the effect of cover (%) as a co-variable, and bargraph B presents the species effect with the effect of cover ignored. In bargraph B, significant differences were observed between treatments that do not share a letter. Bargraph A had no significant differences. Mean air temperature for the month of August 2009 was 19.9°C.

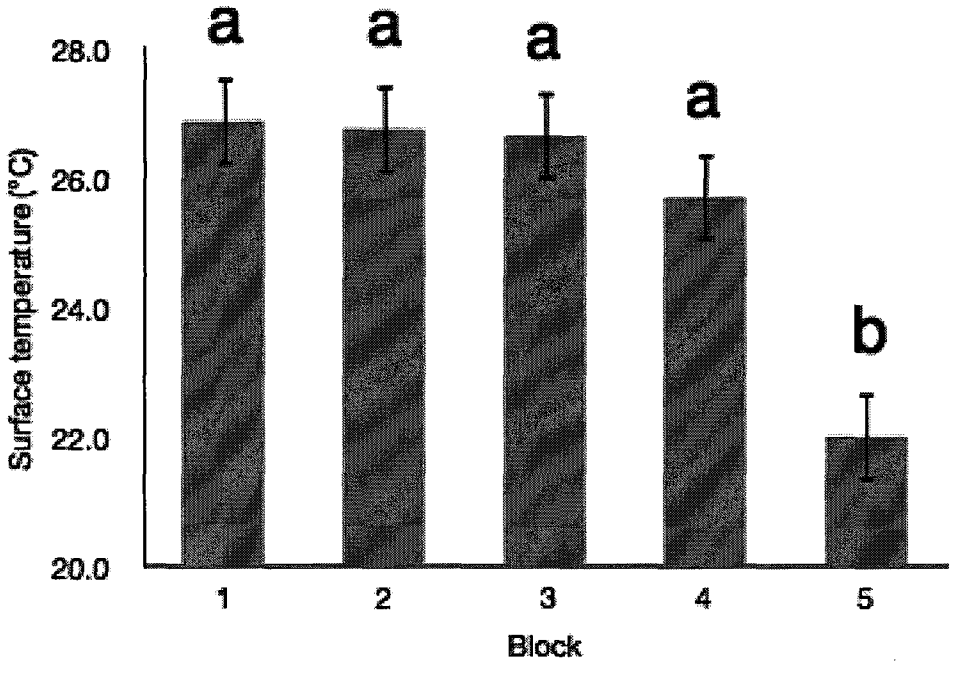

Figure 9. Block effect for August surface temperature (mean±SE).

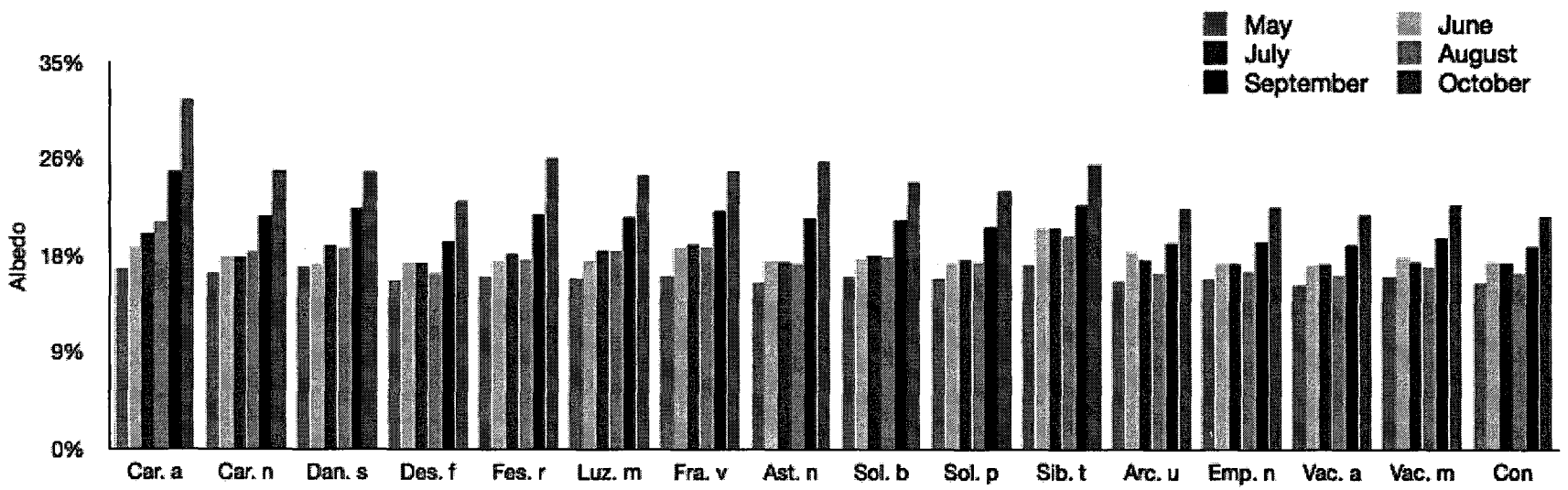

Figure 10. Monthly mean albedo for each species and growing medium only control between May and October 2009.

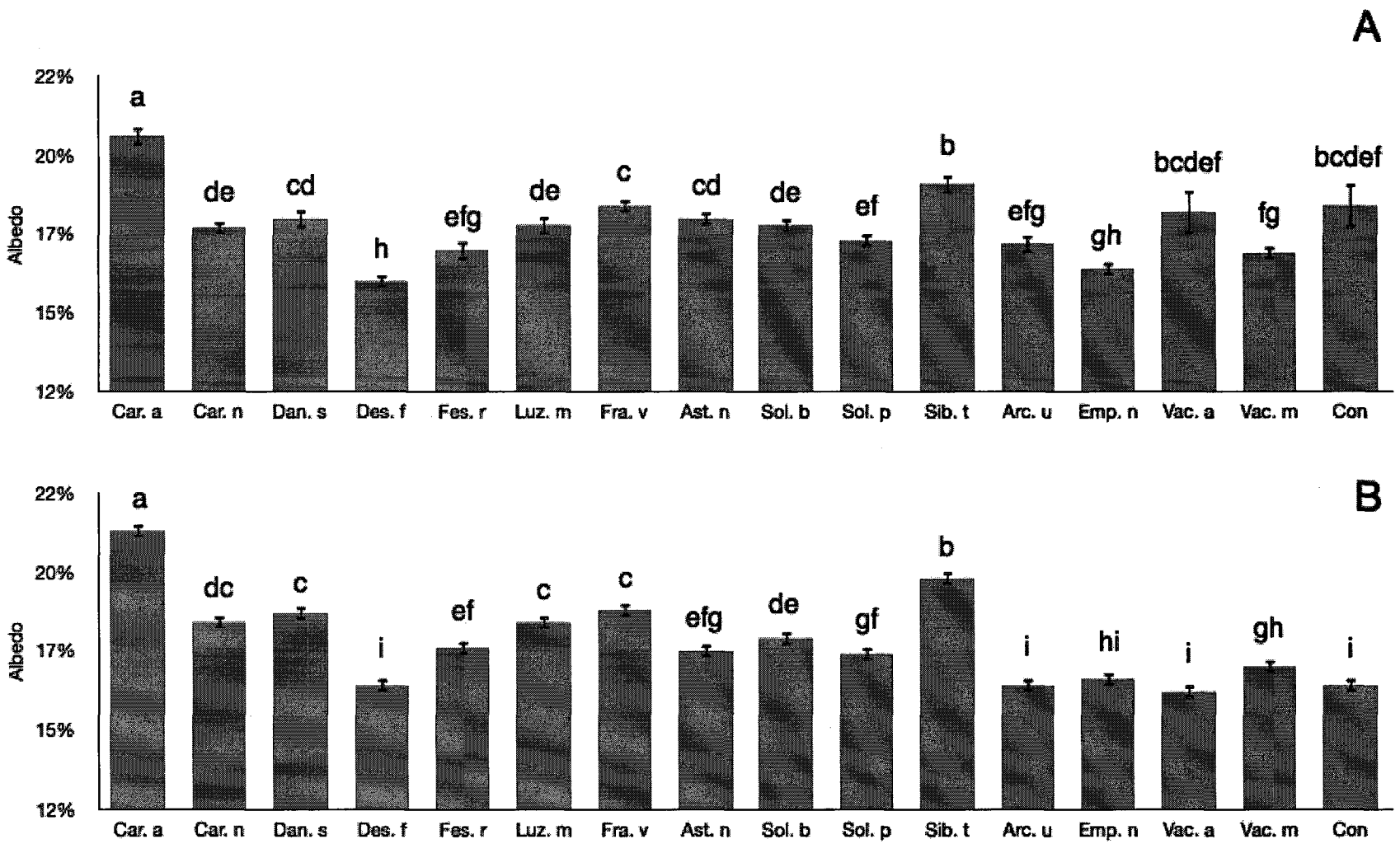

Figure 11. Differences in mean August albedo (mean±SE) for each species and growing medium only control. In bargraph A, the species effect is presented with the effect of cover (%) as a co-variable, and bargraph B presents the species effect with the effect of cover ignored. In bargraph B, significant differences were observed between treatments that do not share a letter.

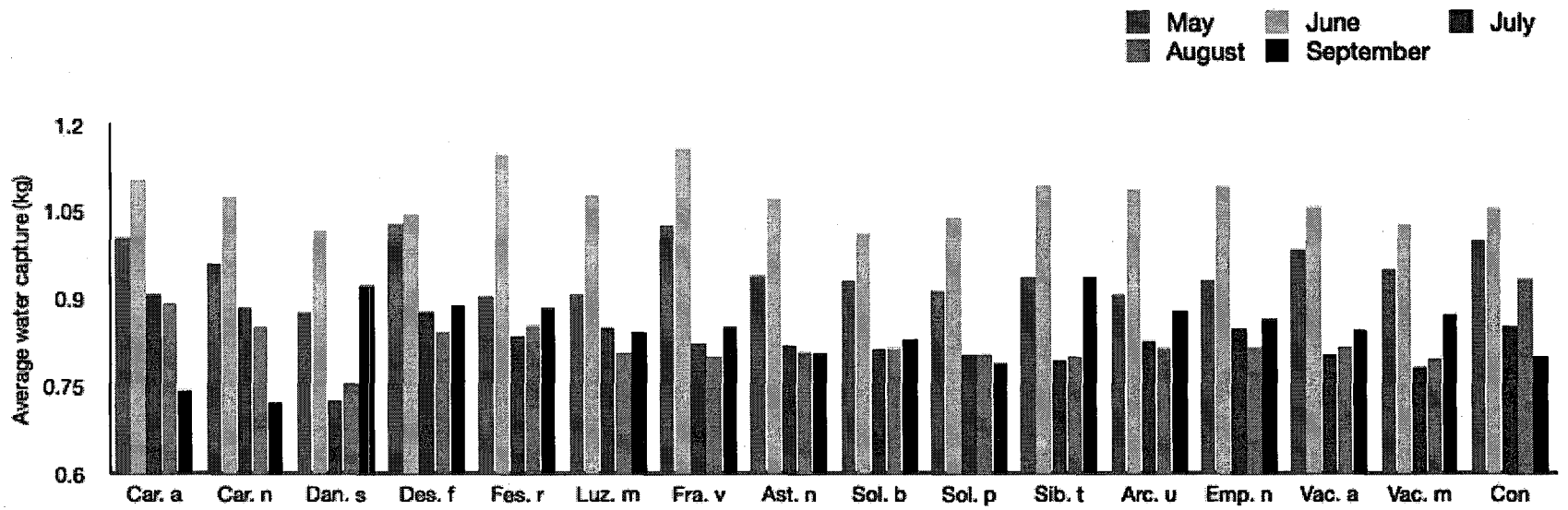

Figure 12. Monthly mean water capture for each species and growing medium only control between May and October 2009. Mean water capture reflects the amount of water retained in each module 10 minutes after 1.30kg was experimentally added for each species and growing medium only control.

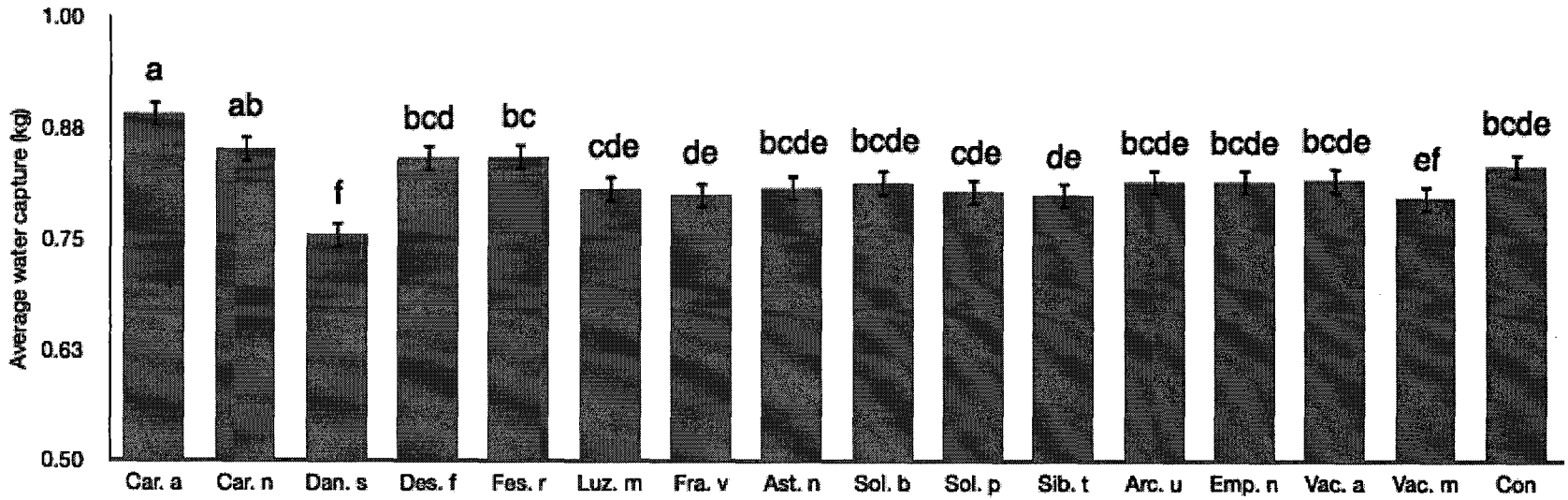

Figure 13. Differences in mean August water capture (mean±SE) for each species and growing medium only control. The effect of cover (%) as a co-variable did not significantly influence species water loss, and so the bargraph reflects the species effect, with cover ignored. Significant differences were observed between treatments that do not share a letter.

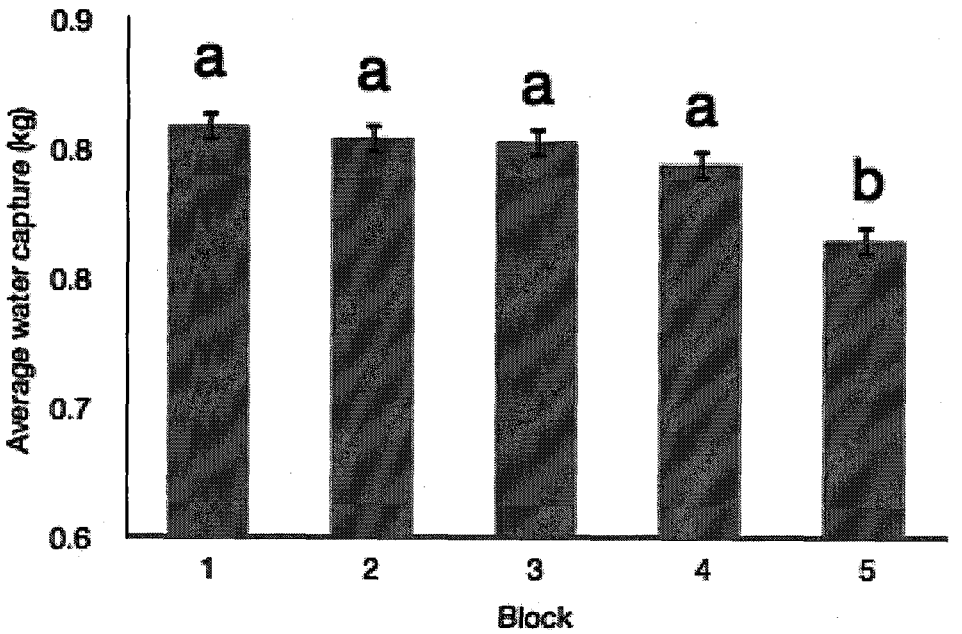

Figure 14. Block effect for August water capture (mean±SE).

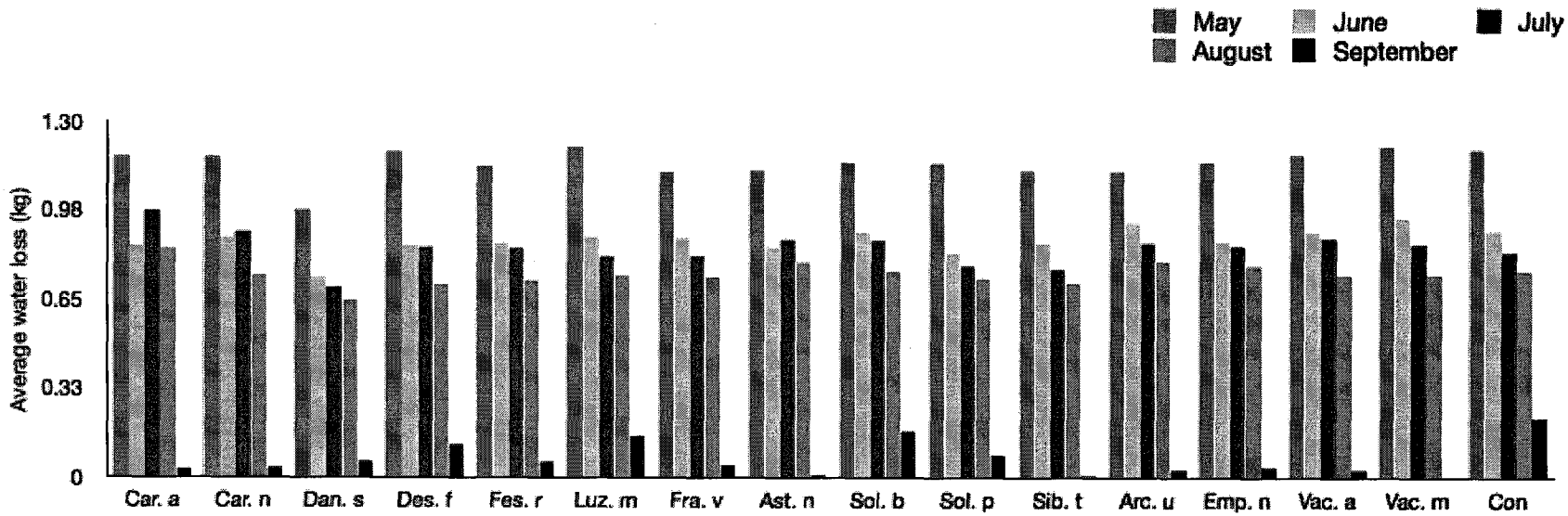

Figure 15. Monthly mean water loss for each species and growing medium only control between May and October 2009. Mean water loss reflects the amount of water lost from 10 minutes after experimentally adding water to 48 hours later.

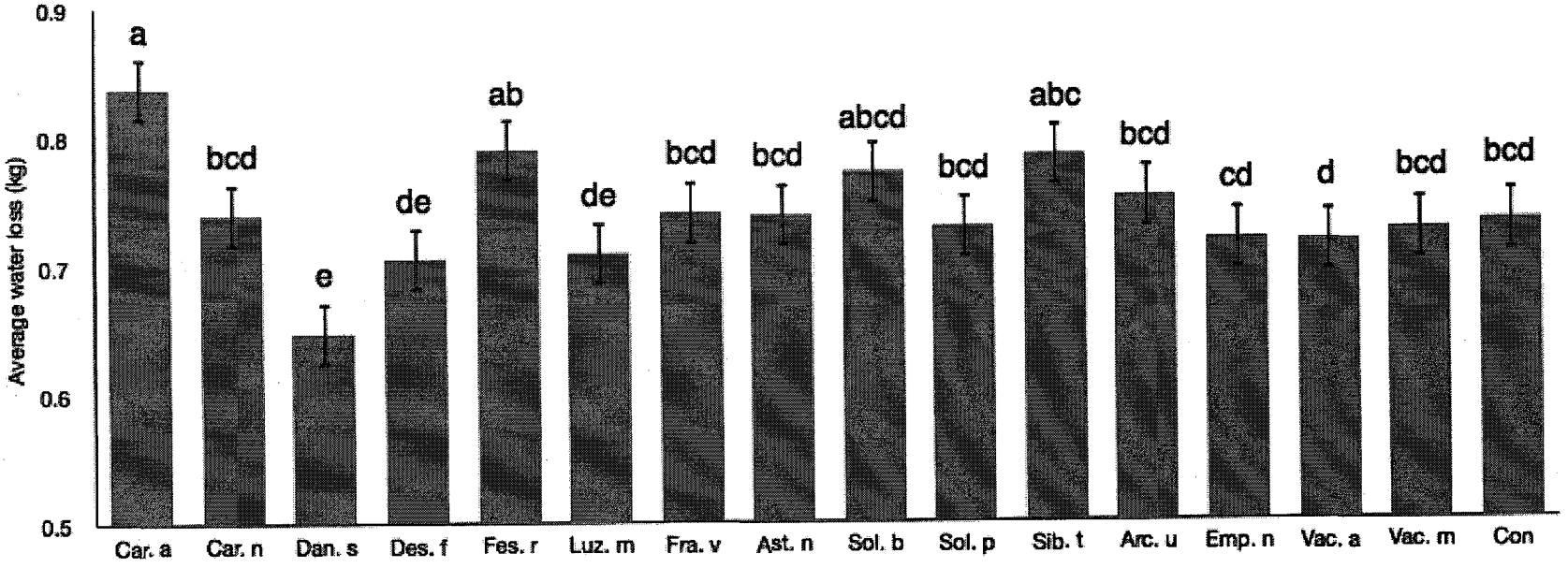

Figure 16. Differences in mean August water loss (mean±SE) for each species and growing medium only control. The effect of cover (%) as a co-variable did not significantly influence species water loss, and so the bargraph reflects the species effect, with cover ignored. Significant differences were observed between treatments that do not share a letter.

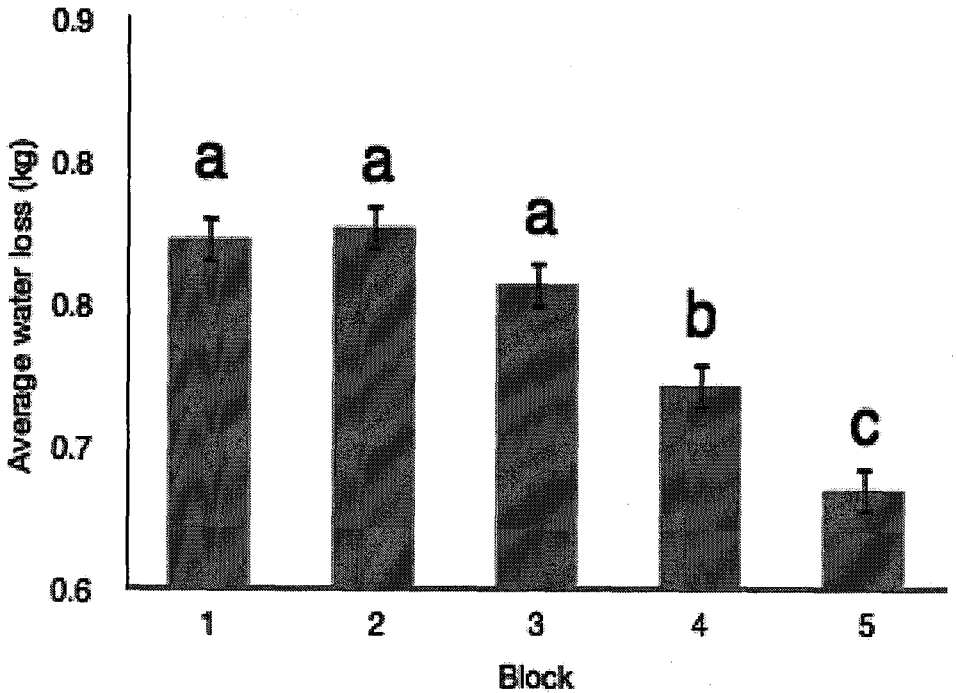

Figure 17. Block effect for August water loss (mean±SE).

CHAPTER 3

INSECT SPECIES DIVERSITY AND COMPOSITION ON INTENSIVE GREEN ROOFS AND ADJACENT URBAN LEVEL-GROUND HABITATS

Abstract

While it is expected that green roofs support a wider variety of insects compared with conventional roof surfaces, few studies have quantified insect diversity on green roofs. Even fewer have attempted to determine whether green roofs can support insect communities comparable to level-ground urban habitats. In this study, insect richness, abundance and diversity indices were compared between five pairs of intensive green roofs and adjacent ground-level habitat patches in downtown Halifax, Nova Scotia. Pitfall traps were set at each site, collected bi-weekly between May-October 2009 and then insects were identified to morphospecies (except where taxonomic expertise was available). No significant differences in richness, abundance, Shannon-Weiner diversity index, Simpson's Index, or Evenness were detected in analyses, which included plant species richness, site area and sampling effort as covariables. However, richness and abundance tended to be greater at ground level for all orders (except Heteroptera), and diversity appeared to increase away from the downtown core. Insect composition differed slightly between green roof and ground-level sites; only 17 species were collected from a single site type in numbers greater than five specimens. Nevertheless, a wide variety of insects, including many uncommon species were collected from green roofs, supporting the idea that these habitats sustain biodiversity in cities.

Keywords: Green roofs, Habitat quality, Insects, Urban biodiversity, Plant richness

Introduction

Green roofing involves covering conventional roof surfaces with vegetation, growing medium and a series of root barrier and waterproofing membranes. There are two main types of green roofs: intensive and extensive. Intensive green roofs have deeper growing medium (usually > 20 cm) and can support a large range of plant types but require more materials and cost. Extensive green roofs are essentially the opposite: lightweight, less expensive, shallow growing medium, and only drought tolerant plant species. These installations go beyond aesthetics; green roofs improve numerous public and private benefits such as stormwater retention, building thermoregulation and the effects of the urban heat island (Oberndorfer et al. 2007). Technical performance dominates the green roof literature, however there is a growing interest in understanding their ecology and interaction with the surrounding urban landscape (Kadas 2006; Lundholm and Peck 2008).

Green roofs differ from ground-level habitat patches in several ways. Generally, green roofs are less accessible and thus experience less human activity. Moreover, they are restricted to a finite growing medium depth and in some cases are located several meters from ground level. Green roofs are characterized as difficult growing environments for plants as they experience full exposure to the sun and wind, as well as alternating extreme drought and flooding (Dunnett and Kingsbury 2010). Despite these conditions, the rate at which green roofs are being installed in many North American cities is increasing dramatically (Green Roofs for Healthy Cities 2009). With municipal policy, construction standards, incentive programs and citizen engagement developing independently in many cities, investigation is warranted into how green roofs can be

optimized ecologically such that they augment urban habitat value and movement of a wide variety of species within and beyond the urban environment (Hauth and Liptan 2003; Oberndorfer et al. 2007).

The ability of green roofs to provide habitat for organisms other than plants is a relatively new emphasis, and the studies published so far have focused primarily on insects (Kadas 2006). The potential for green roofs to support insect diversity was first investigated in Germany (Baumann 2006; Schrader and Boening 2006; also see Brenneisen, 2006), then Switzerland (Breneisen 2006), England (Jones 2002; Kadas 2006) and more recently, the United States (Coffman and Davis 2005; Clark and MacArthur 2007; Coffman 2007) and Canada (Colla et al. 2009; Lundholm et al. 2009). Surprisingly, only a few studies (Kadas 2006; Colla et al. 2009) have compared diversity between green roofs and other urban, ground-level habitat types. Colla et al. (2009) found a variety of native bees at ground-level also using green roofs for foraging or nesting sites in Toronto, Ontario. Similarly, Kadas (2006), who sampled five green roofs and four ground-level brownfield sites, found that green roofs and brownfields support many similar species and suggested that both habitat types be used in combination to conserve invertebrates in London, England. In all of these studies, a general conclusion was that insects colonize green roofs over time even if they aren't designed to sustain insect diversity.

The abundance and diversity of niches occupied by insects are indicative of the essential role they play in many ecological processes including pollination, pest control and decomposition (Heliovaara and Vaisanen 1993; Foley et al. 2005). Maintaining biodiverse cities also presents ethical and educational opportunities in "species-poor"

cities (Miller 2005; Fuller et al. 2007). Some strategies to provide habitat for functionally valuable insect species have successfully included green roofs in their design. For example, a 2.5 acre green roof atop the California Academy of Science building in San Francisco provides habitat for the rare Bay Checkerspot butterfly (*Euphydryas editha bayensis*) (Hall 2007). The ability of green roofs to provide habitat has reached a much greater degree in Basel, Switzerland, where research on the biodiversity potential of green roofs has led to amendments to local laws (Brenneisen 2006). There, green roofs are mandatory on all flat-roofed buildings and must meet plant and growing medium design criteria so to maximize their habitat value for local flora and fauna.

Habitat fragmentation can compromise conservation of insect biodiversity in urban areas (Ehrlich and Murphy 1987; Di Giulio et al. 2001; Goddard et al. 2010), and it is thought that green roofs might serve in connecting fragmented green spaces in cities to facilitate species dispersal within the urban landscape (Kim 2004). Unfortunately, it is still unclear to what extent insect assemblages occupy both green roofs and vegetated space at ground-level. In this study, the similarity of insect diversity between green roof and adjacent ground-level habitat patches was examined by comparing species richness, composition and abundance of insect assemblages.

Methods

Sites

Five green roof sites were selected from a database that describes over 50 green roofs located in and around Halifax, Nova Scotia (Ranalli et al. 2008). The city of Halifax experiences a cold, humid maritime climate and the average monthly air temperature during the study period ranged from 6.9 °C- 19.9 °C whereas total rainfall reached 805

mm (Fogarty 2009). All of the green roofs selected in the study were intensive roofs (> 30 cm growing medium), as these are the most common in the region (> 70% of all green roofs in Halifax) (Table 1). Accessibility to the green roof site for the duration of the study period (May to October 2009) was also an important selection criterion. Ground-level habitat patches were predominantly soil-based, grassy open spaces, with few trees and scattered spontaneously vegetated or rocky areas. Each ground-level site was within 50m and occupied a similar area as each adjacent green roof (Table 2). One exception was the ground-level site paired with the City centre green roof, which was <200m away, because no suitable ground-level site existed closer to the green roof site. Both green roof and ground-level sites were also almost completely exposed to the sun with little or no tree cover. Maintenance regimes, accessibility, site features and vegetation descriptions were recorded for each site. Height from ground level (in meters) and the percent of roof vegetated was recorded for the green roof sites only. The area (m^2) of each green roof and adjacent ground-level habitat patch was calculated in ArcGIS (ESRI, Ottawa, Canada) using a Quickbird Satellite image of the area (photographed June 18th 2006) (Fig. 1). Plant species richness at each site was quantified once during the study period on August 6th 2009 (see Appendix 1).

Collecting

At each green roof and adjacent ground-level site, eight 7oz. yellow plastic beverage cups (7.5cm wide, 11cm deep, Canadian Tire) were used as pitfall traps and set haphazardly within the vegetated areas of the roof that had close to 100% cover and that weren't immediately beside a pathway or vegetation-free zone. Each trap was at least 4m from the next to ensure the extent of the vegetated area of each site was sampled equally.

Pitfall traps are simple to collect and process (Southwood 1978) and their placement in the ground reduces visibility, which was a requirement of building management at two of the green roof sites. They are also inexpensive, easy to replace and widely used in studies comparing insect diversity between two distinct habitats (Southwood 1978), particularly when assessing surface dwelling insects (Luff 1975). It is expected that comparing surface dwelling insects will provide a more conservative measure of what similarities in diversity and composition might exist between green roofs and ground level habitat patches, as vertical isolation can inhibit movement of all but the most mobile insect species (Davis 1978), as shown in the early green roof insect diversity studies completed in Germany (see Brenneisen 2006).

Pitfall traps were inserted into the soil using a bulb planter (8cm width, Canadian Tire); one cup was set in the ground and a second was inserted into the first cup such that the lip of the second cup was flush with the soil surface. This technique permits easy removal of the trap contents without disturbing the trap site (Ward et al. 2001). Each pitfall trap was filled with 120ml of water, dish soap (unscented biodegradable, President's Choice), and table salt (8:1:1). Traps were collected and replenished approximately every 10 days between 10am – 3pm from May 12 to October 29 2009. On several occasions, human activity and weather influenced the contents of traps at specific sites. Some heavy rain events throughout the study period flooded some traps, particularly those on green roofs in open spaces. Following a rain event, collection dates would be adjusted so to reduce decomposition of insects caught in the pitfall traps. Individual traps had to be replaced occasionally, mainly at the Quinpool green roof, where intrusion by inquisitive tenants resulted in approximately one trap being destroyed every second visit.

Otherwise, new traps were set (in the same spot) only when wear and tear left them leaking and unusable. All insects captured in the pitfall traps were stored in ethanol (70% EtOH), then counted and pinned for identification. All samples were identified to morphospecies, a suitable surrogate for species for the purpose of this study (see Oliver and Beattie 1996), except for beetles, which were identified to species in collaboration with Dr. Christopher Majka at the Natural History Museum of Nova Scotia.

Analysis

To compare insect diversity between green roof and ground level sites, insect richness and abundance data (based on counts of individuals) were used to calculate the Simpson's diversity index (D) (as described in Hunter and Gaston 1988), the Shannon-Wiener index (H′) (as described in Pielou 1966) and Evenness (E_{var}) (as described in Smith and Wilson 1996) for each site in four taxon assemblages: "all species"; all species with the two dominant ant species removed (referred to hereafter as "-2 ant spp"); "beetles"; and "carabids" (ground beetles only) (Table 3). Collembolans (although not considered insects) and aphids were included in the "all species" and "-2 ant spp" assemblages as separate, single morphospecies, as were nymphs and larvae (grouped by order) due to the condition of these specimens once removed from the pitfall traps and uncertainty in identifying them correctly. Each of the four taxon assemblages were analyzed separately to determine whether similarity between green roof and ground level habitat patches was more pronounced in certain insect assemblages. To test whether richness, abundance and the diversity indices differed significantly between green roof and ground level habitat or with plant species richness, total site area and sampling effort (the number of times traps were sampled from each site) as covariables, an analysis of

covariance ("aov" function, R package, v 2.8.1) was employed, with paired green roof and ground-level sites nested within "location", as a random factor. Finally, the similarity of each taxon assemblage between adjacent green roof and ground-level sites was compared using the Jaccard's index of similarity (as described in Jaccard 1908).

Results

General

In our study, no significant difference between green roof and ground-level habitat patches was detected in species richness, abundance, Simpson's diversity index, Shannon-Wiener index or Evenness (Table 4). Interestingly, the Shannon-Wiener index recorded from green roof and ground level were similar to those recorded in Kadas (2006), in which differences between extensive green roofs and ground-level brownfield developments were compared. The Jaccard Index of each paired green roof and adjacent ground-level site (when all species are included) was most similar when comparing pooled green roof and ground level sites (see Table 3), and was most dissimilar between the City Centre green roof and ground-level sites whose insect species composition differed the greatest among all adjacent sites in the study. Missing from green roofs were three orders found at ground-level: Ephemeroptera (Mayflies), Neuroptera (Lacewings), and Odonata (Damselflies and Dragonflies) (Fig. 2). These insects are generally large and spend little time at the soil surface. Not surprisingly, these orders were represented in the study by only one specimen from each order caught from a single ground-level site. Their absence from green roofs is probably not due to the inaccessibility of the roofs rather the trapping method was not appropriate for such taxa.

Plant richness, site area and sampling effort were included as covariables in each analysis but none had any significantly influence on insect species composition between sites. Green roofs, however, did harbor more plant species (109) than ground-level sites (89). *Agrostis stolonifera*, *Leontodon taraxacoides*, *Plantago major*, *Ranuculus repens* and *Taraxacum officinale* were the dominant species and were found at all sites in the study. Interestingly, 47.3% of all plant species recorded from all sites were native to Nova Scotia, although this was not included as a variable in the analyses. See Appendix 1 for a complete list of plant species for each site.

Species composition

During the sampling period, 12136 insects from green roofs (representing 253 morphospecies), and 13800 insects from ground-level (representing 294 morphospecies) were collected (see Appendix 2). Of the 361 insect species collected from all sites, 189 were found at both green roof and ground level, whereas 155 species (recorded only once) were unique to either one of the site types. Only 17 species were collected from a single site type in numbers greater than five specimens. Ground-level sites had, on average, 12 more species than green roofs, although one site (City centre) with very low diversity is suspected to have negatively influenced the mean diversity of green roofs. Seventy-eight families in ten orders were collected from ground-level and 73 families in seven orders were collected from green roofs (Table 5).

While some species were captured only once from a single site during the sampling period, a few were extremely prolific and collected in large numbers at every site. Species with wide habitat niches, such as ants, dominate urban areas because of their ability to disperse between vegetation patches divided into various sizes and degrees of

isolation (Heliovaara and Vaisanen 1993; Hunter 2002). As was true in our study, two ant species, a common carpenter ant (*Camponotus* sp.) and pavement ant (*Formica* sp.) comprised approximately 64% and 65% of the green roof and ground level samples respectively. Oddly, *Camponotus* sp. was extremely abundant at ground level (738±330.3) compared to green roofs (16.3±7.3) whereas *Formica* sp. was more common on green roofs (1543.8±631.8) than ground-level (1092.2±430.7). Of the other ant morphospecies collected, almost all were caught more often at ground-level. Aside from ants, the most abundant insect at both green roof and ground level was the flea beetle *Chaetocnema concinna* (Chrysomelidae: Coleoptera) (total caught = 1104). This beetle is a generalist that feeds most often on *Polygonum* sp., a genus of knotgrass found at all sites except the Dalhousie ground site. Interestingly, *C. concinna* was least abundant at the City centre green roof and Massey Hall cemetery, whose rigorous maintenance schedules (in comparison with the other sites) might affect their value as habitat for this species.

Beetles (Coleoptera)

Although richness did not differ, ground-level beetle abundance was almost double that of green roofs (see Table 3). Similarly, ground-beetle (Carabidae) abundance was greater at ground-level but there was no difference in richness. Green roof and ground-level sites shared three of the five most common beetle species collected. The five most common beetles captured from all green roofs were *Chaetocnema concinna* (81.6±47.9), *Philonthus carbonarius* (Staphilinidae) (31.2±14.0), *Phyllobius oblongus* (Curculionidae) (29.2±13.1), *Tachinus addendus* (Staphilinidae) (10.2±3.8) and *Xantholinus linearis* (Staphilinidae) (8.4±3.7). The five most common beetles captured from all ground-level

sites were *Chaetocnema concinna* (139.2±64.6), *Barypeithes pellucidus* (90.0±51.1), *Tachinus addendus* (38.0±14.5), *Philonthus carbonarius* (29.6±15.5) and *Longitarsus luridus* (Chrysomelidae) (17.8±13.4). Some species found almost exclusively on green roofs included: the dominant rove beetle *Xantholinus linearis* found twice as often on green roofs (9.4±3.8) than ground level (4.4±1.7); the clover-head weevil, *Hypera meles* (Curculionidae: Coleoptera) found at three green roofs (4.8±2.4) but only one ground-level site (0.4±0.4); and the eurytopic *Harpalus affinis* (Carabidae: Coleoptera) found almost exclusively on green roofs (7.4±2.4) compared with ground-level (0.4±0.4). Conversely, several species were found almost exclusively at ground-level, the sometimes pest, juniper-root weevil *Barypeithes pellucidus* (Curculionidae: Coleoptera) was found at every site, but 90.0±51.1 were caught at ground-level while only 6.4±2.1 total specimens were collected on roofs and the common predatory ground beetle *Pterostichus melanarius* (Carabidae: Coleoptera) was found almost exclusively on the ground (12.0±10.77) compared with roofs (0.8±0.4).

Several uncommon beetle species were collected in the study including *Phosphaenus hemipterus* (Lampyridae: Coleoptera), a firefly endangered in its native European range. Twenty-three specimens were found at a single green roof site (Queen St.), and 102 at the adjacent ground-level site. This species is larviporous and cannot disperse great distances; it is not known how this species persists in such large numbers in downtown Halifax (Majka and MacIvor 2009a). Another uncommon species found in this study was *Otiorhynchus porcatus* (Curculionidae: Coleoptera), a generalist root weevil, which was the first record of the species for the province of Nova Scotia (Majka

and MacIvor 2009b). This beetle was collected only from the Dalhousie University sites: 20 specimens from the green roof, and 6 from ground level. Lastly, four specimens of the relatively uncommon saproxylic *Atomaria wollastoni* (Cryptophagidae: Coleoptera) (see Majka et al. 2010) were collected from the Saint Mary's green roof and nowhere else.

Discussion

Despite ground-level sites having slightly more species and higher abundance overall, insect diversity within each of the 4 taxon assemblages described in the study did not significantly differ between intensive green roofs and ground-level sites. It must also be considered that the absence of significant differences between ground-level and roof sites may be in part due to the small sample size, and consequent lack of statistical power. Future studies should include more replicates of each habitat type. All insect species ("all species") were included in analyses to see whether any major differences existed between green roofs and ground-level sites, for example, to detect whether only the most mobile species were found on green roofs. In the past, researchers believed that only the most mobile insect species could utilize green roof habitats (see Dunnett and Kingsbury 2010); however, here we show that a wide variety of insects spontaneously colonize intensive green roofs, including medium, large and even flightless insects that are found predominantly at the soil surface of ground-level urban habitats. While there were some differences in morphospecies composition between green roof and ground-level, there were very few differences at the level of family and order. Those differences in order are likely not explained by the inaccessibility of green roofs, but rather, the trapping method employed. Anecdotal evidence of numerous large, flying insects was recorded throughout the study period from all sites, and from collections using haphazard sweepnetting made

the previous summer at the Saint Mary's green roof site, in which over 200 morphospecies were collected (Lundholm et al. 2009). This season, both dragonflies and damselflies were observed often, particularly at the Saint Mary's green roof, the Quinpool green roof and the Dalhousie ground site. Other aesthetically pleasing and valuable bees, butterflies and more were also underrepresented in this study because of the sampling method. As mentioned, sampling was confined to one trapping method (pitfall trapping) due to requests by building management to conceal collecting activity on certain green roofs, as experienced in Coffman and Davis (2005). Another limitation of the trapping method was that decomposition is expected to have influenced the number of collembolans recorded in this study, which was considerably lower than the abundance found in Schrader and Boening (2006).

Analyses using each of the other three assemblages permitted opportunities to examine the diversity and composition of certain groups with more specificity. The "-2 ant spp" assemblage was included because it was of interest to the researchers to compare sites in the absence of the two dominant ant species (representing the bulk of the sample). The "beetles" grouping was included because species identity could be accurately confirmed with available expertise. Finally, the "carabids" group was included because ground beetles are sensitive to environmental stress (Niemelä et al. 2000) and their presence is more or less indicative of the response of at least a subset of other species that occupy the soil surface (Thiele 1977; Rainio and Niemelä 2002). Also, pitfall trapping reliably reflects variation in ground beetle assemblages and their habitat associations (Eyre and Luff 1990).

Whereas only 10 sites (5 green roof, 5 ground-level) were examined in this study, some general trends in insect diversity are evident when taking into account the locations of each of the sites within downtown Halifax. Cities are often characterized as having highly developed downtown cores surrounded by areas of decreasing development and increasing vegetation cover (Niemelä et al. 2000; Pauleit and Duhme 2000). Furthermore, insects generally become more abundant away from the city core (Davis 1978). This was evident in our study, as the Dalhousie and Saint Mary's sites had slightly higher insect richness over other sites and were the furthest from the downtown core: Saint Mary's is located next to a large (> 70 ha) forested park and Dalhousie has a large, heavily vegetated campus. Furthermore, sites located just outside the downtown core, specifically the Queen St. and Quinpool Rd. green roof and ground-level sites had insect richness lower than that of the more vegetated areas of the city (e.g. Saint Mary's and Dalhousie). As well, they had greater insect richness than that of the City centre green roof, which was most centrally located in the downtown core, and furthest from equally sized ground-level habitat patches. The City centre green roof had by far the lowest species richness of any site, as well as the highest number of ants over the collection period (75% of catch was *Formica* spp.). Conversely, the Sackville St. ground-level site (paired with the City centre green roof) had high richness and abundance, as well as the lowest number of ants, likely because it was relatively unmaintained and inaccessible to the public during most of the field season.

Plant species richness was also greater at longer distances from the downtown core; however, it was not a significant covariable of insect diversity among the sites compared. The richness of habitat types created within urban landscapes often results in

high plant species diversity (Shepherd 1994); however, plant diversity often increases away from the downtown core because of reduced dominance of "sealed surfaces" that severely reduce vegetative cover. In Smith et al. (2005), the authors conducted a large-scale examination of the biodiversity of urban gardens in Sheffield, England and found that plant-species richness was a key factor in promoting invertebrate diversity. Plant richness did not have a significant influence on insect diversity in our study, likely due to sample size, contrary to results presented in Smith et al. (2005) who examined 61 sites. Recent research has demonstrated empirical evidence that show increasing the number of plant functional groups (thereby diversity) on green roofs can improve roof cooling and stormwater retention contributing to economic and environmental benefits (Lundholm et al. 2010). In our study, the sites with the highest plant richness were furthest from the downtown core (Dalhousie and Saint Mary's) and were among the sites with the greatest beetle richness and abundance. Despite statistical analyses suggesting plant richness had no effect on insect diversity, selectively increasing plant species on green roofs so to augment local populations will likely improve insect biodiversity (Brenneisen 2006) since many insects feed, pollinate and/or reproduce on specific plant taxa.

Habitat Value of Green Roofs

Urban entomology has historically focused on pest species and how to expel insects from cities (Robinson 2005). Only recently have sentiments changed such that urban environments are now viewed as opportunities to manage beneficial insect species. Moreover, very few diversity studies are conducted in urban environments, which are important in documenting the presence or absence of newly introduced or beneficial insect species. During the course of sampling, several interesting species were identified

from green roofs and at ground-level. Understanding species differences between green roofs and ground-level habitats is a fundamental step in designing green roofs that increase habitat value and augment local biodiversity. Green roofs present many opportunities to create and modify anthropogenic habitat so to harbor a wider variety of species (Rosenzweig 2003). For many insects within the urban environment, the maintenance and creation of good quality habitat is a means for their continued survival (Angold et al. 1999; Hanski and Singer 2001). Clearly, more work is required to determine the role of host-specificity in insect-plant relationships on roofs.

Worth considering is that cities are heterogenous and complex environments (Pickett et al. 2004; Hruska 2006), so to gain a greater perspective on the similarity of insect assemblages occupying both green roofs and ground-level habitats, insect diversity should be investigated over multiple years. Although examined over only one field season (May - October 2009), the variety of common and uncommon species found on green roofs in Halifax reinforce the results of Kadas (2006) whose collections from green roofs in London, England included numerous species, 10% of which are nationally rare or have very limited distribution range, and Coffman (2007) who stated that "unplanned wildlife communities will spontaneously occur in green roofs regardless of planning". Brenneisen (2006) found that insect species diversity increased consistently over a 5-year period on a green roof with growing medium of varying depths, whereas green roofs with a growing medium of homogeneous depth experienced no change in species diversity between years three and five, suggesting that creating different niches on roofs may improve their ability to provide habitat.

As the majority of green roofs in Halifax are intensively planted, no extensive green roofs were included in the study. Had they been, insect diversity and species composition of green roofs might have been much less similar to that of ground-level habitat patches. Extensive green roofs have shallow growing media; moreover, the entire substrate may freeze completely in the winter and dry out in the summer, making it a potentially difficult environment for most sedentary and soil-dwelling insects. Although these are extreme conditions, they would likely not affect species that temporarily use green roofs, for example, to collect pollen or hunt prey.

Conclusion

The absence of significant differences between mean insect diversity and abundance in ground-level and green roof habitats suggests that green roofs could provide equivalent value as urban insect habitats. Even though no clear relationship between insect and plant diversity was evident in our study, maintaining a greater diversity of plants is expected to not only improve green roof economic functions, but also diversity and composition of insects, as well as a host of other fauna on green roofs and in conjunction with ground-level habitat patches. Angold et al. (2006) found that networks of good quality habitats permeating the urban environment is effective in aiding dispersal of invertebrates and plants; thus green roofs should be used to improve existing natural cover, and habitat value in urban areas.

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Tables

Table 1. Characteristics of each green roof included in the study.

Type	*Site*	*Location*	*Area (m^2)*	*Maintenance*	*Accessibility*	*Site Features*	*Veg. Description*	*Height (meters)*	*% roof vegetated*
Green Roof	Life Science Building	Dalhousie University	1496.81	Mowed once monthly, two flower beds maintained.	Accessible through Life Science building, lots of foot traffic in summer months.	Full sun, surrounded by buildings 1-2 storeys on all sides, growing medium depth varying from 12-24".	Some planted beds, lawn patches around small pines, some bare patches.	6	85%
	Green Roof Testing Facility	Saint Mary's University	1160.21	Mowed 3-4 over the field season; research modules weeded often.	Fenced in, accessible only to <12 faculty and students.	Surrounded by buildings 1-3 storeys on all sides, partially shaded, growing medium depth approx. 18".	No trees, lawn patches, research modules planted with native plants.	6	95%
	City Centre Shopping Mall	City Centre	1150.75	Mowed twice monthly, several flower beds, trees pruned.	Accessible only to tenants, foot traffic only on pathways.	Surrounded by buildings on all sides, concrete pathways and patios, growing medium depth approx.18".	Planted beds, pines, spontaneous veg. patches along edges.	12	50%
	Quinpool Towers	Quinpool St.	2824.12	Mowed once monthly, garbage removed often, some damage by tenants.	Accessible only to tenants, used as recreation space, foot traffic heavy in summer.	Full sun, concrete pathways and wooden deck, growing medium depth varying from 8"-18".	Large lawn area, lots of spontaneous veg. and mosses around edges and rock gardens (drainage areas).	9	80%
	Fort Massey Apartments	Queen St.	985.66	Lawn areas mowed monthly, flower beds maintained, mounds of soil in one corner.	Full access, but foot traffic only on pathways.	Beside 10 storey building (shading one side of roof), bordered by quiet street and high-traffic street, growing medium depth approx. 18".	Some planted beds, pines and maple trees, shaded side is all spontaneous vegetation.	6	80%

Table 2. Characteristics of each ground level habitat patch included in the study.

Type	*Site*	*Location*	*Area (m^2)*	*Maintenance*	*Accessibility*	*Site Features*	*Veg. Description*	*Height (meters)*	*% roof vegetated*
Ground Level	Campus green patch	Dalhousie University	1071.66	No maintenance; path was mowed and widened late Aug., garbage picked up frequently.	Wooden fence surrounds; small circular pathway with one entrance/exit unlocked.	Small pond in far corner; site partially shaded by buildings, bordered by parking lot and concrete path.	Dense spontaneous vegetation, some planted species close to pond, unmaintained.	--	--
	Front of Science Building	Saint Mary's University	1219.59	Mowed once monthly, some shrubs pruned.	Full access, but little foot traffic.	Shaded by large maple trees; bordered by road and parking lot.	Planted shrubs and trees intermixed with lawn; some spontaneous patches.	--	--
	Sackville St green patch	City Centre	1915.57	Mowed 1-2 over the field season; dumping spot for city equipment, lots of leaf litter.	Fenced in; gate open between 9am-5pm but several broken spots create full access.	Bordered by street and well-maintained sports park; partially shaded by large trees.	All spontaneous, large patches of *F. virginiana;* trees but no shrubs.	--	--
	Quinpool Recreation Centre	Quinpool St.	1529.99	Mowed once monthly, garbage picked up frequently.	Full access; heavy traffic occasionally, building used for summer courses.	Bordered by parking lots and four-storey building.	Some trees, many spontaneous patches of plants, large lawn space.	--	--
	Massey Hall Cemetery	Queen St.	1016.78	Mowed twice monthly, hedges pruned, leaves raked.	Fenced in; gate open between 9am-5pm, when open, minimal foot traffic.	Bordered by high-traffic road and another cemetery.	Lawns, well-maintained shrubs, few old maples, spontaneous veg. along edge closest to road.	--	--

Table 3. Site characteristics, richness, abundance (total number of specimens captured) and diversity indices [Simpson's (D), Shannon-Weiner (H′), Evenness (E_{var}) and Jaccard's (J)] for green roof (GR) and ground level (GL) habitat patches.

		All Sites		*Dalhousie U.*		*Saint Mary's U*		*City Centre*		*Quinpool St.*		*Queen St.*	
		GR	GL	GR	GL	GR	GL	GR	GL	GR	GL	GR	GL
Site	Area (m^2)	7617.55	6753.59	1496.81	1071.66	1160.21	1219.59	1150.75	1915.57	2824.12	1529.99	985.66	1016.78
	Plant Rich.	109	87	46	52	62	36	35	41	43	38	53	29
	Samling. Eff.	55	57	10	12	13	11	10	13	11	10	11	11
All Species	Richness	253	294	131	131	127	115	76	135	108	117	101	106
	Abundance	12135	13800	991	2877	2269	2134	4203	2768	3291	4292	1516	1595
	D	0.588	0.834	0.862	0.697	0.893	0.660	0.213	0.934	0.546	0.614	0.624	0.894
	H′	2.139	2.918	3.205	2.056	3.128	2.104	0.689	3.537	1.858	2.020	2.170	2.918
	E_{var}	0.249	0.240	0.451	0.342	0.297	0.331	0.317	0.334	0.290	0.261	0.380	0.316
	J	0.685		0.379		0.339		0.336		0.442		0.386	
-2 Ant Spp.	Richness	251	292	129	129	125	113	74	133	106	115	99	104
	Abundance	4360	5638	645	771	1579	711	478	1347	1069	1661	589	1148
	D	0.960	0.962	0.949	0.948	0.927	0.949	0.840	0.930	0.958	0.926	0.958	0.946
	H′	4.091	4.134	3.877	3.774	3.442	3.711	2.926	3.558	3.703	3.476	3.814	3.507
	E_{var}	0.270	0.267	0.505	0.454	0.320	0.428	0.454	0.350	0.338	0.297	0.451	0.348
	J	0.683		0.385		0.331		0.326		0.435		0.386	
Beetles Only	Richness	97	103	46	40	52	37	23	52	39	47	32	45
	Abundance	1446	2653	185	179	505	346	91	695	489	821	175	612
	D	0.898	0.886	0.930	0.916	0.727	0.848	0.891	0.807	0.890	0.753	0.924	0.882
	H′	3.210	2.954	3.227	3.006	2.352	2.538	2.645	2.490	2.690	2.215	2.934	2.647
	E_{var}	0.278	0.245	0.575	0.520	0.393	0.375	0.585	0.324	0.300	0.282	0.486	0.318
	J	0.482		0.387		0.550		0.254		0.441		0.500	
Carabids Only	Richness	18	19	11	8	7	7	2	12	8	7	7	4
	Abundance	206	294	46	51	21	27	6	136	109	72	24	8
	D	0.843	0.825	0.845	0.524	0.726	0.711	0.500	0.731	0.768	0.728	0.747	0.688
	H′	2.103	2.039	2.076	1.163	1.538	1.547	0.693	1.641	1.584	1.527	1.591	1.255
	E_{var}	0.271	0.235	0.598	0.384	0.581	0.610	1.000	0.301	0.265	0.447	0.589	0.813
	J	0.542		0.462		0.167		0.100		0.364		0.667	

Table 4. P-values for the effect of habitat on insect species diversity from the analysis of variance not showing the co-variable (plant richness, site area and sampling effort). No significant difference was recorded from any of the diversity measurements for any of the taxon assemblages analyzed.

Taxon assemblages	*Measure*	*p*
All Spp.	Richness	0.2923
	Abundance	0.9350
	Simpson's (D)	0.4899
	Shannon-Wiener (H')	0.6747
	Evenness (E_{var})	0.3045
-2 Ant Spp.	Richness	0.2923
	Abundance	0.4126
	Simpson's (D)	0.6413
	Shannon-Wiener (H')	0.8053
	Evenness (E_{var})	0.3280
Beetles only	Richness	0.4532
	Abundance	0.1987
	Simpson's (D)	0.5837
	Shannon-Wiener (H')	0.3860
	Evenness (E_{var})	0.1605
Carabids only	Richness	0.7824
	Abundance	0.6324
	Simpson's (D)	0.6856
	Shannon-Wiener (H')	0.8295
	Evenness (E_{var})	0.6051

Table 5. Insect species richness and abundance [richness(abundance)] for each green roof (GR) and ground level (GL) sites included in the study.

Order	*All Sites*		*Dalhousie U*		*Saint Mary's U*		*City Centre*		*Quinpool St.*		*Queen St.*	
	GR	GL	GR	GL	GR	GL	GR	GL	GR	GL	GR	GL
Coleoptera (Beetles)	97(1446)	103(2653)	46(185)	40(179)	52(506)	37(346)	23(91)	51(694)	39(489)	47(821)	32(175)	45(612)
Collembola (Springtails)	1(571)	1(456)	1(86)	1(121)	1(133)	1(56)	1(181)	1(144)	1(90)	1(52)	1(81)	1(83)
Dermaptera (Earwigs)	1(56)	1(62)	1(6)	1(1)	1(2)	1(32)	0(0)	1(1)	1(46)	1(23)	1(2)	1(5)
Diptera (Flies)	73(953)	81(1116)	36(145)	40(197)	30(259)	37(153)	28(88)	44(335)	33(234)	27(180)	37(226)	29(251)
Ephemeroptera (Mayflies)	0(0)	1(1)	0(0)	0(0)	0(0)	0(0)	0(0)	1(1)	0(0)	0(0)	0(0)	0(0)
Heteroptera (True bugs)	21(880)	34(661)	15(159)	17(61)	11(529)	11(42)	8(40)	10(56)	13(119)	18(462)	7(33)	9(40)
Hymenoptera (Bees, wasps, ants)	56(8196)	60(8794)	30(400)	28(2315)	30(691)	24(1622)	14(3801)	24(1517)	20(2312)	20(2750)	22(992)	18(590)
Lepidoptera (Moths)	2(32)	7(46)	1(9)	1(1)	1(14)	2(9)	2(2)	2(19)	0(0)	2(3)	1(7)	3(14)
Neuroptera (Lacewings)	0(0)	1(1)	0(0)	1(1)	0(0)	0(0)	0(0)	0(0)	0(0)	0(0)	0(0)	0(0)
Odonata (Damselflies)	0(0)	1(1)	0(0)	1(1)	0(0)	0(0)	0(0)	0(0)	0(0)	0(0)	0(0)	0(0)
Orthoptera (Grasshoppers)	1(1)	1(7)	0(0)	0(0)	0(0)	1(7)	0(0)	0(0)	1(1)	0(0)	0(0)	0(0)
Psocoptera (Book lice)	1(1)	2(2)	0(0)	0(0)	1(1)	1(1)	0(0)	0(0)	0(0)	1(1)	0(0)	0(0)

Figures

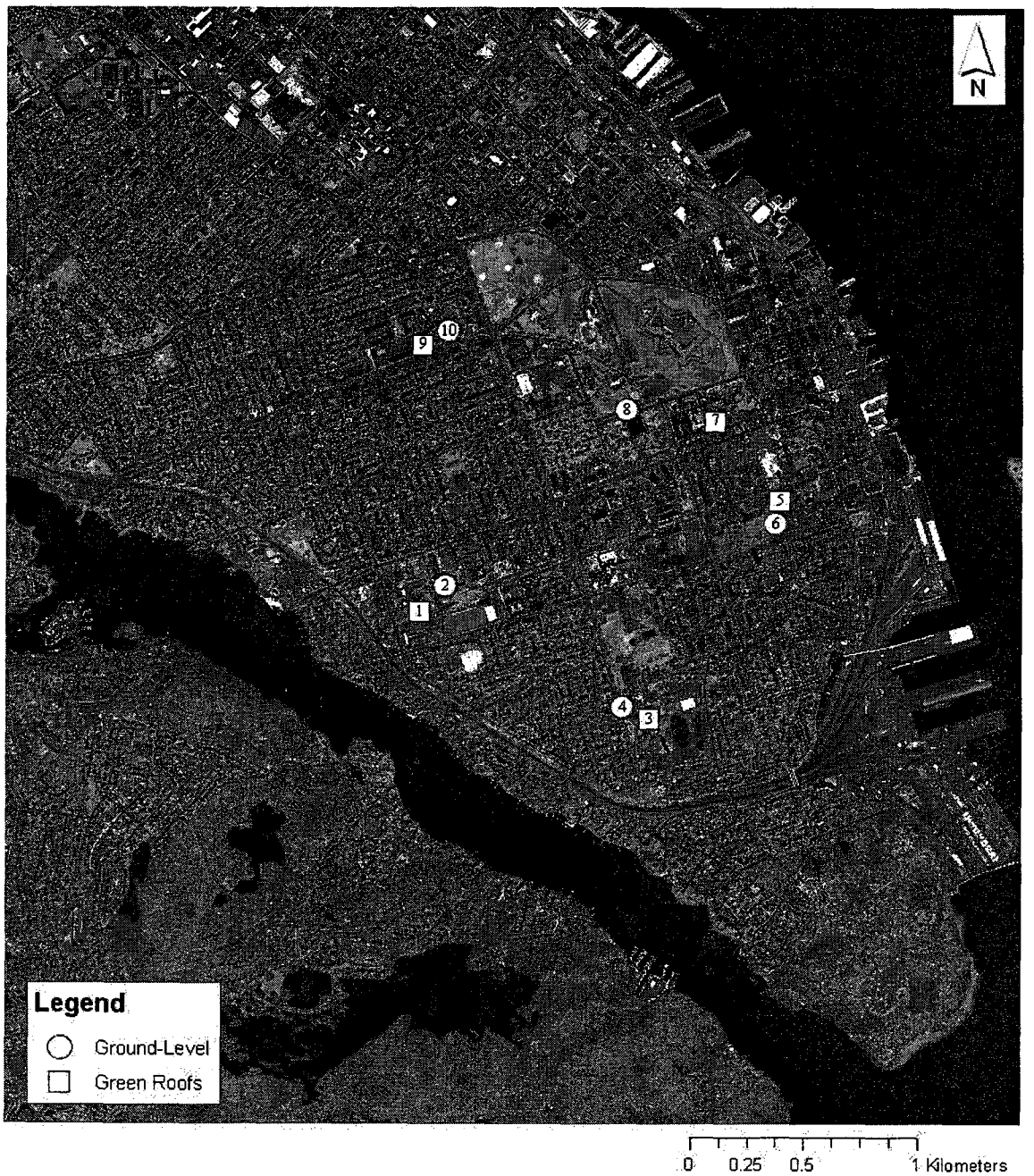

Figure 1. Quickbird Satellite image of Halifax, Nova Scotia identifying the locations of the sites used in the study. Green squares represent intensive green roofs and blue squares represent ground-level habitat patches: Dalhousie (1,2), Saint Mary's (3,4), Queen St. (5,6), City Centre (7,8) and Quinpool St. (9,10).

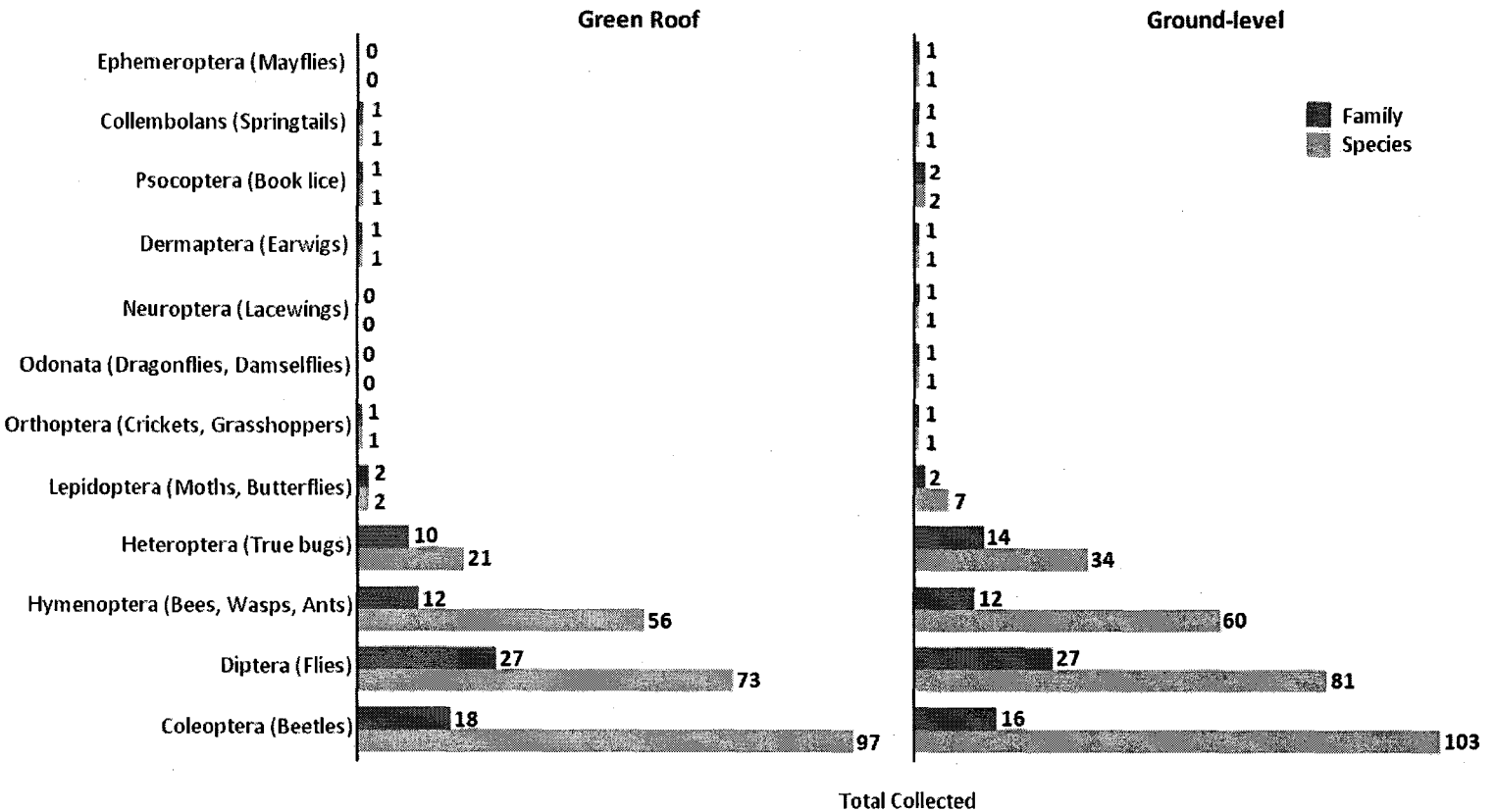

Figure 2. The number of orders, families and species from green roofs and ground-level collected between May-October 2009 in downtown Halifax, Nova Scotia.

CHAPTER 4

SYNTHESIS "GREEN ROOFS AS CONSTRUCTED ECOSYSTEMS: NATIVE PLANT PERFORMANCE AND INSECT DIVERSITY"

Thesis Synthesis

The goals of this thesis were twofold; first, to elucidate the individual performance of locally occurring plant species of various life-form groups on extensive green roofs and their contribution to stormwater retention and roof cooling; and second, to quantify similarities in insect species richness and composition between intensive green roofs and adjacent ground level urban habitat. In chapter two, there were notable differences in performance between species within the same life-form group, particularly within the graminoids, highlighting the value of plant selection on extensive green roofs. A fundamental finding was that differences in exposure to solar radiation (as indicated by the block effect) had stronger effects than differences among plant species on roof surface temperature, water capture and loss. In chapter three, numerous insects were recorded from both green roof and ground-level urban habitat and although many species were found in only one type of habitat (green roof vs. ground-level), no obvious differences in overall insect species composition was evident between habitats and no statistically significant differences in insect species diversity were evident. One difference was that single specimens of three insect groups; Ephemeroptera (Mayflies), Neuroptera (Lacewings), and Odonata (Damselflies and Dragonflies), were found only at ground level however, since insects from these groups are highly mobile, it is expected that they could easily reach green roof habitat.

Whereas each chapter covers different aspects of green roof ecology and function, the results from each chapter are clearly connected, in that developing a wider regional plant palette for green roofing could increase plant diversity and

improve habitat design, thereby undoubtedly increasing invertebrate biodiversity (e.g. Smith et al. 2005). Although this was not clear in this study, it is suspected that if more sites had been included, a stronger relationship between plant and insect diversity might have been detected. Albeit different experimental designs were employed, results from both chapters are implicated in green roof performance and should be considered in future research within Atlantic Canada.

Green Roof Plant Selection

In chapter two of this study, all plant species but one had greater than 80% survival, and ten species reached greater than 90% groundcover. Over a single growing season, the top performing species reduced roof surface temperature by an average of 3.44°C (*C. argyrantha*) and increased solar reflectivity by 22% (*S. tridentata*) over the growing-medium only controls. Moreover, the best species retained 75.3% of experimentally added stormwater (*C. argyrantha*). Several of the locally occurring species examined in this study, including graminoids (*C. argyrantha*, *C. nigra*, *L. multiflora*), forbs (*F. virginiana*) and creeping shrubs (*S. tridentata*) performed equally or greater to the non-native industry standard plant species (*S. acre*, *S. spurium*, *P. compressa*) commonly employed on extensive green roofs, as examined in Lundholm et al. (2010) using the same experimental set up. Results from this study in conjunction with data in Lundholm et al. (2010) suggest that several species (and likely many, many more) found through out rocky and coastal barren habitats in Atlantic Canada are easily propagated and thrive on extensive green roofs within a Maritime climate. Based on experimental data from this study, recommendations for extensive green roof installations in this region might include using *C. argyrantha* or *F. rubra* in place of

Poa spp., a mix of *L. multiflora* and *Solidago* spp. in place of some *Sedum* spp., as well as *F. virginiana* and *S. tridentata* which performed well and have long growing seasons, flower each year, and are aesthetically pleasing. Continued testing of locally occurring species over time may eventually lead to their widespread propagation and usage on green roofs, as well as possibly education and conservation opportunities for the coastal barrens habitats in Atlantic Canada. To ensure that these top performing species are included into the green roof industry, an important step highlighted in this study is to keep track of the germination and propagation techniques used to grow the species selected, including growing medium characteristics, as many of these species are not yet commonly grown in large quantities or within the horticulture industry.

In this study, exposure to solar radiation influenced extensive green roof performance over and above that of the plants. This was evident in the randomized block design, in which daily exposure to sun increased from the westernmost section of the study area (block 1) to the easternmost (block 5) which significantly influenced surface temperature, water capture and water loss. These results highlight the difficult growing conditions present on green roofs, and the need for quantitative assessment of species survival on green roofs under a variety of environmental conditions to ensure green roofs are designed with the most regionally suitable plant community.

It is possible to speculate as to how each of the species and life-form groups examined in chapter two might improve habitat value for beneficial insect species, or how planted green roof diversity might influence insect composition, as somewhat investigated in chapter three. Almost all plants within the graminoids life-form group were among the top performing species, and although they are wind pollinated, the

variety in growth form of each species examined would provide a diversity of niches for numerous invertebrate and bird species. Several of the plants described in chapter two were flowering perennials, including *F. virginiana*, *S. tridentata*, *S. bicolor*, *S. puberula* and *A. novae-belgii*, all of which would serve as resources for an assortment of pollinating insects.

Green Roof Habitat Value

No significant differences in richness, abundance or any of the diversity indices were found in the analyses, suggesting many insect species within urban areas do not distinguish between green roof and ground level when in search of suitable habitat space. Of 361 species collected, 189 were common to both green roof and ground level sites, whereas 155 species (recorded only once) were unique to one site type. Only 17 species were collected exclusively from one site type in numbers greater than five specimens.

Unlike ground-level urban habitat, green roofs are relatively inaccessibly to most urban citizens, suggesting they might support species more prone to direct anthropogenic disturbance. In this study, several unique species were identified from green roofs in large numbers, most notably, *Phosphaenus hemipterus* (Lampyridae: Coleoptera), an endangered firefly in its native range, and a new record for *Otiorhynchus porcatus* (Curculionidae: Coleoptera), a generalist weevil. With pitfall trapping being the only trapping method employed it is likely this study does not wholly represent all possible insect inhabitants, however, our collections clearly show that green roofs are colonized by many functionally valuable species that are also found at ground level. This corroborates with evidence in Kadas (2006) who found

numerous beetles and spiders on green roofs and on urban ground level brownfields in London, England, 10% of which were nationally threatened or endangered.

Even though many of the insect groups collected could not be identified to species with certainty, our findings support previous studies that indicate green roofs, in place of conventional roof surfaces, may assist in mitigating concerns of declining in biodiversity in urban areas (Ockinger et al. 2009), as well as improve planning initiatives for biodiversity at the regional scale (Dvorak and Volder 2010). Beyond plant selection, the age and depth of the growing medium, as well as the growing medium components and where they are sourced likely influence habitat value, and although not examined in this study, these features should be considered when designing green roofs. For example, Brenneisen (2006) found that using growing medium made of local soils and by varying the growing medium depth over the surface of the roof, insect diversity increased over time compared to green roofs without these features included. His results were so well received that they have been incorporated into green roof construction by-laws in the city of Basel, Switzerland. Surely small adjustments to green roof design that vastly improve their value to local flora and fauna would be well received in North America, however this type of data is severely lacking. Nevertheless, strategies that reconcile anthropogenic space with constructed habitats such as green roofs (Rosenzweig 2003), whether intensive or extensive, are urban space-conscious means of augmenting biodiversity conservation strategies and planning within cities, and more plainly, a way of improving the lives of all urban flora and fauna.

Conclusion

Widespread public engagement, interdisciplinary collaboration between those in research and design, the creation of by-laws and incentive programs, and numerous short- and long-term research projects across North America indicate that green roofs will continue to become an increasingly visible component of the urban landscape. For most, green roof vegetation is viewed as a component of an engineered system - designed to survive and remain green (when not covered in snow), while contributing to economic savings and conveying a building owner's attitude towards environmental awareness. However, it is becoming clear that the plants and growing medium specified have ramifications for technical performance, as well as the contribution of the constructed ecosystem to the surrounding "natural" environment. To continue improving the social, economic and environmental value of green roofs, their ecology require further investigation. Many of the protocols for collecting data in chapter two and three of this study were developed just prior to or during this study, and denote methodologies worth repeating in future studies that wish to evaluate plant species, and their performance in retaining stormwater and roof cooling, as well as studies examining invertebrate diversity on green roofs.

Long-term evaluation of the benefits described in this study, and the suitability of selected North American plant species should continue, particularly since there are thousands of untested native (and non-native) plant species (Dvorak and Volder 2010), and no doubt, hundreds that would thrive under different green roof conditions and in different localities. Furthermore, research on green roof invasibility and the role of plant selection in reducing maintenance of detrimental plant species, such as tree seedlings, is sorely missing from the academic literature. Those conducting biodiversity and ecological

studies such as these in the future might also benefit from incorporating a psychological component (e.g. Fuller et al. 2007), wherein the expectations of urban citizens and their levels of preference and acceptance for different types of green roof vegetation and maintenance styles could be measured, which might decrease the need to remove invading, yet functionally valuable species, such as dandelions and buttercups which many people may in fact find desirable.

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APPENDIX

Appendix 1. Plant species richness at each green roof and ground level habitat; plant species did not affect insect diversity between site type.

Taxonomic name	Common name	Functional group	SMU	Queen	Sackville	Quinpool	DAL	SMU	Queen	Sackville	Quinpool	DAL
			Ground	Ground	Ground	Ground	Ground	Roof	Roof	Roof	Roof	Roof
Achillea millefolium	Common yarrow	Tall forb	Yes	Yes	Yes	Yes	Yes	No	No	Yes	Yes	Yes
Aegopodium podagraria	Goutweed	Tall forb	No	No	No	No	No	No	No	No	No	Yes
Elytrigia repens	Couch grass	Grass	No	No	No	No	No	Yes	No	No	No	No
Agrostis gigantean	Redtop	Grass	No	No	No	No	Yes	No	No	No	No	No
Agrostis stolonifera	Creeping bent	Grass	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Aquilegia canadensis	Red columbine	Tall forb	No	No	No	No	No	No	No	No	No	No
Arctostaphylos uva-ursi	Bearberry	Creeping shrub	No	No	No	No	No	Yes	No	No	No	No
Aster lateriflorus	Calico aster	Tall forb	Yes	No	Yes	No	Yes	Yes	Yes	No	No	Yes
Aster novae-belgii	New York aster	Tall forb	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes
Astilbe biternata	False goat's beard	Tall forb	No	No	No	No	No	No	Yes	No	No	No
Bellis perennis	Common daisy	Tall forb	No	No	No	Yes	No	No	No	No	No	No
Bidens frondosa	Devil's beggartick	Tall forb	No	No	No	No	No	No	Yes	No	No	No
Brassica campestris	Rapeseed	Tall forb	No	No	No	No	No	Yes	No	No	No	No
Campanula rapunculoides	Creeping bellflower	Tall forb	No	No	No	No	No	No	No	No	No	Yes
Campanula rotundifolia	Hairbell	Tall forb	No	No	No	No	No	Yes	No	No	No	No
Capsella bursa-pastoris	Shepherd's purse	Tall forb	No	No	Yes	No	No	Yes	No	No	No	No
Carex argyrantha	Hay sedge	Grass	No	No	No	No	No	Yes	No	No	No	No
Carex lurida	Shallow sedge	Grass	No	No	No	No	Yes	No	No	No	No	No
Carex nigra	Black sedge	Grass	No	No	No	No	No	Yes	No	No	No	No
Carex scoparia	Broom sedge	Grass	No	No	No	No	Yes	Yes	No	No	No	No
Centaurea nigra	Knapweed	Tall forb	No	No	No	No	Yes	No	No	Yes	Yes	Yes
Cerastium arvense	Field chickweed	Creeping forb	Yes	Yes	Yes	Yes	No	Yes	Yes	No	Yes	Yes
Cerastium vulgatum	Mouse ear chickweed	Creeping forb	Yes	Yes	No	No	No	No	No	Yes	No	No
Chenopodium album	Goosefoot	Tall forb	No	No	No	No	No	Yes	No	Yes	Yes	Yes
Chrysanthemum leucanthemum	Oxeye daisy	Tall forb	No	No	No	Yes	Yes	No	Yes	No	No	Yes
Chrysanthemum 'ornamental'	Chrysanthemum	Tall forb	No	No	No	No	No	No	Yes	Yes	Yes	No
Convallaria majalis	Lily-of-the-valley	Tall forb	No	No	No	No	No	No	No	No	No	Yes
Conyza canadensis	Canadian horseweed	Tall forb	No	No	No	Yes	No	Yes	Yes	Yes	Yes	Yes
Cornus sericea	Red Osier dogwood	Tall shrub	No	No	No	No	Yes	No	No	No	No	Yes

Taxonomic name	Common name	Functional group	SMU	Queen	Sackville	Quinpool	DAL	SMU	Queen	Sackville	Quinpool	DAL
			Ground	Ground	Ground	Ground	Ground	Roof	Roof	Roof	Roof	Roof
Coronopus didymus	Lesser Swinecress	Creeping forb	No	Yes	No	No	No	No	Yes	No	No	No
Danthonia spicata	Poverty grass	Grass	No	No	No	No	No	Yes	No	No	No	Yes
Daucus carota	Queen Anne's lace	Tall forb	No	Yes	No	Yes	Yes	No	Yes	No	Yes	No
Deschampsia flexuosa	Wavy hairgrass	Grass	Yes	No	Yes	No	Yes	Yes	No	No	No	Yes
Elymus repens	Couch grass	Grass	No	No	Yes	No	No	No	No	No	No	No
Empetrum nigrum	Black Crowberry	Creeping shrub	No	No	No	No	No	Yes	No	No	No	No
Epilobium ciliatum	Willow herb	Tall forb	Yes	No	Yes	No	No	No	Yes	Yes	No	Yes
Equisteum arvense	Common Horsetail	Tall forb	No	No	No	No	Yes	No	Yes	No	No	No
Erigeron modestus	Plain's Fleabane	Tall forb	No	No	No	No	No	Yes	No	No	No	No
Erysimum cheiranthoides	Wormseed wallflower	Tall forb	No	No	Yes	Yes	No	Yes	No	Yes	No	No
Euthamia graminifolia	Lance-leafed goldenrod	Tall forb	No	No	No	No	Yes	No	No	No	No	No
Festuca pratensis	Meadow fescue	Grass	No	No	No	No	Yes	No	No	No	No	No
Festuca rubra	Red fescue	Grass	Yes	No	Yes	Yes	Yes	Yes	Yes	No	Yes	No
Fragaria virginiana	Virginia strawberry	Creeping forb	No	No	Yes	Yes	No	No	No	No	No	Yes
Galeopsis tetrahit	Common hempnettle	Tall forb	No	No	No	No	No	Yes	Yes	No	No	No
Galinsoga quadriradiata	Shaggy soldier	Tall forb	No	No	No	No	No	No	Yes	No	No	No
Gallium mollugo	False baby's breath	Tall forb	Yes	No	Yes	Yes	No	Yes	No	No	Yes	No
Gaultheria procumbens	Eastern Teaberry	Creeping shrub	No	No	No	No	No	Yes	No	No	No	No
Geranium robertianum	Herb robert	Creeping forb	No	No	No	No	No	No	No	No	No	Yes
Gnaphalium uliginosum	Marsh cudweed	Annual	Yes	Yes	Yes	Yes	No	Yes	Yes	No	Yes	Yes
Hieracium cespitosum	Meadow hawkweed	Tall forb	Yes	No	No	Yes	Yes	Yes	No	No	No	Yes
Hieracium kalmii	Kalm's hawkweed	Tall forb	No	Yes	Yes	Yes	No	No	Yes	Yes	Yes	Yes
Hieracium pilosella	Mouse ear hawkweed	Tall forb	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Juncus offusus	Common rush	Grass	No	No	No	No	Yes	No	No	No	No	No
Juncus tenuis	Poverty rush	Grass	No	No	No	Yes	Yes	No	Yes	Yes	Yes	No
Leontodon taraxacoides	Lesser hawkbit	Tall forb	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Lepidium densiflorum	Pepperweed	Tall forb	Yes	No	No	No	No	No	Yes	Yes	Yes	No
Linaria vulgaris	Common toadflax	Tall forb	No	No	Yes	No	No	No	No	No	Yes	No
Lobelia inflata	Indian tobacco	Tall forb	No	No	No	No	No	No	Yes	No	No	No
Luzula multiflora	Woodrush	Grass	No	No	No	Yes	No	Yes	No	Yes	No	No
Matricaria discoidea	Pineapple weed	Annual	Yes	No	Yes	Yes	No	Yes	Yes	Yes	Yes	No
Medicago lupina	Black medick	Creeping forb	No	No	Yes	Yes	No	Yes	No	Yes	Yes	Yes
Myosotis sylvatica	Forget-me-not	Creeping forb	Yes	No	No	No	No	No	Yes	No	No	Yes
Myrica pennsylvanica	Northern bayberry	Tall shrub	No	No	No	No	Yes	No	No	No	No	No
Oenothera biennis	Evening primose	Tall forb	No	No	No	No	No	No	Yes	No	No	Yes
Onoclea sensibilis	Sensitive fern	Tall forb	No	No	Yes	No	No	No	No	No	No	No

Taxonomic name	Common name	Functional group	SMU	Queen	Sackville	Quinpool	DAL	SMU	Queen	Sackville	Quinpool	DAL
			Ground	Ground	Ground	Ground	Ground	Roof	Roof	Roof	Roof	Roof
Oxalis stricta	Common wood sorrel	Creeping forb	Yes	Yes	Yes	Yes	No	Yes	Yes	No	Yes	Yes
Parthenocissus quinquefolia	Virginia creeper	Creeping shrub	No	No	No	No	No	No	No	No	No	Yes
Persicaria vulgaris	Lady's thumb	Tall forb	No	No	No	Yes	Yes	No	Yes	Yes	Yes	No
Phleum pratense	Timothy grass	Grass	No	Yes	No	Yes	Yes	Yes	No	No	Yes	No
Plantago lanceolata	Narrow-leaf plantain	Tall forb	No	No	No	No	No	Yes	No	No	No	Yes
Plantago major	Common plantain	Tall forb	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Plantago maritima	Seaside plantain	Tall forb	No	No	No	No	No	Yes	No	No	No	No
Poa annua	Meadow grass	Annual	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes
Poa compressa	Canada bluegrass	Grass	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
Poa pratensis	Kentucky bluegrass	Grass	No	Yes	Yes	No	No	No	Yes	Yes	Yes	No
Polygonum aviculare	Common knotgrass	Creeping forb	Yes	Yes	Yes	Yes	No	No	Yes	Yes	Yes	No
Polygonum convolvulus	Wild Buckwheat	Creeping forb	No	No	No	No	No	Yes	Yes	No	No	Yes
Potentilla recta	Sulphur cinquefoil	Tall forb	No	No	Yes	No	No	No	Yes	No	No	No
Potentilla simplex	Common cinquefoil	Creeping forb	No	No	No	No	Yes	Yes	Yes	No	No	Yes
Prunella vulgaris	Self-heal	Creeping forb	Yes	Yes	Yes	Yes	Yes	Yes	No	No	Yes	Yes
Ranuculus repens	Creeping buttercup	Creeping forb	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Rhodiola rosea	Roseroot	Succulent	No	No	No	No	No	Yes	No	No	No	No
Rosa multiflora	Multiflora rose	Tall shrub	No	No	No	No	Yes	No	Yes	No	No	No
Rubus fruticosus	Blackberry	Tall Shrub	No	No	No	No	Yes	No	No	No	No	No
Rubus hispidus	Bristly dewberry	Creeping Shrub	No	No	No	No	Yes	No	No	No	No	No
Rumex acetosella	Sheep's sorrel	Creeping forb	No	No	No	Yes	No	No	No	No	No	Yes
Rumex crispus	Curly dock	Tall forb	Yes	No	Yes	No	Yes	Yes	No	No	No	No
Sagina procumbens	Pearlwort	Creeping forb	Yes	No	Yes	No	No	Yes	No	No	Yes	No
Scirpus atrovirens	Green bulrush	Grass	No	No	No	No	Yes	No	No	No	No	No
Sedum acre	Goldmoss stonecrop	Succulent	No	No	No	No	No	Yes	No	No	Yes	No
Sedum rubrotinctum	Pork and Beans	Succulent	No	No	No	No	No	Yes	No	No	No	No
Sedum spurium	Two-row stonecrop	Succulent	No	No	No	No	No	Yes	No	No	No	No
Senecio viscosus	Sticky groundsel	Tall forb	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	No
Senecio vulgaris	Common groundsel	Tall forb	Yes	No	No	No	No	No	No	No	Yes	No
Sibbaldiopsis tridentata	Three-toothed cinquefoil	Creeping shrub	No	No	No	No	No	Yes	No	No	No	No
Sisymbrium officinale	Hedge mustard	Tall forb	No	No	Yes	No	No	No	No	No	No	No
Solanum dulcamara	Bittersweet nightshade	Creeping shrub	No	Yes	Yes	No	Yes	Yes	Yes	No	Yes	No
Solanum nigrum	Black nightshade	Creeping shrub	No	No	Yes	Yes	No	No	No	No	No	Yes
Solidago bicolor	White goldenrod	Tall forb	No	No	No	No	No	Yes	No	No	No	No
Solidago canadensis	Canadian goldenrod	Tall forb	No	No	Yes	No	Yes	No	No	No	No	Yes

Taxonomic name	Common name	Functional group	SMU	Queen	Sackville	Quinpool	DAL	SMU	Queen	Sackville	Quinpool	DAL
			Ground	Ground	Ground	Ground	Ground	Roof	Roof	Roof	Roof	Roof
Solidago puberula	Downy goldenrod	Tall forb	No	No	No	No	No	Yes	No	No	No	No
Solidago rugosa	Wrinkle leaf goldenrod	Tall forb	No	No	No	No	Yes	No	No	No	No	No
Sonchus arvensis	Field sowthistle	Tall forb	No	No	No	No	No	No	Yes	No	No	No
Sonchus oleraceus	Common sowthistle	Tall forb	No	No	Yes	Yes	Yes	No	Yes	No	No	Yes
Sorbus americana	Amer. mountain ash	Tree	No	No	No	No	Yes	No	No	No	No	No
Spirea vanhouteii	Bridal wreath	Tall shrub	No	No	No	No	No	No	Yes	No	No	No
Stellaria media	Common chickweed	Annual	Yes	No	No	No	Yes	No	Yes	Yes	Yes	Yes
Stellaria graminea	Mouse ear chickweed	Creeping forb	Yes	No	No	No	No	No	No	No	No	No
Tanacetum vulgare	Tansy	Tall forb	No	No	No	No	No	Yes	No	No	No	No
Taraxacum officinale	Dandelion	Tall forb	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Tilia europaea	Common Linden	Tree	No	Yes	Yes	No	Yes	No	No	No	No	No
Trifolium arvense	Rabbit-foot clover	Creeping forb	No	No	No	Yes	No	No	Yes	No	No	No
Trifolium hybridum	Alsike clover	Creeping forb	No	No	No	No	Yes	No	No	No	No	No
Trifolium pratense	Red clover	Creeping forb	No	No	No	No	Yes	No	No	No	No	Yes
Trifolium repens	White clover	Creeping forb	Yes	Yes	Yes	Yes	No	Yes	No	Yes	Yes	Yes
Tussilago farfara	Colt's foot	Creeping forb	Yes	No	No	Yes	Yes	Yes	Yes	No	No	No
Ulmus glabra	Scots Elm	Woody plant	No	Yes	No	No	Yes	No	No	No	No	No
Vaccinium angustifolium	Low bush blueberry	Creeping shrub	No	No	No	No	No	Yes	No	No	No	No
Vaccinium macrocarpon	Cranberry	Creeping shrub	No	No	No	No	Yes	Yes	No	No	No	No
Vaccinium vitis-idaea	Lingonberry	Creeping shrub	No	No	No	No	No	Yes	No	No	No	No
Veronica chamaedrys	Germander speedwell	Creeping forb	No	No	No	No	No	No	Yes	No	Yes	No
Veronica officinalis	Common speedwell	Creeping forb	Yes	Yes	No	No	Yes	Yes	Yes	Yes	Yes	Yes
Veronica serpyllifolia	Thymeleaf speedwell	Creeping forb	Yes	No	Yes	No	No	No	Yes	No	No	Yes
Vicia cracca	Bird vetch	Creeping forb	No	No	No	No	Yes	Yes	No	Yes	Yes	Yes
Aesculus sp.	Horse chestnut	Tree	No	Yes	No	No	No	No	No	No	No	No
Rhododendron maximum	Rhododendron	Tall shrub	Yes	Yes	No	No	No	No	No	Yes	Yes	No
Acer platanoides	Norway maple	Tree	Yes	No	Yes	Yes	Yes	Yes	Yes	No	No	No
Taxus braccata	Common yew	Tall shrub	No	Yes	No	No	No	No	Yes	Yes	No	No
Juniperus communis	Common juniper	Creeping shrub	No	No	No	No	No	No	No	Yes	Yes	No
Petunia hybrida	Garden petunia	Tall forb	No	No	No	No	No	No	Yes	Yes	Yes	No
TOTAL			36	29	41	38	52	62	53	35	43	46

Appendix 2. Complete list of insect species collected from each of the green roof and ground level habitat patches in the study.

Genus	Species	Family	Order	SMU Ground	Queen Ground	Sackville Ground	Quinpool Ground	DAL Ground	SMU Roof	Queen Roof	Sackville Roof	Quinpool Roof	DAL Roof	Total	Green Roof	Ground
Perapion	*curtirostre*	Apionidae	Coleoptera		6						1		3	10	4	6
Rhyncolus	*brunneus*	Apionidae	Coleoptera	1	3						1			5	1	4
Cytilus	*alternatus*	Byrridae	Coleoptera	1	4	5	4	3	1	9		5	1	33	16	17
Simplocaria	*semistriata*	Byrridae	Coleoptera			2	1		3	1				7	4	3
Cantharis	*rufa*	Cantharidae	Coleoptera	2					1					3	1	2
Rhyonycha	*mollis*	Cantharidae	Coleoptera				1							1	0	1
Acupalpus	*pauperculus*	Carabidae	Coleoptera			1								1	0	1
Agonum	*muelleri*	Carabidae	Coleoptera					2		1				3	1	2
Amara	*communis*	Carabidae	Coleoptera	4	3	15	30	34	7	2	3	26	9	133	47	86
Amara	*aenea*	Carabidae	Coleoptera	1		8			2			4		15	6	9
Anisodactylus	*nigerrimus*	Carabidae	Coleoptera					1	1				2	4	3	1
Bembidion	*properans*	Carabidae	Coleoptera		3	7	19		8			31	5	73	44	29
Bembidion	*rusticum (rusticum)*	Carabidae	Coleoptera						1					1	1	0
Carabus	*granulatus*	Carabidae	Coleoptera		1									1	0	1
Carabus	*nemoralis*	Carabidae	Coleoptera	13		3	3	8		7	3		12	49	22	27
Clivina	*fossor*	Carabidae	Coleoptera	2		1								3	0	3
Dyschirius	*globulosus*	Carabidae	Coleoptera			1			1					2	1	1
Dyschirius	*globulosus*	Carabidae	Coleoptera									1		1	1	0
Elaphropus	*incurvus*	Carabidae	Coleoptera						1					1	1	0
Elaphropus	*granarius*	Carabidae	Coleoptera				1							1	0	1
Harpalus	*somnulentus*	Carabidae	Coleoptera			1	9	1		3		16	3	33	22	11
Harpalus	*rufipes*	Carabidae	Coleoptera			40	7			9		1	1	58	11	47
Harpalus	*affinis*	Carabidae	Coleoptera			2				1		29	7	39	37	2
Notiophilus	*biguttatus*	Carabidae	Coleoptera	4	1	2		3					2	12	2	10
Notiophilus	*aeneus*	Carabidae	Coleoptera					1					1	2	1	1
Olisthopus	*parmatus*	Carabidae	Coleoptera	1										1	0	1
Pterostichus	*melanarius*	Carabidae	Coleoptera	2		55	3			1			3	64	4	60
Stenolophus	*ochropezus*	Carabidae	Coleoptera					1						1	0	1
Stenolophus	*conjunctus*	Carabidae	Coleoptera										1	1	1	0
Stenolophus	*conjunctus*	Carabidae	Coleoptera									1		1	1	0
Altica	*kalmiae*	Chrysomelidae	Coleoptera						2					2	2	0
Chaetocnema	*concinna*	Chrysomelidae	Coleoptera	107	127	67	385	10	258	3	5	106	36	1104	408	696
Cryptocephalus	*notalus (notalus)*	Chrysomelidae	Coleoptera				1							1	0	1
Longitarsus	*luridus*	Chrysomelidae	Coleoptera	7	7	4	71		9	8			11	117	28	89
Longitarsus	*jacobeae*	Chrysomelidae	Coleoptera				1							1	0	1
Tricholochmaea	*kalmiae*	Chrysomelidae	Coleoptera	1										1	0	1
Coccinella	*septempunctata*	Coccinellidae	Coleoptera				1							1	0	1

Genus	Species	Family	Order	SMU	Queen	Sackville	Quinpool	DAL	SMU	Queen	Sackville	Quinpool	DAL	Total	Green Roof	Ground
				Ground	Ground	Ground	Ground	Ground	Roof	Roof	Roof	Roof	Roof			
Harmonia	*axyridis*	Coccinellidae	Coleoptera			3		2	1					6	1	5
Propylaea	*quotuordecimp-unctata*	Coccinellidae	Coleoptera						1					1	1	0
Psyllobora	*vigintimaculata*	Coccinellidae	Coleoptera	1										1	0	1
Atomaria	*wollastoni*	Cryptophagidae	Coleoptera						4					4	4	0
Amalus	*scortillum*	Curculionidae	Coleoptera						1					1	1	0
Anthonomus	*signatus*	Curculionidae	Coleoptera						1					1	1	0
Bagous	*restrictus*	Curculionidae	Coleoptera		1		4	1	31			2		39	33	6
Barypeithes	*pellucidus*	Curculionidae	Coleoptera	21	106	283	13	27	1	14	12	1	4	482	32	450
Ceutorhynchus	*erysimi*	Curculionidae	Coleoptera						1					1	1	0
Dalopius	*vagus*	Curculionidae	Coleoptera	11	17	4		7						39	0	39
Dryophthorus	*americanus*	Curculionidae	Coleoptera										1	1	1	0
Eutrichapion	*cyanicinctum*	Curculionidae	Coleoptera						1					1	1	0
Glocianus	*punctiger*	Curculionidae	Coleoptera		3								1	4	1	3
Hylobius	*congener*	Curculionidae	Coleoptera		3								1	4	1	3
Hypera	*meles*	Curculionidae	Coleoptera				2		13			5	6	26	24	2
Isochnus	*populicola*	Curculionidae	Coleoptera						5					5	5	0
Listronotus	*delumbis*	Curculionidae	Coleoptera									1		1	1	0
Listronotus	*delumbis*	Curculionidae	Coleoptera	1		1								2	0	2
Otiorhynchus	*sulcatus*	Curculionidae	Coleoptera	2	2	1	26	3	1	5	3		2	45	11	34
Otiorhynchus	*singularis*	Curculionidae	Coleoptera	6										6	0	6
Otiorhynchus	*porcatus*	Curculionidae	Coleoptera								1		2	3	3	0
Otiorhynchus	*ligneus*	Curculionidae	Coleoptera			1								1	0	1
Otiorhynchus	*ovatus*	Curculionidae	Coleoptera								1			1	1	0
Otiorhynchus	*porcatus*	Curculionidae	Coleoptera					6					20	26	20	6
Phyllobius	*oblongus*	Curculionidae	Coleoptera	12					7			67	1	87	75	12
Polydrusus	*sericeus*	Curculionidae	Coleoptera			3		6						9	0	9
Rhinoncus	*castor*	Curculionidae	Coleoptera			4								4	0	4
Rhinoncus	*castor*	Curculionidae	Coleoptera						1					1	1	0
Rhyncolus	*brunneus*	Curculionidae	Coleoptera				2	1						3	0	3
Sciaphilus	*asperatus*	Curculionidae	Coleoptera	4	1	2	1	4		3	3	6	1	25	13	12
Scierus	*annectans*	Curculionidae	Coleoptera									1		1	1	0
Sitona	*lepidus*	Curculionidae	Coleoptera	1		1	4		11					17	11	6
Sphenophorus	*venatus*	Curculionidae	Coleoptera						2			2		4	4	0
Sphenophorus	*venatus*	Curculionidae	Coleoptera		3	2	5		4	1	1	6	3	25	15	10
Trachyphloeus	*bifoveolatus*	Curculionidae	Coleoptera		2		1	1						4	0	4
Xyleborus	*sayi*	Curculionidae	Coleoptera			2					1			3	1	2
Trogoderma	*variable*	Dermestidae	Coleoptera									1		1	1	0
Hydaticus	*aruspex*	Dytiscidae	Coleoptera					1						1	0	1
Agriotes	*lineatus*	Elateridae	Coleoptera						2			1	3	6	6	0
Agriotes	*obscurus*	Elateridae	Coleoptera	12	9	32	9	2	9	4	3	16	3	99	35	64

Genus	Species	Family	Order	SMU	Queen	Sackville	Quinpool	DAL	SMU	Queen	Sackville	Quinpool	DAL	Total	Green Roof	Ground
				Ground	Ground	Ground	Ground	Ground	Roof	Roof	Roof	Roof	Roof			
Agriotes	*sputator*	Elateridae	Coleoptera	2	11		1		7	2		6		29	15	14
Corymbitodes	*elongaticollis*	Elateridae	Coleoptera		1						2			3	2	1
Dalopius	*vagus*	Elateridae	Coleoptera					1						1	0	1
Dalopius	*cognatus*	Elateridae	Coleoptera	2	4		2		2		5			15	7	8
Hemicrepidus	*hemipodus*	Elateridae	Coleoptera		1									1	0	1
Hypnoides	*abbreviatus*	Elateridae	Coleoptera		1	2			1	4				8	5	3
Melanotus	*decumanus*	Elateridae	Coleoptera	1	2			1	3					7	3	4
Margarinotus	*immunis*	Histeridae	Coleoptera			6								6	0	6
Cercyon	*haemorrhoi-dalis*	Hydrophilidae	Coleoptera			1		2	3		2		2	10	7	3
Lucidota	*atra*	Lampyridae	Coleoptera									1		1	1	0
Phosphaneus	*hemipterus*	Lampyridae	Coleoptera		102					23				125	23	102
Cyrtusa	*subtestacea*	Leiodidae	Coleoptera						2					2	2	0
Epuraea	*truncatella*	Nitidulidae	Coleoptera								1			1	1	0
Meligethes	*viridescens*	Nitidulidae	Coleoptera						3					3	3	0
Olibrus	*semistriatus*	Phalacridae	Coleoptera										2	2	2	0
Aegialia	*humeralis*	Scarabidae	Coleoptera	1										1	0	1
Onthophagus	*nuchicorni*	Scarabidae	Coleoptera		1									1	0	1
Phyllophaga	*anxia*	Scarabidae	Coleoptera	2						1				3	1	2
Sacodes	*pulchella*	Scirtidae	Coleoptera			1								1	0	1
Nicrophorus	*tomentosus*	Silphidae	Coleoptera					1						1	0	1
Acidota	*subcarinata*	Staphilinidae	Coleoptera	2			2		1					5	1	4
Acidota	*crenata*	Staphilinidae	Coleoptera									1		1	1	0
Aleochara	*curtula*	Staphilinidae	Coleoptera		11	5	4					4		24	4	20
Aleochara	*sp. 1*	Staphilinidae	Coleoptera		19	14	41			1		15		90	16	74
Anotylus	*rugosus*	Staphilinidae	Coleoptera		3		1			2				6	2	4
Anotylus	*insecatus*	Staphilinidae	Coleoptera			1								1	0	1
Atheta	*sp.*	Staphilinidae	Coleoptera	5	6	14	13		3	12		11	2	66	28	38
Baeocera	*apicalis*	Staphilinidae	Coleoptera			2								2	0	2
Bledius	*basalis*	Staphilinidae	Coleoptera						1					1	1	0
Carpelimus	*obesus*	Staphilinidae	Coleoptera	1										1	0	1
Drusilla	*canaliculata*	Staphilinidae	Coleoptera		5									5	0	5
Gabrius	*picipennis*	Staphilinidae	Coleoptera		4	3	4			2		4	3	20	9	11
Ilyobates	*bennetti*	Staphilinidae	Coleoptera		1						1			2	1	1
Ischnosoma	*pictum*	Staphilinidae	Coleoptera										1	1	1	0
Mycetoporus	*consors*	Staphilinidae	Coleoptera		1	1		1				1	3	7	4	3
Mycetoporus	*horni*	Staphilinidae	Coleoptera			2	1					1		4	1	3
Philonthus	*carbonarius*	Staphilinidae	Coleoptera	14	29	15	89	1	17	29	5	81	7	287	139	148
Philonthus	*cognatus*	Staphilinidae	Coleoptera	6	4	4	1		8			1		24	9	15
Philonthus	*politus*	Staphilinidae	Coleoptera					2						2	0	2
Philonthus	*caeruleipenni s*	Staphilinidae	Coleoptera					1						1	0	1

Genus	Species	Family	Order	SMU Ground	Queen Ground	Sackville Ground	Quinpool Ground	DAL Ground	SMU Roof	Queen Roof	Sackville Roof	Quinpool Roof	DAL Roof	Total	Green Roof	Ground
Quedius	*fuliginosus*	Staphilinidae	Coleoptera		1		1	4					1	7	1	6
Rugilus	*angustatus*	Staphilinidae	Coleoptera					2						2	0	2
Rugilus	*angustatus*	Staphilinidae	Coleoptera			2	1	2		1	2	1		9	4	5
Stenus	*erythropes*	Staphilinidae	Coleoptera	3		4	2		6			3	1	19	10	9
Stenus	*flavicornis*	Staphilinidae	Coleoptera						1					1	1	0
Tachinus	*addendus*	Staphilinidae	Coleoptera	71	58	34	24	3	14	4	23	8	2	241	51	190
Tachinus	*addendus*	Staphilinidae	Coleoptera		1									1	0	1
Tachinus	*corticinus*	Staphilinidae	Coleoptera		2	1	3		2	2				10	4	6
Tachinus	*corticinus*	Staphilinidae	Coleoptera				1							1	0	1
Tachyporus	*dispar*	Staphilinidae	Coleoptera		6	8	3	3	5	4		3	1	33	13	20
Tachyporus	*borealis*	Staphilinidae	Coleoptera			1	1		2				1	5	3	2
Tachyporus	*nitidulis*	Staphilinidae	Coleoptera			1								1	0	1
Tasgius	*melanarius*	Staphilinidae	Coleoptera					1					1	2	1	1
Tinotus	*morion*	Staphilinidae	Coleoptera										1	1	1	0
Xantholinus	*linearis*	Staphilinidae	Coleoptera	3	3	1	11	4	21	1	9	14	2	69	47	22
Trixagus	*chevrolati*	Throscidae	Coleoptera		2			1					2	5	2	3
Trixagus	*carinicollis*	Throscidae	Coleoptera				1	5		1			2	9	3	6
# beetle larva		Various	Coleoptera	16	31	19	10	19	12	14	3	5	6	135	40	95
Collembola	*all*	Collembola	Collembola	56	83	144	52	121	133	81	181	90	86	1027	571	456
Forficula	*auricularia*	Forficulidae	Dermaptera	32	5	1	23	1	2	2		46	6	118	56	62
Agromyzidae	*sp. 1*	Agromyzidae	Diptera		1						1		1	3	2	1
Anthomyiidae	*sp. 3*	Anthomyiidae	Diptera	1		1	1	2						5	0	5
Anthomyiidae	*sp. 4*	Anthomyiidae	Diptera	1	5	11		1	6	3	1		2	30	12	18
Anthomyiidae	*sp. 2*	Anthomyiidae	Diptera		2			13		7			2	24	9	15
Anthomyiidae	*sp. 1*	Anthomyiidae	Diptera		16	3		2		1	1		1	24	3	21
Penthetria	*heteroptera*	Bibionidae	Diptera							1				1	1	0
Calliphoridae	*sp. 6*	Calliphoridae	Diptera	1	1					1			1	4	2	2
Calliphoridae	*sp. 5*	Calliphoridae	Diptera	2	4	8		1	1	1	3	1		21	6	15
Calliphoridae	*sp. 1*	Calliphoridae	Diptera			6				2				8	2	6
Calliphoridae	*sp. 3*	Calliphoridae	Diptera	2	4	2	2			5		6		21	11	10
Calliphoridae	*sp. 4*	Calliphoridae	Diptera				3			1				4	1	3
Calliphoridae	*sp. 2*	Calliphoridae	Diptera	1						3				4	3	1
Pollenia	*sp. 1*	Calliphoridae	Diptera			1					3	4		8	7	1
Chironomidae	*sp. 1*	Chironomidae	Diptera	43	28	52	26	8	39	5	17	29	19	266	109	157
Chironomidae	*sp. 2*	Chironomidae	Diptera								3			3	3	0
Chlorops	*sp. 1*	Chloropidae	Diptera						7		1			8	8	0
Epichlorops	*sp. 1*	Chloropidae	Diptera		2		3	3	3	6		4	4	25	17	8
Thaumatomyia	*sp. 1*	Chloropidae	Diptera	12	6	15	40	1	35	2	12	71	5	199	125	74
Clusiidae	*sp. 2*	Clusiidae	Diptera										1	1	1	0
Clusiidae	*sp. 1*	Clusiidae	Diptera							4				4	4	0
Culicidae	*sp. 1*	Culicidae	Diptera					1						1	0	1
Condylostylus	*sp. 1*	Dolichopodidae	Diptera	2	4	13	5	4		4			4	36	8	28

Genus	Species	Family	Order	SMU	Queen	Sackville	Quinpool	DAL	SMU	Queen	Sackville	Quinpool	DAL	Total	Green Roof	Ground
				Ground	Ground	Ground	Ground	Ground	Roof	Roof	Roof	Roof	Roof			
Condylostylus	*sp. 2*	Dolichopodidae	Diptera									3		3	3	0
Dolichopus	*sp. 2*	Dolichopodidae	Diptera	3	1	10	19	26	11	16	10	12	10	118	59	59
Dolichopus	*sp. 1*	Dolichopodidae	Diptera			3	1	11			1		1	17	2	15
Drosophila	*sp. 1*	Drosophilidae	Diptera	1		63	7	11	6	9	10	5	10	122	40	82
Drosophilidae	*sp. 3*	Drosophilidae	Diptera	4		4			2			1	4	15	7	8
Drosophilidae	*sp. 1*	Drosophilidae	Diptera			3								3	0	3
Drosophilidae	*sp. 2*	Drosophilidae	Diptera			3	6		2	1	2	11	4	29	20	9
Drosophilidae	*sp. 5*	Drosophilidae	Diptera	9						1	1			11	2	9
Drosophilidae	*sp. 4*	Drosophilidae	Diptera								2	1		3	3	0
Dryomyza	*sp. 1*	Dryomyzidae	Diptera			2		7		3				12	3	9
Empid	*sp. 1*	Empididae	Diptera			1								1	0	1
Empididae	*sp. 2*	Empididae	Diptera	1	1									2	0	2
Platypalpus	*sp. 1*	Empididae	Diptera					3		1			2	6	3	3
Platypalpus	*sp. 2*	Empididae	Diptera			3		1		1			2	7	3	4
Suillia	*so. 1*	Heleomyzidae	Diptera	1				2				1		4	1	3
Heteromyzidae	*sp. 1*	Heleomyzidae	Diptera	1								1		2	1	1
Lonchaea	*sp. 1*	Lonchaeidae	Diptera		1		2	3						6	0	6
Milichiidae	*sp. 1*	Milichiidae	Diptera						13			7		20	20	0
Milichiidae	*sp. 2*	Milichiidae	Diptera		6	17	13		22	9	2	19	3	91	55	36
Coenosia	*sp. 1*	Muscidae	Diptera				6		1					7	1	6
Muscdae	*sp. 2*	Muscidae	Diptera		3			3						6	0	6
Muscidae	*sp. 3*	Muscidae	Diptera	2	5	3			2	6				18	8	10
Muscidae	*sp. 1*	Muscidae	Diptera					1				2		3	2	1
Muscidae	*sp. 4*	Muscidae	Diptera		2				2				1	5	3	2
Mycetophilidae	*sp. 6*	Mycetophilidae	Diptera	3	3				2		1	3	9	21	15	6
Mycetophilidae	*sp. 1*	Mycetophilidae	Diptera	1		1				1	2	1		6	4	2
Mycetophilidae	*sp. 4*	Mycetophilidae	Diptera					1						1	0	1
Mycetophilidae	*sp. 5*	Mycetophilidae	Diptera			1								1	0	1
Mycetophilidae	*sp. 7*	Mycetophilidae	Diptera			4							5	9	5	4
Mycetophilidae	*sp. 3*	Mycetophilidae	Diptera					2	7				5	14	12	2
Mycetophilidae	*sp. 2*	Mycetophilidae	Diptera	1										1	0	1
Geomyza	*tripunctata*	Opomyzidae	Diptera				4		1				1	6	2	4
Opomyza	*petrei*	Opomyzidae	Diptera	4		1	4	5	19	8		4	1	46	32	14
Phoridae	*sp. 1*	Phoridae	Diptera	9	115	21	10	5	11	55	3	7	5	241	81	160
Phoridae	*sp. 2*	Phoridae	Diptera							1			1	2	2	0
Loxocera	*cylindrica*	Psilidae	Diptera									1	2	3	3	0
Rhagio	*sp. 1*	Rhagionidae	Diptera						3					3	3	0
Sarcophagidae	*sp. 10*	Sarcophagidae	Diptera	2		3								5	0	5
Sarcophagidae	*sp. 8*	Sarcophagidae	Diptera	1	6									7	0	7
Sarcophagidae	*sp. 1*	Sarcophagidae	Diptera							1				1	1	0
Sarcophagidae	*sp. 4*	Sarcophagidae	Diptera		2	1				1				4	1	3
Sarcophagidae	*sp. 3*	Sarcophagidae	Diptera	7	2	1	1	1			3	2	2	19	7	12

Genus	Species	Family	Order	SMU Ground	Queen Ground	Sackville Ground	Quinpool Ground	DAL Ground	SMU Roof	Queen Roof	Sackville Roof	Quinpool Roof	DAL Roof	Total	Green Roof	Ground
Sarcophagidae	*sp. 5*	Sarcophagidae	Diptera							1				1	1	0
Sarcophagidae	*sp. 9*	Sarcophagidae	Diptera									3		3	3	0
Sarcophagidae	*sp. 6*	Sarcophagidae	Diptera	1	5	4		6				1		17	1	16
Sarcophagidae	*sp. 7*	Sarcophagidae	Diptera	3				1					3	7	3	4
Sarcophagidae	*sp. 2*	Sarcophagidae	Diptera	2		1			4			1	1	9	6	3
Scathophaga	*sp. 1*	Scathophagidae	Diptera											1	1	0
Scathophagidae	*sp. 3*	Scathophagidae	Diptera					1						1	0	1
Scathophagidae	*sp. 1*	Scathophagidae	Diptera					5		3	1		1	10	5	5
Scathophagidae	*sp. 2*	Scathophagidae	Diptera	2		2	3	1						8	0	8
Scathophagidae	*sp. 1*	Scathophagidae	Diptera			1		5			1			7	1	6
Scatopsidae	*sp. 1*	Scatopsidae	Diptera								1			1	1	0
Eugnoristes	*sp. 1*	Sciaridae	Diptera					2						2	0	2
Dictya	*sp. 1*	Sciomyzidae	Diptera					1						1	0	1
Tetanocera	*valida*	Sciomyzidae	Diptera					2						2	0	2
Themira	*sp. 1*	Sepsidae	Diptera		1	14	4	41	3	23	2	1		89	29	60
Sphaeroceridae	*sp. 2*	Sphaeroceridae	Diptera		2		1	2		4	1	4	23	37	32	5
Sphaeroceridae	*sp. 1*	Sphaeroceridae	Diptera			1				2			2	5	4	1
Epistrophe	*sp. 1*	Syrphidae	Diptera			1								1	0	1
Eumerus	*sp. 1*	Syrphidae	Diptera								1			1	1	0
Euphodes	*sp. 1*	Syrphidae	Diptera				1		2					3	2	1
Syrphidae	*sp. 1*	Syrphidae	Diptera	1					2					3	2	1
Carcelia	*sp. 1*	Tachinidae	Diptera	1										1	0	1
Tachinidae	*sp. 8*	Tachinidae	Diptera		1			1						2	0	2
Tachinidae	*sp. 6*	Tachinidae	Diptera			1	2				1	1		5	2	3
Tachinidae	*sp. 2*	Tachinidae	Diptera	3		1	1							5	0	5
Tachinidae	*sp. 3*	Tachinidae	Diptera	1		2								3	0	3
Tachinidae	*sp. 5*	Tachinidae	Diptera	1										1	0	1
Tachinidae	*sp. 1*	Tachinidae	Diptera	21	18	43	4	8	2	13	1	5	3	118	24	94
Tachinidae	*sp. 7*	Tachinidae	Diptera			1							1	2	1	1
Tachinidae	*sp. 4*	Tachinidae	Diptera	1		1								2	0	2
Ragoletis	*sp. 1*	Tephritidae	Diptera					1						1	0	1
Limnophila	*sp. 1*	Tipulidae	Diptera						1			2		3	3	0
Tipulidae	*sp. 3*	Tipulidae	Diptera			4	8	2	48	20		19	3	104	90	14
Tipulidae	*sp. 1*	Tipulidae	Diptera			1								1	0	1
Tipulidae	*sp. 2*	Tipulidae	Diptera						1					1	1	0
# fly larva			Diptera	1	4		3		1			1	1	11	3	8
Ephemeroptera	*sp. 1*	Ephemeroptera	Ephemeroptera			1								1	0	1
Acompocoris	*pygmaeus*	Anthocoridae	Heteroptera			2								2	0	2
Anthocoris	*sp .1*	Anthocoridae	Heteroptera		1	1								2	0	2
Aphids	*various*	Aphdidae	Heteroptera	9	9	11	21	1	26	11	15	36	13	152	101	51
Jalysus	*wickhami*	Berytidae	Heteroptera	9		3	62	4	13		1	5	6	78	25	78

Genus	Species	Family	Order	SMU	Queen	Sackville	Quinpool	DAL	SMU	Queen	Sackville	Quinpool	DAL	Total	Green Roof	Ground
				Ground	Ground	Ground	Ground	Ground	Roof	Roof	Roof	Roof	Roof			
Clastopter	*obtusa*	Cercopidae	Heteroptera			1								1	0	1
Neophilaenus	*lineatus*	Cercopidae	Heteroptera					1						1	0	1
Philaenus	*spumarius*	Cercopidae	Heteroptera				3	1				1		5	1	4
Aphrophora	*alni*	Cercopidae	Heteroptera	1			1	5		1			2	10	3	7
Ponana	*sp. 1*	Cercopidae	Heteroptera				5		1			1	1	8	3	5
Agallia	*quadripunctata*	Cicandellidae	Heteroptera	1	3		1	2				1		8	1	7
Anoscopus	*serratulae*	Cicandellidae	Heteroptera			3	74		14			10	24	125	48	77
Balclutha	*sp. 1*	Cicandellidae	Heteroptera					4						4	0	4
Cicandellidae	*sp. 1*	Cicandellidae	Heteroptera	4	2			25		3		6	6	46	15	31
Cicandellidae	*sp. 5*	Cicandellidae	Heteroptera				24	1						25	0	25
Cicandellidae	*sp. 2*	Cicandellidae	Heteroptera				7		29		1		1	38	31	7
Cicandellidae	*sp. 3*	Cicandellidae	Heteroptera		3	29	76		60	10	11	45	93	327	219	108
Cicandellidae	*sp. 4*	Cicandellidae	Heteroptera	14	19		89		265		7	1	1	396	274	122
Exitianus	*exitiosus*	Cicandellidae	Heteroptera		1		72		105	1	1	7		187	114	73
Paraulacizes	*sp. 1*	Cicandellidae	Heteroptera			2								2	0	2
Gerris	*sp. 1*	Gerridae	Heteroptera					1						1	0	1
Blissus	*sp. 1*	Lygaeidae	Heteroptera	1	1				1					3	1	2
Ophiderma	*sp. 1*	Membracidae	Heteroptera	1										1	0	1
Heterotoma	*meriopterus*	Miridae	Heteroptera										1	1	1	0
Phytocoris	*sp. 1*	Miridae	Heteroptera		1				1					2	1	1
Phytocoris	*sp. 2*	Miridae	Heteroptera				2							2	0	2
Stenodema	*sp. 1*	Miridae	Heteroptera					1						1	0	1
Anaptus	*major*	Nabidae	Heteroptera					2					1	3	1	2
Nabis	*sp. 1*	Nabidae	Heteroptera					2						2	0	2
Collaria	*sp. 1*	Nabiidae	Heteroptera				3							3	0	3
Psyllopsis	*fraxini*	Psyllidae	Heteroptera	1			1	2		2	3		1	10	6	4
Arhyssus	*sp. 1*	Rhophalidae	Heteroptera					1						1	0	1
Eremocoris	*sp. 1*	Rhyparochromidae	Heteroptera			1						1		2	1	1
Kalania	*tricoris*	Tingidae	Heteroptera				7					3	2	12	5	7
# true bug larva	*various*		Heteroptera	1		3	14	8	14	5	1	2	7	55	29	26
Apidae	*sp. 1*	Apidae	Hymenoptera										1	1	1	0
Apidae	*sp. 2*	Apidae	Hymenoptera										1	1	1	0
Apis	*mellifera*	Apidae	Hymenoptera	1		1	2	2	2	3		1	2	14	8	6
Bombus	*perplexus*	Apidae	Hymenoptera							1				1	1	0
Bombus	*impatiens*	Apidae	Hymenoptera	1			1	2					1	5	1	4
Braconidae	*sp. 3*	Braconidae	Hymenoptera			1								1	0	1
Braconidae	*sp. 2*	Braconidae	Hymenoptera		3	1			1	1			1	7	3	4
Braconidae	*sp. 1*	Braconidae	Hymenoptera				3		1	1				5	2	3
Braconidae	*sp. 4*	Braconidae	Hymenoptera										1	1	1	0
Braconidae	*sp. 5*	Braconidae	Hymenoptera			1								1	0	1

Genus	Species	Family	Order	SMU	Queen	Sackville	Quinpool	DAL	SMU	Queen	Sackville	Quinpool	DAL	Total	Green Roof	Ground
				Ground	Ground	Ground	Ground	Ground	Roof	Roof	Roof	Roof	Roof			
Crabronidae	*sp. 2*	Crabronidae	Hymenoptera			1								1	0	1
Crabronidae	*sp. 1*	Crabronidae	Hymenoptera				1						1	2	1	1
Ectemnius	*sp. 1*	Crabronidae	Hymenoptera						1					1	1	0
Ectemnius	*sp. 2*	Crabronidae	Hymenoptera	1					1					2	1	1
Cynipidae	*sp. 1*	Cynipidae	Hymenoptera	1	3	2	4		14	1	1	1	2	29	19	10
Cynipidae	*sp. 2*	Cynipidae	Hymenoptera							1				1	1	0
Diapriidae	*sp. 1*	Diapriidae	Hymenoptera	2	11	3	21	2	10	1		18	5	73	34	39
Pantoclis	*sp. 1*	Diapriidae	Hymenoptera				1		7			2		10	9	1
Eulophidae	*sp. 2*	Eulophidae	Hymenoptera				1							1	0	1
Eulophidae	*sp. 1*	Eulophidae	Hymenoptera						1					1	1	0
Campontus	*sp. 1*	Formicidae	Hymenoptera	1284	1	1	4	1412	3	5	1	40	7	2758	56	2702
Campontus	*sp. 2*	Formicidae	Hymenoptera		8			16			20		1	45	21	24
Formica	*sp. 3*	Formicidae	Hymenoptera	273	446	1420	2627	695	552	922	3724	2182	339	13180	7719	5461
Formica	*sp. 1*	Formicidae	Hymenoptera	2	47	27		54	1		37	5	3	176	46	130
Formica	*sp. 4*	Formicidae	Hymenoptera				1				1	13		15	14	1
Formica	*sp. 5*	Formicidae	Hymenoptera						1					1	1	0
Formica	*sp. 2*	Formicidae	Hymenoptera	2	1		14		3	1	1	1		23	6	17
Formicinae	*sp. 1*	Formicidae	Hymenoptera				12	2	11	2		10		37	23	14
Formicinae	*sp. 5*	Formicidae	Hymenoptera					1		9				10	9	1
Formicinae	*sp. 4*	Formicidae	Hymenoptera	1			35	2	1			9		48	10	38
Lasius	*sp. 1*	Formicidae	Hymenoptera				1	8	4	1	1	3	2	20	11	9
Myrmica	*sp. 1*	Formicidae	Hymenoptera	9	12	7	2	10	13	2		11		66	26	40
Myrmica	*sp. 2*	Formicidae	Hymenoptera	13	45	10		80	23	18	4	3	3	199	51	148
Myrmicinae	*sp. 2*	Formicidae	Hymenoptera		1									1	0	1
Myrmicinae	*sp. 1*	Formicidae	Hymenoptera	1										1	0	1
Ponera	*sp. 1*	Formicidae	Hymenoptera	1				1	2			2	9	15	13	2
Halictidae	*sp. 3*	Halictidae	Hymenoptera									1		1	1	0
Halictidae	*sp. 2*	Halictidae	Hymenoptera					3					1	4	1	3
Halictidae	*sp. 1*	Halictidae	Hymenoptera									1		1	1	0
Sphecodes	*sp. 1*	Halictidae	Hymenoptera					1						1	0	1
Gelis	*sp. 1*	Ichneumonidae	Hymenoptera	2	1					2				5	2	3
Gelis	*sp. 2*	Ichneumonidae	Hymenoptera							1				1	1	0
Ichneumonidae	*sp. 3*	Ichneumonidae	Hymenoptera			1								1	0	1
Ichneumonidae	*sp. 15*	Ichneumonidae	Hymenoptera			3		4	2		3	1	1	14	7	7
Ichneumonidae	*sp. 6*	Ichneumonidae	Hymenoptera					5	1				1	7	2	5
Ichneumonidae	*sp. 4*	Ichneumonidae	Hymenoptera	10		1							1	12	1	11
Ichneumonidae	*sp. 1*	Ichneumonidae	Hymenoptera	3		2				1			1	7	2	5
Ichneumonidae	*sp. 10*	Ichneumonidae	Hymenoptera	3	1	1								5	0	5
Ichneumonidae	*sp. 12*	Ichneumonidae	Hymenoptera					1					2	3	2	1
Ichneumonidae	*sp. 19*	Ichneumonidae	Hymenoptera			6								6	0	6
Ichneumonidae	*sp. 18*	Ichneumonidae	Hymenoptera			1								1	0	1
Ichneumonidae	*sp. 2*	Ichneumonidae	Hymenoptera		1									1	0	1

Genus	Species	Family	Order	SMU	Queen	Sackville	Quinpool	DAL	SMU	Queen	Sackville	Quinpool	DAL	Total	Green Roof	Ground
				Ground	Ground	Ground	Ground	Ground	Roof	Roof	Roof	Roof	Roof			
Ichneumonidae	*sp. 17*	Ichneumonidae	Hymenoptera	1										1	0	1
Ichneumonidae	*sp. 16*	Ichneumonidae	Hymenoptera										2	2	2	0
Ichneumonidae	*sp. 9*	Ichneumonidae	Hymenoptera			1								1	0	1
Ichneumonidae	*sp. 20*	Ichneumonidae	Hymenoptera					1						1	0	1
Ichneumonidae	*sp. 14*	Ichneumonidae	Hymenoptera										1	1	1	0
Ichneumonidae	*sp. 5*	Ichneumonidae	Hymenoptera				1	1						2	0	2
Ichneumonidae	*sp. 7*	Ichneumonidae	Hymenoptera					3		3		2	1	9	6	3
Phygadeuontani (tribe)	*sp. 1*	Ichneumonidae	Hymenoptera			1				3				4	3	1
Pompilidae	*sp. 2*	Pompilidae	Hymenoptera										1	1	1	0
Pompilidae	*sp. 1*	Pompilidae	Hymenoptera					1						1	0	1
Dolerus	*sp. 1*	Tenthredinidae	Hymenoptera					1						1	0	1
Tenthredinidae	*sp. 5*	Tenthredinidae	Hymenoptera	1					1					2	1	1
Tenthredinidae	*sp. 2*	Tenthredinidae	Hymenoptera			2		1	3					6	3	3
Tenthredinidae	*sp. 1*	Tenthredinidae	Hymenoptera		1						3			4	3	1
Tenthredinidae	*sp. 4*	Tenthredinidae	Hymenoptera		3					1				4	1	3
Tenthredinidae	*sp. 3*	Tenthredinidae	Hymenoptera			2		1	1		1			5	2	3
Tenthredo	*sp. 1*	Tenthredinidae	Hymenoptera		1		1		1					3	1	2
# parasite		Various	Hymenoptera	6	4	21	17	4	24	12	2	6	6	102	50	52
Ancistrocerus	*sp. 1*	Vespidae	Hymenoptera	1										1	0	1
Polistes	*fuscatus*	Vespidae	Hymenoptera	1			1		1				1	4	2	2
Vespula	*vulgaris*	Vespidae	Hymenoptera	2					4		2		1	9	7	2
Vespula	*maculifrons*	Vespidae	Hymenoptera					1	1					2	1	1
Vespula	*flavopilosa*	Vespidae	Hymenoptera										1	1	1	0
Moth	*sp. 1*	Lepidoptera	Lepidoptera		2									2	0	2
Moth	*sp. 5*	Lepidoptera	Lepidoptera		1									1	0	1
Moth	*sp. 4*	Lepidoptera	Lepidoptera				1							1	0	1
Moth	*sp. 2*	Lepidoptera	Lepidoptera			1								1	0	1
Moth	*sp. 3*	Lepidoptera	Lepidoptera				2							2	0	2
Lymantra	*dispar*	Lymantriidae	Lepidoptera	1							1			2	1	1
# caterpillar			Lepidoptera	8	11	18		1	14	7	1		9	69	31	38
Hemerobiidae	*sp. 1*	Hemerobiidae	Neuroptera					1						1	0	1
Enallagma	*sp. 1*	Coenagrionidae	Odonata					1						1	0	1
Ceuthophilus	*sp. 1*	Rhaphidophori-dae	Orthoptera	7										7	0	7
Orchelimum	*sp. 1*	Tettigonidae	Orthoptera									1		1	1	0
Philotarsus	*picicornis*	Philotarsidae	Psocoptera				1							1	0	1
Valenzuela	*sp. 1*	Caeciliusidae	Psocoptera	1					1					2	1	1
TOTAL				2268	1595	2768	4292	2877	2135	1516	4203	3291	991	25936	12136	13800