

**NATIVE PLANT EVALUATION AND GREEN ROOF PERFORMANCE: THE  
INFLUENCE OF COMPOSITION AND RICHNESS ON ECOSYSTEM FUNCTIONS**

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

September, 2009, Halifax, Nova Scotia

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# **Certification**

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by

**Melissa A. Ranalli**

**A Thesis Submitted to Saint Mary's University, Halifax, Nova Scotia,  
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**September 21, 2009, Halifax, Nova Scotia**

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# **NATIVE PLANT EVALUATION AND GREEN ROOF PERFORMANCE: THE INFLUENCE OF COMPOSITION AND RICHNESS ON ECOSYSTEM FUNCTIONS**

**By Melissa A. Ranalli**

## **ABSTRACT**

Despite the variety of green roof benefits at least partly dependent on the vegetation layer, the influence of plant composition is often ignored, with only limited types of vegetation commonly used. The goal of this thesis is to explore how the composition of a green roof's vegetation layer can affect, and might be used to improve, green roof functioning in a maritime setting, and to assess the potential of native coastal barren species by examining the relationship between species composition, functional group composition, and functional group richness, and: 1) green roof vegetation traits; and 2) green roof environmental functions. Grass and tall forb species had the most favoured canopy characteristics (e.g., increased cover). The inclusion of grasses, and tall forbs or succulents, also optimized temperature moderation and stormwater management functions. Further, most native species showed comparable or more favourable traits and performance compared to the common green roof species tested.

September, 2009

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## **Chapter 1**

### **Native plant evaluation and green roof performance: the influence of composition and richness on ecosystem functions - introduction**

## SOME ENVIRONMENTAL IMPACTS OF URBAN AREAS

Urbanization and the replacement of vegetated landscapes with impermeable surfaces have not surprisingly, caused a number of environmental, and climatological problems. In particular, there is less infiltration of precipitation and warmer air temperatures in cities compared to the vegetated landscapes of rural areas (Oke 1978; Jennings & Jarnagin 2002; Moran 2004; Lazzarin, Castellotti & Busato 2005). The volume and rate of urban runoff associated with heavy rainfall events can result in combined sewer overflows (in cities with combined sewage-stormflow systems), increased erosion, and reduced water table replenishment (Jennings & Jarnagin 2002; Dunnett & Kingsbury 2004a; Moran 2004). Perhaps the most well known climatic difference between most urban and rural areas is the elevated air temperatures (by 3-10 °C) in cities compared to rural areas, known as the Urban Heat Island Effect (UHIE; Oke 1978; Liu & Baskaran 2003; Moran 2004; Lazzarin, Castellotti & Busato 2005).

The UHIE is caused in part by the greater amount of solar radiation that is absorbed by conventional roofing and building materials compared to the vegetation that has largely been removed in cities (Oke 1978; Liu & Baskaran 2003; Dunnett & Kingsbury 2004a). The absorbed energy, which heats city surfaces (and increases the cooling demand of city buildings), is then re-radiated as heat at night, raising city temperatures compared to rural areas (Liu & Baskaran 2003; Dunnett & Kingsbury 2004a). Because rooftops represent a large proportion of the impermeable area in urban centers, their physical characteristics strongly influence the urban environment (Dunnett & Kingsbury 2004a; Gaffin *et al.* 2005). Through habitat creation, visual relief, stormwater management (via water capture), and air and roof temperature moderation, green roofs represent one strategy whereby some of the detrimental impacts of cities (and conventional roofing) might be mitigated (Onmura, Matsumoto & Hokoi 2001; Bass

*et al.* 2003; Liu & Baskaran 2003; Brenneisen 2006; Kadas 2006; Mentens, Raes & Hermy 2006; Oberndorfer *et al.* 2007). While green roofs provide many economic, environmental, and aesthetic benefits, because the focus of this thesis was on the stormwater management and cooling functions provided by green roofs, the following brief introduction to the use of green roofs as an urban mitigation strategy is limited to these two topics.

### GREEN ROOFS AS A MITIGATION STRATEGY

Although green roofs take many forms, all modern systems tend to share a common design: vegetation in a relatively light-weight growing medium, with underlying abiotic layers providing anchorage, drainage and protection of the roof surface. Through their ability to store rainwater (in the substrate layer, drainage layer, in plant tissues or on plant surfaces), and to release it back to the atmosphere over an extended period of time, green roofs reduce the total amount, delay the onset, and reduce the flow rate of roof runoff (Köhler *et al.* 2001; Rowe *et al.* 2003; Dunnett & Kingsbury 2004a; Liu & Baskaran 2005; Mentens, Raes & Hermy 2006; Dunnett *et al.* 2008). Stormwater capture likely also affects the thermal benefits green roofs provide through its influence on evapotranspiration (Compton & Whitlow 2006).

The ability of green roofs to reduce roof, and ambient air temperatures, is one of the major reasons for their construction. Greened rooftops have been shown to reduce the median daily temperature fluctuation of a roof membrane from 45 °C to only 6 °C (Liu & Baskaran 2003). These cooling benefits are achieved primarily through the shading, insulation and evapotranspiration provided by green roof medium and plants (Bass 2001; Onmura, Matsumoto & Hokoi 2001; Bass *et al.* 2003; Liu & Baskaran 2003; Dunnett & Kingsbury 2004a). Potentially further contributing to temperature reductions, green roofs are also thought to have greater albedo (reflective ability) values than

conventional roofing materials (Lazzarin, Castellotti & Busato 2005), but this trend was not consistent across studies (Larr & Grimme 2006) and is somewhat presumptive considering the lack of actual green roof albedo data (Getter & Rowe 2006). A finding that has been consistent across studies, is the ability of green roofs to reduce heat flow from the building to the external environment (compared to conventional roofs), which stabilizes internal temperature and reduces a building's energy demand for space conditioning, resulting in energy conservation in built structures with greened rooftops (Niachou *et al.* 2001; Liu & Baskaran 2003; Wong *et al.* 2003). Despite the fact that green roof benefits are largely a function of the vegetation layer, research into stormwater attenuation, temperature moderation and energy conservation tends to ignore the influence of plant composition (the species and functional types present) and potential differences between taxa (Compton & Whitlow 2006; Dunnett *et al.* 2008).

#### THE ROLE OF GREEN ROOF VEGETATION

The shallow substrate depths common to extensive green roofs (the type most commonly deployed) result in periodic drought (in the absence of rain or irrigation), thus, drought tolerance and avoidance have been the key criteria used for plant species selection (Dunnett & Kingsbury 2004b; Wolf & Lundholm 2008). As a result, *Sedum* species (succulents capable of withstanding water shortages and the extreme weather conditions of rooftops), and stress-tolerant grasses are commonly used on extensive roofs. *Sedum* species have also been researched most often, usually in monoculture (Rowe *et al.* 2003; Gaffin *et al.* 2005; Lazzarin, Castellotti & Busato 2005; Van Woert *et al.* 2005), with very little investigation into what other types of vegetation or combinations might be used to either, provide the same magnitude of benefits, or potentially even enhance green roof performance (Dunnett & Kingsbury 2004b; Compton & Whitlow 2006; Dunnett *et al.* 2008; Wolf & Lundholm 2008). The favoritism of certain succulent

and grass species is at least partly a function of the extreme conditions on rooftops, which limit the types of plants able to survive, but is also partly due to a lack of examination of alternative species and richness levels (i.e., the number of different species or types of plants). The studies that have examined the effect of plant species composition and richness in terms of green roof benefits (and not just survival), suggest that functional differences between species may be large enough to influence green roof performance (Compton & Whitlow 2006; Dunnett *et al.* 2008; Wolf & Lundholm 2008).

Vegetation characteristics such as growth habit, tissue water-storage capacity, plant density, and canopy structure are thought to influence the amount of rain that is captured, uptaken, and eventually evapotranspired (Oke 1978; Crockford & Richardson 2000; Compton & Whitlow 2006; Dunnett *et al.* 2008; Wolf & Lundholm 2008). While, transpiration is thought to be key to the cooling benefits of green roofs (Wolf & Lundholm 2008) (Gaffin *et al.* 2005; Gaffin *et al.* 2006), the extent to which plant transpiration contributes to cooling (separate from the insulative properties of the substrate and membrane layers) is not well understood. Although the relationship between plant composition, evapotranspiration, and actual roof temperature has not been directly examined, research highlighting differences in uptake and evapotranspiration between species, indirectly suggests species composition likely affects green roof temperature moderation. For example, compared to (albeit conservative) data on *Sedum* species grown in a greenhouse, (Compton & Whitlow 2006) showed that both *Spartina alterniflora* and *Solidago Canadensis* species showed evapotranspiration rates 4-8 times larger, suggesting that cooling might be enhanced through the use of species other than *Sedum* ones. Further, Wolf & Lundholm (2008) showed that the plant species associated with the largest amount of evapotranspiration, differed depending on overall water availability. Therefore, in order to maintain maximal water uptake and

evapotranspirative cooling during wet and dry periods, a mixture of species may be desirable (Compton & Whitlow 2006; Wolf & Lundholm 2008), particularly, a mixture of species from habitats with conditions similar to those of a green roof (Lundholm 2006; Dunnett *et al.* 2008).

Basing green roof plant selection on naturally occurring, local plant communities can be advantageous, for example, native vegetation will likely require less maintenance than non-natives since natives may be better adapted to local conditions (Brenneisen 2006; Kadas 2006; Lundholm 2006; Dunnett *et al.* 2008). Interestingly, Oberndorfer (2006) found that Nova Scotia coastal barrens are characterized by some of the same stressful environmental conditions common to roofs, such as, high winds, rocky areas of shallow substrate depth, and variability in soil moisture content. Further, species found on the barrens (Oberndorfer 2006) possess physical traits (e.g., low mat-forming growth, and succulent leaves) Dunnett & Kingsbury (2004a) suggested successful green roof species would likely have (based on similarities among drought- and exposure-tolerant species). Thus, coastal barren species are a logical starting point for alternative species testing in Halifax, Nova Scotia. Based on the relationship between diversity and ecosystem functions (e.g., biomass production, or nutrient and water uptake) seen in other ecosystems, the potential relationship between plant biodiversity and green roof functioning is also worthy of study.

## BIODIVERSITY AND ECOSYSTEM FUNCTION

The term 'biodiversity' has been used to describe variation at a number of biotic scales, from genotypic differences within a species to the earth's biome distribution (Purvis & Hector 2000; Mooney 2002). While biodiversity has perhaps most often been used to describe the number of species present (species richness), different elements of biodiversity can have different effects on ecosystem properties (the sizes of material

compartments and rates of fluxes), therefore, explicit definitions of the terms used here are necessary. Throughout this thesis I will use the term 'richness' when referring to the number of species or functional types of plants present, 'composition' when discussing presence or absence of specific taxa, and I will use 'biodiversity' or 'diversity' only when a general, broad term is appropriate. I focus mostly on richness and composition and at the species or functional group levels. Here, a 'functional group' is a set of species that are thought to have similar effects on green roof canopy characteristics, and functions based on their similarity in form (e.g., grasses).

The relationship between biodiversity and ecosystem functions has been researched extensively, however, there remains a considerable amount of debate over the interpretation of findings (Andre, Brechignac & Thibault 1994; Aarssen 1997; Huston 1997; Tilman 1997; Naeem 2000). Some have argued that biodiversity can improve ecosystem functioning, since different species have different niches and together perform better than some subset; others have argued that since there are many more species than ecosystem functions, the role of biodiversity is neutral or negative; or that biodiversity improves ecosystem functioning over an extended period since species that seem redundant at one time become important following some environmental change; and finally, recent work has introduced the idea that even greater levels of biodiversity may be required to optimize several functions simultaneously (Vandermeer *et al.* 2002; Swift, Izac & Noordwijk 2004; Hector & Bagchi 2007). Interestingly, it is possible that all of the above interpretations may be valid, depending on the temporal scope of a particular study.

Complementarity and facilitation are the two main interaction mechanisms that promoteoveryielding (where differences between species lead to improved performance) in mixtures relative to monocultures (Ewel 1986; Loreau 1998).

Complementarity occurs when competition between species is lower than that between individuals of the same species as a result of niche partitioning. If different species use different resources, or use the same resources at different times, a more species-rich community is expected to use environmental resources more completely, leading to increases in ecosystem properties or functions (Ewel 1986; Hooper 1998). However, most diversity-function studies suggest there is a point in each ecosystem at which niche occupancy is saturated and further increases in diversity have negligible effects on ecosystem functions, with the number of species at which function is saturated being determined by a variety of abiotic and biotic conditions (Elmqvist *et al.* 2003).

Facilitation occurs if interspecific neighbors alleviate harsh environmental conditions or enhance resource availability for other species, increasing desirable ecosystem pools or process rates (Berkowitz, Canham & Kelly 1995; Fridley 2001). The selection probability (or sampling) effect (where more rich communities have a greater chance of including the most productive species) is a different mechanism from the complementarity and facilitation ones described above. The sampling effect hypothesis presumes that competitive success is positively related to the species trait affecting ecosystem function (Troumbis *et al.* 2000; Hooper *et al.* 2005). Important to keep in mind, is that all of the above mechanisms can operate within the same system, they are not mutually exclusive of each other (Kinzig, Pacala & Tilman 2001; Hooper *et al.* 2005). Therefore, in order to distinguish the sampling effect from complementarity or facilitation, comparisons of individual species' performances in monocultures relative to mixtures, are required (Tilman, Lehman & Thomson 1997; Hooper 1998; Loreau 1998; Loreau & Hector 2001).

The applied nature of green roofs and their container-like form, allows ecosystem boundaries and functions to be clearly defined. Since various plant species and levels of

richness can be included in each module (microcosm) of a modular green roof, these systems provide an interesting opportunity to examine the role of composition and richness in green roof vegetation development and green roof functioning.

## OBJECTIVES

The goal of this thesis was to examine the role of species composition, functional group composition, and functional group richness in green roof canopy structure, and green roof environmental functions in order to identify the most successful green roof planting treatment(s) for an Atlantic Canadian city. Further, the suitability of native coastal barren species (for use on green roofs) was also investigated. By examining the vegetative properties of multiple species and levels of functional richness, while simultaneously quantifying indicators of temperature moderation and water capture, this thesis represents a comparatively thorough investigation of how green roof vegetation influences green roof performance. The specific objectives addressed in this thesis were:

Chapter 2: To determine what species, functional group of plants, or combination of functional groups, optimizes green roof canopy properties, such as, vegetation cover, a proxy of aboveground biomass, relative growth rates, plant height, and an index of canopy diversity, variables that have been shown to, or, are thought to, influence green roof performance. Further, the canopy properties of native coastal barren species were evaluated against commonly used, non-native grass and *Sedum* species to assess the suitability of native species for green roof systems.

Chapter 3: To assess whether increased richness optimizes green roof functions such as substrate temperature reductions, reflectivity, stormwater capture and evapotranspiration, or whether, species or functional group composition is more important. Finally, I compared the performance of the native coastal barren species,

with that of commonly used grass and *Sedum* species, in order to determine whether the use of natives might hinder or enhance the provision of green roof benefits.

Chapters two and three are written as independent manuscripts for publication.

In chapter two I have included data sampled in 2007 by other students, however, all statistical analyses and interpretations of data, in both chapters, are my own.

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## **Chapter 2**

### **Native plant evaluation and the green roof canopy: the influence of vegetation composition and functional group richness on canopy structure**

## Abstract

Green roof vegetation is thought to or has been shown to influence nearly every function provided by green roofs. However, despite the variety of functions at least partly dependent on vegetation, only limited types of vegetation are commonly used (and studied), primarily because of their proven ability to tolerate rooftop environments. Further, the only vegetation properties often examined, and thus, emphasized as important, are survival and plant cover. Thus, Nova Scotian coastal barren species, and commonly used non-native green roof species were used to assess the influence of plant composition and functional richness on a variety of green roof canopy traits that have been shown to, or, are thought to, influence green roof performance; and to assess the potential for native species. A one-way, Randomized Complete Block design, and Analysis of Variance for unbalanced designs were used to analyze vegetation trait data. Based on the vegetative properties studied here (cover, biomass, rate of change in cover, height, and canopy diversity), grass and tall forb functional groups (and *S. rubra*) were the most effective green roof taxa, having some of the most favored characteristics (e.g., extensive coverage, and fast increases in cover). Natives were among the top performers across traits, with the common green roof species, *P. compressa*, also showing desirable characteristics (e.g., as the tallest species). Because no single species was the 'best species' for all traits, mixtures of even the few species with the most desirable traits (e.g., *D. flexuosa*, *D. spicata*, *P. compressa*, *S. bicolor*, *P. maritima*, and possibly *S. rubra*), might be the best option to simultaneously maximize survival, cover, speed of growth, and height. This study highlights the need to examine green roof canopy traits over multiple years to properly inform species selection.

**Key-words:** biomass, composition, diversity index, functional group, green roof, Nova Scotia, richness, vegetation cover

## **Introduction**

Green roof services operate at a range of scales, with some operating on an individual building, and others occurring on the “neighbourhood” scale, only if a relatively large number of roofs are vegetated in a particular area (Dunnett & Kingsbury 2004a). These benefits can be classified into three broad (somewhat interrelated) categories: economic, environmental, and aesthetic benefits (Dunnett & Kingsbury 2004a), with the vegetation layer influencing each type.

Green roof vegetation characteristics are thought to, or, have been shown to influence nearly every function provided by green roof systems. The moderation of heat flow through a greened roofing system, and associated energy savings provided by green roofs, are thought to be achieved primarily through the shading, insulation, and evapotranspiration provided by both green roof plants and growing medium (Terjung & O'Rourke 1981; Liu & Baskaran 2003; Dunnett & Kingsbury 2004a; Liu & Baskaran 2005). While green roofs have been shown to extend the life of roof membranes (by approximately two times) by preventing direct exposure to the elements, and by moderating daily and annual temperature fluctuations of roofing materials (Dunnett & Kingsbury 2004a), not all green roof planting combinations seem to have the same magnitude of influence on temperature moderation. For example, a German study's results interpreted in Dunnett & Kingsbury (2004a) showed that the reductions in daily temperature variations, and maximum roof temperatures, seem to be largely influenced by the type of vegetation used, with a diverse variety of grasses and forbs showing greater reductions than grasses alone.

Green roof vegetation can also reduce the amount and rate of stormwater runoff in a couple of ways: rainwater falling on a green roof can be (1) taken up by the plant layer and either stored in plant tissues or transpired over an extended period, or (2)

intercepted by plant surfaces and evaporated (Dunnett *et al.* 2008). Thus, vegetation characteristics, such as, canopy structure, rate of uptake, and transpiration rate are expected to influence the overall hydrological performance of green roofs (Dunnett *et al.* 2008; Wolf & Lundholm 2008). Finally, whether a green roof is accessible or just visible to building users and onlookers, the beneficial effects of being around vegetation include reduced stress levels, lower blood pressure, reduced muscle tension and an increase in positive feelings (Ulrich *et al.* 1991; Dunnett & Kingsbury 2004a). The influence of vegetation composition on the aesthetic value of green roofs is just one of the many ways in which plant composition is overlooked (Dunnett, Nagase & Hallam 2008).

Because there are different goals or reasons for green roof implementation, there are also slightly different demands on the vegetation layer. However, despite the variety of green roof functions at least partly dependent on vegetation (described above), only limited types of vegetation are commonly used. The shallow substrate depths common to extensive green roofs result in periodic drought, thus, not surprisingly, drought tolerance has been the key criterion used for plant species selection (Dunnett & Kingsbury 2004b; Compton & Whitlow 2006; Wolf & Lundholm 2008). Non-native grass and *Sedum* species (succulents capable of withstanding water shortages) are commonly used on North American extensive roofs because they have been successful on European green roofs: requiring minimal maintenance, providing adequate cover, and tolerating dry growing conditions and extreme rooftop weather conditions (Dunnett & Kingsbury 2004a; Monterusso, Rowe & Rugh 2005; Van Woert *et al.* 2005). *Sedum* species are especially favored because they form relatively shallow roots, store water in their vegetative parts, and can exhibit Crassulacean Acid Metabolism (CAM) photosynthesis, minimizing water loss through reduced or inhibited diurnal transpiration (Sayed 2001; Dunnett & Kingsbury 2004a). Because of their proven survival on

rooftops, *Sedum* species have also been researched most often, usually in monoculture (Rowe *et al.* 2003; Gaffin *et al.* 2005; Lazzarin, Castellotti & Busato 2005; Van Woert *et al.* 2005).

Studies explicitly examining green roof plants have tended to focus on topics related to plant selection in terms of survival of rooftop conditions, or the impact of plant establishment method on plant cover (Emilsson 2003; Rowe, Monterusso & Rugh 2005). There has been very little investigation into what types of vegetation, or combinations of species might be used to either, provide the same magnitude of benefits, or potentially even enhance green roof performance compared to common green roof species, through, for example, differences in physical structure or increased transpirative cooling (Dunnett & Kingsbury 2004b; Compton & Whitlow 2006; Dunnett *et al.* 2008; Wolf & Lundholm 2008). Studies that have examined alternative species and mixtures of species in terms of green roof benefits, suggest that functional differences between species may be large enough to influence green roof performance (Dunnett *et al.* 2008; Wolf & Lundholm 2008). For example, Dunnett *et al.* (2008) suggested that the variation in runoff that occurred between the different types of monocultures and mixtures tested was due to plant species traits, such as, leaf structure (and its influence on evapotranspirative losses), and water content. While the majority of green roof vegetation research has involved only a few plant types, this is partly a result of the extreme environmental conditions of roofs, and the relatively shallow substrates often used in green roof construction, both of which limit the range of plants able to survive on rooftops (Dunnett *et al.* 2005; Compton & Whitlow 2006).

Some of the challenges roofs impose on vegetation establishment, growth and survival are extreme temperatures, high wind speeds and periods of drought as well as periods of substrate saturation (Rowe, Monterusso & Rugh 2005; Compton & Whitlow

2006; Dunnett *et al.* 2008). Because rooftops receive more direct solar radiation than ground level areas, concrete buildings store heat in their external walls (and reradiate this heat during the evening), and hot air may exhaust onto a roof from building vents, roofs tend to experience high temperatures (Dunnett & Kingsbury 2004a). However, the thin substrate layers of extensive green roofs can also result in plant root exposure to extremely cold temperatures (Dunnett & Kingsbury 2004a). The high temperatures and high wind speeds common on roofs can dry out vegetation and growing medium, and cause physical damage to vegetation as well (Dunnett & Kingsbury 2004a). Further, because green roof substrate layers are thin, they can also saturate during a single rain event. Thus, tolerance to many environmental extremes must be considered in species selection. While basing green roof plant selection on naturally occurring, local plant communities can be advantageous (e.g., native vegetation can be used to replace lost habitat), local species may not survive the harsh conditions of a roof, unless, however, they can tolerate (or preferably, thrive in) conditions similar to those found on rooftops (Dunnett & Kingsbury 2004a).

The set of physical conditions common to green roofs (i.e., their 'habitat template') has a natural analog in Nova Scotia: the coastal barren ecosystems (Lundholm 2006). Conditions on Nova Scotian coastal barrens, and associated plant species, have much in common with rooftop environments and the types of plants expected to successfully inhabit green roofs, respectively. Oberndorfer (2006) found that these barrens are characterized by high winds, areas of shallow substrate depth, variability in soil moisture content, and an absence of tree cover, some of the same conditions common to green roofs. Nova Scotian barrens have also been shown to be an extremely heterogeneous habitat type, characterized by both exposed bedrock, as well as, moist bogs; each supporting a variety of plant species (Oberndorfer 2006).

While some species are more commonly found in either exposed, or bog areas, species are not necessarily exclusive to those types of areas (Oberndorfer 2006), suggesting that some barren species might be able to tolerate the range of soil moisture conditions found on green roofs. Further, short, shrubby, ericaceous vegetation is common in coastal barren communities, a family of vegetation capable of enduring water shortages, as well as, wet conditions (Oberndorfer 2006). A succulent (*Rhodiola rosea*), and low-growing, mat-forming species (e.g., *Empetrum nigrum*) have also been found on the barrens (Oberndorfer 2006) - types of plants that are expected to be capable of surviving green roof conditions (Dunnett & Kingsbury 2004a).

Since the adaptation to a similar environment often favors the development of similar growth forms, there are certain plant traits suggested to be common among species capable of surviving green roof conditions (Dunnett & Kingsbury 2004a). First, low, mat-forming or cushion-forming species should be ideal because they tend to provide good cover of the growing surface and can maintain good cover even after injury (Dunnett & Kingsbury 2004a). Low-growing vegetation might also be less vulnerable to wind damage compared to taller species. Further, many mat-forming species are adapted to dry growing conditions (Dunnett & Kingsbury 2004a). Second, ground-hugging subshrub species that are compact and twiggy in form, with small evergreen leaves often experience either heat-, or wind-induced water shortages in their natural habitats, making them ideal green roof candidates (Dunnett & Kingsbury 2004a). Third, species with succulent leaves or grey foliage are able to survive dry conditions due to their water-storage capacity and their ability to avoid desiccation, respectively (Dunnett & Kingsbury 2004a). Fourth, plants that are naturally shallow rooting (as opposed to tap-rooted species) will be better adapted to grow in the thin medium layer of extensive green roofs (Dunnett & Kingsbury 2004a). Finally, short life cycles and efficient

reproduction will serve to fill gaps in vegetation cover and ensure long-term cover (Dunnett & Kingsbury 2004a). Obviously, not all traits will be found in a single species, therefore, mixtures of species with one or some of the above characteristics might be the best approach to ensure successful establishment and survival of the vegetation layer (Dunnett & Kingsbury 2004a; Wolf & Lundholm 2008). Which vegetative form(s) will be associated with the most optimal green roof functioning is yet to be determined, but will likely depend on the type of function under study, and the particular climate of an area.

Factors at least partly associated with plant growth form, such as, plant height, cover, and growth rate (or the ability to spread into gaps), are thought to influence plant survival and overall green roof functioning. For example, relatively reduced runoff for the herb, *Leontodon hispidus* (compared to grass and sedge species), was suggested to have been partly due to its fast growth early in the year (Dunnett *et al.* 2008).

Conversely, the relatively slow establishment of *Spartina alterniflora* was blamed for its reduced water uptake in a New York green roof study (Compton & Whitlow 2006).

Further, based on several green roof studies and findings from crop and forest systems, vegetation characteristics such as plant density, and canopy structure, are thought to influence the amount of rain that is captured, uptaken, and eventually evapotranspired (Oke 1978; Dunnett *et al.* 2008; Wolf & Lundholm 2008). Other components of canopy structure that might influence green roof functioning are plant height and structural layering (Oke 1978; Wolf & Lundholm 2008). Yet, the only vegetative properties that tend to be examined, and thus, emphasized as important, are survival, and various approximations of plant cover (e.g., Monterusso, Rowe & Rugh 2005; Rowe, Monterusso & Rugh 2005), but see (Dunnett, Nagase & Hallam 2008). Beyond simple survival and plant cover estimates, additional vegetative descriptors, such as, plant biomass, the relative change in plant cover, plant height, and a diversity index should be estimated in

order to: 1) better describe (and compare) a variety of green roof plantings, as well as to, 2) gauge the performance of candidate planting schemes since at least some of these descriptors are thought to influence green roof performance.

In order for alternative, native species, and mixtures of species to be considered as suitable green roof planting options, basic vegetative research on both industry standard, and alternative species, is required. Since various plant species and levels of richness (i.e., the number of species or functional types) can be included in each module (microcosm) of a modular green roof, these systems provide an interesting opportunity to examine the vegetative characteristics for a variety of alternative planting combinations.

Generally, the aim of this work was to determine and describe how species, functional types of plants (defined here by growth habit), and combinations of plants, affected green roof canopy traits that have been shown to, or, are thought to, influence green roof performance. Specifically, I addressed the following questions:

- What are the initial survival rates of both common green roof species, and alternative ones, such as, native coastal barren species, on an extensive green roof in Halifax?
- Is a commonly valued property of green roof vegetation, plant cover, increased by higher levels of species and functional group richness (i.e., overyielding) through, for example, complementarity (where differences in resource use between species lead to a more complete use of resources, and improved performance in mixtures relative to monocultures), or facilitation (when interspecific neighbors alleviate environmental conditions or enhance resource availability for other species, increasing desirable ecosystem functions)? Or, is species or functional group composition of greater importance?
- What is the relative importance of composition and richness in more novel indicators of green roof plant performance, such as, a proxy of aboveground plant biomass, the

relative change in vegetation cover, average maximum and minimum plant height, and the Shannon index ( $H$ ) of canopy diversity (which accounts for abundance and evenness of the assemblages of interest)?

- Finally, how does the vegetative performance of native coastal barren species compare to commonly used, non-native grass and *Sedum* species?

## **Materials and methods**

### **STUDY SITE**

The study site was on top of the 35-year-old, 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 study roof was approximately 5 m above ground level, and relatively sheltered: there were buildings 1-3 stories higher adjacent to the roof along the west, south and east sides. The majority of the study was conducted between May and October of 2007 with final survivorship measured in May of 2008.

During the months of May to October, Halifax is characterized by daily maximum temperatures between 13.1-23 °C, daily minimum temperatures between 5.5-14.8 °C, and monthly precipitation values (almost entirely rainfall) of 98.3-135.4 mm (Environment Canada 2008). Halifax vegetation endures winters characterized by intermittent snow cover and throughout November to April, Halifax typically experiences daily maximum temperatures between -0.2-8.4 °C, daily minimum temperatures between -8.6-1.2 °C, and monthly precipitation values of 113.8-160.2 mm (Environment Canada 2008).

In order to very basically describe the temperature conditions specific to the period and location of this study, air temperatures on the roof site were recorded every 15 minutes from July 2007 to April 2008 using two Hobo loggers suspended 2 m above roof-level (Onset Computer Corporation, Pocasset, MA, USA) from a roof-top shed

(which was relatively protected from the elements) and from an adjacent building (which was more exposed). Air temperatures were also recorded at a coastal barren site, Chebucto Head (25 km southeast of Halifax), during the summer months of 2007. Additionally, five Springfield rain gauges were set up along the perimeter of the study site during the summer of 2007 to calculate the volume of water that modules received during rain events. The volume of rain in gauges was recorded the morning following rain events.

One hundred and forty Botanicals Nursery LLC (Wayland, MA, USA) modules (microcosms) were used, each one representing a single sampling unit. A single module assembly consisted of a square, plastic, free-draining tray measuring 36 cm x 36 cm along the inside perimeter, lined with a composite nonwoven water-retention layer (Huesker Inc., Charlotte, NC, USA), followed by an Enkamat (Colbond Inc., Enka, NC, USA) above acting as a drainage layer, a site of attachment for plant roots and a filter layer, which was topped with the substrate and plant layers (Fig. 1). The substrate layer was initially approximately 6 cm deep for all modules and consisted of Sopraflor X growing medium (Soprema Inc., Drummondville, QC, Canada). Sopraflor X consists of crushed brick, blond peat, perlite, sand and vegetable compost, has a pH of 6.0-7.0, a total porosity of 60-70%, a bulk density of 1150-1250 kg·m<sup>-3</sup> and an organic matter content (by dry weight) of 5-10% (details from Soprema Inc.). Independent analyses were in approximate agreement with the manufacturer's specifications (Table 1). Prior to this study, the library roof structure consisted of a layer of grass growing in approximately 40 cm of clay soil, over a waterproofing membrane that covers a concrete slab. Therefore, weed barrier fabric (Quest Plastics Ltd., Mississauga, ON, Canada) was laid over the grass (under the green roof modules) to prevent plants from rooting into the underlying soil.

## PLANT MATERIAL AND EXPERIMENTAL DESIGN

Species selection was driven by several factors: 1) the similarity of a species' natural habitat to the conditions on a green roof, 2) past green roof use, and 3) growth habit. Of the 15 species that were examined, 11 are indigenous to Nova Scotia, three (*Poa compressa*, *Sedum acre* and *Sedum spurium*) are commonly used on green roofs in Europe and North America (Durhman *et al.* 2004; Köhler 2006), and one (*Spergularia rubra*) was thought to be a potential green roof candidate based on its form (Dunnett & Kingsbury 2004a) and ability to inhabit both dry and moist soil conditions (Table 2). Native species were selected from coastal barren habitats because of the similarity between these habitats and extensive green roofs (e.g., Fig. 2; Lundholm 2006; Oberndorfer 2006).

I chose three species from each of five functional groups to examine the influence of plant growth habit richness on green roof vegetative performance (Table 3). I defined plant functional type based on growth form since measured variables such as, percent vegetation cover, relative change in cover, biomass, plant height, and survival will likely be partly a function of growth habit (e.g., Monterusso, Rowe & Rugh 2005). Based on the growth forms that are expected to be successful on green roofs or that have been commonly used on green roofs (Dunnett & Kingsbury 2004a), the five functional groups included were: 1) subshrubs (or creeping shrubs), low-growing shrubby species; 2) grasses; 3) ground-covering (or creeping) forbs, low growing plants without woody tissue; 4) tall forbs, tall growing plants without woody tissue; and 5) succulents, fleshy, water-retaining plants (Table 2).

In order to understand the role of functional group composition and richness in canopy structure, I examined 3 replicates of each species in monoculture (in blocks 1, 3, and 5), 5 replicates (1 per block) of each of the one functional group plantings, and of all

the possible combinations of three functional groups, and finally, 20 replicates (4 per block) of the combination of all five groups (Table 3). When one, three or all five functional groups were included in individual modules, all three species within that functional group were planted. Therefore, there were 5 possible planting treatments when only one functional group was planted (i.e., either all subshrub species were planted, or all grasses, or all ground-covering forbs, all tall forbs, or all three succulent species), 10 combinations when three functional groups were included, and only a single possible combination when all five functional groups were included in a module (Table 3). To maintain initial species composition, seedlings of species not originally planted were removed throughout the study period.

Through the use of plant plugs, I ensured that the initial number of plants, 21 plants per module, was consistent among all modules, regardless of the number of functional groups planted in any given module. Twenty-one plants per module was chosen as the richness level because it represented a reasonable (in terms of growing space) multiple of the number of species per functional group. The module planting arrangement involved staggering four rows of four plants (on 9 cm centers) and a centre row of five plants (on 7 cm centers). The planting sequence involved alternating functional types (if more than one type was included in a module), with the functional type and species pattern being randomly chosen (without replacement) until all species to be included had been selected once, after which, the same pattern was repeated throughout the module. By repeating the initial randomly chosen sequence, all species had an equal chance of interacting with, or being exposed to, the other functional types and species included, and any conditions they might have created (e.g., shading). Additionally, this evenly distributed pattern facilitated the detection of a lower and upper level of vegetation (average minimum and maximum plant height), if they existed.

Seeds and cuttings were propagated as plugs in the Saint Mary's University greenhouse between the summer of 2006, through to the spring of 2007. Due to a shortage of seedlings, some plants of *Gaultheria procumbens*, *Vaccinium vitis-idaea* and *P. compressa* were collected from Nova Scotian coastal barrens in May of 2007, namely, Chebucto Head which is approximately 25 km southeast of Halifax and Polly's cove, 45 km southwest of Halifax. Collected plants were put into plugs using Pro-Mix potting soil (Premier Horticulture, Riviere-du-Loup, QB, Canada) - the same potting soil that was used for seed germination - and allowed to establish for at least two weeks prior to planting. Plants did differ in size between and within species at the time of planting. To control for differences within species, I planted a mix of both relatively large and small plants in all treatments with that particular species. Differences in initial size between species were accounted for during the relative change in cover analysis (see below for details).

Modules were planted between June 5 - 19, 2007 and were watered by hand three to six times per week until July 18, 2007. After which, modules received water primarily through rain events, only receiving 750 mL of supplemental irrigation on three separate occasions (July 26, July 27 and August 3 of 2007). Plants that had died after planting (primarily individuals of *Empetrum nigrum*, *Campanula rotundifolia* or *V. vitis-idaea*) were replaced between June 20-29, after which, individual deaths were simply recorded.

A one-way, Randomized Complete Block design was used (Table 3) with modules organized in five long, narrow blocks, each block being two modules wide. 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. To control for the effect of environmental variation within blocks on

measured green roof canopy traits, modules were randomly ordered within blocks and were also rotated within a block six times throughout the study.

#### MEASUREMENT OF GREEN ROOF CANOPY TRAITS

In order to describe and compare the vegetative performance of typical and alternative green roof planting treatments, I measured species survival, vegetation cover, the relative change in vegetation cover, average maximum and minimum plant height, aboveground biomass, and the Shannon index of canopy diversity.

##### *Species survival*

After the initial establishment period (June 5-29, 2007), plants that had died were not replaced. Summer survivorship was measured in September, 2007 and winter survivorship was measured in May, 2008. On each occasion, each module was inspected, and the state (dead or alive) of individual plants was recorded, based on leaf presence, plant color, and plant limpness. For each species, the number of individuals alive at each sampling time was converted to a percentage based on the total number planted in the whole experiment.

##### *Vegetation cover*

Final vegetation cover was estimated between August 13-21, 2007 with the point-intersect or the point interception method (Floyd & Anderson 1987), using a 3-dimensional welded metal frame, the Ranalli box (Domenico Ranalli, Regina, SK, Canada), as long and wide as individual modules, and 30 cm high (Fig. 3). The frame divided the module into 25 subplots. At the 16 equally spaced intersection points of subplot corners (sampling points), a narrow (6 mm diameter) vertical rod (welded to the frame) was oriented towards the vegetation (Fig. 3). The percentage of rods touching vegetation equaled the amount of cover for that module.

#### *Aboveground plant biomass index*

Because of the long-term research objectives for this modular green roof, destructive harvesting was not a feasible means of estimating aboveground biomass. Instead, the alternative point intercept method was also used to estimate biomass between August 13-21, 2007 (Jonasson 1988). Plot biomass has been shown to be strongly correlated with the total number of contacts between plant parts and pins (or rods) arranged along an evenly spaced grid pattern (Jonasson 1988). Thus, the 16 intersection rods (points) on the Ranalli box were used to count the total number of plant hits or contacts for each module, which was used to estimate relative differences in biomass.

#### *Rate of relative change in cover*

Because some individuals, both, within and between species, were initially smaller than others, the rate of relative change in cover was calculated for each treatment in order to make unbiased comparisons of their ability to spread. Initial (June 27, 2007) and final (September 11, 2007) visual estimates of vegetation cover were used to calculate the rate of relative change in cover as follows:

Rate of relative change in cover = ((Final % cover- Initial % cover)/Initial % cover)/ days.

#### *Average maximum and minimum plant height*

To quantitatively describe and compare the average maximum and minimum plant height among treatments, the intercept rods of the Ranalli box were used as sampling points for plant height. At each rod, the tallest, and shortest individuals touching the rod were identified, and measured to the nearest 1 mm. Height was measured by placing a metric ruler alongside, the tallest and shortest plants, and the distance between the substrate surface and the tallest most part of the plant (leaf, floral structure, or stem), in its natural position, represented its height. In this way, the Ranalli

box served as a means to select individuals for height measurements. For each module, all of the tallest plant height values (measured at each rod) were then averaged to calculate average maximum plant height, and the shortest plant height values were averaged to calculate average minimum plant height. Both, average maximum, and minimum plant height were measured between August 13-21, 2007.

#### *Shannon index of canopy diversity*

The Shannon index ( $H'$ ) is a measure of biodiversity that accounts for both species number (or richness), as well as, evenness (Krebs 1989), with greater values indicative of greater diversity. The Shannon index is increased by either the presence of more species, or by having relatively equally sized populations (e.g., 7 individuals of each of *P. compressa*, *D. flexuosa*, and *D. spicata*). Instead of looking at the number of individual plants, here the number of species hits or contacts (recorded for the estimate of plant biomass) was used in the index calculation to measure the diversity of the vegetation canopy for each treatment. Along each of the 16 intercept rods of the Ranalli box, the number of contacts for each species touching a rod was recorded, and summed for individual modules. The Shannon index of canopy diversity was then calculated as follows:

$$H' = -\sum_{i=1}^s p_i \ln p_i$$

where  $s$  = the number of species touching at least one rod for a given module, and;

where  $p_i$  = the proportion of total hits for the  $i$ th species for a given module.

Since both functional group richness and species richness were initially controlled through the planting design, the Shannon index of canopy diversity should have been similar among treatments within a functional group richness level (e.g., 3 functional

group plantings). Therefore, any differences between treatments with the same number of functional groups included, should primarily reflect a change in canopy evenness throughout the summer study period (since, the Shannon index was measured between August 13-21, 2007).

## STATISTICAL ANALYSES

Separate linear mixed effects models were fit to vegetation cover, vegetation biomass, rate of relative change in cover, average maximum and minimum plant height, and the Shannon index data, with the block variable treated as a random factor (Pinheiro & Bates 2000; Pinheiro *et al.* 2007). The species monoculture treatments were not included in the analysis of the Shannon index data because the maximum index value attainable for all monocultures is zero. I used Analysis of Variance (ANOVA) for unbalanced designs and employed marginal sum of squares in F-tests to test for the significance of explanatory variables (with  $\alpha = 0.05$ ). "Treatment" contrasts were used in all ANOVA analyses, which involved comparing all treatments to the most diverse treatment (5-ALL). The planting treatment factor was tested as the sole predictor.

Model comparisons and restricted likelihood ratio tests (*RLRT*'s) were used to determine the significance of the block effect (Pinheiro & Bates 2000; Pinheiro *et al.* 2007). Tukey-Kramer adjustments for multiple comparisons (with  $\alpha = 0.05$ ) were used to test for pairwise differences between treatments (Hothorn *et al.* 2007). Except for the Shannon index of diversity, only significant comparisons between monocultures of the same functional group, or between higher order richness treatments (including one, three or five functional group plantings) and their lower order components (individual species, one functional group, or three functional group plantings, respectively) will be presented here. For diversity index data, only significant comparisons between

treatments with the same number of functional groups will be presented. Because the block factor was inherent to the experimental design, even when the *RLRT*'s indicated that the block factor was not significant, it was left in the predictive model during the post-hoc multiple comparison analyses.

Prior to analyses, vegetation cover, vegetation biomass, rate of relative change in cover, average maximum and minimum plant height, and the Shannon index data were visually inspected for normality and outliers using quantile-quantile plots, histograms, scatter plots and box plots. There were very few outliers, which were removed only if there was a valid reason recorded in my field notes for the outlying values. When data did not appear normally distributed, log, square root and square transformed data were inspected for improvements. To ensure that the assumptions of ANOVA were met, scatter plots and box plots were used to visually check that the within-group errors were centered at zero, had constant variance across groups, and were independent of the group levels (Pinheiro & Bates 2000). Quantile-quantile plots were used to check the normality of the random effects. In addition, Kolmogorov-Smirnov tests were used to statistically test the normality of model residuals, and Levene's test was used to test for homogeneity of variance across treatment groups (Fox 2007). All analyses were completed using R: A Language and Environment for Statistical Computing (R Foundation for Statistical Computing, Vienna, Austria) and most bar graphs were made in R with the *sciplot* package (Morales & Team 2007).

## **Results**

### *Air temperature and precipitation*

While, the green roof site and Chebucto Head site experienced similar air temperatures during the summer of 2007, with most recorded values falling between 10-

20 °C, based on the frequency distribution of measured temperatures, it appears that air temperatures were more often cooler at Chebucto Head compared to the roof site (Fig. 2). Specifically, 76% of Chebucto Head values were in the 10-20 °C range, while only 63% of values fell within the same range on the green roof, and 29% of roof temperatures were between 20-30 °C, yet only 13% of Chebucto Head temperatures were this warm (Fig. 2). Across all air temperature values measured between July - October 2007, the roof site mean was 17.7 °C, the maximum value was 34.4 °C, and the minimum temperature recorded was 5 °C. For the same period at Chebucto Head, the mean of recorded air temperatures was 15.7 °C, the maximum was 30.8 °C, and the minimum was 3.6 °C. Roof site fall and winter temperatures (Table 4) seemed to be more extreme than Halifax normals (Environment Canada 2008), with maximum temperatures largely exceeding the normal range of -0.2-8.4 °C, and daily minimum temperatures tending to be cooler than -8.6-1.2 °C.

Green roof precipitation (rainfall) values measured between July-November, 2007 were mostly in Halifax's normal range of 98.3-153.7 mm (Environment Canada 2008), with the exception of October, which was unusually dry, and September, which was wetter than usual (Figure 4).

#### *Species survival*

The rooftop weather conditions did not seem to negatively affect plant survival, since, most perennial species showed high rates of survival (Table 5). By the end of the first growing season, none of the study species experienced losses greater than 7%, and after the first winter, only *V. vitis-idaea*, *R. rosea*, and *S. spurium* showed losses greater than 10% (Table 5). Grass and tall forb species showed especially high percentages of both, summer (97.5-100%), and winter survival (91.0-100%), with the native grass, *Deschampsia flexuosa*, and tall forb, *Solidago bicolor*, both showing survival rates of

100% after the first year (Table 5). The native succulent, *R. rosea*, showed the lowest amount of summer and winter survival, with 93.4% of original plugs surviving the summer period, and 81.7% alive following the first winter (Table 5). Although survival rates were relatively similar among species, vegetation cover values differed quite dramatically among planting treatments.

#### *Vegetation cover*

Vegetation cover values ranged between 18-100% (with monocultures accounting for both extreme values and), with the most diverse treatment (5-ALL) exhibiting 72% cover (Fig. 5). The planting treatment factor accounted for some of this variability ( $F_{30, 105} = 20.07$ ,  $p < 0.0001$ ), while the block factor did not improve the predictive power of the model ( $RLRT = 0.29$ ,  $df = 1$ ,  $p = 0.588$ ). Most of the treatments that had significantly different cover values compared to the 5-ALL treatment, had smaller cover values (Fig. 5 and Table 6). Specifically, the subshrub treatments (*G. procumbens*, *E. nigrum*, *V. vitis-idaea*, and 1-Sub), the annual, *M. groenlandica*, tall forb, *C. rotundifolia* and succulent monocultures, *R. rosea* and *S. spurium*, showed some of the smallest cover values (Fig. 5 and Table 6). Those treatments that did have significantly greater cover values than 5-ALL were the native grass monocultures (*D. spicata* and *D. flexuosa*), the combination of grass species (1-G), the ground-covering forb, *S. rubra*, and the native tall forb, *P. maritima*. None of the three functional group plantings showed significantly greater cover values than 5-ALL. The three functional group treatments that showed the most reduced amounts of cover (3-Sub+CF+Suc, 3-Sub+CF+TF, and 3-Sub+TF+Suc), all contained subshrub species, and either covering forbs or succulent species (the single functional group treatments that showed the smallest amounts of cover), but did not contain the functional group that achieved the greatest cover, the grass group (Fig. 5 and Table 6). Interestingly, nearly all of the three

functional group treatments that outperformed their component single functional group plantings contained grass species (Table 7). There was also variation among species belonging to the same functional group, with *R. rosea* and *S. spurium* monocultures showing reduced cover compared to their structural counterpart, *S. acre*, *C. rotundifolia* showing reduced cover compared to the other tall forb monocultures, *P. maritima* and *S. bicolor*, and *M. groenlandica* showing less cover than the other two ground-covering forb species, *S. procumbens* and *S. rubra* (Table 7).

#### *Aboveground plant biomass index*

Total plant hit (related to aboveground biomass) data had to be transformed to meet the assumptions of ANOVA. The square roots of total plant hit data were analyzed, and back transformed (squared) values are presented in figure form. The block factor did not help to explain differences in biomass ( $RLRT = 1.17$ ,  $df = 1$ ,  $p = 0.28$ ) but the planting treatment factor did ( $F_{30, 105} = 21.02$ ,  $p < 0.0001$ ).

Like the cover results, monoculture treatments accounted for both the smallest and largest amounts of biomass (Fig. 6). Plant hit data and vegetation cover data showed a strong correlation ( $r_{138} = 0.81$ ,  $p < 0.0001$ ), thus, similar to the vegetation cover results (Fig. 5), the 1-Sub treatment, and (subshrub) monocultures such as, *G. procumbens*, and *V. vitis-idaea*, and (succulents) *R. rosea*, and *S. spurium*, showed the smallest amounts of plant hits, whereas, the 1-G treatment and monocultures such as (the native grasses), *D. spicata* and *D. flexuosa*, and (the covering forbs) *S. rubra*, and *S. procumbens* showed some of the largest amounts of biomass (Fig. 6). The higher diversity treatments that included the grass functional group, and particularly the grass functional group in combination with the covering forbs, also showed relatively large amounts of biomass. However, unlike the cover results, *P. compressa*, *S. bicolor*, *P. maritima*, and 1-TF showed reduced total hit numbers (Fig. 5 and 6).

#### *Rate of relative change in cover*

Again, monoculture treatments accounted for both the smallest and largest rates of relative change in vegetation cover, with values ranging from -0.0043/day for *R. rosea*, to 0.0153/day for *S. rubra* (Fig. 7). Again, the treatment factor, and not the block factor, explained a significant amount of variation in the rates of relative change in cover ( $F_{30, 104} = 17.95$ ,  $p < 0.0001$  and  $RLRT = 6.38 \cdot 10^{-7}$ ,  $df = 1$ ,  $p = 0.999$ , respectively). *Spergularia rubra* and *P. compressa* spread the most considering their initial cover values, with the 1-TF treatment, as well as, the tall forb monocultures also showing considerable relative increases in plant cover (Fig. 7 and Table 8). Further, compared to their structural counterparts, *S. rubra* and *P. compressa* also showed comparatively fast increases in cover (Fig. 7 and Table 9). Unlike their counterparts, *M. groenlandica* and *R. rosea* monocultures actually decreased in cover from the beginning compared to the end of the study (Fig. 7 and Table 9), while the 1-Sub treatment and subshrub monocultures (*G. procumbens*, *E. nigrum*, and *V. vitis-idaea*) showed virtually no change in cover (Fig. 7 and Table 8). All of the three functional group treatments showed modest increases in cover, similar in value to the 5-ALL treatment (Fig. 7).

#### *Average maximum and minimum plant height*

To meet the assumptions of ANOVA, the natural logarithm of both mean maximum, and mean minimum vegetation height data were analyzed. The treatment but not the block factors were significant in both average maximum ( $F_{30, 105} = 31.25$ ,  $p < 0.0001$  and  $RLRT = 2.55 \cdot 10^{-8}$ ,  $df = 1$ ,  $p = 0.9999$ , respectively), and average minimum ( $F_{30, 105} = 26.19$ ,  $p < 0.0001$  and  $RLRT = 3.27 \cdot 10^{-8}$ ,  $df = 1$ ,  $p = 0.9999$ , respectively) plant height analyses. The maximum and minimum height patterns were very similar, for example, antilogged mean maximum height ranged from 23 mm for *S. procumbens* to 465 mm for *P. compressa*, and antilogged mean minimum plant height ranged from 23

mm for *S. procumbens* to 449 mm for *P. compressa* (Fig. 8). Despite these vast ranges between treatments, most planting treatments showed both mean maximum and minimum heights less than 100 mm (Fig. 8). After *P. compressa*, the native grass species and *P. maritima* showed the greatest heights. Not surprising then, virtually all treatments that achieved either average maximum or minimum heights greater than 100 mm included grass species (Fig. 8). Further, the three functional group treatments that showed the greatest heights included the grass functional group. Conversely, the treatments that showed the shortest average maximum (23-73 mm) and average minimum (23-59 mm) heights included succulent, ground-covering forb or subshrub species (and not grasses among the more functionally rich treatments; Fig. 8). Interestingly, the more functionally rich treatments (in addition to the *D. spicata* and 1-G treatments) that included grasses and either succulent, ground-covering forb or subshrub groups, appeared to have a sizeable difference in average maximum and minimum vegetation height, suggestive of some form of an upper and lower canopy (Fig. 9).

#### *Shannon index of canopy diversity*

Similar to all of the other canopy traits examined, the treatment factor but not the block factor, explained variation in Shannon index values ( $F_{15, 75} = 31.75$ ,  $p < 0.0001$  and  $RLRT = 1.33 \cdot 10^{-8}$ ,  $df = 1$ ,  $p = 0.9999$ , respectively). Shannon index values ranged from 0.38 for 1-Suc to 1.74 for 5-ALL (Fig. 10). As might be expected, virtually all of the one and three functional group treatments showed canopy diversity values lower than the 5-ALL treatment, with the exception of 3-G+CF+Suc, 3-G+CF+TF and 3-CF+TF+Suc (Fig. 10 and Table 10). Index values among treatments consisting of the same number of functional groups were mostly similar, with the exceptions of 1-Suc, whose index of canopy diversity was significantly lower than 1-CF, 1-G, and 1-TF, and 3-CF+TF+Suc,

whose index value was significantly larger than that of 3-Sub+CF+TF (Fig. 10 and Table 11).

## Discussion

This study suggests that plant functional type, and especially species composition, affected green roof canopy traits that influence (or are thought to influence) the functioning of green roofs, primarily through differences in stature and growth rate, considering the marginal differences in survival. Despite the finding that air temperatures tended to be slightly milder at the Chebucto Head barren site compared to the green roof study site, most of the natives tested showed high survival rates ( $\geq 81.7\%$  in the first year), suggesting these species are suitable green roof planting options (in terms of survivability) for maritime cities climatically similar to Halifax, and that the Nova Scotian coastal barrens represent suitable habitats from which to choose green roof candidate species. The observed survivorship is particularly noteworthy, considering fall and winter temperatures measured on the roof site may have been more extreme than typical for Halifax (but could have also seemed more extreme due to the proximity of one of the Hobo loggers to an adjacent building).

The survival rates reported here are comparable to previous studies that have examined the initial survivorship of a mixture of species (Monterusso, Rowe & Rugh 2005; Dunnett, Nagase & Hallam 2008), with the exception that the lowest survival rates seen here were relatively high compared to the lowest rates found in the Michigan and European studies, possibly due to their somewhat reduced initial irrigation frequency (Dunnett, Nagase & Hallam 2008), reduced precipitation, and more extreme temperatures (Monterusso, Rowe & Rugh 2005). While still reasonably successful, contrary to Dunnett, Nagase and Hallam's (2008) findings, the native succulent, *R.*

*rosea*, showed the lowest survival rates, losing 6.6% of individuals over the first growing season, and 11.7% of individuals over the fall and winter period. *Sedum spurium*, was also one of the species most negatively affected by winter conditions. Since these species have been shown to be particularly successful in past work (Monterusso, Rowe & Rugh 2005; Rowe, Rugh & Durhman 2006; Dunnett, Nagase & Hallam 2008), their high mortality rates may have been partly due to their relatively poor status after an aphid infestation, prior to the winter season (M. Ranalli personal observation). However, even if the lower survival rates for *S. spurium* and *R. rosea* reflect their increased susceptibility to pests compared to the other species tested, these findings still indicate a reduced ability to survive Halifax's urban environment.

The species that showed the highest rates of survival after both the first summer and winter, were the native grass *D. flexuosa* and the native tall forbs, *S. bicolor* and *P. maritima*, showing survival rates akin to those of the popular green roof species *S. acre* and *P. compressa*. Species belonging to the grass and forb growth forms have been found to be successful in previous studies as well (Monterusso, Rowe & Rugh 2005; Dunnett, Nagase & Hallam 2008). Thus, in terms of their abilities to survive, *D. flexuosa*, *S. bicolor* and *P. maritima* seem to be particularly safe options for extensive green roofs in Halifax. These species were also successful at establishing relatively large amounts of cover.

In non-green roof systems, vegetation cover and plant density are known to increase water capture through increased foliage interception of rainwater (Oke 1978). While Dunnett *et al.* (2008) examined the relationship between shoot biomass and green roof water runoff (finding no relationship between the two), the role of vegetation cover in green roof functioning (e.g., evapotranspirative cooling, water capture) has not been thoroughly examined. Yet, extensive cover is generally desired, because good coverage

is thought to reduce weed establishment, substrate erosion, increase green roof cooling (through increased transpiration or shading), and is considered aesthetically pleasing (Van Woert *et al.* 2005; Rowe, Rugh & Durhman 2006; Dunnett, Nagase & Hallam 2008; Wolf & Lundholm 2008). Regardless of reason, if the highest percentage cover is desired in the first year, again the two native grass species, the grass mixture, the native tall forb *P. maritima*, and the ground-covering forb, *S. rubra*, proved to be good options.

The aboveground biomass indices (total plant hits) and vegetation cover results were very similar in pattern. This finding is not surprising considering percentage cover and biomass have been shown to be related in previous studies, especially for herbaceous (as opposed to tree or shrub) species (e.g., Alaback 1986). However, compared to the cover results, *P. compressa*, *S. bicolor*, *P. maritima*, and 1-TF showed relatively reduced total hit numbers. This likely reflects the less branchy nature of these species, which would not have been as easily detected in the cover estimates since, the number of rods with as little as one hit (as opposed to the total number of plant contacts) were used to estimate cover. Similar to the cover results, monocultures of the native grasses, the grass mixture, and the covering forb, *S. rubra* were found to establish large amounts of biomass. It should be noted that the large amounts of cover and total hits seen in the native grass treatments seem to be partly due to their comparatively large initial size and not their rate of increase in cover. However, these results are still valuable as a baseline against which to compare growth of the grass treatments in subsequent years. Regardless of growth rate, the grass functional group in particular was associated with increased coverage (and biomass) in the mixed treatments (of three or more functional groups), highlighting its supremacy in this canopy trait.

Although increases in species and functional group richness levels (similar to those examined here) have been associated with biomass overyielding (production in

mixtures that exceeds that of the best monoculture; e.g., Tilman *et al.* 2001; Mulder *et al.* 2002; Hooper & Dukes 2004), the indices of biomass examined here did not show a similar pattern. However, it should be noted that long-term studies assessing the relationship between diversity and stand biomass have often reported a lack of overyielding in the first, or, early years, followed by a strong diversity effect in later years of the study (Tilman *et al.* 2001; Mulder *et al.* 2002; Hooper & Dukes 2004). Thus, data from the second and third growing seasons (which will also have greater temporal resolution) will be essential to evaluating more definitively any functional group richness effect on cover and biomass, and the stability of these variables. Further, actual weights of aboveground biomass (harvesting) may be required to accurately detect differences between treatments and a potential diversity effect.

While they did not provide the largest amounts of cover, the 5-ALL treatment and mixtures of any two functional groups (especially tall forbs and covering forbs) in addition to the grass group, established relatively consistent coverage (between 70-80%) after the first growing season. Similarly, the biomass index was greatest (> 50 hits) among the higher diversity treatments that included grasses, especially in combination with the covering forbs. Thus, in instances when a mixed planting is desired, the inclusion of grass species (particularly with covering or tall forbs) seems to provide insurance of relatively extensive (but not complete) cover, at least in the first year.

While, *M. groenlandica* established relatively good coverage early in the summer, as an annual, it had flowered and died prior to the time of cover estimation, resulting in a relatively low value compared to the other covering forbs examined. However, if seeds of this species are found to germinate in future years, it may still prove to have potential as a green roof plant, if not, this species seems to be a waste of money and planting effort in terms of cover provision and survival. The *R. rosea* and *S. spurium* treatments,

and those that included the subshrub species (in monoculture, single functional group, and three functional group plantings), also showed consistently reduced amounts of cover and total hits (unless they were mixed with grass species), likely because these succulent and subshrub species showed either reductions, or virtually no change in cover throughout the study.

The fast development of vegetation cover is valued because the faster planted individuals spread, the fewer the number of plants required to achieve a certain amount of cover, and the less expensive a green roof installation will be (Monterusso, Rowe & Rugh 2005). Again, composition had a major influence on the relative change in cover values seen across treatments.

Similar to findings reported here, *P. compressa* was found to have one of the fastest growth rates when compared to alpine and subalpine *Poa* species (grown under controlled conditions), mainly because of its large specific leaf area (leaf area per leaf dry mass) compared to the other species tested (Atkin, Botman & Lambers 1996). While Grime and Hunt (1975) did not study *P. compressa*, they showed that under optimal growing conditions, a related species, *Poa annua*, also had one of the fastest maximum growth rates among the 132 species they examined (including *C. rotundifolia*, *D. flexuosa*, two *Plantago* species, *S. acre*, and *V. vitis-idaea*, species studied here). Also similar to the results reported here, species of the genera *Campanula* and *Plantago*, showed average, to slightly greater than average rates of growth (Grime & Hunt 1975). Thus, in a field where fast, extensive vegetation cover, and survivability are highly favored, it is not surprising that *P. compressa* has often been used in green roof planting schemes, and it, along with the native tall forbs, seemed to also show relatively fast growth in this maritime site.

While *S. rubra* also showed a fast rate of growth in the first season, it should be noted that the growth of this species had just peaked prior to the final cover estimation (which was used to calculate the rate of relative change in cover). Conversely, individuals of *M. groenlandica* had reached maturity and flowered very early in the growing season, with most individuals dying back by the time the second estimate of cover was made. Thus, the utility (in terms of fast provision of cover) of these annual species will depend largely on seed germination and establishment in future years.

The capacity for *S. acre* to provide cover relatively quickly compared to other succulents, does not seem to be limited to this study (Durhman *et al.* 2004; Monterusso, Rowe & Rugh 2005; Rowe, Rugh & Durhman 2006). For example, among 25 succulent species tested at Michigan State University, *S. acre* showed one of the greatest increases in cover in the first season and remained one of the dominant species (in terms of amount of cover) after three growing seasons (Rowe, Rugh & Durhman 2006). Further, *S. acre* has been shown to have a greater capacity to spread and establish extensive green roof coverage compared to *S. spurium* (Durhman *et al.* 2004; Monterusso, Rowe & Rugh 2005). However, *S. acre*'s superiority over *R. rosea* should be further investigated since this finding might reflect *R. rosea*'s loss of foliage after an aphid infestation (M. Ranalli personal observation).

The very slow growth rates seen for the creeping subshrub species examined have also been found in previous work and seem to be intrinsic to these species (Grime & Hunt 1975; Donohue, Foster & Motzkin 2000). Even in the absence of environmental effects that depress growth, Donohue, Foster and Motzkin (2000) found *G. procumbens* to be a slow colonizer, and that the slow recruitment of new stems, combined with reduced seedling establishment, limited *G. procumbens*' population growth (in central Massachusetts, USA). Among 132 species common to Britain, *V. vitis-idaea* had the

second slowest growth rate overall (Grime & Hunt 1975). Further, (Grime & Hunt 1975) found that all 14 woody species tested had relatively small maximum growth rates, and the herbaceous species with the smallest growth rates, were those small in stature (similar to the subshrubs examined here). Thus, inherent limitations in the colonizing ability of the subshrubs suggests the species belonging to this functional group must either be planted in high density (which could increase costs), or combined with fast-growing species to achieve extensive green roof cover in the first season. As their name implies, subshrubs were also among the shortest species examined.

Canopy architecture has been shown to influence the physical position of the principal plane of solar radiation absorption and the resulting transmission of solar radiation, with the principal plane generally lying close to the highest point of a vegetative stand, and the transmission of solar radiation into a stand showing an almost logarithmic decay with depth of penetration (Oke 1978). Therefore, in general, tall vegetation stands with relatively high main areas of heat exchange (relative to the underlying substrate), should be associated with the greatest substrate temperature reductions. Further, increases in plant height have also been significantly related to reductions in roof water runoff (Dunnett *et al.* 2008). Therefore, where temperature moderation or runoff reduction is the main purpose of green roof construction, tall vegetation stands might be preferred.

Both the average maximum (14 cm) and average minimum (11 cm) heights of the 5-ALL treatment (15 species) were greater than the mean plant height (8.2 cm) measured for a 15-species mixture with a comparable substrate depth of 10 cm (Dunnett, Nagase & Hallam 2008), demonstrating that the most diverse species mixture examined here was capable of reaching comparatively tall heights, likely mostly due to the grasses. The finding that nearly all treatments (monocultures and mixtures) that

achieved average maximum heights greater than 100 mm included grass species, suggests grasses (especially *P. compressa*) are ideal planting options for optimizing functions associated with increased vegetation height. Although many extensive roofs are planted solely with *Sedum* species, because succulent (and ground-covering forb and subshrub) species were so short in stature, these species should be mixed with grasses in order to achieve greater canopy height and associated benefits. Because of the height differences between the grasses and the low-growing functional groups examined, mixtures of these functional groups resulted in sizeable differences between maximum and minimum vegetation height.

While two separate monocultures accounted for the tallest and shortest canopy heights (*P. compressa* and *S. procumbens*, respectively), maximum and minimum heights within a treatment were relatively similar in magnitude for nearly all monocultures and single functional group plantings, suggesting these treatments had a canopy of relatively uniform height. If multiple canopy layers can improve cooling benefits through substrate shading at multiple heights or, if multiple layers improve the habitat quality or aesthetics of a green roof, then more functionally diverse plantings should be favored. Specifically, if an upper and lower canopy is desired, the more functionally rich treatments (3 or 5 functional groups) that included grasses and either succulent, ground-covering forb, or subshrub groups, are the best options, since these treatments showed marked differences in average maximum and minimum vegetation height. The *D. spicata* and 1-G treatments also showed variation in height, however, at least in the case of *D. spicata*, this difference might be driven by the lack of flowering stems among some individuals.

Given that the Shannon index of a treatment was increased by either having more species with plant contacts (with the Ranalli box), or by having relatively equal

numbers of contacts among species, it is not surprising that the most functionally rich treatments (3, and especially 5 functional groups) showed the greatest index values of canopy diversity. Further, as expected, most treatments of a particular functional richness level were similar in value. However, there were a few anomalies that suggest that even after one growing season, some species can become more dominant (or inferior) in the canopy.

The relatively low canopy diversity value for 1-Suc compared to the other single functional group plantings, further highlights the poor establishment of the common green roof succulent, *S. spurium*, and the native, *R. rosea*, compared to *S. acre*'s ability to spread. Considering the diversity index in conjunction with the survival, cover, biomass, and relative growth rate results, suggests that *S. acre* began to dominate the canopy of the 1-Suc treatment, which would have lowered its diversity value. Thus, in mixed plantings that consist only of several succulents, perhaps a lower proportion of *S. acre* should be included in order to encourage canopy evenness. Data from future growing seasons will help to further assess the aggressiveness of *S. acre* over the longer term.

The finding that some of the three functional group plantings (3-G+CF+Suc, 3-G+CF+TF and 3-CF+TF+Suc) achieved diversity values statistically equivalent to the 5-ALL treatment, suggests these treatments had more even (or, more equal numbers of hits among species in their) canopies compared to other treatments of this richness level (since, all three functional group plantings contained the same number of species, and the diversity index can only be increased by either a greater number of species with hits, or a greater evenness in hits among species). However, the three functional group treatments that included the subshrub group tended to show slightly lower indices, which

can again likely be attributed to the low cover, biomass (total hit), and relative growth rate values for these species.

As seen here and in other studies, not all species are equally well adapted for green roof conditions, for example, some species show greater survival rates than others, or comparatively higher growth rates (Monterusso, Rowe & Rugh 2005; Rowe, Rugh & Durhman 2006; Dunnett, Nagase & Hallam 2008). Although diversity indices are not usually determined in green roof studies, the changes in species composition and abundance that have been reported in past work are presumably also associated with changes in canopy diversity indices. In one of the only green roof studies that examined diversity indices, Dunnett, Nagase & Hallam (2008) reported decreases in green roof species richness and Shannon's index with time, with an increase in Shannon's index in the third year of study. Therefore, indices from subsequent years are needed to evaluate the compatibility and stability of specific mixtures, and the level of plant richness that might be sustained in a shallow green roof system over an extended period.

The first year's results from this extensive green roof experiment illustrate how species, functional types of plants, and functional group richness affected canopy traits that influence (or likely influence) green roof functions. The finding that all perennial species showed high survival rates after the first winter, confirms that Halifax's climate should not impede green roof development, and that the Nova Scotian coastal barrens represent suitable habitats from which to choose green roof candidate species. However, based on the vegetative properties studied here, some taxa were more effective green roof plants than others, with grass and tall forb functional groups (and the covering forb, *S. rubra*) generally having some of the most favored characteristics (e.g., extensive coverage, and relatively fast rates of growth). Native species were among the

top performers across traits, with the common green roof species, *P. compressa*, also showing desirable characteristics (especially as the tallest species).

While, both species and functional group composition were important determinants of canopy structure and development, a richness effect (overyielding) was not found for any of the canopy traits examined in the first year of study. However, because overyielding has generally not been observed in the early years of non-green roof experiments (but is seen in later years if present), data from subsequent years will be needed to more completely evaluate any functional group richness effect on canopy characteristics. However, it should be noted that no single species was the 'best species' for all traits. Thus, these early findings suggest that mixtures of even the few species with the most desirable characteristics (for example, *D. flexuosa*, *D. spicata*, *P. compressa*, *S. bicolor*, *P. maritima*, and possibly *S. rubra*) might be the best option to simultaneously maximize survival, cover, speed of growth and height. These results serve as an initial record of the structural and ecological traits of the species and planting combinations examined here, and in conjunction with data from future growing seasons, will not only provide information on the particular taxa and combinations examined, but will also provide some insight into what other combinations of functional groups or species might be most successful over the long-term.

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**Table 1.** Sopraflor X green roof substrate (Soprema Inc., Drummondville, QC, Canada) properties as determined by independent testing (Nova Scotia Agriculture, Truro, NS, Canada); n = 3.

Substrate property	Mean	S.E.
pH	7.6	0.3
Organic matter (%)	9.4	0.8
P <sub>2</sub> O <sub>5</sub> (Kg/ha)	363	42
K <sub>2</sub> O (Kg/ha)	383	72
Ca (Kg/ha)	4769	381
Mg (Kg/ha)	554	51
Na (Kg/ha)	51	3
S (Kg/ha)	135	22
Fe (ppm)	123	3
Mn (ppm)	31	3
Cu (ppm)	1.36	0.12
Zn (ppm)	7.4	0.5
B (ppm)	2.10	0.33
Nitrate – N (ppm)	13.4	4.4
CEC (meq/100 g)	14.8	1.2
<b>Base Saturation</b>		
K (%)	2.7	0.3
Ca (%)	80.5	0.4
Mg (%)	15.6	0.1
Na (%)	0.8	0.1
H (%)	0.6	0

**Table 2.** Growth form (plant functional group) and origin of the 15 study species.

Plant species	Growth form	Origin
<i>Danthonia spicata</i> (L.) Beauv.	grass	indigenous
<i>Deschampsia flexuosa</i> (L.) Trin.	grass	indigenous
<i>Poa compressa</i> L.	grass	introduced
<i>Minuartia groenlandica</i> (Retz.) Ostenf.	ground-covering forb	indigenous
<i>Sagina procumbens</i> L.	ground-covering forb	indigenous
<i>Spergularia rubra</i> (L.) J. Presl & C. Presl	ground-covering forb	introduced
<i>Empetrum nigrum</i> L.	subshrub	indigenous
<i>Gaultheria procumbens</i> L.	subshrub	indigenous
<i>Vaccinium vitis-idaea</i> L.	subshrub	indigenous
<i>Rhodiola rosea</i> L.	succulent	indigenous
<i>Sedum acre</i> L.	succulent	introduced
<i>Sedum spurium</i> M. Beib.	succulent	introduced
<i>Campanula rotundifolia</i> L.	tall forb	indigenous
<i>Plantago maritima</i> L.	tall forb	indigenous
<i>Solidago bicolor</i> L.	tall forb	indigenous

*R. rosea* was previously classified in the genus *Sedum*.

**Table 3.** The one-way Randomized Complete Block experimental design used here. Treatments listed represent all of the possible combinations of functional groups (all of which, were examined here). When one, three or all five functional groups were included in individual treatments, all three species within a functional group were planted. 'G' represents the grasses, 'CF' represents the ground-covering forbs, 'Sub', the subshrub species, 'Suc', the succulent species, and 'TF', the tall forbs. Numbers in parentheses represent the number of species in each treatment followed by the total number of replicates for each treatment.

<u>Number of functional groups per module</u>			
	1	3	5
Treatments	G (3) x5 CF (3) x5 Sub (3) x5 Suc (3) x5 TF (3) x5	Sub+G+CF (9) x5 Sub+TF+Suc (9) x5 Sub+G+Suc (9) x5 Sub+CF+TF (9) x5 Sub+G+TF (9) x5 Sub+CF+Suc (9) x5	All (15) x20
	<u>Monocultures</u>	G+CF+TF (9) x5 G+CF+Suc (9) x5 G+TF+Suc (9) x5 CF+TF+Suc (9) x5	
	D.spicata (1) x3 D.flexuosa (1) x3 P.compressa (1) x3 G.procumbens (1) x3 E.nigrum (1) x3 V.vitis-idaea (1) x3 S.rubra (1) x3 S.procumbens (1) x3 M.groenlandica (1) x3 C.rotundifolia (1) x3 S.bicolor (1) x3 P.maritima (1) x3 R.rosea (1) x3 S.spurium (1) x3 S.acre (1) x3		

**Table 4.** Air temperature mean, maximum and minimum for the roof site between November, 2007 and April, 2008.

Month	Mean (°C)	Maximum (°C)	Minimum (°C)
November	5.1	17.0	-5.3
December	-2.5	9.8	-12.3
January	-1.7	10.2	-15.4
February	-1.6	11.0	-11.7
March	-0.4	11.8	-8.4
April	6.4	18.3	-2.0

**Table 5.** Percent survival of perennial species (across planting treatments), over the first year of study (2007-2008). Percentages represent survival of original plant plugs planted June 5-19, 2007.

Plant species	Growth form	Survival (%)	
		Sept. 2007	May 2008
<i>Danthonia spicata</i> (L.) Beauv.	grass	99.5	97.5
<i>Deschampsia flexuosa</i> (L.) Trin.	grass	100	100
<i>Poa compressa</i> L.	grass	100	99.0
<i>Sagina procumbens</i> L.	ground-covering forb	100	94.3
<i>Empetrum nigrum</i> L.	subshrub	99.5	99.0
<i>Gaultheria procumbens</i> L.	subshrub	94.7	90.8
<i>Vaccinium vitis-idaea</i> L.	subshrub	95.9	89.2
<i>Rhodiola rosea</i> L.	succulent	93.4	81.7
<i>Sedum acre</i> L.	succulent	100	99.5
<i>Sedum spurium</i> M. Beib.	succulent	100	89.2
<i>Campanula rotundifolia</i> L.	tall forb	97.5	91.0
<i>Plantago maritima</i> L.	tall forb	100	99.5
<i>Solidago bicolor</i> L.	tall forb	100	100

**Table 6.** Treatments with vegetation cover (%) values significantly different from the highest richness treatment, 5-ALL. 'G' represents the grasses, 'CF' represents the ground-covering forbs, 'Sub', the subshrub species, 'Suc', the succulent species, and 'TF', the tall forbs. Values were estimated near the end of the growing season (August 13-21, 2007).

Treatment	Difference from 5-ALL (%)	S.E.	df	t value	p value
5-ALL = 72 ± 2 %					
3-G+TF+Suc	10	5	105	1.92	0.057 .
3-G+CF+TF	9	5	105	1.69	0.094 .
3-Sub+CF+Suc	-32	5	105	-6.00	< 0.0001 ***
3-Sub+CF+TF	-22	5	105	-4.14	0.0001 ***
3-Sub+TF+Suc	-11	5	105	-2.04	0.0439 *
1-CF	-11	5	105	-2.04	0.0439 *
1-G	24	5	105	4.49	< 0.0001 ***
1-Suc	-20	5	105	-3.67	0.0004 ***
1-TF	9	5	105	1.69	0.094 .
1-Sub	-50	5	105	-9.26	< 0.0001 ***
<i>S. spurium</i>	-49	7	105	-7.43	< 0.0001 ***
<i>R. rosea</i>	-54	7	105	-8.06	< 0.0001 ***
<i>P. maritima</i>	17	7	105	2.59	0.011 *
<i>C. rotundifolia</i>	-35	7	105	-5.24	< 0.0001 ***
<i>M. groenlandica</i>	-37	7	105	-5.55	< 0.0001 ***
<i>S. rubra</i>	15	7	105	2.27	0.025 *
<i>V. vitis-idaea</i>	-54	7	105	-8.06	< 0.0001 ***
<i>E. nigrum</i>	-39	7	105	-5.86	< 0.0001 ***
<i>G. procumbens</i>	-47	7	105	-7.12	< 0.0001 ***
<i>D. flexuosa</i>	28	7	105	4.15	0.0001 ***
<i>D. spicata</i>	21	7	105	3.21	0.0017 **

Significance codes: 0.001 '\*\*\*' 0.01 '\*\*' 0.05 '\*' 0.1 '.'

**Table 7.** Multiple comparisons (Tukey contrasts) of vegetation cover (%). 'G' represents the grasses, 'CF' represents the ground-covering forbs, 'Sub', the subshrub species, 'Suc', the succulent species, and 'TF', the tall forbs. Only significant comparisons between monocultures of the same functional group, or between higher order richness treatments (including one, three or five functional group plantings) and their lower order components (individual species, one functional group, or three functional group plantings, respectively) are presented.

Linear hypotheses	Estimate (%)	S.E.	z value	p value
3-Sub+CF+Suc - 5-ALL = 0	-32	5	-6.001	<0.01 ***
3-Sub+CF+TF - 5-ALL = 0	-22	5	-4.137	0.012 *
1-Suc - 3-G+TF+Suc = 0	-30	7	-4.422	<0.01 **
1-Sub - 3-Sub+G+CF = 0	-53	7	-7.739	<0.01 ***
1-Sub - 3-Sub+G+TF = 0	-51	7	-7.554	<0.01 ***
1-TF - 3-Sub+CF+TF = 0	31	7	4.606	<0.01 **
1-Sub - 3-Sub+CF+TF = 0	-28	7	-4.054	0.016 *
1-G - 3-Sub+G+Suc = 0	26	7	3.869	0.031 *
1-Sub - 3-Sub+G+Suc = 0	-48	7	-7.002	<0.01 ***
1-Sub - 3-Sub+TF+Suc = 0	-39	7	-5.712	<0.01 ***
1-Suc - 3-G+CF+Suc = 0	-28	7	-4.054	0.017 *
S. spurium - 1-Suc = 0	-30	8	-3.793	0.045 *
R. rosea - 1-Suc = 0	-34	8	-4.324	<0.01 **
C. rotundifolia - 1-TF = 0	-44	8	-5.599	<0.01 ***
S. spurium - S. acre = 0	-54	9	-6.185	<0.01 ***
R. rosea - S. acre = 0	-58	9	-6.660	<0.01 ***
C. rotundifolia - P. maritima = 0	-52	9	-5.947	<0.01 ***
C. rotundifolia - S. bicolor = 0	-44	9	-4.995	<0.01 ***
S. procumbens-M. groenlandica = 0	48	9	5.471	<0.01 ***
S. rubra - M. groenlandica = 0	52	9	5.947	<0.01 ***

Significance codes: 0.001 '\*\*\*' 0.01 '\*\*' 0.05 '\*' 0.1 '.'

Adjusted *p* values are reported

**Table 8.** Treatments with rate of relative change in cover [(change in vegetation cover (%)/initial vegetation cover (%))/time period (days)] values significantly different from the highest richness treatment, 5-ALL. 'G' represents the grasses, 'CF' represents the ground-covering forbs, 'Sub', the subshrub species, 'Suc', the succulent species, and 'TF', the tall forbs. Initial cover values were estimated on June 27, 2007 and final estimates were made on September 11-12, 2007.

Treatment	Difference from 5-ALL (/day)	S.E.	<i>t</i> value	<i>p</i> value
5-ALL = 0.0029 ± 0.0004 (/day)				
3-Sub+G+CF	-0.0018	0.0008	-2.18	0.032 *
3-Sub+G+Suc	-0.0016	0.0008	-2.01	0.047 *
1-CF	-0.0018	0.0008	-2.22	0.029 *
1-TF	0.0028	0.0008	3.43	0.0009 ***
1-Sub	-0.0025	0.0008	-3.09	0.0025 **
<i>S. spurium</i>	-0.0026	0.0012	-2.20	0.030 *
<i>R. rosea</i>	-0.0072	0.0010	-7.17	< 0.0001 ***
<i>P. maritima</i>	0.0018	0.0010	1.83	0.070 .
<i>S. bicolor</i>	0.0026	0.0010	2.56	0.012 *
<i>M. groenlandica</i>	-0.0060	0.0010	-6.02	< 0.0001 ***
<i>S. rubra</i>	0.0124	0.0010	12.36	< 0.0001 ***
<i>V. vitis-idaea</i>	-0.0029	0.0010	-2.89	0.0046 **
<i>E. nigrum</i>	-0.0025	0.0010	-2.48	0.015 *
<i>G. procumbens</i>	-0.0029	0.0010	-2.89	0.0046 **
<i>P. compressa</i>	0.0119	0.0010	11.87	< 0.0001 ***

Significance codes: 0.001 (\*\*\*\*) 0.01 (\*\*\*) 0.05 (\*\*) 0.1 (\*)  
*df* = 104

**Table 9.** Multiple comparisons (Tukey contrasts) of relative change in cover [(change in vegetation cover (%)/initial vegetation cover (%))/time period (days)]. 'G' represents the grasses, 'CF' represents the ground-covering forbs, 'Sub', the subshrub species, 'Suc', the succulent species, and 'TF', the tall forbs. Only significant comparisons between monocultures of the same functional group, or between higher order richness treatments (including one, three or five functional group plantings) and their lower order components (individual species, one functional group, or three functional group plantings, respectively) are presented.

Linear hypotheses	Estimate (/day)	S.E.	z value	p value
1-TF - 3-G+CF+TF = 0	0.0038	0.0010	3.72	0.055 .
1-TF - 3-Sub+G+TF = 0	0.0036	0.0010	3.56	0.093 .
1-TF - 3-Sub+TF+Suc = 0	0.0039	0.0010	3.79	0.045 *
M. groenlandica - 1-CF = 0	-0.0042	0.0012	-3.59	0.084 .
S. rubra - 1-CF = 0	0.0142	0.0012	12.00	<0.01 ***
P. compressa - 1-G = 0	0.0123	0.0012	10.44	<0.01 ***
R. rosea - 1-Suc = 0	-0.0063	0.0012	-5.35	<0.01 ***
R. rosea - S. acre = 0	-0.0078	0.0013	-5.92	<0.01 ***
S. procumbens-M. groenlandica = 0	0.0070	0.0013	5.34	<0.01 ***
S. rubra - M. groenlandica = 0	0.0184	0.0013	13.94	<0.01 ***
S. rubra - S. procumbens = 0	0.0113	0.0013	8.60	<0.01 ***
D. flexuosa - P. compressa = 0	-0.0127	0.0013	-9.62	<0.01 ***
D. spicata - P. compressa = 0	-0.0113	0.0013	-8.58	<0.01 ***

Significance codes: 0.001 '\*\*\*' 0.01 '\*\*' 0.05 '\*' 0.1 '.'

Adjusted *p* values are reported

**Table 10.** Treatments with Shannon index values of canopy diversity significantly different from the highest richness treatment, 5-ALL. The species monoculture treatments were not included in the analysis because the maximum index value attainable for all monocultures is zero. 'G' represents the grasses, 'CF' represents the ground-covering forbs, 'Sub', the subshrub species, 'Suc', the succulent species, and 'TF', the tall forbs. Values were estimated near the end of the growing season (August 13-21, 2007).

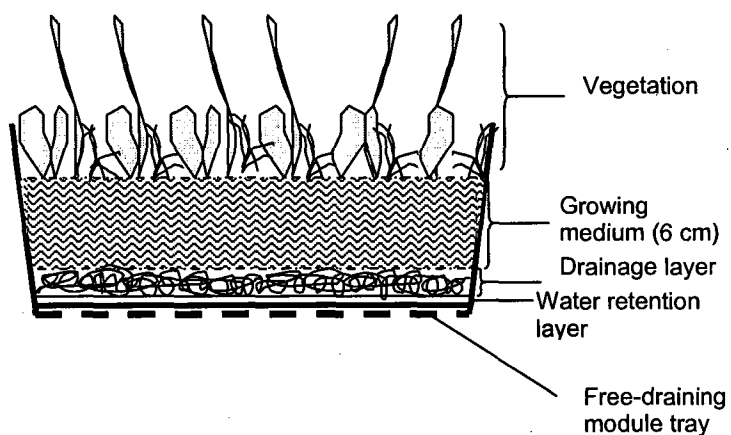
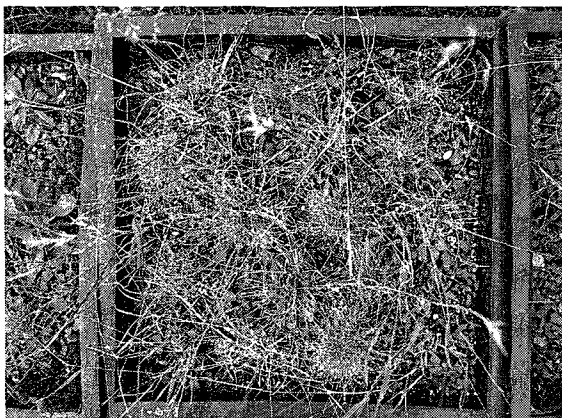
Treatment	Difference from 5-ALL	S.E.	df	t value	p value
5-ALL = 1.74 ± 0.04					
3-G+TF+Suc	-0.21	0.09	75	-2.32	0.023 *
3-Sub+G+CF	-0.31	0.09	75	-3.30	0.0015 **
3-Sub+CF+Suc	-0.42	0.09	75	-4.53	< 0.0001 ***
3-Sub+G+TF	-0.36	0.09	75	-3.89	0.0002 ***
3-Sub+CF+TF	-0.49	0.09	75	-5.24	< 0.0001 ***
3-Sub+G+Suc	-0.34	0.09	75	-3.63	0.0005 ***
3-Sub+TF+Suc	-0.31	0.09	75	-3.38	0.0012 **
1-CF	-0.94	0.09	75	-10.17	< 0.0001 ***
1-G	-0.88	0.09	75	-9.47	< 0.0001 ***
1-Suc	-1.36	0.09	75	-14.72	< 0.0001 ***
1-TF	-0.93	0.09	75	-10.03	< 0.0001 ***
1-Sub	-1.15	0.09	75	-12.48	< 0.0001 ***
Significance codes: 0.001 '***' 0.01 '**' 0.05 '*' 0.1 '.'					

**Table 11.** Multiple comparisons (Tukey contrasts) of Shannon index values of canopy diversity. The species monoculture treatments were not included in the analysis because the maximum index value attainable for all monocultures is zero. 'G' represents the grasses, 'CF' represents the ground-covering forbs, 'Sub', the subshrub species, 'Suc', the succulent species, and 'TF', the tall forbs. Only significant comparisons between treatments with the same number of functional groups are presented.

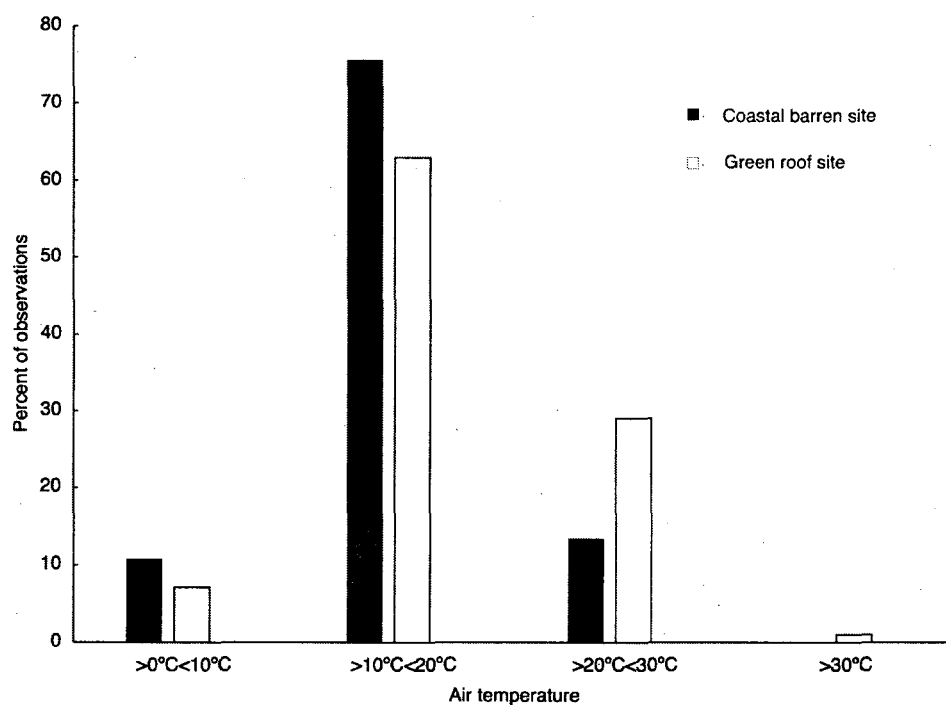
Linear hypotheses	Estimate	S.E.	z value	p value
3-Sub+CF+TF - 3-CF+TF+Suc = 0	-0.41	0.12	-3.528	0.034 *
1-Suc - 1-CF = 0	-0.42	0.12	-3.599	0.028 *
1-Suc - 1-G = 0	-0.49	0.12	-4.150	<0.01 **
1-TF - 1-Suc = 0	0.43	0.12	3.708	0.018 *

Significance codes: 0.001 '\*\*\*' 0.01 '\*\*' 0.05 '\*' 0.1 '.'

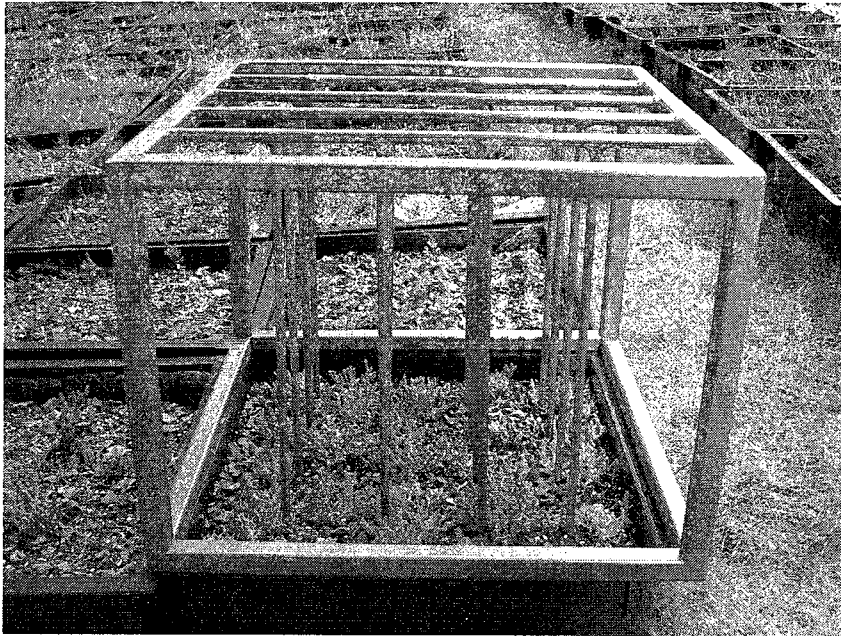
Adjusted *p* values are reported



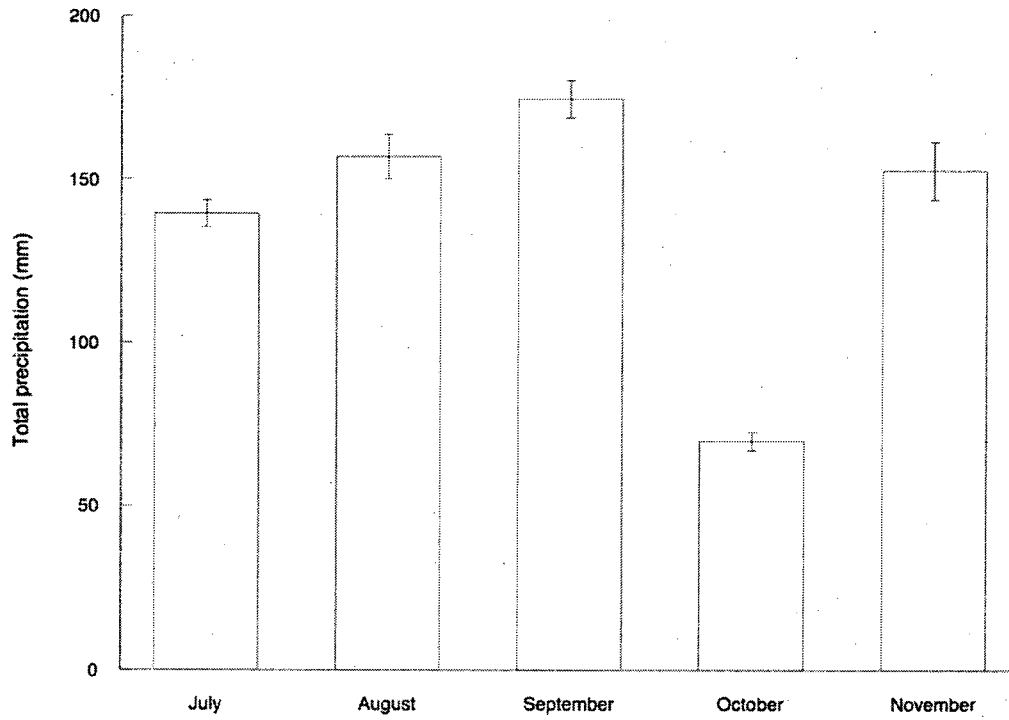
**Fig. 1.** A module assembly (sampling unit), which consisted of, a square, plastic, free-draining tray lined with a filter fabric (retention layer) and a drainage layer beneath the growing medium and vegetation layers.



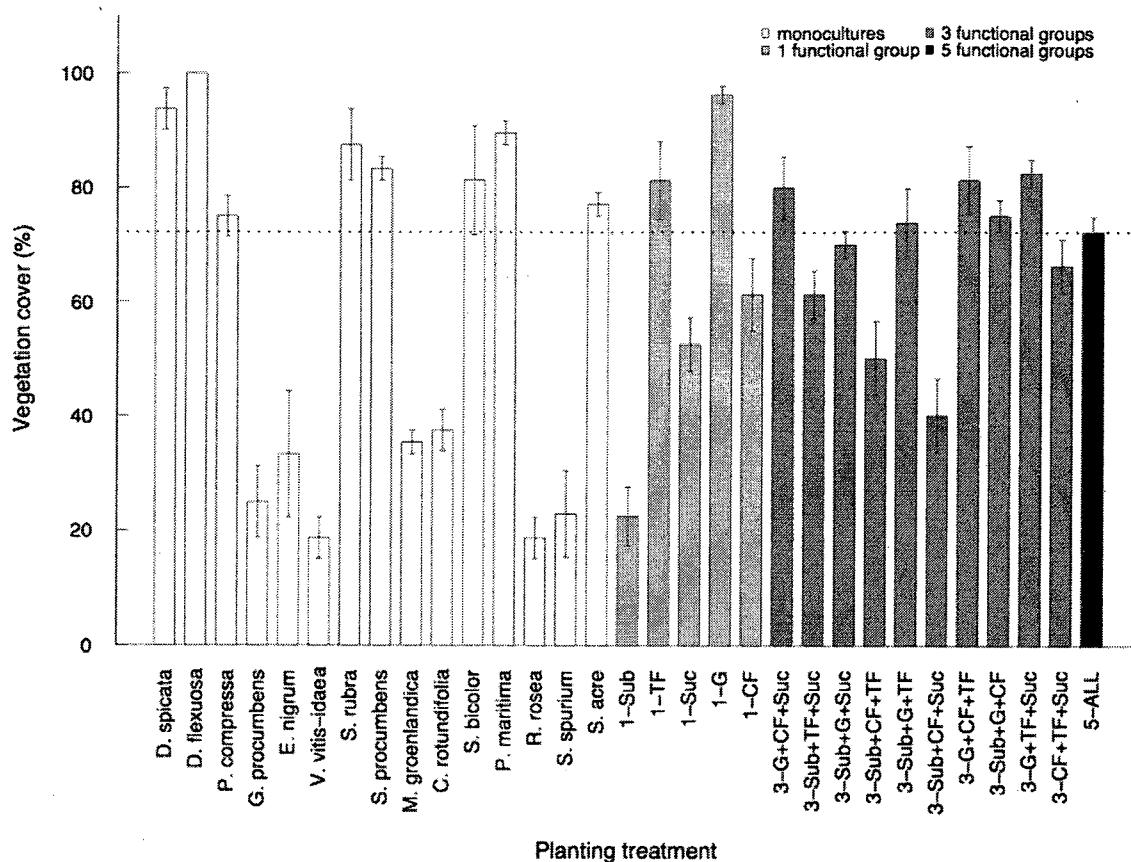
**Fig. 2.** Ambient temperature frequencies of a coastal barren site, Chebucto Head (25 km southeast of Halifax), and the green roof study site in Halifax. Values were measured between July 23 - October 16, 2007.



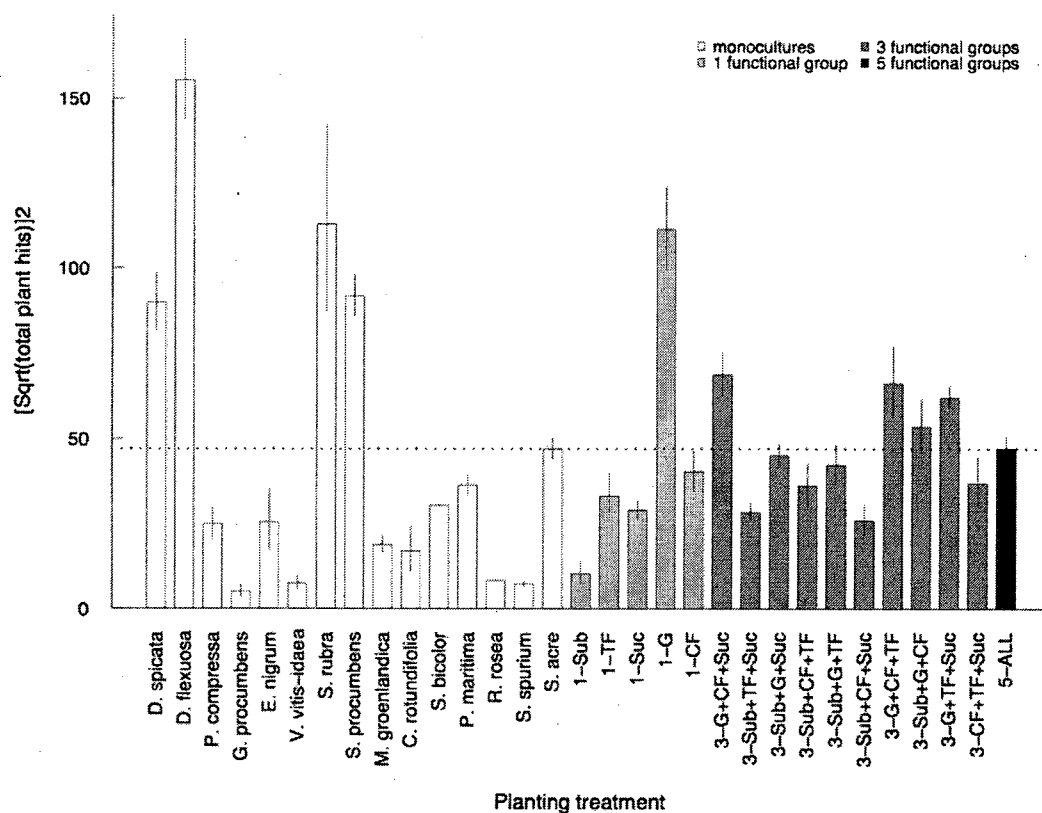
**Fig. 3.** The metal frame (Ranalli box) used to measure vegetation cover, total plant hits (index of aboveground biomass), relative change in cover, plant height, and Shannon's diversity index. The 16 vertical rods are located at the intersection points of subplot corners.



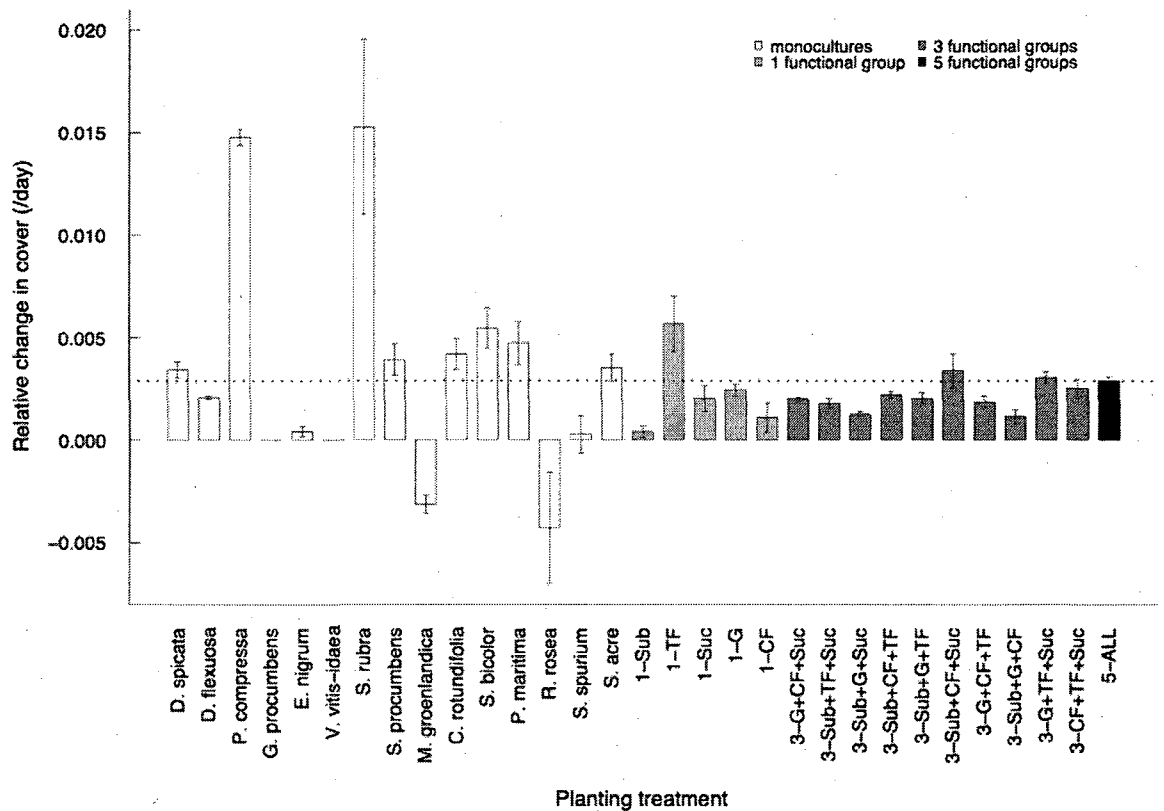
**Fig. 4.** Mean total monthly precipitation ( $\pm 1$  S.E.) measured between July 1-November 28, 2007 on the green roof site. Values represent mean totals from three (July) or five (August-November) rain gauges.



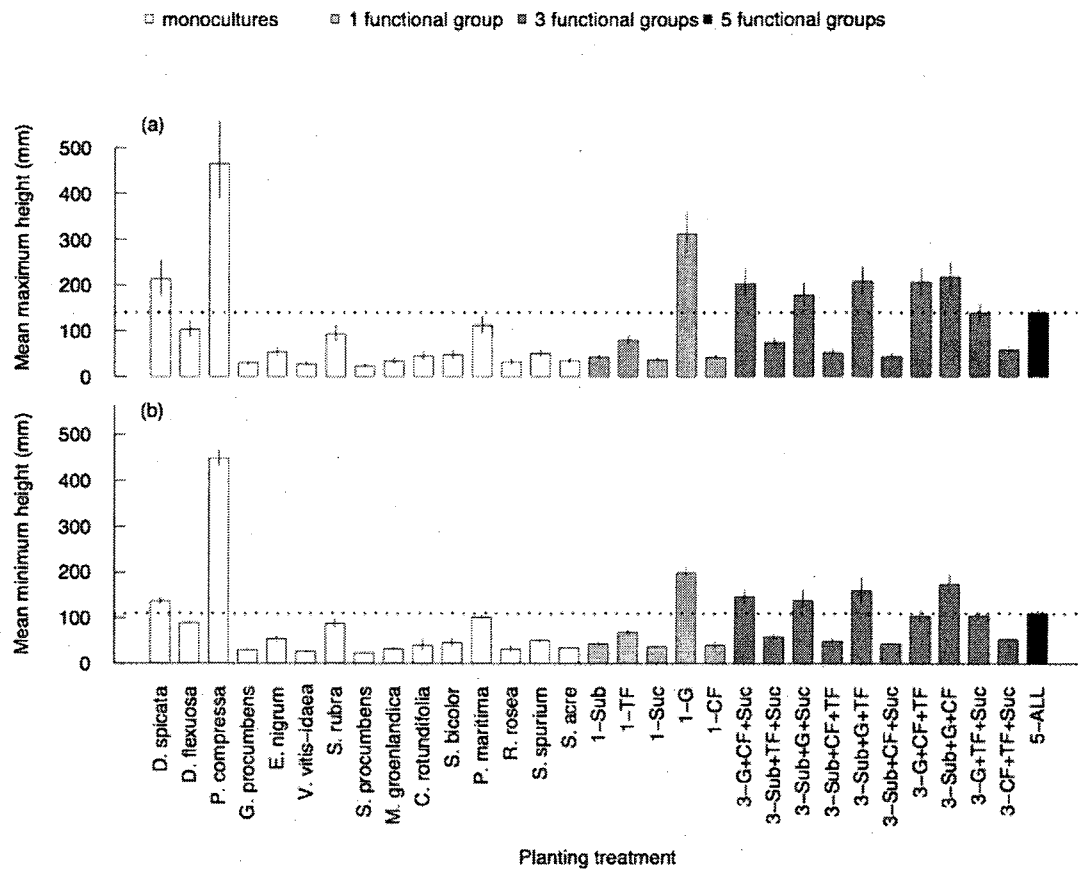
**Fig. 5.** Mean vegetation cover ( $\pm 1$  S.E.) of green roof modules with different functional diversity levels. 'G' represents the grasses, 'CF' represents the ground-covering forbs, 'Sub', the subshrub species, 'Suc', the succulent species, and 'TF', the tall forbs. The '5-ALL' treatment included all five functional groups. The dotted line highlights the average cover value (72%) of the 5-ALL treatment.



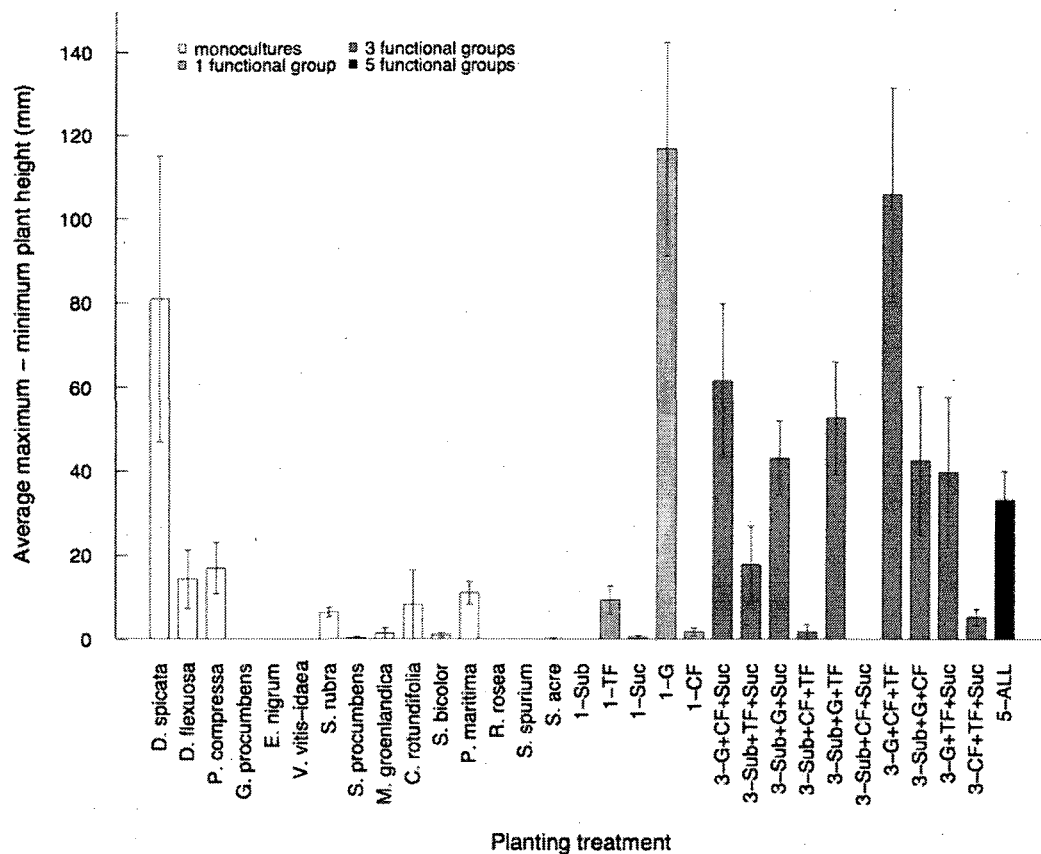
**Fig. 6.** Square of total plant hit (aboveground biomass) data ( $\pm 1$  S.E.) measured between August 13-21, 2007. 'G' represents the grasses, 'CF' represents the ground-covering forbs, 'Sub', the subshrub species, 'Suc', the succulent species, and 'TF', the tall forbs. The '5-ALL' treatment included all five functional groups. The dotted lines highlight the mean (47 hits) of the 5-ALL treatment.



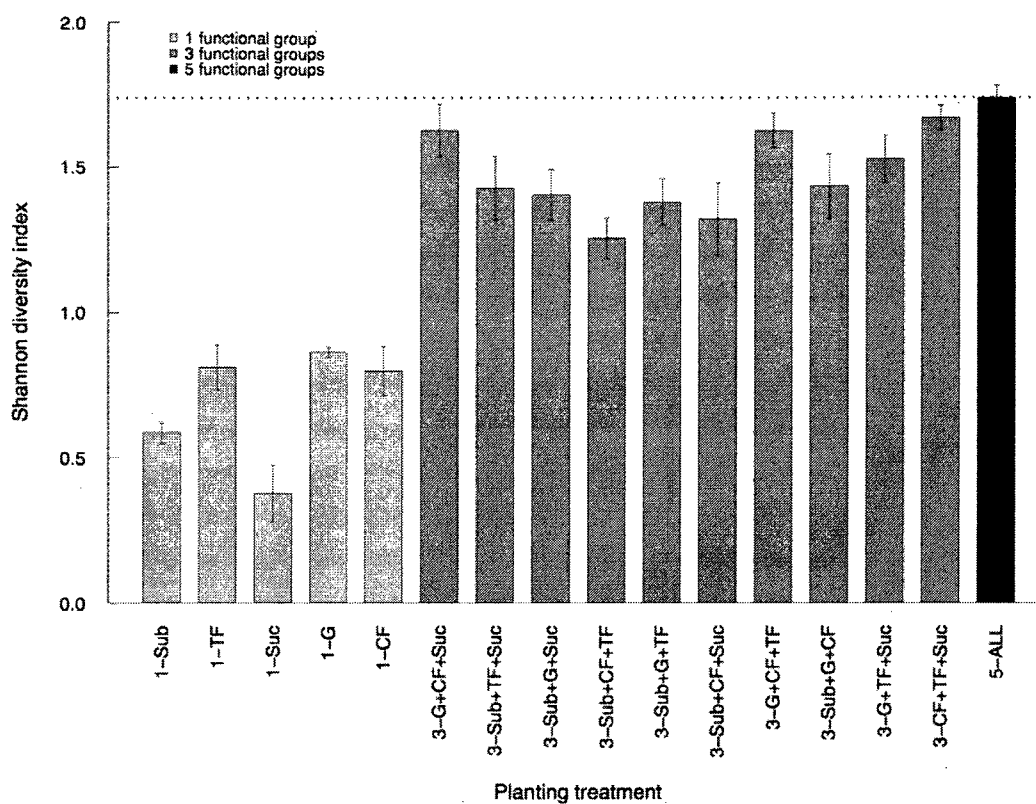
**Fig. 7.** Mean rate of relative change in cover [(change in vegetation cover (%)/initial vegetation cover (%))/time period (days)] ( $\pm 1$  S.E.) of green roof modules with different functional diversity levels. 'G' represents the grasses, 'CF' represents the ground-covering forbs, 'Sub', the subshrub species, 'Suc', the succulent species, and 'TF', the tall forbs. The '5-ALL' treatment included all five functional groups. The dotted line highlights the average rate of relative change (0.0029/day) of the 5-ALL treatment.



**Fig. 8.** Antilog of mean maximum (a), and antilog of mean minimum (b) plant height ( $\pm 1$  S.E.) measured between August 13-21, 2007. 'G' represents the grasses, 'CF' represents the ground-covering forbs, 'Sub', the subshrub species, 'Suc', the succulent species, and 'TF', the tall forbs. The '5-ALL' treatment included all five functional groups. The dotted lines highlight the antilogs of the average maximum (140 mm) and minimum (110 mm) plant heights for the 5-ALL treatment.



**Fig. 9.** Differences between average maximum and minimum plant height ( $\pm 1$  S.E.) measured between August 13-21, 2007. 'G' represents the grasses, 'CF' represents the ground-covering forbs, 'Sub', the subshrub species, 'Suc', the succulent species, and 'TF', the tall forbs. The '5-ALL' treatment included all five functional groups.



**Fig. 10.** Shannon index of canopy diversity values ( $\pm 1$  S.E.) measured between August 13-21, 2007. The species monoculture treatments were not included because the maximum index value attainable for all monocultures is zero. 'G' represents the grasses, 'CF' represents the ground-covering forbs, 'Sub', the subshrub species, 'Suc', the succulent species, and 'TF', the tall forbs. The '5-ALL' treatment included all five functional groups. The dotted line highlights the mean (1.74) of the 5-ALL treatment.

## **Chapter 3**

**Native plant evaluation and green roof functions: the influence of  
vegetation composition and functional group richness on stormwater  
capture and temperature moderation benefits**

## **Abstract**

Through stormwater capture, roof temperature reductions and reductions in heat flow between the building and external environment, green roofs can mitigate some of the negative environmental impacts of urban areas. However, despite the fact that green roof benefits are likely largely a function of the vegetation layer, green roof research tends to ignore the influence of plant composition. Yet, studies of other managed ecosystems suggest that plant diversity can increase ecosystem functions if species are complementary or facilitative. Nova Scotian coastal barren species were used in modular assemblies to assess the effects of composition and functional richness on green roof performance; and to determine if coastal barren species can provide the same magnitude of green roof benefits as commonly used (non-native) green roof species. A one-way, Randomized Complete Block design, and Analysis of Variance for unbalanced designs were used to analyze measures of thermal and capture performance. Higher levels of functional richness (3 functional groups) were shown to optimize substrate temperature reductions, but more commonly (in terms of albedo, capture and cumulative water loss), provided insurance of desirable performance (even if not the most optimal), instead of extremely poor or favorable performance. Most native species examined showed at least equivalent, and for some green roof functions, improved performance compared to the common green roof species tested here. This study emphasizes the need to consider green roof vegetation in terms of green roof functions, and not just survivability.

**Key-words:** composition, green roof benefits, functional group, Nova Scotia, richness, vegetation cover

## Introduction

Urbanization and the replacement of vegetated landscapes with impermeable, urban surfaces (e.g., asphalt and conventional roofing), have not surprisingly, caused a number of environmental, and climatological issues of concern. Specifically, due to the drastic changes in the surface and atmospheric properties, there is less infiltration of precipitation and warmer air temperatures in cities compared to the vegetated landscapes of rural areas (Oke 1978; Jennings & Jarnagin 2002; Moran 2004; Lazzarin, Castellotti & Busato 2005). Because rooftops represent a large proportion of the impermeable area in urban centers, their physical characteristics strongly influence the urban environment (Dunnett & Kingsbury 2004a; Gaffin *et al.* 2005) and should, therefore, be addressed in mitigation strategies. Through stormwater management (via water capture), and air and roof temperature moderation, green roofs represent one strategy whereby some of the detrimental impacts of conventional roofing (specifically), and cities (in general) might be mitigated (Onmura, Matsumoto & Hokoi 2001; Bass *et al.* 2003; Liu & Baskaran 2003; Brenneisen 2006; Kadas 2006; Mentens, Raes & Hermy 2006; Oberndorfer *et al.* 2007).

As a result of their ability to store rainwater (in the substrate layer, drainage layer, in plant tissues or on plant surfaces), and to release it back to the atmosphere over an extended period of time, green roofs reduce the total amount, delay the onset, and reduce the flow rate of roof runoff (Köhler *et al.* 2001; Rowe *et al.* 2003; Dunnett & Kingsbury 2004a; Liu & Baskaran 2005; Mentens, Raes & Hermy 2006; Dunnett *et al.* 2008). Water capture also influences the thermal benefits of green roofs since the greater the amount of stormwater retained, the greater the amount of potential evapotranspiration, and thus, the greater a green roof's potential for evaporative cooling (Compton & Whitlow 2006).

The ability of green roofs to reduce roof temperatures, in addition to reducing heat gain through the roof, is one of the major reasons for their construction. These cooling benefits are achieved primarily through the shading, insulation, and evapotranspiration provided by green roof medium and plants (Bass 2001; Onmura, Matsumoto & Hokoi 2001; Bass *et al.* 2003; Liu & Baskaran 2003; Dunnett & Kingsbury 2004a). By reducing heat flow between the building and the external environment (relative to conventional roofs), green roofs also result in energy conservation (through reduced energy demand for space conditioning) in built structures (Niachou *et al.* 2001; Liu & Baskaran 2003; Wong *et al.* 2003). For example, compared to a grey colored reference roof, a green roof in Ottawa, Ontario, was shown to reduce average daily energy demand (due to heat flow through the roof alone) by approximately 6 kWh per day during spring and summer months (Liu & Baskaran 2003). Likely further contributing to the temperature moderation benefits are the greater albedo (reflective ability) values green roofs are thought to have compared to conventional roofing materials: based on the albedo values of vegetated landscapes, such as, forests and crops (Christopherson 2003), and based partly on actual green roof data (Lazzarin, Castellotti & Busato 2005). However, despite Getter and Rowe's (2006) suggestion that green roof albedo is between 0.7-0.85 (depending on substrate water content), to my knowledge, albedo has only been directly measured on a green roof by few (Lazzarin, Castellotti & Busato 2005; Larr & Grimme 2006), with Laar and Grime's (2006) results suggesting green roofs can have lower reflective abilities compared to concrete and fiber cement roofing. Clearly, more research quantifying green roof albedo is necessary if any kind of generalizations about albedo's contribution to cooling are to be made.

Despite the fact that green roof benefits are largely a function of the vegetation layer, research into stormwater attenuation, temperature moderation and energy

conservation tends to ignore the influence of plant composition (the species and functional types present) and potential differences between taxa (Compton & Whitlow 2006; Dunnett *et al.* 2008). The shallow substrate depths common to extensive green roofs (the type most often deployed) result in periodic drought, thus, drought tolerance and avoidance have been the key criteria used for plant species selection (Dunnett & Kingsbury 2004b; Wolf & Lundholm 2008). *Sedum* species (usually not native to North America) are especially favored in extensive green roof applications because they form relatively shallow roots, store water in their vegetative parts, and can exhibit Crassulacean Acid Metabolism (CAM) photosynthesis which minimizes water loss through reduced or inhibited diurnal transpiration (Sayed 2001; Dunnett & Kingsbury 2004a). Because of their proven survival on rooftops, *Sedum* species have also been researched most often, usually in monoculture (Rowe *et al.* 2003; Gaffin *et al.* 2005; Lazzarin, Castellotti & Busato 2005; Van Woert *et al.* 2005b). There has been very little investigation into other types of vegetation or combinations of species that might be used to either, provide the same magnitude of benefits, or potentially even enhance green roof performance (Dunnett & Kingsbury 2004b; Compton & Whitlow 2006; Dunnett *et al.* 2008; Wolf & Lundholm 2008). The studies that have examined the effect of plant species composition and richness (i.e., the number of species or groups) in terms of green roof benefits, suggest that functional differences between species may be large enough to influence green roof performance (Compton & Whitlow 2006; Dunnett *et al.* 2008; Wolf & Lundholm 2008).

Based on several green roof studies and findings from crop and forest systems, vegetation characteristics such as growth habit, tissue water-storage capacity, plant density, and canopy structure are thought to influence the amount of rain that is captured, uptaken, and eventually evapotranspired (Oke 1978; Crockford & Richardson

2000; Compton & Whitlow 2006; Dunnett *et al.* 2008; Wolf & Lundholm 2008). In one of the few studies that tested the effect of different types of vegetation (grasses, sedges and herbs), and species richness on runoff quantity, variation in runoff was not shown to be related to species richness, instead, species traits seemed to have been more influential (Dunnett *et al.* 2008). For example, relatively reduced runoff for the herb, *Leontodon hispidus*, was suggested to have been due to its fast growth early in the year, its comparatively high rate of evapotranspiration (possibly creating a greater capacity for the soil to retain water, and reduce runoff), and the high water content in its tissues, which might have implied a relatively high demand on soil water supplies (Dunnett *et al.* 2008). In a separate experiment with a controlled watering regime, *Sedum* species were the least effective at reducing runoff (Dunnett *et al.* 2008), supporting the suggestion that alternative plant forms might improve, or at least not worsen, green roof performance, especially when differences in transpiration are considered (Dunnett *et al.* 2008).

While the insulative properties of the substrate and membrane layers are well documented (Del Barrio 1998; Eumorfopoulou & Aravantinos 1998; Niachou *et al.* 2001; Onmura, Matsumoto & Hokoi 2001; Theodosiou 2003), the extent to which plant transpiration contributes to green roof cooling is not well understood. Transpiration, which is partly dependent on soil water content, is thought to be key to the cooling benefits of green roofs (Gaffin *et al.* 2005; Gaffin *et al.* 2006; Wolf & Lundholm 2008), accounting for approximately 25% of total cooling provided by green roofs (Takakura, Kitade & Goto 2000). Although the relationship between plant composition and actual roof or air temperature has not been directly examined, research highlighting differences in uptake and evapotranspiration between species, indirectly indicates species composition likely affects green roof temperature moderation. For example, Compton and Whitlow (2006) showed that both *Spartina alterniflora* and *Solidago Canadensis*

species showed evapotranspiration rates 4-8 times larger than (albeit conservative) rates for *Sedum* species grown in a greenhouse, suggesting that cooling might be enhanced through the use of species other than *Sedum* ones. Further, Wolf and Lundholm's (2008) study showed that the plant species associated with the largest amount of evapotranspiration, differed according to overall water availability. Therefore, in order to maintain optimal water uptake and evapotranspirative cooling during wet and dry periods, a mixture of species may be desirable (Compton & Whitlow 2006; Wolf & Lundholm 2008). Specifically, a mixture of species from natural ecosystems with environmental conditions analogous to those of a green roof, might increase the likelihood of plant survival and optimize green roof performance (Lundholm 2006; Dunnett *et al.* 2008).

Basing green roof plant selection on naturally occurring, local plant communities can be advantageous. For example, native vegetation provides habitat for native birds and insects and will likely require less maintenance (Brenneisen 2006; Kadas 2006; Lundholm 2006; Dunnett *et al.* 2008). Oberndorfer (2006) found that Nova Scotian coastal barrens are characterized by some of the same stressful environmental conditions common to roofs, such as, high winds, rocky areas of shallow substrate depth, and variability in soil moisture content. Short, shrubby, ericaceous species (e.g., *Empetrum nigrum*), and a succulent species (*Rhodiola rosea*) have been found on the barrens (Oberndorfer 2006), possessing physical traits (such as low mat-forming growth, and succulent leaves) Dunnett and Kingsbury (2004a) suggested successful green roof species should likely have. Thus, the coastal barrens represent an ideal habitat type from which to select and test native maritime species. While there has been no direct examination of the relationship between species diversity and ecosystem function (e.g., plant production, or nutrient and water uptake) on the Nova Scotia barrens, the diversity-

function relationship has been studied elsewhere, offering some insight into the potential relationship between plant biodiversity and green roof functioning.

There has been extensive research into the relationship between biodiversity and ecosystem functions, however, there remains a considerable amount of debate over the interpretation of findings (Andre, Brechignac & Thibault 1994; Aarssen 1997; Huston 1997; Tilman 1997; Naeem 2000). The main arguments for the function of biodiversity that have emerged are: (1) biodiversity can improve ecosystem functioning, since different species have different niches and perform slightly different functions and together perform better than some subset; (2) since there are many more species than ecosystem functions, there is redundancy between species and the role of biodiversity is neutral or negative; (3) biodiversity can improve ecosystem functioning over an extended period since species that seem redundant at one time become important following some environmental change; and (4) recent work has introduced the idea that even greater levels of biodiversity may be required to optimize several functions simultaneously (Vandermeer *et al.* 2002; Swift, Izac & Noordwijk 2004; Hector & Bagchi 2007). Interesting to note, is the possibility that all of the above interpretations may be valid, depending on the temporal scope of a study.

The most widely accepted diversity-function theories are based on biomass production within a single trophic level, and in natural ecosystems (Kinzig, Pacala & Tilman 2001). In these systems, greater plant species diversity has been shown to increase total biomass in two distinct ways: (1) through overyielding (via complementarity or facilitation), where functional differences between species lead to greater resource uptake and total biomass than any component monoculture; and (2) through the sampling effect, where more rich communities have a greater chance of including the most productive species (Ewel 1986; Aarssen 1997; Huston 1997; Tilman,

Lehman & Thomson 1997; Loreau 1998). Regardless of the mechanism, most diversity-function studies suggest there is a point in each ecosystem at which niche occupancy is saturated and further increases in diversity have negligible effects on ecosystem function, with the number of species at which function is saturated being determined by a variety of abiotic and biotic conditions (Elmqvist *et al.* 2003).

The applied nature of green roofs and their container-like form, allow ecosystem functions and boundaries to be clearly delineated. Although most diversity-function research has focused on biomass production, this function is of limited importance in and of itself in green roof systems. However, at least some green roof functions might be related to productivity (e.g., transpiration), suggesting the classical theory describing the relationship between biodiversity and productivity (e.g., Kinzig, Pacala & Tilman 2001) might be relevant to the green roof field. Since various plant species and levels of richness can be included in each module (microcosm) of a modular green roof, these systems provide an interesting opportunity to examine the role of composition and richness in green roof functioning.

Generally, the aim of this work was to determine what species, functional types of plants, or combinations of plants, optimize green roof functions in a modular system. Specifically, I addressed the following questions:

- Are green roof functions such as substrate temperature reductions, reflectivity, and stormwater capture and evapotranspiration improved by increasing species and plant functional group richness?
- Or, does species or functional group composition have a larger role in measured green roof functions?
- Finally, can native coastal barren species provide the same magnitude of green roof benefits as commonly used grass and *Sedum* species?

## Materials and methods

### STUDY SITE

The study was conducted between May and October of 2007 on top of the 35-year-old, 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). During this time of year, Halifax is characterized by daily maximum temperatures between 13-23 °C, daily minimum temperatures between 6-15 °C and monthly precipitation values (almost entirely rainfall) of 98-135 mm (Environment Canada 2008). The study roof was approximately 5 m above ground level, and relatively sheltered: there were buildings 1-3 stories higher adjacent to the roof along the west, south and east sides. Prior to this study, the library roof structure consisted of a layer of grass growing in approximately 40 cm of clay soil, over a waterproofing membrane that covers a concrete slab. Because there was already a layer of grass on the roof, weed barrier fabric (Quest Plastics Ltd., Mississauga, ON, Canada) was laid over the grass (under our green roof modules) to minimize any influence the grass might have potentially had on the measured variables.

One hundred and fifty Botanicals Nursery LLC (Wayland, MA, USA) modules (microcosms) were used, each one representing a single sampling unit (Fig. 1a). A single module assembly consisted of a square, plastic, free-draining tray measuring 36 cm x 36 cm along the inside perimeter, lined with a composite nonwoven water-retention layer (Huesker Inc., Charlotte, NC, USA), followed by an Enkamat (Colbond Inc., Enka, NC, USA) above acting as a drainage layer, a site of attachment for plant roots and a filter layer, which was topped with a substrate and plant layer. The substrate layer was initially approximately 6 cm deep for all modules and consisted of Sopraflor X growing medium (Soprema Inc., Drummondville, QC, Canada). Sopraflor X consists of crushed brick, blond peat, perlite, sand and vegetable compost, has a pH of 6.0-7.0, a total

porosity of 60-70%, a bulk density of 1150-1250 kg·m<sup>-3</sup> and an organic matter content (by dry weight) of 5-10% (details from Soprema Inc.). Independent analyses were in approximate agreement with the manufacturer's specifications (Table 1).

## PLANT MATERIAL AND EXPERIMENTAL DESIGN

Species selection was driven by several factors: 1) the similarity of a species' natural habitat to the conditions on a green roof, 2) growth habit, and 3) past green roof use. Of the 15 species that were examined, 11 are indigenous to Nova Scotia, three non-native species (*Poa compressa*, *Sedum acre* and *Sedum spurium*) are commonly used on green roofs in Europe and North America (Durhman *et al.* 2004; Köhler 2006), and one (*Spergularia rubra*) was thought to be a potential green roof candidate based on its form (Dunnett & Kingsbury 2004a) and ability to inhabit both dry and moist soil conditions (both of which are common on green roofs; Table 2). Similarly, native species were selected from coastal barren, rocky habitats, habitats with conditions comparable to those of an extensive green roof environment: shallow soil, high winds, intermittent flooding and drought, and absence of tree cover (Lundholm 2006; Oberndorfer 2006).

I chose three species from each of five functional groups to examine the influence of plant growth habit richness in green roof performance (Table 2). I defined plant functional type (or group) based on growth form since different growth forms might show differences in the amount of shading provided, rainfall intercepted, water storage, or the rate of evapotranspiration (Dunnett *et al.* 2005; Wolf & Lundholm 2008), which might influence the green roof benefits studied here (see below). Based on the growth forms that are expected to be successful on green roofs or that have been commonly used on green roofs (Dunnett & Kingsbury 2004a), the five functional groups included were: 1) subshrubs (or creeping shrubs), low-growing shrubby species; 2) grasses; 3) ground-covering (or creeping) forbs, low growing plants without woody tissue; 4) tall

forbs, tall growing plants without woody tissue; and 5) succulents, fleshy, water-retaining plants (Table 2).

In order to understand the role of functional group composition and richness, I examined 3 replicates of each species in monoculture (in blocks 1, 3 and 5), 5 replicates (1 per block) of each of the one functional group plantings, and of all the possible combinations of three functional groups, and finally, 20 replicates (4 per block) of the combination of all five groups. When one, three or all five functional groups were included in individual modules, all three species within that functional group were planted. Therefore, there were 5 possible planting treatments when only one functional group was planted (i.e., either all subshrub species were planted, or all grasses, or all ground-covering forbs, all tall forbs, or all three succulent species), 10 combinations when three functional groups were included, and only a single possible combination when all five functional groups were included in a module (Table 3). To maintain initial species composition, seedlings of species not originally planted were removed throughout the study period. Additionally, 10 unvegetated modules (two per block) with only potting soil plugs (with no plants) inserted into the substrate layer served as controls.

Through the use of plant plugs, I ensured that the initial number of plants, 21 plants per module, was consistent among all modules, regardless of the number of functional groups planted in any given module. The module planting arrangement involved staggering four rows of four plants (on 9 cm centers) and a centre row of five plants (on 7 cm centers). The planting sequence involved alternating functional types (if more than one type was included in a module), with the functional type and species pattern being randomly chosen (without replacement) until all species to be included had been selected once, after which, the same pattern was repeated throughout the module.

By repeating the initial randomly chosen sequence, all species had an equal chance of interacting with, or being exposed to, the other functional types and species included, and any conditions they might have created (e.g., soil water deficit).

Seeds and cuttings were propagated as plugs in the Saint Mary's University greenhouse between the summer of 2006, through to the spring of 2007. Due to a shortage of seedlings, some plants of *Gaultheria procumbens*, *Vaccinium vitis-idaea* and *P. compressa* were collected from Nova Scotian coastal barrens in May of 2007, namely, Chebucto Head which is approximately 25 km southeast of Halifax and Polly's cove, 45 km southwest of Halifax. Collected plants were put into plugs using Pro-Mix potting soil (Premier Horticulture, Riviere-du-Loup, QB, Canada) - the same potting soil that was used for seed germination - and allowed to establish for at least two weeks prior to planting, which was at least eight weeks prior to the collection of data. Plants did differ in size between and within species at the time of planting. To control for differences within species, I planted a mix of both relatively large and small plants in all treatments with that particular species. Differences in size between species were considered during analyses, when vegetation cover (which was visually estimated on September 11, 2007) was included as a covariable.

Modules were planted between June 5 - 19, 2007 and were watered by hand three to six times per week until July 18, 2007. After which, modules received water primarily through rain events, only receiving 750 mL of supplemental irrigation on three separate occasions (July 26, July 27 and August 3 of 2007). Plants that had died after planting (primarily individuals of *Empetrum nigrum*, *Campanula rotundifolia* or *V. vitis-idaea*) were replaced between June 20-29, after which, individual deaths were simply recorded.

A one-way, Randomized Complete Block design was used (Table 3) with modules organized in five long, narrow blocks, each block being two modules wide. 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 (Fig. 1b). To control for the effect of environmental variation within blocks on measured green roof functions, modules were randomly ordered within blocks and were also rotated within a block six times throughout the study.

#### MEASUREMENT OF GREEN ROOF FUNCTIONS

In order to compare the cooling potential of typical and alternative green roof planting treatments, I measured substrate bottom and surface temperature, albedo, total water capture, and cumulative water loss (evapotranspiration).

##### *Temperature*

Taylor 9878 Slim-Line Pocket Digital Thermometers (Commercial Solutions Inc., Edmonton, AB, Canada) were used to measure the surface and base (i.e., where the substrate and engineered membranes met, 6 cm below the surface) temperatures of the substrate layer on two separate days. Temperature readings were taken near the center of modules, near solar noon (between 10:30 am and 1:30 pm AST) when the site was sunlit, since after 1:30 pm, the western side of the site was shaded by surrounding buildings. The two days of temperature data presented here, August 7 and September 14 of 2007, represent patterns from overcast and sunny days, respectively. While September 14<sup>th</sup> does not typically represent the warmest day of the summer season, it represents the warmest one among the days in which we were able to measure substrate temperature.

### *Albedo*

In order to directly characterize green roof albedo for the various types of vegetation examined here, incident and reflected solar radiation was measured for each module on September 26, 2007 once growth had peaked (since albedo might be related to aboveground biomass or vegetation cover). Measurements were made under clear-sky conditions just prior to solar noon (between 10:45 am and 12:30 pm AST) when the sun appears highest in the sky and the variability of incoming solar radiation remains relatively constant (Sailor, Resh & Segura 2006). At the time of measurement, each module was removed from the remaining modules (at least 2 m away) and placed on top of grey colored weed barrier fabric (Quest Plastics Ltd., Mississauga, ON, Canada) to ensure that the grass on the study roof, as well as adjacent modules, were not significantly contributing to the measured reflectance values. Incoming and reflected solar radiation measurements were made with a pair of fixed position LI-200SL LI-COR pyranometer sensors (LI-COR Biosciences, Lincoln, NE, USA), whose spectral response included the 400-1100 nm spectral range. The lowermost pyranometer was located 25 cm from the ground. The height of 25 cm was chosen by slowly raising the downward facing pyranometer upward above the vegetation canopy until the reflected radiation value was maximized. At greater heights, the reflectance value decreased (likely because of the grey material modules were placed on) and at a lower height, the pyranometer would have been in the canopy for many planting treatments. The pyranometer voltage outputs of 1.00 mv per  $100 \text{ W} \cdot \text{m}^{-2}$  were amplified by a ratio of 150:1 by a Vernier Instrumentation Amplifier (Vernier Software & Technology, Beaverton, OR, USA), digitized by a Vernier 12-bit LabPro A/D interface (Vernier Software & Technology, Beaverton, OR, USA) and processed using Vernier's EasyData software in a TI-83

programmable calculator (Texas Instruments, Dallas, TX, USA). Here, albedo is expressed as:  $(\text{reflected radiation}/\text{incoming radiation}) \times 100\%$ .

#### *Water capture and evapotranspiration*

A PX-Series Checkweighing bench scale (ATRON Systems Inc., West Caldwell, NJ, USA) was used to weigh individual modules to determine gravimetric substrate moisture content following three separate rain events (July 19-21, July 29-30, and August 8, 2007). Because modules were weighed once the water retention and drainage layers had been inserted, following the addition of substrate, as well as after planting, the weight of each component of individual module assemblies was known, and so was the weight of substrate in each module. Measured differences in weight throughout the course of the study (for a given module) primarily reflected either the natural addition of rainwater or losses due to evapotranspiration.

Five Springfield rain gauges were set up along the perimeter of the study site to calculate the volume (and mass) of water that fell into individual modules during rain events. The volume of rain in gauges was recorded the morning following a rain event. After each of the three rain events, modules were weighed once per day, for a period of one to four days (depending on the timing of the rain event). The amount of water actually captured by individual modules during a rain event was calculated as the difference between the first weight of modules following a rain, and the initial weight of the module, substrate and vegetation assembly (at the beginning of the study). Total water capture represents the sum of the weights of water captured across rain events.

Water loss, an indirect estimate of evapotranspiration, was calculated for each module as the difference between the initial (heaviest) module mass immediately following a rain event and the final (lightest) module mass several days following a rain

event. Although the amount of time between the end of a rainfall and the beginning of a weighing event was not the same across rain events (i.e., modules were weighed the morning following a rain, regardless of when the rain had stopped the previous day or night), for each weighing day, all modules were weighed within 1.5 hours of each other for a single event, in order to reduce as much as possible differences in weight (between modules) resulting from differences in time of measurement. Unlike the instantaneous nature of water capture, measured water loss reflected the evaporation and transpiration that had occurred over the course of a 72-hour period (for each of the first two rain events). Cumulative water loss was also expressed as a sum of water lost across events.

#### STATISTICAL ANALYSES

Separate linear mixed effects models were fit to temperature, albedo, water capture, and cumulative water loss data with the block variable treated as a random factor (Pinheiro & Bates 2000; Pinheiro *et al.* 2007). I used Analysis of Variance (ANOVA) for unbalanced designs and employed marginal sum of squares in F-tests (one term is removed at a time) to test the significance of explanatory variables (with  $\alpha = 0.05$ ). “Treatment” contrasts were used in all ANOVA analyses, which involved comparing all planted treatments to the controls. Because the planting treatment factor was the predictor variable of interest, it was first tested independently, as the sole predictor, after which, relevant covariables were tested.

To account for the variation in size between species, vegetation cover (visually estimated on September 11, 2007) was tested as a covariable in all analyses. Additionally, in the analyses of substrate surface and bottom temperature, other covariables tested were: albedo and cumulative water loss since these factors are hypothesized to influence temperature values. In the model of cumulative water loss,

the total amount of water capture was examined as a possible covariable. If potential covariables were correlated (based on Pearson's product-moment correlation coefficient;  $r \geq 0.7$ ,  $\alpha = 0.05$ ), then only the better predictor of the two was tested in a given model.

Model comparisons and restricted likelihood ratio tests (*RLRT*'s) were used to determine the significance of the block effect (Pinheiro & Bates 2000; Pinheiro *et al.* 2007). Tukey-Kramer adjustments for multiple comparisons (with  $\alpha = 0.05$ ) were used to test for pairwise differences between treatments in all analyses (Hothorn *et al.* 2007). Only significant comparisons between treatments with at least one species in common or between species in the same functional group will be presented here. Because the block factor was inherent to the experimental design, even when the *RLRT* indicated that the block factor was not significant, it was left in the predictive model during the post-hoc multiple comparison analyses.

Prior to analyses, temperature, albedo, water capture, and cumulative water loss data were visually inspected for normality and outliers using quantile-quantile plots, histograms, scatter plots and box plots. Outliers were few, and were removed only if there was a valid reason recorded in my field notes for the outlying values. When data did not appear normally distributed, log, square root and square transformed data were inspected for improvements. To ensure that the assumptions of ANOVA were met, scatter plots and box plots were used to visually check that the within-group errors were centered at zero, had constant variance across groups, and were independent of the group levels (Pinheiro & Bates 2000). Quantile-quantile plots were used to check the normality of the random effects. In addition, Kolmogorov-Smirnov tests were used to statistically test the normality of model residuals, and Levene's test was used to test for homogeneity of variance across treatment groups (Fox 2007). All analyses were

completed using R: A Language and Environment for Statistical Computing (R Foundation for Statistical Computing, Vienna, Austria) and bar graphs were made in R with the sciplot package (Morales & Team 2007).

## Results

### *Substrate temperature*

On the cloudy day measurement event (August 7, 2007), the substrate bottom temperatures of planted treatments ranged from 21.5 - 22.2 °C and surface temperatures ranged from 22.1 - 23.7 °C, while the bottom and surface temperatures of the controls were, 22.1 °C and 23.1 °C, respectively. The planting treatment factor did not explain the little variation in substrate bottom ( $F_{31, 114} = 1.31, p = 0.16$ ) or surface temperatures ( $F_{31, 114} = 1.44, p = 0.09$ ). Instead, only the block factor explained a significant amount of variation in both the substrate bottom ( $RLRT = 162.93, df = 1, p < 0.0001$ ) and surface temperatures ( $RLRT = 160.10, df = 1, p < 0.0001$ ), with temperatures increasing from block 1 to block 5 (from west to east along the site). Conversely, the planting combination did affect substrate bottom ( $F_{31, 112} = 2.40, p = 0.0005$ ) and surface temperatures ( $F_{31, 112} = 2.49, p = 0.0003$ ) on the warmer, sunny measurement event of September 14, 2007.

The spread of substrate temperature values was slightly greater under sunny, clear sky conditions (September 14, 2007) with bottom temperatures ranging between 19.6 - 22.2 °C (1.4 °C cooler to 1.2 °C warmer than controls; Fig. 2a) and surface temperatures ranging between 24 - 27.9 °C (2.3 °C cooler to 1.6 °C warmer than controls; Fig. 2b). Although the differences are relatively small, it is apparent that temperatures tended to be more consistently cooler in the more functionally rich treatments, i.e., those with 3 or 5 functional groups (Fig. 2 and Table 4). Specifically

worth noting, is the low surface temperatures observed in several of the 3 functional group treatments as compared to their constituent 1 functional group plantings, and compared to their constituent monocultures, for example, the 3-G+TF+Suc planting combination (Fig. 2 and Table 5). When looking at bottom temperatures, the native grass, *D. spicata* and the grass mixture, 1-G, were in exception, showing significantly cooler temperatures than controls (Fig. 2 and Table 4). The *S. acre* monoculture had one of the lowest average surface temperatures measured (Fig. 2 and Table 4). Not surprising then, grasses and either succulents or tall forbs were in all of the higher diversity plantings that showed reduced temperatures relative to the controls (Fig. 2 and Table 4), and the grass, tall forb and succulent mixture was the treatment that had the lowest substrate surface temperature, and the second lowest bottom temperature. Some of the treatments actually showed higher temperatures than the unvegetated controls. The *G. procumbens* monoculture and the 1-Sub treatment (which included *G. procumbens* plants) were the only treatments with significantly warmer bottom temperatures than the controls and *S. procumbens* was the only treatment to show significantly warmer surface temperatures than the controls (Table 4).

Although there were some minor differences in the patterns of statistical significance for bottom and surface temperature measurements (Table 4 and 5), substrate bottom and surface temperatures were positively correlated with each other ( $r_{146} = 0.74$ ,  $p < 0.0001$ ). The block location also explained variation in both substrate bottom ( $RLRT = 131.32$ ,  $df = 1$ ,  $p < 0.0001$ ) and surface temperatures ( $RLRT = 88.60$ ,  $df = 1$ ,  $p < 0.0001$ ) as well, with average temperatures increasing by 0.5-1.0 °C per block from the westernmost block to the easternmost block (from block 1 to 5). Albedo was the only covariable that explained some of the variation in temperature, with greater albedo values associated with bottom temperature reductions. When albedo was

included in the bottom temperature model, the planting treatment factor was no longer significant ( $F_{31, 111} = 1.29$ ,  $p = 0.17$ ), instead, albedo had more explanatory power ( $F_{1, 111} = 4.22$ ,  $p = 0.04$ ) while block location was still important ( $RLRT = 122.88$ ,  $df = 1$ ,  $p < 0.0001$ ).

### *Albedo*

Planted modules reflected between 18.6-23.6% of incoming solar radiation (in the 400-1100 nm range) while the unplanted controls reflected 19.4% (Fig. 3). Therefore, reflectivity values of the vegetated modules ranged from 96% to 122% of the value found for the bare substrate controls. Some of this variability could be explained by the treatment factor ( $F_{31, 113} = 10.83$ ,  $p < 0.0001$ ), while the block factor was insignificant ( $RLRT = 1.94$ ,  $df = 1$ ,  $p = 0.164$ ). Based on the albedo values reported for other types of vegetation and non-vegetated surfaces (Oke 1978; Christopherson 2003), it is not surprising that very few planting treatments had lower albedo values than the unplanted controls (Fig. 3), and in fact, no treatment had a significantly lower albedo than the controls (Table 6). Treatments that did have an insignificantly lower albedo relative to the controls, tended to consist of species that did not appear healthy or active at the time of measurement (M. Ranalli personal observations). The 1-G treatment and the *D. flexuosa* grass monoculture were among those with the highest albedo values, as were the *S. bicolor* and *S. procumbens* monocultures (Fig. 3 and Table 6). The 1-G, 1-TF and 1-Suc treatments were the only single functional group plantings that had significantly greater albedo values than the controls (Fig. 3 and Table 6). Not surprising then, the combination of grasses, tall forbs and succulents (3-G+TF+SUC) showed one of the highest albedo values among all treatments, and the greatest albedo value among the most species rich treatments (those with 3-15 species; Fig. 3 and Table 6). Worth noting, the 3-G+TF+Suc treatment, included 6 of the 8 species that had the highest

albedo among monocultures (Table 6). In the species rich treatments, only those in which either grasses or tall forbs had been included, showed significantly greater albedo values than the controls (Fig. 3 and Table 6). The above patterns seem to have been largely influenced by the amount of vegetation cover present in each treatment, since, after the effect of vegetation cover on albedo had been accounted for (as a covariable), different comparative relationships emerged.

Because albedo was strongly linked to vegetative cover ( $r_{147} = 0.72$ ,  $p < 0.0001$ ), and cover differed primarily between, but also within planting treatment replicates, its effect had to be estimated in order to determine species and treatment specific albedo values, independent of cover. Therefore, differences in albedo among treatments were analyzed with an Analysis of Covariance (ANCOVA) with treatment as a fixed factor, block as a random factor and vegetation cover as a covariable. The ANCOVA showed that treatment was still a significant explanatory variable ( $F_{31, 112} = 4.55$ ,  $p < 0.0001$ ), block location still did not improve the predictive power of the albedo model ( $RLRT = 4.26 \times 10^{-8}$ ,  $df = 1$ ,  $p = 0.9998$ ) and interestingly, it showed that vegetative cover was highly significant ( $F_{1, 112} = 27.29$ ,  $p < 0.0001$ ), with albedo increasing by  $1.1 \pm 0.2\%$  for each 10% increase in cover. Once the effect of cover was accounted for, *P. compressa* and *V. vitis-idaea* were the species whose vegetative properties (apart from cover) had the greatest reflective ability (Table 7). When the separate effect of cover was ignored, *V. vitis-idaea* did not appear to have an albedo value different from the controls (Fig. 3). In contrast, the reflective abilities of *S. rubra* and *G. procumbens* monocultures, which initially seemed close in magnitude to that of the controls, were the lowest once cover was accounted for (Table 7). Even after the effect of cover had been removed, the 3-G+TF+Suc treatment had the greatest albedo among the most species rich treatments

(those with 3-15 species; Table 7), and the fourth greatest albedo overall (after *P. compressa*, *V. vitis-idaea* and *M. groenlandica*).

#### *Water capture and evapotranspiration*

During the study period, there were three rain events (73 mm, 32 mm and 31 mm of rainfall, respectively) from which total capture was estimated. The first two events were followed by a 3-4 day period of dry weather, which was needed to estimate cumulative water loss. On average, modules each received a total of  $17.5 \pm 0.4$  Kg of rain and initially (following a rain event) retained approximately 9-26% of the incident water.

Similar to the sunny day thermal results, both the planting treatment factor and the block factor explained a significant amount of variation in total water capture values ( $F_{31, 114} = 3.02$ ,  $p < 0.0001$  and  $RLRT = 3.76$ ,  $df = 1$ ,  $p = 0.053$ , respectively). The total amount of water captured for planted treatments ranged from 1.454 - 4.427 Kg of water (Fig. 4), values that represent 42% to 127% of the amount captured by the controls. Water capture tended to increase from block 1 to 5 (Fig. 5), likely as a result of the angle of rainfall (M. Ranalli personal observations) and potentially as a result of the solar radiation and temperature gradients across the site, if these influenced modular water deficits, and thus, modular water storage ability (Fig 1b). Interestingly, most planted treatments captured less water across rain events compared to the bare substrate controls (Fig. 4). Specifically, all significant differences in capture between vegetated modules and controls, reflected reduced water capture (by at least 1.178 Kg) compared to the controls (Table 8). The only treatment that nearly surpassed the controls in water capture was the 3-G+CF+TF combination (Table 8). While most of the treatments with reduced water capture values were monocultures (*P. compressa*, *S. rubra*, *S. procumbens*, *S. bicolor*, *P. maritima* and *R. rosea*), even a pair of the most diverse

treatments (3-G+TF+Suc and 5-ALL) captured significantly less water than the controls (Table 8 and 9). Support for the importance of composition can be seen in the comparison of 3-G+TF+Suc and 3-Sub+G+TF capture values, with the latter capturing significantly more water while only differing in composition by a single functional group (Table 9). Similarly, species composition was an important determinant of cumulative water loss.

Average cumulative water loss (following the July 19-21 and July 29-30 rain events) from planted modules, an indirect estimate of total evapotranspiration, ranged from approximately 1.573 - 2.188 Kg of water (Fig. 6), values that represent 84% to 117% of the total water loss found for the controls. Unlike the above analyses, the block factor was not significant ( $RLRT = 3.28$ ,  $df = 1$ ,  $p = 0.070$ ), instead, the planting treatment factor explained the majority of the variation in water loss values ( $F_{31, 114} = 4.81$ ,  $p < 0.0001$ ). While there was a tendency for planted modules to show reduced capture compared to the controls, the opposite trend was seen for cumulative water loss values (Fig. 6). Only three treatments (*D. spicata*, *D. flexuosa* and *S. acre* monocultures) showed significantly lower water loss values compared to the controls, whose values represented evaporation alone (Table 8). In order to have lower water loss than the controls, the above treatments must have inhibited evaporation to a greater extent than they transpired. Besides the 5-ALL and 1-CF treatments (in which *S. rubra* plants were included), only monocultures showed significantly greater losses than the controls (Fig. 6 and Table 8). *Spergularia rubra*, an annual in the ground covering forb group, showed the largest amount of water loss among treatments, followed by *P. maritima*, *P. compressa* and *S. spurium* monocultures, respectively (Fig. 6 and Table 8). Cumulative water loss also varied between species of the same functional group, notably, amongst the grasses (*P. compressa* showed greater losses than the two native

grasses, *D. spicata* and *D. flexuosa*) and the ground covering forbs (*S. rubra* showed greater losses than both indigenous *S. procumbens* and *M. goenlandica* monocultures; Table 9).

## Discussion

This study suggests that both functional richness and composition influenced the green roof functions studied here, likely through their connections to canopy structure, vegetation cover, plant phenology, leaf characteristics and root growth; factors that have been shown to influence the types of response variables measured here in past (mostly non-green roof) research. The results showed that higher levels of functional richness (3 functional groups), optimized some green roof benefits (substrate temperature reductions), but more commonly (in terms of albedo, water capture and cumulative water loss), provided insurance of favorable performance (even if not the most optimal), instead of extremely poor or extremely favorable performance (as in the case of monocultures). The success of functionally and species rich planting treatments depended both on functional group, and species composition (i.e., both functional groups and species within functional groups showed variability). Specifically, the inclusion of grasses, and tall forbs, or succulents, was essential to optimize most of the green roof benefits studied here, with the best performing monoculture or combination, differing among benefits. Further, most native coastal barren species examined showed at least equivalent, and for some green roof functions, improved performance compared to the common green roof succulent and grass species tested here. Although planting treatment influenced every green roof benefit studied here, the effect of cloud cover on substrate temperatures trumped all vegetative influences detectable in this study.

The relatively small differences between treatments in substrate bottom ( $< 1^{\circ}\text{C}$ ) and surface ( $1.4^{\circ}\text{C}$ ) temperatures, on the cloudy day measurement event, is not surprising considering the strong damping effect clouds exert on diurnal surface radiation budget variation and subsequent soil temperature variation (Oke 1978). The lack of a significant difference in substrate temperatures between planting treatments and controls suggests that the (physical and physiological) influence of vegetation on substrate surface and bottom temperatures is relatively minor when skies are overcast, especially compared to the factors influencing block values. This seems reasonable considering cloudy weather is associated with reduced insolation, daytime air temperatures and evapotranspiration (Oke 1978), all of which are likely connected to vegetative performance. Yet, clouds only reflect an average of 55% of incoming radiation (Oke 1978), therefore, up to 45% of incoming radiation could have contributed to differences in average block temperature, for example, due to differences in midday insolation from building shadows. The results do indicate that functional group composition can have a much more influential role in substrate temperatures when skies are clear.

Since 80-100% of Halifax's sky consists of cloud cover for at least half of each month (Environment Canada 2008), the number of days in which plant composition can influence green roof performance is relatively limited, at least for measures directly related to solar radiation, such as albedo and substrate temperature reductions. Thus, using plant combinations that perform the most favorably on clear days is essential to the optimization of thermal benefits in this maritime city. The clear sky temperature results suggest that the combination of grass species (1-G), and mixtures with grasses, and tall forbs, or succulents, reduced substrate temperatures most effectively. These combinations seem to have optimized at least several concomitant phenomena associated with reduced soil temperatures: (1) the development of an upper level canopy

(with a high plane of heat exchange), and a lower layer of vegetation that both provided substrate shading, (2) albedo, and (3) to a lesser extent, evapotranspirative cooling.

Because previous green roof studies examining thermal benefits have tended to use conventional roofing surfaces (and not bare substrate) as control treatments, temperature reductions between this study and others are not comparable. However, the influence of different types of vegetation on substrate temperatures can partly be explained by non-green roof studies. Canopy architecture has been shown to influence the physical position of the principal plane of mass and heat exchange (Oke 1978). Very generally, the principal plane of heat exchange (such as solar radiation absorption) lies close to the top of a vegetative stand with the transmission of solar radiation into a stand showing an almost logarithmic decay with depth of penetration (Oke 1978). Not surprising then, the temperature of a soil column (e.g., within the top 50 cm of a barley crop) tends to decrease with depth and is dependent on the amount of shading provided by the canopy (Oke 1978). Therefore, in general, tall stands (with high main areas of heat exchange relative to the underlying substrate), that also provide relatively large amounts of canopy shading, and potentially serve as a barrier to wind, thereby slowing the replacement of cooled air with warm air, should be associated with the coolest substrate temperatures; which is what was seen in this study.

Of all the growth forms examined, grass species such as *P. compressa* and *D. spicata* grew to be the tallest, with *D. spicata* and *D. flexuosa* also establishing some of the greatest amounts of cover, presumably providing some of the greatest amounts of shading. While reaching much shorter heights, the succulent species, *S. acre*, as well as the tall forbs, *S. bicolor* and *P. maritima*, also established large amounts of vegetative cover. Thus, it seems logical that the combination of grasses and either succulents or tall forbs provided a relatively high plane of heat exchange (comparatively far from the

substrate), and canopy shading at multiple heights, contributing in large part to the reduced substrate temperatures observed in the combination of those functional groups. The monocultures or single functional groups that were associated with either reduced substrate surface (*S. acre*) or bottom (1-G and *D. spicata*) temperatures, were those that were among the tallest and/or established the largest amounts of vegetative cover, likely providing the largest amount of shade (in the case of *S. acre*, regardless of canopy height). Conversely, comparatively little cover was one factor that likely contributed to the warmer temperatures found in the *G. procumbens* and 1-Sub treatments.

The finding that the *G. procumbens* monoculture and the 1-Sub treatment showed significantly warmer bottom temperatures (and in the case of *G. procumbens*, nearly significantly warmer surface temperatures) than control modules suggests that *G. procumbens* might be better suited to provide winter green roof benefits than summer ones. In a city such as Halifax, where snow cover does not generally last more than 1-3 days before melting, the use of the evergreen *G. procumbens* on a green roof might serve to warm the substrate during the winter, reducing heat transfer from the underlying building to the substrate and colder air, thereby, reducing energetic demands for heating. The winter performance of the *G. procumbens* and 1-Sub treatments is yet to be studied, however, the elevated substrate temperatures measured for these two treatments in this study, is likely the result of: (1) the relatively small amount of cover that species within the subshrub functional group achieved (including *G. procumbens*), and (2) the red-brown vegetation color seen in most individuals of *G. procumbens*.

By achieving comparatively little vegetative cover, the relatively dark, underlying substrate of the *G. procumbens* and 1-Sub treatments was exposed to incoming radiation, which would have facilitated radiation absorption. But for these two treatments to have shown significantly warmer bottom temperatures than the bare substrate

controls, something other than the small amount of cover influenced substrate temperature, the obvious explanation being related to vegetation color. *Gaultheria procumbens* was the only species to turn red in color (its autumn color) shortly after planting. One possible explanation for the increased bottom temperatures seen in the *G. procumbens* and 1-Sub treatments (in which *G. procumbens* represented 33% of all plants) is that the red color of *G. procumbens* was an indication of plant senescence, and that belowground plant material was actually decomposing, which could have raised substrate bottom temperatures. Further, *G. procumbens* and 1-Sub treatments also had the lowest measured albedo values, values lower than the bare substrate controls (but not significantly so). Since bottom temperatures tended to increase with decreasing albedo, the reduced albedo and presumed elevated radiation absorption of the *G. procumbens* and 1-Sub treatments, likely led to the transfer of heat energy to the substrate. This suggestion is supported by previous reports of substrate cover and color influencing reflectivity and soil temperature (Oke 1978; Decoteau, Kasperbauer & Hunt 1989; Niachou *et al.* 2001), and by the relationship between albedo and substrate temperature seen in other treatments in this study (i.e., high albedo was associated with cooler substrate bottom temperatures).

In the Loutraki region of Greece, cooler green roof temperatures were measured in areas covered by dark green vegetation, and higher temperatures in areas of red vegetation or bare soil (Niachou *et al.* 2001). Similarly, although mulch is not equivalent to plant material, Decoteau, Kasperbauer and Hunt's (1989) findings suggest that red colored material (mulch) above a soil surface can affect albedo and soil temperatures. Decoteau, Kasperbauer and Hunt (1989) found that red mulch was associated with relatively low reflectivity (9% of photosynthetically active radiation), and relatively high root zone temperatures (at a soil depth of 5 cm). Further, the treatments in our study

with some of the most reduced substrate temperatures, were also those that showed some of the greatest albedo values (such as the 1-G grass mixture, the grass, tall forb and succulent mixture, and the succulent *S. acre* monoculture), suggesting that substrate temperature reductions were linked to the reflective ability of the vegetation cover. While possible explanations for the higher surface temperatures in *S. procumbens* monocultures compared to controls are not as obvious, because this species established a large amount of cover, was green in color, and had high albedo values, this finding is not unlike those of an alpine study in northern Japan that looked at similar growth forms.

Mikio's (2004) study showed that the soil temperatures in patches dominated by cushion plants, or lichens and mosses, exceeded those of bare soil patches. This is likely due to a combination of factors that reduce turbulent heat losses (Oke 1992). Because of their compact form, cushion plants maintain a large boundary layer resistance while their short height also minimizes wind speeds (Oke 1992). Although *S. procumbens* is technically not a cushion plant (or a moss), its clumped growth pattern is somewhat similar to both cushion plants and mosses, suggesting the elevated surface temperatures seen in *S. procumbens* monocultures could be a true effect of its form. This may also have implications for cool season thermal properties of the roof, since, *S. procumbens* maintains its cushion growth form for much of the late fall and early spring when heat loss through the roof is a significant determinant of building energy consumption.

The finding that the 3-G+TF+Suc mixture had significantly lower surface temperatures than the monoculture plantings of some of its constituent species (i.e., *D. spicata* and *R. rosea*), underscores one major benefit of using a diversity of species and functional groups (instead of monocultures) in the early stages of North American green

roof implementation: the less desirable effects of particular species or functional groups might be moderated if the others included perform favourably. However, this might only be true if the majority of the other species included have a desirable effect on the particular function, otherwise, more rich plantings might have a 'dilution' effect on performance. For example, the substrate temperature reductions of the planting that included all functional groups (and species), 5-ALL, were smaller in magnitude (by up to 2 times) compared to the less diverse treatments that were significantly cooler than the controls.

Similar to their influence on substrate temperature (and as suggested above), stand architecture and plant phenology play an influential role in vegetation reflectivity (Oke 1978; Diaz *et al.* 2005). For example, leaf orientation (partly dependent on water stress and plant physiology), can affect albedo, with horizontal leaves better reducing radiation penetration compared to vertical ones (Oke 1978; Etherington 1982; Bonan 1997). This likely partly explains why monocultures like *D. flexuosa*, *S. bicolor*, *S. procumbens*, and *P. maritima* had some of the highest albedo values; they all had predominantly horizontal leaves. While *S. acre* leaves are relatively small in surface area, this species was likely among the top performers because it has thick leaves (~2550  $\mu\text{m}$ ; Golovko, Dalke & Bacharov 2008), and also possesses a thick cuticle, traits known to increase albedo (Knapp & Carter 1998; Slaton, Hunt & Smith 2001).

The importance of plant phenology in albedo is highlighted by the reduced reflectivity seen in the *G. procumbens*, *S. rubra*, *M. groenlandica*, and *R. rosea* monocultures; monocultures mostly lacking in green foliage. Most individuals of *G. procumbens* had turned red shortly after planting, possibly increasing radiation absorption (see above). While the *S. rubra* treatment reached greater cover than *M. groenlandica* monocultures, both are annual species, and had flowered earlier in the

summer, prior to measuring albedo. Consequently, stems and leaves of both species had begun senescing before albedo was measured, which likely reduced measured reflectivity values. This suggestion is supported by Song's (1999) results in which albedo was found to decrease from spring to early winter in a prairie grassland, as plants senesced, and by Jackson, Slater & Pinter's (1983) work, in which the reflectance (in the 0.5-0.7  $\mu\text{m}$  wavelength range) in plots of wheat decreased dramatically after flowering occurred. Finally, at the time of measurement, *R. rosea* plants were in the process of sprouting new stems and leaves (after being infected with aphids), and therefore, had relatively little vegetative cover to reflect insolation. Thus, it is not surprising that *R. rosea* monocultures showed reduced reflectivity since, in this study and in previous work (depending on the type of soil examined), albedo has been shown to be higher in vegetated plots compared to bare ones (Ritchie 1971). The tendency for treatments at least partly composed of grass species to show high reflectivity, is also supported by previous work.

While Diaz *et al.* (2005) were comparing plant communities with greater size differences, they found that grasses were among the functional types with the greatest albedo values (compared to deciduous trees and shrubs, and conifers). Similarly, the finding that only those high richness treatments that included either, grasses, or tall forbs, showed greater albedo values than the controls, highlights the importance of functional composition in green roof albedo. For example, the 3-G+TF+Suc treatment likely had one of the highest albedo values because the functional groups included in this treatment each performed well individually (i.e., the 1-G, 1-TF and 1-Suc treatments). Therefore, there was a relatively high density of successful functional groups in the grass, tall forb and succulent planting combination compared to the other high richness treatments. Interestingly, once differences in vegetation cover (i.e.,

reflective surface area) had been considered, the 3-G+TF+Suc treatment remained one of the top performers, while the performance of other treatments (e.g., *D. flexuosa* and *S. bicolor*) seems to have been driven largely by cover.

In addition to the possible influence of leaf orientation and phenology, the treatments that showed the largest reflectivity values seem to have done so in part, because of the large amount of cover the functional types in these treatments achieved. After the effect of cover had been accounted for (as a covariable), the influence of species' specific traits on albedo became more obvious. The *P. compressa* and *V. vitis-idaea* monocultures were found to have the greatest albedo values among all treatments, both outperforming other monocultures within each of their respective functional groups, as well as the most diverse planting. While leaf reflectance has been shown to increase with leaf pubescence (Rosenberg, Blad & Verma 1983), the presence of leaf bicolouration (lighter abaxial than adaxial leaf surfaces), the presence of a cuticle thicker than 1  $\mu\text{m}$  (Slaton, Hunt & Smith 2001), as well as with leaf thickness (Knapp & Carter 1998), none of these traits were obvious in *P. compressa*. One possible, explanation for *P. compressa*'s enhanced reflective ability is this species' tall, slender, flattened, and flexible stems. When observed from above, *P. compressa* monocultures appeared to have relatively little vegetative cover compared to the other grass species. However, a moderate wind (common on the roof study site) was capable of bowing *P. compressa* plants, which might have served to increase the reflective surface area of this species. In a sense, the 'effective' cover might have been underestimated for *P. compressa*. Conversely, wind was not able to largely alter the stem or leaf orientation of the low growing *V. vitis-idaea* plants. Instead, once its small amount of cover had been considered, *V. vitis-idaea* treatments showed relatively high reflectivity, likely because of several influential leaf traits.

*Vaccinium vitis-idaea* plants have horizontal, thick (354-391  $\mu\text{m}$  thick), bicolored, coriaceous (leathery) leaves that are shiny above, likely due to their 5-7  $\mu\text{m}$  thick adaxial surface cuticle (Semerdjieva *et al.* 2003). All of these traits have been separately shown to increase reflectivity (Oke 1978; Knapp & Carter 1998; Slaton, Hunt & Smith 2001), and together, seem to explain the finding that *V. vitis-idaea* monocultures had the second highest reflectivity (after *P. compressa*). Interestingly, even after the effect of cover had been removed, the 3-G+TF+Suc treatment still had one of the greatest albedo values among all plant combinations tested, likely due to a combination of factors. Firstly, the 3-G+TF+Suc treatment included (11%) *P. compressa*, the species with the highest reflectivity. Secondly, among the single functional group plantings, the grass combination (1-G) had the highest albedo. Further, although the subshrub and ground-covering forb monoculture treatments, *V. vitis-idaea*, *M. groenlandica*, and *S. procumbens* had some of the highest albedo values, these species belonged to functional groups which also each included one of the two species that showed the lowest reflectivity (*G. procumbens* and *S. rubra*). Thus, in the treatments in which subshrub or ground-covering forb species were included as a group, the successful performance of *V. vitis-idaea*, and *M. groenlandica* and *S. procumbens* seems to have been overshadowed by the poor performance of their structural counterparts, *G. procumbens* and *S. rubra*, respectively. While, separating the effect of plant cover from the other vegetative effects of treatments is interesting, cover is partly inherent with species and treatment identity. Therefore, in order for the above patterns to be of use, green roof planting schemes should account for differences in plant size and species' abilities to spread.

Vegetation characteristics, such as, cover and plant density, are known to also have a positive effect on water capture by increasing foliage interception of rain water (Oke 1978). Although the overall percentage of rainwater retained (9-26%) among modules is consistent with previous reports of 15-40% retention among similar substrate depths (Beattie & Berghage 2004), it was somewhat surprising to find that all significant differences between vegetated modules and controls reflected reduced water capture for the vegetated modules, since most green roof research has shown that vegetated treatments tend to have at least slightly higher substrate moisture levels compared to unvegetated treatments (Van Woert *et al.* 2005b), and overall, retain more water than controls (Rowe *et al.* 2003; Van Woert *et al.* 2005a). However, while Dunnett *et al.* (2008) measured runoff (water that was not captured) for species mostly different than the ones studied here, some of their results are in agreement with the results of this study. For example, in one of their experiments, bare controls showed the smallest amount of runoff (and presumably, the greatest capture), and all treatments that were significantly different from the controls had significantly greater amounts of runoff (Dunnett *et al.* 2008). In a second greenhouse experiment, Dunnett *et al.* (2008) found that their mixture of four grass species had less runoff compared to their forb mixture, with the mixture of *Sedum* species having the greatest amount of runoff. Similarly, among single functional group species mixtures, the grass mixture in this study captured more rain than did the tall forb mixture, with the succulent mixture capturing the smallest amount. Dunnett *et al.* (2008) attributed the success of the grass species in reducing runoff to their dense root systems, since they found a negative relationship between average root dry weight and the average amount of water runoff, but found no significant relationship between average shoot dry weight and runoff. Dunnett *et al.*'s (2008) finding might explain why the grass mixture performed the best among single functional group

plantings; and why *D. spicata* and *D. flexuosa* monocultures, with their fibrous root systems, captured more water than did *P. compressa*, which has creeping roots with slender rhizomes. Dunnett *et al.*'s (2008) results might also shed some light on why functionally rich treatments tended to capture more water than did monocultures.

Since most of the treatments with reduced water capture values were monocultures, and most of the functionally rich treatments captured the same amount, or, a non-statistically significant, slightly greater amount of water than did the controls, it seems as though the inclusion of more functional groups provided some insurance of elevated water capture. The success of treatments like 1-G and 3-G+CF+TF compared to their constituent monocultures and single functional group plantings, might partly reflect differences in rooting depth and lateral spread between species and functional groups, i.e., spatial complementarity of root systems (Schenk & Jackson 2002), which could have increased the total spatial occupation of roots, and thus, could have increased water retention in some of the more rich treatments. However, the finding that a pair of the most diverse treatments (3-G+TF+Suc and 5-ALL) captured significantly less water than the controls, suggests composition is also important. Further supporting the importance of composition, the 3-G+TF+Suc treatment captured significantly less water than the 3-Sub+G+TF and 3-G+CF+TF treatments, yet only differed by a single functional group. The most rich treatment may have performed so poorly for several reasons: (1) the combination of certain functional groups (especially the mixture of all functional groups) and species resulted in a 'dilution' effect, (2) caused plants to become root bound, and/or (3) the poor performance may reflect a weakness in the water capture measurement method used here.

The finding that nearly half of all species captured significantly less water than the controls, due to whatever negative effect they had on measured water capture, might

explain why the combination of all species and functional groups captured less rainwater than many of the one or three functional group plantings. The 5-ALL planting always contained the poorly performing species or functional groups, and the density of the best performing species would be relatively low (diluted) compared to the one and three group plantings, which would not necessarily contain the less successful species or groups. A second possible explanation for the poor performance of the richest treatment, is that these plantings became slightly root bound compared to most of the less rich treatments, potentially rendering the substrate less porous, reducing water retention capacity. This might have occurred if this most functionally and species rich treatment was associated with a more complete use of rooting space, or, because this treatment was associated with increased water loss via evapotranspiration (since root growth has been shown to be enhanced by reduced water availability; Padilla, de Dios Miranda & Pugnaire 2007). A third possibility is that, although the indirect method of estimating water capture used in this study was the most logistically feasible, it involved two major sources of error that may have resulted in the underestimation of capture for certain modules.

The relatively large variance in water capture values indicates that the capture estimation method was less precise compared to methods used to estimate other green roof functions in this study. Capture estimates were calculated as the sum of differences between initial masses of module assemblies (at the beginning of the study), and the mass of those modules following rain events (later in the summer). Since, substrate mass was likely reduced in quantity (and water storage capacity) as planting treatments accumulated biomass, capture estimates of fast-growing treatments may have been underestimated (due to greater reductions in substrate mass). This suggestion is supported by the finding that *V. vitis-idaea* and *E. nigrum*, two slow-growing treatments

that established relatively little vegetative cover, captured the greatest amount of water among monocultures. Further, the end of a rain event and the time of measurement were temporally separated, thus, any water lost from modules through evapotranspiration, prior to being weighed (during the evening and early morning after a rain event), would have reduced apparent estimates of water capture. This might partly explain why some of the plantings that seem to have captured the least amount of rain, also showed the greatest amounts of cumulative water loss; especially since reduced capture should have presumably corresponded to reduced soil moisture, which should have reduced water loss in these treatments (Oke 1978). Considering the potential weakness in the method used to estimate water capture, it is not entirely surprising that differences in water capture did not help to explain the variation in cumulative water loss.

Evapotranspiration can play a dominant role in the energy balance of a stand, reducing leaf and substrate (and ultimately roof) temperatures by using energy that would have otherwise gone toward heating plant or substrate matter (Oke 1978). The rate of transpiration is dependent on the amount of water available to a plant (soil moisture), the supply of energy, which is required to vaporize water, and the difference in vapor concentration (pressure) between substomatal cavities and the surrounding air (Kramer & Boyer 1995; Wolf & Lundholm 2008). Plants play an especially active role in water loss and the subsequent cooling achieved, when soil moisture is relatively low, water becomes a limiting factor, and evaporation from the soil surface is minimal (Oke 1978; Wolf & Lundholm 2008); conditions periodically common in extensive green roof systems. While research elucidating the transpirational behaviour of individual plants or leaves of individual species is insightful, scaling up from leaves and plants, to stands, presents problems (Kramer & Boyer 1995). For example, because factors like light intensity, and wind speed, tend to decrease with depth into plant stands, and the

important boundary layer resistance is that of the canopy rather than that of individual leaves, the effects of leaf size, shape, and stomatal aperture are likely to be less important in the water relations of stands than for individual plants (Kramer & Boyer 1995). While the green roof stands studied here are relatively small in size, for example, compared to crops and forests, it seems that stand characteristics tended to strongly influence cumulative water loss, with species and functional group traits also playing a role.

In this study, I assumed that increased water loss from the module-substrate-plant microcosms relative to the controls was due to active transpiration by plants. Therefore, the finding that the *D. flexuosa*, *D. spicata*, and *S. acre* treatments had less water loss than the plant-less controls, suggests these species had a conservative water use strategy, in addition to forming a canopy that inhibited water evaporation from the substrate, at least in the 3-4 day period after a rain event which was the period used here to estimate water loss. Previous research has shown similar patterns of reduced water loss compared to controls for *D. flexuosa*, *D. spicata* and *S. acre* under relatively wet substrate conditions (Wolf & Lundholm 2008). In combination with low (or likely low) rates of transpiration (Korner, Scheel & Bauer 1979), the above treatments probably showed reduced water loss due to their relatively large amounts of vegetative cover, which, through the provision of shade, reduced substrate temperatures, and likely reduced the supply of energy available to vaporize water. This suggestion is supported by Ekern's (1965) study which showed that pineapple, a CAM plant, has such a low rate of daytime transpiration that a mature stand with a relatively large amount of cover, can reduce the rate of evapotranspiration compared to a younger stand with the soil partly exposed. Here, the partial exposure of substrate was also associated with larger amounts of water loss.

While greater aboveground biomass (or vegetation cover) is likely roughly associated with increased stomatal numbers, and thus, might be expected to be associated with increased evapotranspiration (water loss), this was not the pattern observed here. The treatments that showed the greatest amounts of cumulative water loss were those monocultures that had moderate amounts of vegetative cover (likely allowing for evaporation from the substrate), and consisted of growth forms associated with relatively moderate to high maximum leaf conductance, a measure of potential transpirational water loss (Korner, Scheel & Bauer 1979). According to Korner, Scheel and Bauer's (1979) summary of the behaviour of 246 plant species belonging to 13 morphologically and/or ecologically separate groups, herbs (or forbs) from open habitats, and wild growing graminoids, showed greater maximum leaf conductance values than did woody plants or succulents. My results are in general agreement with Korner, Scheel and Bauer's (1979) findings since, *Spergularia rubra*, an annual in the ground covering forb group, showed the largest amount of water loss among treatments, followed by the tall forb *P. maritima*, and the grass *P. compressa*. Similarly, Weeks (2008) reported a higher rate of evapotranspiration for a mixture of perennials compared to one of grass species. Interestingly, *S. spurium*, a succulent, was one of the top performing treatments. Similarly, among the succulent species tested by Wolf and Lundholm (2008), *S. spurium* generally showed the greatest amount of total water loss. This treatment likely outperformed the other succulent monocultures, *S. acre* and *R. rosea*, as well as some of the other plantings, because it developed a moderate amount of vegetative cover, and because the substrate was likely moist enough to prevent this species from shifting to CAM photosynthesis, a type of photosynthesis associated with improved water use efficiency (Sayed 2001).

Worth noting is the disparity in performance seen for some of the species belonging to the same functional groups, with non-natives generally performing better than the native species tested. The common green roof species, *P. compressa*, showed greater cumulative water loss than the two native grasses, *D. spicata* and *D. flexuosa*, the *S. rubra* treatment (although not a common green roof species), showed greater losses than both indigenous *S. procumbens* and *M. goenlandica* ground covering forb treatments, and the non-native green roof species, *S. spurium*, outperformed another common green roof species, *S. acre*, and the native *R. rosea* (although not significantly so). Since the indigenous *P. maritima* monoculture and the 5-ALL mixture were also among the top performers, the use of natives did not necessarily hinder evapotranspirative cooling, however, neither did the inclusion of non-natives. The differences between species within functional groupings (with nearly every functional group each possessing one of the best performing species), might partly explain why the water loss values found among the highest diversity treatments, were similar in magnitude.

Nearly every treatment with three or more species showed greater water loss than the controls, however, only the 1-CF (which included *S. rubra*) and 5-ALL treatments lost significantly more water than the controls. Although not all differences were significant, the higher diversity treatments showed a relatively narrow range of cumulative water loss values, all losing between 15-100 g more water than controls. Thus, like the substrate temperature, albedo and water capture assessments, the inclusion of morphologically and physiologically different groups in the higher diversity treatments provided some insurance of desirable performance, even if these treatments did not exhibit the greatest amount of cumulative water loss observed. Further, since most of the non-succulent species are not as well suited to severe drought, the

combination of low growing *Sedum* species and/or the native grasses, with species that have greater water loss rates, might provide further insurance of desirable performance, if for example, the *Sedum* and native grass species reduce drought-induced mortality by prolonging wetter soil conditions.

Although the importance of the vegetation layer to green roof functioning has often been ignored (Dunnett *et al.* 2005), this study showed that vegetation can influence green roof performance. I showed that both functional composition and richness affected green roof cooling, and stormwater capture benefits, with the best performing treatment differing among the benefits studied. While, both functional groups and species within functional groups showed variability, the inclusion of grasses, and tall forbs, or succulents, optimized most of the performance indicators studied here, with the best performing monoculture or functional group combination differing among indicators. Further, when there is an interest in native plant use (e.g., urban habitat creation for native birds and insects) in cities such as Halifax, NS (and other localities with a similar climate), many native coastal barren species examined proved to be valid options, often showing equivalent, and improved performance compared to the commonly used, non-native succulent and grass species tested. One of the most interesting findings was that moderate to high richness treatments provided insurance of favorable performance (even if not the most optimal) across functions, instead of extremely poor or extremely favorable performance (as in the case of monocultures). Also interesting, was the finding that large amounts of vegetative cover might have conflicting effects on two separate assessments of green roof cooling (substrate temperature and cumulative water loss), at least for the short measurement periods employed here.

Green roofs are thought to provide cooling benefits through the provision of shade, increased albedo (compared to conventional roofing), and through

evapotranspiration. Although vegetation cover was not a significant covariable in most of the analyses (likely because it was so strongly related to planting treatment, the main independent variable), its pattern helped to explain many of the differences in treatment behaviour. Interestingly, the influence of cover on albedo, and the presumed influence of cover on substrate temperature, is somewhat different in direction to its influence on cumulative water loss (in which very large amounts of cover apparently prevented water loss). While this study examined only a single roof site over a single season of study, it highlights that the relative importance of canopy architecture and shading, versus evapotranspiration, in rooftop cooling should be examined in future studies, since, greater vegetation cover is often assumed to be associated with improved green roof performance.

For constructed ecosystems like green roofs, functional and species richness can be manipulated in order to optimize green roof performance. However, 'optimal performance' can become harder to define when one is interested in multiple benefits over an extended period. While this study highlights the need for more research into the role of the vegetation layer in green roof performance, and the need for the long-term study of the effects of functional group diversity (as these effects on green roof performance will likely change as green roof plant communities mature), the relatively consistent performance of the richer functional group treatments (especially those consisting of grasses and tall forbs or succulents) for nearly all green roof functions examined, suggests that combinations of these functional groups (and species) should strongly be considered when the goal of green roof implementation is mainly thermal regulation.

One of the largest barriers to the implementation of green roof technology is financial cost. Green technologies, such as green roofs, often involve higher initial costs

that are offset by long-term, economic and environmental gains (Schnare 2005). While the magnitude of the differences in measured performance among treatments seemed small in this study, when applied on a larger scale (such as a roof-sized plot), and over multiple years, these differences could be large enough to significantly alter the thermal performance of an underlying building (and thereby, the costs of space conditioning), and might also affect a roof's life (by moderating temperature fluctuations). If green roofs are to become more common in North American cities such as Halifax, long-term economic benefits must be shown to outweigh the higher initial costs. Thus, studies that address means of optimizing long-term green roof performance under local conditions, should serve to accelerate the economic viability of green roof implementation.

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**Table 1.** Sopraflor X green roof substrate (Soprema Inc., Drummondville, QC, Canada) properties as determined by independent testing (Nova Scotia Agriculture, Truro, NS, Canada); n = 3.

Substrate property	Mean	SE
pH	7.6	0.3
Organic matter (%)	9.4	0.8
P <sub>2</sub> O <sub>5</sub> (Kg/ha)	363	42
K <sub>2</sub> O (Kg/ha)	383	72
Ca (Kg/ha)	4769	381
Mg (Kg/ha)	554	51
Na (Kg/ha)	51	3
S (Kg/ha)	135	22
Fe (ppm)	123	3
Mn (ppm)	31	3
Cu (ppm)	1.36	0.12
Zn (ppm)	7.4	0.5
B (ppm)	2.10	0.33
Nitrate – N (ppm)	13.4	4.4
CEC (meq/100 g)	14.8	1.2
<b>Base Saturation</b>		
K (%)	2.7	0.3
Ca (%)	80.5	0.4
Mg (%)	15.6	0.1
Na (%)	0.8	0.1
H (%)	0.6	0

**Table 2.** Growth form (plant functional group) and origin of the 15 study species.

Plant species	Growth form	Origin
<i>Danthonia spicata</i> (L.) Beauv.	grass	indigenous
<i>Deschampsia flexuosa</i> (L.) Trin.	grass	indigenous
<i>Poa compressa</i> L.	grass	introduced
<i>Minuartia groenlandica</i> (Retz.) Ostenf.	ground-covering forb	indigenous
<i>Sagina procumbens</i> L.	ground-covering forb	indigenous
<i>Spergularia rubra</i> (L.) J. Presl & C. Presl	ground-covering forb	introduced
<i>Empetrum nigrum</i> L.	subshrub	indigenous
<i>Gaultheria procumbens</i> L.	subshrub	indigenous
<i>Vaccinium vitis-idaea</i> L.	subshrub	indigenous
<i>Rhodiola rosea</i> L.	succulent	indigenous
<i>Sedum acre</i> L.	succulent	introduced
<i>Sedum spurium</i> M. Beib.	succulent	introduced
<i>Campanula rotundifolia</i> L.	tall forb	indigenous
<i>Plantago maritima</i> L.	tall forb	indigenous
<i>Solidago bicolor</i> L.	tall forb	indigenous

*R. rosea* was previously classified in the genus *Sedum*.

**Table 3.** The one-way Randomized Complete Block experimental design used here. Treatments listed represent all of the possible combinations of functional groups (all of which, were examined here). When one, three or all five functional groups were included in individual treatments, all three species within a functional group were planted. 'G' represents the grasses, 'CF' represents the ground-covering forbs, 'Sub', the subshrub species, 'Suc', the succulent species, and 'TF', the tall forbs. Numbers in parentheses represent the number of species in each treatment followed by the total number of replicates for each treatment.

Number of functional groups per module				
	0	1	3	5
Treatments	Control (0) x10	G (3) x5 CF (3) x5 Sub (3) x5 Suc (3) x5 TF (3) x5  <u>Monocultures</u> D.spicata (1) x3 D.flexuosa (1) x3 P.compressa (1) x3 G.procumbens (1) x3 E.nigrum (1) x3 V.vitis-idaea (1) x3 S.rubra (1) x3 S.procumbens (1) x3 M.groenlandica (1) x3 C.rotundifolia (1) x3 S.bicolor (1) x3 P.maritima (1) x3 R.rosea (1) x3 S.spurium (1) x3 S.acre (1) x3	Sub+G+CF (9) x5 Sub+TF+Suc (9) x5 Sub+G+Suc (9) x5 Sub+CF+TF (9) x5 Sub+G+TF (9) x5 Sub+CF+Suc (9) x5 G+CF+TF (9) x5 G+CF+Suc (9) x5 G+TF+Suc (9) x5 CF+TF+Suc (9) x5	All (15) x20

**Table 4.** Treatments with substrate bottom or surface temperatures significantly different from the unplanted controls (measured on September 14, 2007). 'G' represents the grasses, 'CF' represents the ground-covering forbs, 'Sub', the subshrub species, 'Suc', the succulent species, and 'TF', the tall forbs. Temperature readings were taken near the center of modules, while in sunlight (between 10:30 am and 1:30 pm AST).

Treatment	Difference from controls (°C)	S.E.	df	t value	p value
<i>Bottom temperature</i>					
Control = 21.0 ± 0.7 °C					
D. spicata	-1.1	0.6	112	-1.94	0.054 *
G. procumbens	1.2	0.6	112	2.09	0.039 *
S. acre	-1.0	0.6	112	-1.77	0.080 .
1-Sub	1.0	0.5	112	2.10	0.038 *
1-G	-1.4	0.5	112	-2.95	0.004 **
3-Sub+G+Suc	-0.9	0.5	112	-1.97	0.051 *
3-G+TF+Suc	-1.3	0.5	112	-2.78	0.006 **
5-ALL	-0.7	0.3	112	-1.97	0.052 *
<i>Surface temperature</i>					
Control = 26.3 ± 0.7 °C					
G. procumbens	1.4	0.8	112	1.86	0.066 .
S. procumbens	1.6	0.8	112	2.13	0.036 *
R. rosea	1.3	0.8	112	1.68	0.095 .
S. acre	-2.0	0.8	112	-2.65	0.009 **
3-G+CF+Suc	-1.2	0.6	112	-1.98	0.051 *
3-Sub+G+TF	-1.3	0.6	112	-2.01	0.047 *
3-G+TF+Suc	-2.3	0.6	112	-3.71	0.0003 ***
5-ALL	-0.8	0.4	112	-1.73	0.087 .

Significance codes: 0.001 (\*\*\*\*) 0.01 (\*\*\*) 0.05 (\*\*) 0.1 (.)

**Table 5.** Multiple comparisons (Tukey contrasts) of mean substrate temperature for September 14, 2007. 'G' represents the grasses, 'CF' represents the ground-covering forbs, 'Sub', the subshrub species, 'Suc', the succulent species, and 'TF', the tall forbs. Only significant comparisons between treatments with at least one species in common or between species in the same functional group are presented.

Linear hypotheses	Estimate (°C)	S.E.	z value	p value
<i>Bottom temperature</i>				
5-ALL - 1-Sub = 0	-1.7	0.4	-3.827	0.039 *
<i>Surface temperature</i>				
3-G+TF+Suc - D. spicata = 0	-3.2	0.8	-3.806	0.044 *
3-G+TF+Suc - R. rosea = 0	-3.6	0.8	-4.285	< 0.01 **
3-G+TF+Suc - 3-Sub+CF+TF = 0	-2.7	0.7	-3.699	0.063 .
3-CF+TF+Suc - 3-G+TF+Suc = 0	2.9	0.7	4.088	0.015 *

Significance codes: 0.001 '\*\*\*' 0.01 '\*\*' 0.05 '\*' 0.1 '.'

Adjusted *p* values are reported

**Table 6.** Treatments with albedo (%) values significantly different from the unplanted controls. 'G' represents the grasses, 'CF' represents the ground-covering forbs, 'Sub', the subshrub species, 'Suc', the succulent species, and 'TF', the tall forbs. Values represent a single measurement event near the end of the experimental period (September 26, 2007).

Treatment	Difference from controls (%)	S.E.	df	t value	p value
Control = 19.4 ± 0.3 %					
D. spicata	2.4	0.6	113	4.00	0.0001 ***
D. flexuosa	4.0	0.6	113	6.56	< 0.0001 ***
P. compressa	2.8	0.6	113	4.71	< 0.0001 ***
E. nigrum	1.3	0.6	113	2.12	0.036 *
S. procumbens	3.7	0.6	113	6.06	< 0.0001 ***
S. bicolor	4.0	0.6	113	6.58	< 0.0001 ***
P. maritima	2.0	0.6	113	3.38	0.001 ***
S. acre	2.9	0.6	113	4.81	< 0.0001 ***
1-TF	2.4	0.5	113	4.73	< 0.0001 ***
1-Suc	1.2	0.5	113	2.38	0.019 *
1-G	4.2	0.5	113	8.46	< 0.0001 ***
3-G+CF+Suc	2.4	0.5	113	4.84	< 0.0001 ***
3-Sub+TF+Suc	2.2	0.5	113	4.32	< 0.0001 ***
3-Sub+G+Suc	2.6	0.5	113	5.15	< 0.0001 ***
3-Sub+CF+TF	1.0	0.5	113	1.99	0.049 *
3-Sub+G+TF	2.5	0.5	113	5.08	< 0.0001 ***
3-G+CF+TF	2.3	0.5	113	4.70	< 0.0001 ***
3-Sub+G+CF	1.0	0.5	113	2.08	0.040 *
3-G+TF+Suc	3.6	0.5	113	7.21	< 0.0001 ***
3-CF+TF+Suc	1.2	0.5	113	2.44	0.016 *
5-ALL	2.2	0.4	113	6.30	< 0.0001 ***

Significance codes: 0.001 '\*\*\*' 0.01 '\*\*' 0.05 '\*' 0.1 '.'

**Table 7.** Multiple comparisons (Tukey contrasts) of albedo (%) after accounting for vegetation cover (as a covariable). 'G' represents the grasses, 'CF' represents the ground-covering forbs, 'Sub', the subshrub species, 'Suc', the succulent species, and 'TF', the tall forbs. Only significant comparisons between treatments with at least one species in common or between species in the same functional group are presented.

Linear hypotheses	Estimate (%)	S.E.	z value	p value
P. compressa - D. spicata = 0	3.6	0.9	3.915	0.024 *
3-G+CF+Suc - P. compressa = 0	-2.6	0.7	-3.475	0.100 .
3-G+CF+TF - P. compressa = 0	-2.8	0.8	-3.712	0.048 *
3-Sub+G+CF - P. compressa = 0	-2.7	0.6	-4.270	<0.01 **
5-ALL - P. compressa = 0	-2.7	0.6	-4.101	0.012 *
V. vitis-idaea - G. procumbens = 0	3.5	0.8	4.256	<0.01 **
1-Sub - V. vitis-idaea = 0	-3.1	0.7	-4.304	<0.01 **
S. procumbens - S. rubra = 0	2.6	0.7	3.720	0.048 *
3-G+CF+Suc - S. rubra = 0	2.2	0.6	3.576	0.074 .
5-ALL - S. rubra = 0	2.1	0.5	3.975	0.019 *
3-G+TF+Suc - 1-Suc = 0	1.9	0.5	3.566	0.075 .

Significance codes: 0.001 '\*\*\*' 0.01 '\*\*' 0.05 '\*' 0.1 '.'

Adjusted p values are reported

**Table 8.** Treatments with total water capture and water loss (evapotranspiration) values significantly different from the unplanted controls. 'G' represents the grasses, 'CF' represents the ground-covering forbs, 'Sub', the subshrub species, 'Suc', the succulent species, and 'TF', the tall forbs. Values represent totals summed across rain events.

Treatment	Difference from controls (Kg)	S.E.	df	t value	p value
<i>Total water capture</i>					
Control = $3.486 \pm 0.326$ Kg					
P. compressa	-1.814	0.643	114	-2.82	0.006 **
G. procumbens	-1.247	0.643	114	-1.94	0.055 .
S. rubra	-1.759	0.643	114	-2.73	0.007 **
S. procumbens	-1.882	0.643	114	-2.93	0.004 **
S. bicolor	-1.677	0.643	114	-2.61	0.010 **
P. maritima	-2.025	0.643	114	-3.15	0.002 **
R. rosea	-1.822	0.643	114	-2.83	0.006 **
1-Suc	-0.883	0.533	114	-1.66	0.100 .
3-G+CF+TF	0.941	0.533	114	1.77	0.080 .
3-G+TF+Suc	-2.032	0.533	114	-3.81	0.0002 ***
5-ALL	-1.178	0.377	114	-3.13	0.002 **
<i>Cumulative water loss</i>					
Control = $1.875 \pm 0.030$ Kg					
D. spicata	-0.197	0.060	114	-3.27	0.001 **
D. flexuosa	-0.302	0.060	114	-5.02	< 0.001 ***
P. compressa	0.161	0.060	114	2.67	0.009 **
S. rubra	0.313	0.060	114	5.18	< 0.001 ***
P. maritima	0.163	0.060	114	2.70	0.008 **
S. spurium	0.144	0.060	114	2.39	0.018 *
S. acre	-0.129	0.060	114	-2.14	0.034 *
1-TF	0.092	0.050	114	1.84	0.068 .
1-CF	0.131	0.050	114	2.62	0.010 **
5-ALL	0.105	0.035	114	2.97	0.004 **
Significance codes: 0.001 '***' 0.01 '**' 0.05 '*' 0.1 '.'					

**Table 9.** Multiple comparisons of mean total water capture and water loss. 'G' represents the grasses, 'CF' the ground-covering forbs, 'Sub', the subshrub species, 'Suc', the succulent species, and 'TF', the tall forbs. Only significant comparisons between treatments with at least one species in common or between species in the same functional group are presented here.

Linear hypotheses	Estimate (Kg)	S.E.	z value	p value
<i>Total water capture</i>				
3-G+CF+TF - P. compressa = 0	2.755	0.713	3.864	0.035 *
3-G+CF+TF - S. rubra = 0	2.700	0.713	3.787	0.045 *
3-G+CF+TF - S. procumbens = 0	2.823	0.713	3.960	0.025 *
3-G+CF+TF - S. bicolor = 0	2.618	0.713	3.672	0.070 .
3-Sub+G+TF - P. maritima = 0	2.638	0.713	3.701	0.061 .
3-G+CF+TF - P. maritima = 0	2.966	0.713	4.161	0.011 *
3-G+TF+Suc - 1-G = 0	-2.238	0.615	-3.637	0.076 .
3-G+TF+Suc - 3-Sub+CF+TF = 0	-2.390	0.615	-3.884	0.031 *
3-G+TF+Suc - 3-Sub+G+TF = 0	-2.645	0.615	-4.298	<0.01 **
5-ALL - 3-Sub+G+TF = 0	-1.791	0.486	-3.682	0.067 .
3-G+TF+Suc - 3-G+CF+TF = 0	-2.973	0.615	-4.832	<0.01 ***
5-ALL - 3-G+CF+TF = 0	-2.119	0.486	-4.356	<0.01 **
<i>Cumulative water loss</i>				
P. compressa - D. spicata = 0	0.358	0.074	4.810	<0.01 ***
1-G - D. spicata = 0	0.237	0.067	3.552	0.099 .
3-G+CF+Suc - D. spicata = 0	0.268	0.067	4.016	0.020 *
3-Sub+G+Suc - D. spicata = 0	0.240	0.067	3.597	0.085 .
3-Sub+G+TF - D. spicata = 0	0.262	0.067	3.926	0.028 *
3-G+CF+TF - D. spicata = 0	0.271	0.067	4.061	0.017 *
3-Sub+G+CF - D. spicata = 0	0.243	0.067	3.642	0.073 .
5-ALL - D. spicata = 0	0.302	0.057	5.330	<0.01 ***
P. compressa - D. flexuosa = 0	0.463	0.074	6.220	<0.01 ***
1-G - D. flexuosa = 0	0.342	0.067	5.123	<0.01 ***
3-G+CF+Suc - D. flexuosa = 0	0.373	0.067	5.587	<0.01 ***
3-Sub+G+Suc - D. flexuosa = 0	0.345	0.067	5.168	<0.01 ***
3-Sub+G+TF - D. flexuosa = 0	0.367	0.067	5.497	<0.01 ***
3-G+CF+TF - D. flexuosa = 0	0.367	0.067	5.632	<0.01 ***
3-Sub+G+CF - D. flexuosa = 0	0.348	0.067	5.213	<0.01 ***
3-G+TF+Suc - D. flexuosa = 0	0.324	0.067	4.854	<0.01 ***
5-ALL - D. flexuosa = 0	0.407	0.057	7.181	<0.01 ***
S. procumbens - S. rubra = 0	-0.315	0.074	-4.229	<0.01 **
M. groenlandica - S. rubra = 0	-0.302	0.074	-4.050	0.018 *
3-G+CF+Suc - S. rubra = 0	-0.242	0.067	-3.614	0.081 .
3-Sub+CF+TF - S. rubra = 0	-0.239	0.067	-3.569	0.094 .
3-Sub+CF+Suc - S. rubra = 0	-0.300	0.067	-4.482	<0.01 **
3-G+CF+TF - S. rubra = 0	-0.239	0.067	-3.569	0.094 .
3-Sub+G+CF - S. rubra = 0	-0.267	0.067	-3.988	0.022 *
5-ALL - S. rubra = 0	-0.208	0.057	-3.658	0.070 .
S. acre - S. spurium = 0	-0.273	0.074	-3.669	0.068 .
5-ALL - S. acre = 0	0.234	0.057	4.126	0.013 *

Significance codes: 0.001 (\*\*\*\*) 0.01 (\*\*\*) 0.05 (\*\*) 0.1 (\*)

Adjusted p values are reported

(a)

(b)

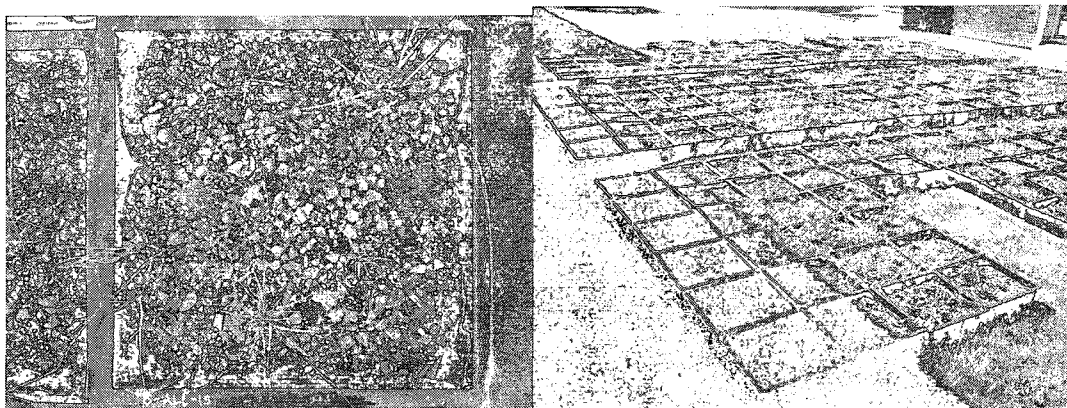
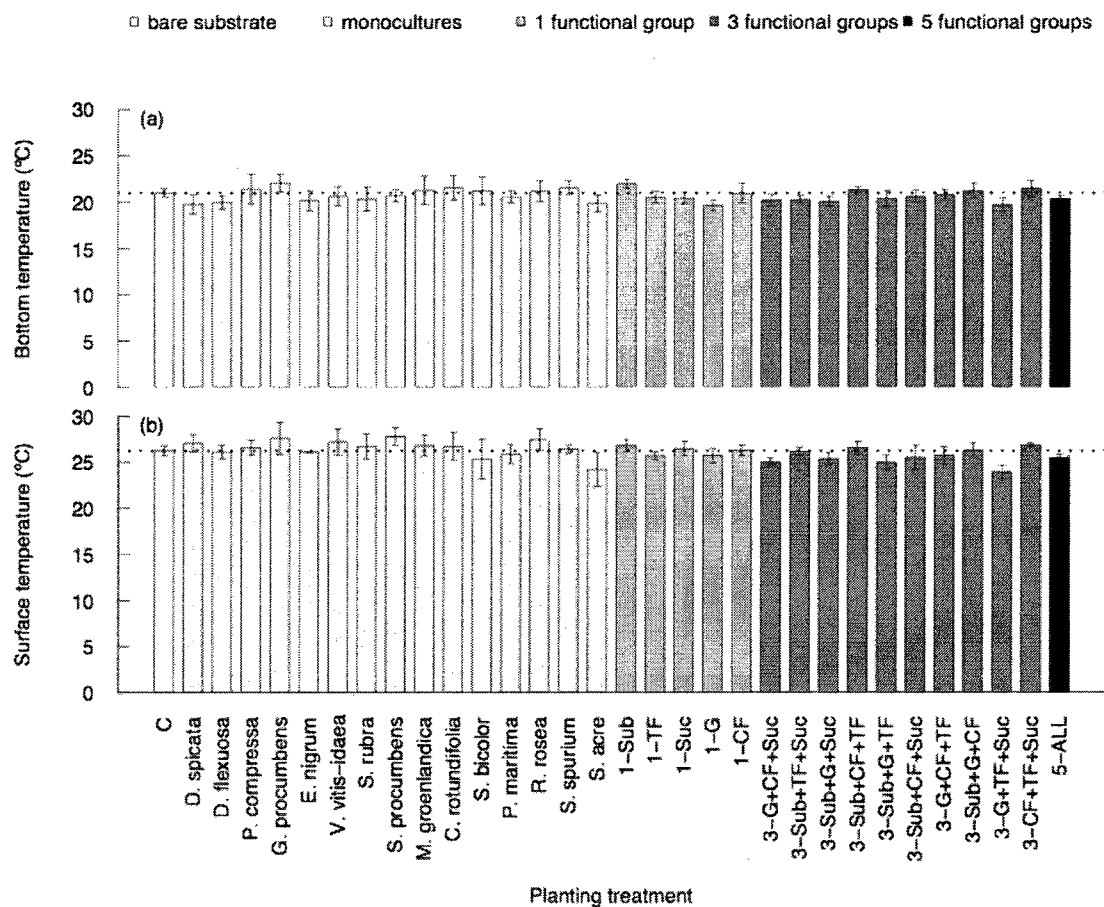
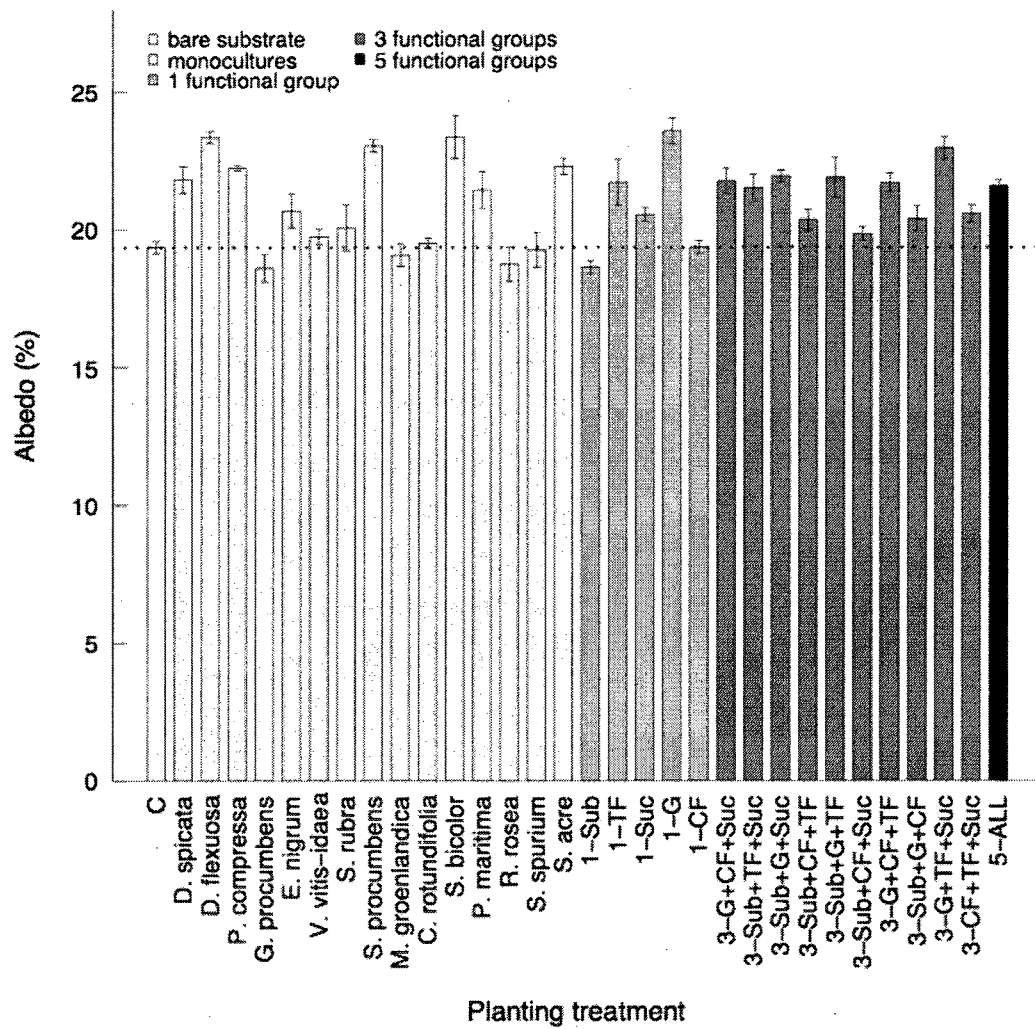


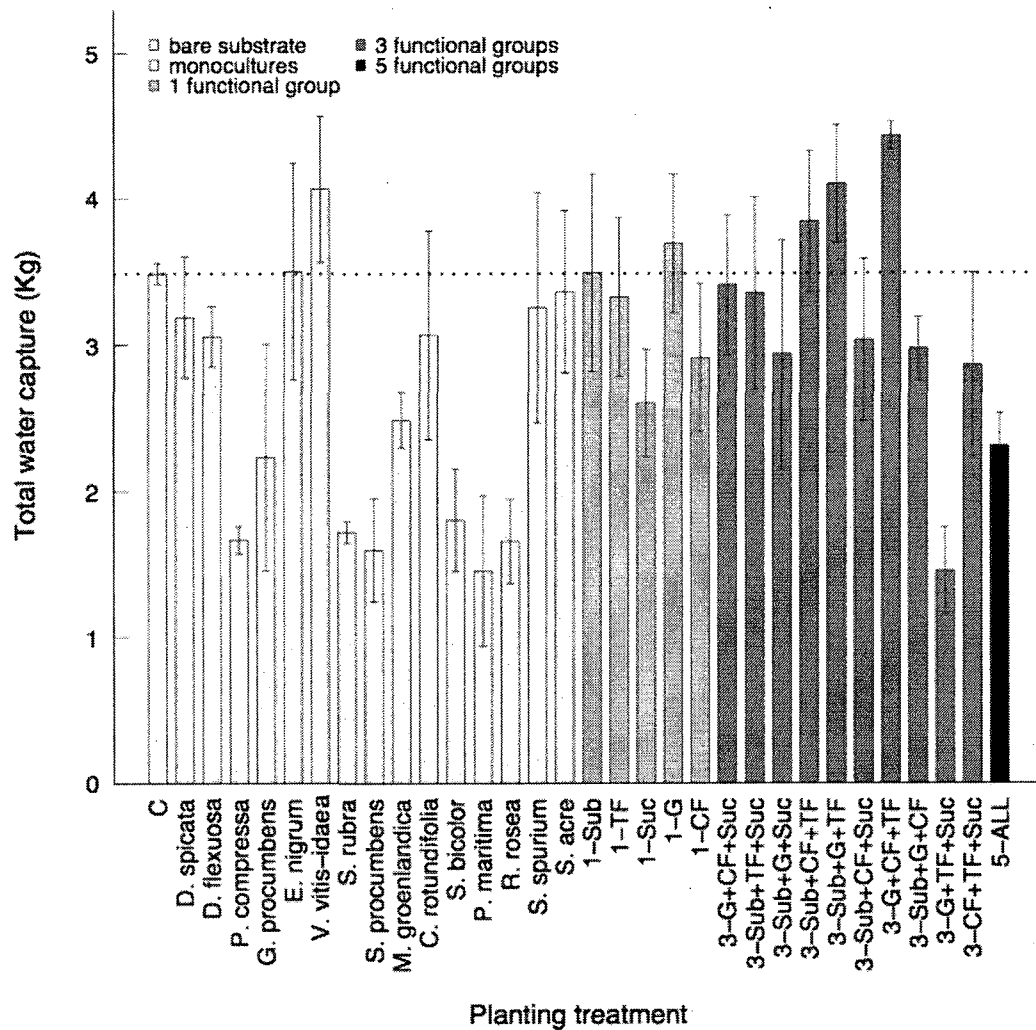
Fig. 1. (a) A module assembly (sampling unit) which consisted of a square, plastic, free-draining tray lined with a drainage layer and a filter fabric layer beneath the substrate layer. (b) The north section of the study site in Halifax, Nova Scotia, Canada, showing the orientation of the solar radiation gradient. The photo was taken from the north easterly corner of the site at 11:30 am AST on September 13, 2007, just prior to the disappearance of the shadow on the east side.



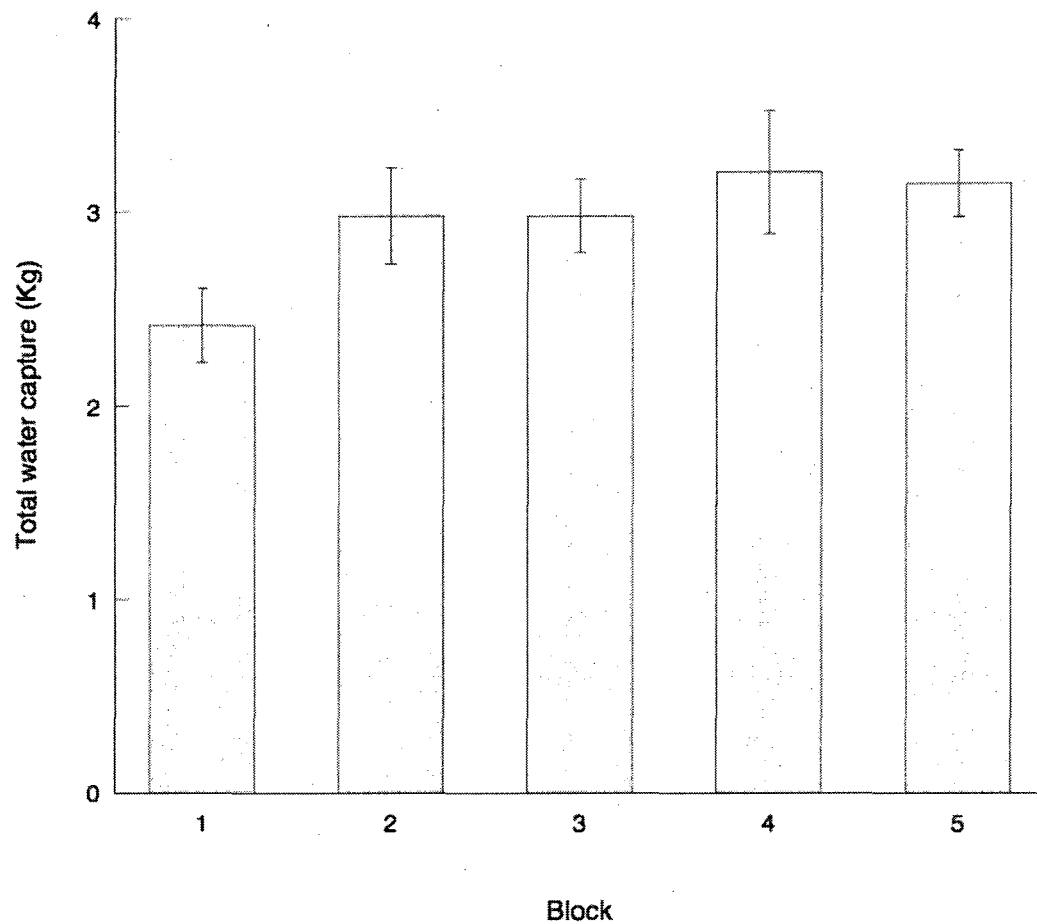
**Fig. 2.** (a) Mean substrate bottom and (b) surface temperatures ( $\pm 1$  S.E.) from green roof modules with different functional diversity levels, measured on September 14, 2007. The bar labeled 'C' represents the bare substrate controls, 'G' represents the grasses, 'CF' represents the ground-covering forbs, 'Sub', the subshrub species, 'Suc', the succulent species, and 'TF', the tall forbs. The '5-ALL' treatment included all five functional groups. The dotted line highlights the mean temperature of the controls.



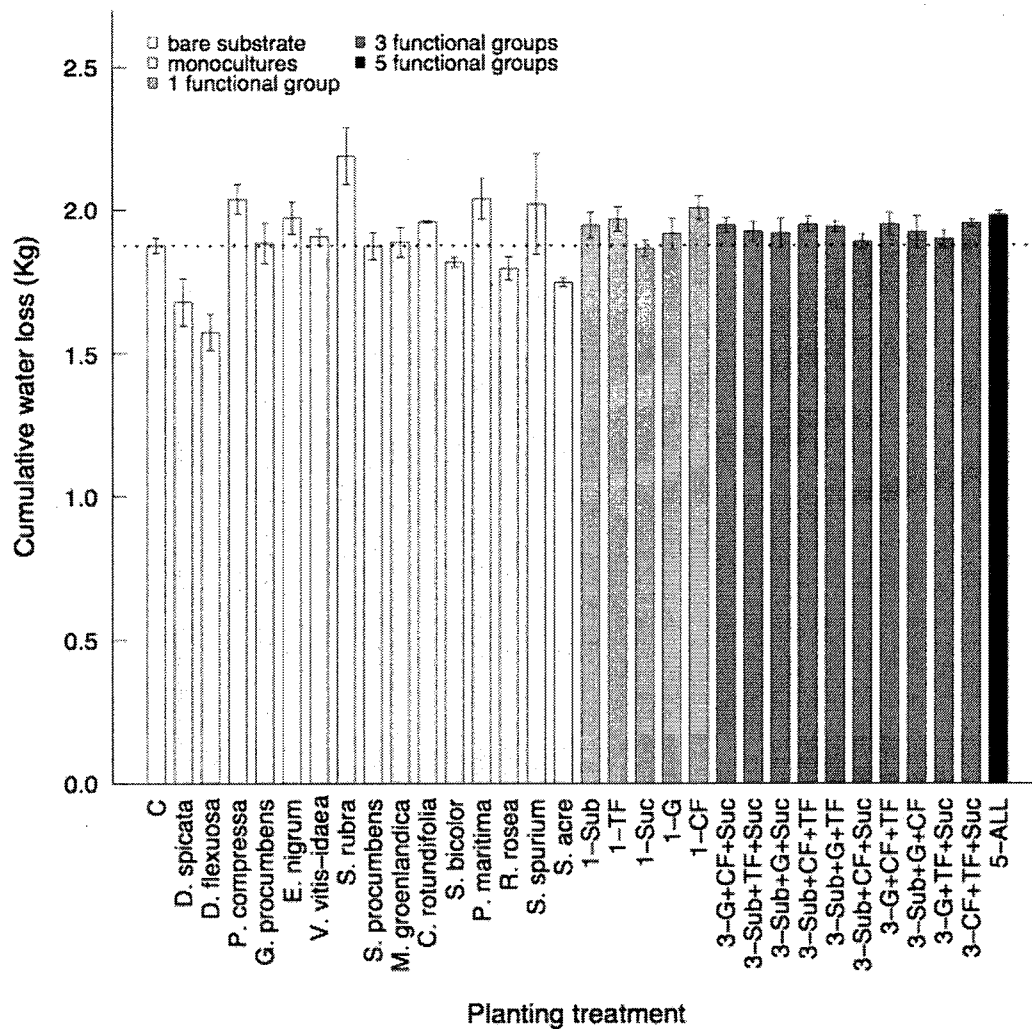
**Fig. 3.** Mean albedo ( $\pm 1$  S.E.) of green roof modules with different functional diversity levels. The bar labeled 'C' represents the bare substrate controls, 'G' represents the grasses, 'CF' represents the ground-covering forbs, 'Sub', the subshrub species, 'Suc', the succulent species, and 'TF', the tall forbs. The '5-ALL' treatment included all five functional groups. The dotted line highlights the average albedo value of the controls.



**Fig. 4.** Mean total water capture ( $\pm 1$  S.E.) of green roof modules with different functional diversity levels. Values represent totals from all 3 rain events sampled. The bar labeled 'C' represents the bare substrate controls, 'G' represents the grasses, 'CF' represents the ground-covering forbs, 'Sub', the subshrub species, 'Suc', the succulent species, and 'TF', the tall forbs. The '5-ALL' treatment included all five functional groups. The dotted line highlights the mean total capture of the bare substrate controls.



**Fig. 5.** Mean total water capture ( $\pm 1$  S.E.) of green roof modules, grouped by block. Values represent totals from all 3 rain events sampled. 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. Block 1 was situated at the westernmost part of the site, and block 5 at the easternmost location.



**Fig. 6.** Mean cumulative water loss ( $\pm 1$  S.E.) of green roof modules with different functional diversity levels. Values represent water loss summed across both rain events sampled. The bar labeled 'C' represents the bare substrate controls, 'G' represents the grasses, 'CF' represents the ground-covering forbs, 'Sub', the subshrub species, 'Suc', the succulent species, and 'TF', the tall forbs. The '5-ALL' treatment included all five functional groups. The dotted line highlights the mean cumulative water loss of the controls.

## **Chapter 4**

### **Native plant evaluation and green roof performance: the influence of composition and richness on ecosystem functions - synthesis**

The goal of this thesis was to explore how the composition of a green roof's vegetation layer can affect some of the many functions performed by green roofs in a maritime city. Specifically, I examined the role of species composition, functional group composition, and functional group richness in: 1) green roof canopy structure, and 2) green roof environmental functions, while also 3) investigating the potential of native coastal barren species by comparing their performance to several common, non-native green roof species. By studying and describing the vegetative properties of multiple species and combinations of functional groups, while simultaneously quantifying the provision of benefits, a relatively comprehensive understanding of how green roof vegetation influences green roof performance was achieved, emphasizing the importance of thoughtful species selection.

Species and functional group composition were found to strongly influence canopy traits. Specifically, based on the vegetative properties favored most by the green roof industry (e.g., survival, extensive coverage, and relatively fast rates of growth), grass and tall forb functional groups were the most effective green roof taxa. Native species such as *D. flexuosa*, *D. spicata*, *S. bicolor*, and *P. maritima* were among the top performers across all canopy characteristics, and showed very high survival rates after the first summer and winter (along with most of the other perennials). The common green roof grass, *P. compressa*, also showed desirable properties (e.g., it was the tallest treatment), highlighting the success of the grass group, and that some common green roof species perform well in different continents. As previously discussed in this thesis, no single species was the 'best' species among all canopy traits. Thus, the canopy trait data suggests that mixtures of even the few species or functional types (especially grasses and tall forbs) with the most desirable characteristics, might be the best option to simultaneously maximize survival, cover, growth rate and height - canopy

characteristics that are thought to, or have been shown to be linked to the functioning of green roofs.

Although the importance of the vegetation layer in green roof functioning (e.g., runoff reduction, rooftop cooling) has often been ignored, this study showed that vegetation does influence green roof performance (substrate temperature reductions, albedo, water capture and cumulative water loss). Water capture (but see the Chapter 3 discussion of the potential flaws in the water capture estimates) and to some extent, cumulative water loss functions seemed to be most affected by planting treatment with planted modules capturing approximately 58% less to 27% more water than the controls, and having cumulative water loss values 16% smaller to 17% greater than the controls. Specifically, through their influence on canopy structure and cover, and presumably also through their connection to plant phenology, leaf characteristics and root growth, both composition and richness influenced the green roof benefits studied here. While increased levels of functional richness optimized some green roof benefits (substrate temperature reductions), more commonly (in terms of albedo, water capture and cumulative water loss), higher levels of richness provided insurance of favorable performance (even if not the best), instead of extremely poor or extremely favorable performance (as in the case of monocultures).

The relative success of planting treatments depended both on functional group, and on species composition (both functional groups and species within functional groups showed variability). In general, the inclusion of grass species, and tall forbs or succulents, was essential to optimize most of the green roof functions studied here, with the best performing treatment (monoculture or mixture) differing among benefits. For example, the *S. rubra* monoculture treatment showed the greatest amount of cumulative water loss while the mixture of grass species had the greatest albedo. Again, most

native coastal barren species examined showed at least equivalent, and for some green roof functions, improved performance compared to the common green roof succulent and grass species tested. Thus, when there is an interest in native plants, the use of most natives (examined here) should not hinder the development of favorable vegetative properties or functional green roof benefits, but instead, the use of natives can enhance them.

In terms of both vegetative properties and green roof performance, Nova Scotian coastal barrens were shown to represent suitable habitats from which to choose green roof candidate species, and the successful native species (especially the grasses and tall forbs) should be considered as valid additions to the palette of (often non-native) species options for cities such as Halifax, NS, and other localities with a similar climate. Further, the success of the habitat template approach to species selection that was seen here, underscores the potential (and need for study) of other natural analogs of green roof habitats, and their associated species, in localities across Canada and abroad.

For constructed ecosystems like green roofs, the composition of the vegetation layer can be manipulated in order to optimize survival, aesthetic appeal and/or environmental functions specific to the locality and particular project. However, optimal performance can become harder to achieve when one is interested in multiple benefits, and over multiple years, making species selection complicated. Further, the opportunity to pre-screen a variety of species monocultures and mixtures, will not always be possible. A valuable finding of this study was that, mixtures of at least three functional groups (especially those including grasses) provided some insurance of favorable performance, across functions. Thus, multiple benefits are more likely to be guaranteed with a diverse planting, especially in the worst-case scenario of an unawareness of the relative performance of different species in an assemblage. Conversely, this study

showed that different treatments (monocultures or mixtures) often optimized different benefits. Thus, in cases where a green roof is being constructed for a single purpose (e.g., considering HRM building owners do not pay a stormwater tax, they may only be interested in optimizing temperature moderation), this study suggests a list of planting treatments to optimize a given function.

It is important to note that different indicators of green roof cooling (e.g., albedo and cumulative water loss) showed different 'best' treatments. This highlights another avenue of investigation worthy of attention, the relative importance of different mechanisms contributing to green roof cooling. Green roofs are thought to provide cooling benefits through the provision of shade, increased albedo (compared to conventional roofing), and through evapotranspiration. However, the treatment with the greatest cover (and presumably shade) was different from the one with the greatest albedo, and different from the one with the greatest cumulative water loss. Knowing the relative importance of canopy architecture and shading, versus albedo, versus evapotranspiration, in rooftop cooling, could influence species and functional group selection, and should therefore, also be examined in future studies.

While this initial investigation into the relationship between green roof vegetation, and canopy traits and functional performance, highlighted the success of the grass and tall forb functional groups (as well as the *S. rubra* and *S. acre* species to some extent), and mixtures that include these plants, it is important to keep in mind the temporal and spatial scales of the study. Results presented here (and in many green roof studies) represent data from a single roof, mostly over a single season. The continuous (including over the winter season), long-term study of the effects of composition and functional group diversity is needed, since these effects on green roof performance will

likely vary with environmental conditions, and as green roof plant communities mature (i.e., overyielding may be seen in future years).

One of the largest barriers to the implementation of green roof technology is financial cost. Green technologies, such as green roofs, often involve higher initial costs that are offset by long-term, economic and environmental gains. While the magnitude of the differences in measured performance among treatments seemed small in this study, when applied on a larger scale (such as a roof-sized plot), and over multiple years, these differences could be large enough to significantly alter the thermal performance of an underlying building (and thereby, the costs of space conditioning), and might also affect a roof's life (by moderating temperature fluctuations). If green roofs are to become more common in North American cities such as Halifax, long-term economic benefits must be shown to outweigh the higher initial costs. Thus, studies similar to this one, that address new means of optimizing green roof performance under local conditions, should serve to accelerate the economic viability of green roof implementation.