The Effect of Green Roof Characteristics on Pollinator Communities

By
Hughstin Grimshaw-Surette

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Approved: Dr. Jeremy Lundholm
Supervisor
Department of Biology

Approved: Dr. Sheila Colla
External Examiner
Department of Environmental Studies
York University

Approved: Dr. Laura Weir
Supervisory Committee Member
Department of Biology

Approved: Dr. Christopher Cutler
Supervisory Committee Member
Department of Plant, Food, and Environmental Sciences
Dalhousie University

Date: April 17, 2020

Abstract

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Abstract: Habitat loss and fragmentation caused by urban expansion are commonly believed to be drivers of insect pollinator decline. Green roofs within urban landscapes are expected to mitigate the effects of urbanization by providing essential food and nesting resources for pollinators in these resource-limited environments. However, not all green roofs are similar and may not provide equivalent habitat value. This research sought to quantify the effect of green roof characteristics such as floral richness, floral display area, height, surface area, and surrounding landscape-level features on the pollinator communities in these systems. Pollinator communities that were surveyed included bees, hover flies, and butterflies. In general, green roof floral richness and floral display area were the strongest predictors of pollinator richness and abundance, while green roof height had a negative influence on pollinator richness. This research outlined key green roof characteristics that promote a diverse and abundant pollinator community in the urban landscape.

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1: Introduction

1.1: Insect Pollinators

Insects such as bees, butterflies, and hover flies provide essential ecological services, including pollinating flowering plants in agricultural and wild ecosystems. It is estimated that 78% of flowering plant species in temperate ecosystems and 94% in tropical ecosystems depend on animal pollination for reproduction (Ollerton et al., 2011). Alarmingly these ecologically and economically significant organisms are under threat and several species are experiencing population declines worldwide (Gallai et al., 2009; Goulson et al., 2015; Potts et al., 2016). Reductions in the abundance and the extinction of these organisms will have severe ecological and evolutionary consequences for plants, food webs, and ecosystem functions (Vanbergen & Insect Pollinators Initiative, 2013).

1.1.1: Insect Pollinator Population Trends

Quantifying the decline of pollinators is difficult due to the lack of population baseline data and the differential vulnerability between species (Colla & Packer, 2008; Potts et al., 2010). Due to domestication, the best quantitative data is for the western honeybee (*Apis mellifera*) (Goulson et al., 2015). However, this is an agriculturally managed species and trends may be more related to socio-economic factors rather than ecological or environmental stressors (Moritz & Erler, 2016). Therefore, declines in managed colonies should be considered a domesticated animal management problem rather than a conservation issue (Colla & MacIvor, 2017). Attempts to assist this species by introducing colonies outside of agricultural systems may have negative effects on native pollinator communities and plant communities by spreading diseases, disrupting pollination systems, and increasing competition (Colla & MacIvor, 2017; Singh et al., 2010).

Butterflies are the most monitored and documented non-pest insect taxon (Thomas, 2016). The majority of this research is limited to Europe with declines being observed prior to 1900's (Habel et al., 2016; Thomas, 2016). Nonetheless, butterfly species decline has also been documented in North America (Pleasants et al., 2013; Swengel et al., 2011). In regard to bee species the most robust population data exists for bumble bees, genus *Bombus*. As of 2017, 44% of known global bumble bee species had been evaluated for extinction risk and one third of these examined species are experiencing population declines (Arbetman et al., 2017). In both Europe and North America rapid decline of bumble bee species region occupancy has been observed (Soroye et al., 2020). Eleven of the twenty-one eastern native North American bumble bee species are believed to have experienced substantial population declines, while eight of twenty-one species are believed to have stable or increasing populations (Colla et al., 2012). Similar results were also found examining eight historically abundant bumble bees in the United States (Cameron et al., 2011). Comparable bumble bee population trends have also been observed in Europe (Fitzpatrick et al., 2007; Goulson et al., 2008; Williams, 1982).

Population data for other wild pollinators are sparse due to the lack of coordinated monitoring and the absence of baseline data (Potts et al., 2010). This data is especially deficient in North America as the majority of studies are conducted in Europe. The IUCN European Red List of Bees published in 2014 assessed all 1965 species of bees native to Europe and determined 56.7% of species did not have sufficient data to assign a population status (Nieto et al., 2014). This study also concluded 9.2% of native European bee species are threatened (Nieto et al., 2014). Biesmeijer et al. (2006) compared national native bee records before and after 1980 to assess population trends. A large fraction of studied 10 km by 10 km cells experienced significant declines in bee richness (Britain: 52% & Netherlands: 67%). This study also noted declines of hover flies. However these shifts were less consistent in comparison to the bee communities (Biesmeijer et al., 2006).

1.1.2: Causes of Pollinator Declines

Insect pollinator declines are understood to be caused by the effects of several stressors (Goulson et al., 2015; Vanbergen & Insect Pollinators Initiative, 2013). Stressors negatively influencing pollinator communities include habitat loss and fragmentation, climate change, agrochemical usage, limited floral resources, invasive species, parasites and pathogens (Goulson et al., 2015; Vanbergen & Insect Pollinators Initiative, 2013).

Habitat Lost and Reductions in Floral Resources

A meta-analysis examining 54 published studies found that extreme habitat alteration had a significant negative effect on wild bee species richness abundance (Winfree et al., 2009). Pollinators such as bees require habitat that encompasses both diverse nesting and floral resources in close proximity (Kearns & Oliveras, 2009). The alteration and degradation of native habitat to intensive agricultural lands and urban areas reduce the availability and diversity of these floral and nesting resources (Vanbergen & Insect Pollinators Initiative, 2013). It is important to note that due to differing foraging traits species are affected differently. Insect pollinators that exhibit specialism or have limited flight ranges are the most severely impacted by habitat loss and fragmentation (Biesmeijer et al., 2006; Williams & Osborne, 2009). This can alter plant and pollinator relationships and the extinction of species on a local and regional scale (Burkle et al., 2013).

Agrochemicals, Invasive Species, and Pests

The conversion of native habitat into intensive agricultural land also introduces agrochemicals, invasive species, and pests (Goulson et al., 2015). Agrochemicals such as pesticides are the most controversial stressor affecting pollinator decline due to their clear economic benefits (Goulson et al., 2015). A commonly used pesticide under scrutiny for its negative effects on pollinators are neonicotinoids (Woodcock et al., 2016). Neonicotinoids are systemic and are transported through the plant into the pollen and nectar at trace levels (Woodcock et al., 2016). Despite the low concentration of the insecticide, negative effects on pollinators have been observed such as reduced wild bee density, reduced solitary bee nesting, decreased bumble bee colony growth, learning and memory loss, reduced reproduction, and impaired navigation abilities (Fischer et al., 2014; Laycock et al., 2014; Rundlöf et al., 2015; Sandrock et al., 2014; Stanley et al., 2015; Whitehorn et al., 2012; Woodcock et al., 2017). Other studies have also failed to show a significant effect of some neonicotinoids on wild pollinators (Laycock et al., 2014; Piiroinen et al., 2016).

Non-native pollinators such as honeybees may create competitive pressures for native bees for nectar and pollen resources (Thomson, 2006; Vanbergen & Insect Pollinators Initiative, 2013). Honeybees form large colonies and a normal farm apiary of 40 hives gathers enough nectar and pollen to sustain 4 million solitary bees (Cane & Tepedino, 2017). The presence of honeybees in ecosystems can reduce native bee abundance, alter floral interactions, and reduce native bee worker size (Forup & Memmott, 2005; Goulson & Sparrow, 2008; Hudewenz & Klein, 2013). The introduction of non-native pollinators can also lead to disease and pest spillover into native pollinator populations leading to population declines (Cameron et al., 2011; Singh et al., 2010).

Climate Change

Climate change is expected to have a negative influence on pollinator and plant relationships by altering phenologies and ranges (Goulson et al., 2015; Soroye et al., 2020). In addition, interactions between climate change and other stressors is predicted to accelerate biodiversity loss (Soroye et al., 2020). In both Europe and North America bumble bee extirpation rates have shown to increase in relation to temperatures that surpass historical tolerances (Soroye et al., 2020). These changes in climatic conditions are shifting bumble bee ranges (Kerr et al., 2015). A multi-continental study examining Europe and North America found bumble bees are not expanding northwards as their southern ranges are diminished from increasing temperature. This significantly constricts the range of bumble bee species (Kerr et al., 2015).

Mismatching phenologies can lead to de-synchronization between pollinator adult flight emergence and flowering time (Willmer, 2012). However, current evidence suggests the shifts in phenologies are changing at a similar pace and effects may be less than originally feared (Bartomeus et al., 2011). Additionally, if high levels of biodiversity are maintained it will help buffer the effects of the altered phenologies (Bartomeus et al., 2013).

1.2: Pollinators in the Urban Environment

Urbanization is commonly associated with biodiversity degradation due to the destruction and alteration of native habitat and is argued as a major influence for pollinator decline (Mcdonald et al., 2008; Winfree et al., 2009). However, there is increasing evidence that urban landscapes can support diverse pollinator communities (Baldock et al., 2015; Fortel et al., 2014; Sirohi, Jackson et al., 2015; Winfree et al., 2009). Urban landscapes are commonly associated with high values of plant species richness and increased temperatures, which are both positively correlated with pollinator richness and abundance (Fischer et al., 2016; Grimm et al., 2008). Additionally, urban and suburban landscapes can provide an important refuge for pollinators away from the pressures such as herbicides and pesticides which are associated with intensive agriculture systems (Hall et al., 2017).

Urban areas have been documented to support both an equal and greater species richness of pollinators in comparison to neighboring rural and natural areas (Baldock et al., 2015; Martins et al., 2017; Sirohi et al., 2015). However, urban areas have also been observed to support lower values of pollinator species richness and abundance (Bates et al., 2011; Hernandez & Frankie, 2009; Winfree et al., 2009). The contradictory results of these studies may be caused by differing intensities of urbanization, varying abiotic and biotic factors, and the significant differences between cities (Matteson et al., 2012; Winfree et al., 2009). Evidence suggests that intermediate levels of urbanization are optimal for supporting species rich pollinator communities and higher levels of urbanization may result in a significant loss in species richness (Fortel et al., 2014; Winfree et al., 2009).

Several biotic and abiotic factors that affect the viability of urbanized areas to support a species rich and abundant pollinator community have also been identified (Matteson et al., 2012). The availability of floral and nesting resources in urban areas have been well documented as strong determinants of pollinator richness and abundance (Blackmore & Goulson, 2014; Hennig & Ghazoul, 2012; Hülsmann et al., 2015; Matteson

& Langellotto, 2010; Wojcik, 2011), while the area of impervious surfaces and shade from adjacent buildings have a negative effect (Ahrné, Bengtsson, & Elmqvist, 2009; Matteson & Langellotto, 2010). There are also expected “winners” and “losers” of urbanization due to varying life history and morphological traits (Fischer et al., 2016; Hülsmann et al., 2015; Matteson et al., 2008). This can alter pollinator community composition favoring generalists and non-natives in the urban environment (Hernandez & Frankie, 2009; Matteson et al., 2008).

1.3: Green Roofs

Researchers examining urban pollinators have argued that the reduction of floral richness and the alteration of floral composition associated with increased levels of urbanization have stronger influences than urbanization itself (Hülsmann et al., 2015; Wojcik, 2011). This implies that with proper management of urban green spaces, urban areas especially areas with intermediate urbanization have the potential to support a species rich and abundant pollinator community (Ahrné et al., 2009; Davis et al., 2017). However, due to the constant pressures from development, open space for habitat restoration is limited and green spaces are typically restricted to small fragmented patches (Ishimatsu & Ito, 2011). Unoccupied space with the potential for increasing green space in urban areas includes the rooftops of buildings (Ishimatsu & Ito, 2011). The land coverage of roofs within urban areas can represent up to 32% of the landscape (Frazer, 2005). The implementation of vegetated rooftops is one viable technique to increase urban green space and increase the surface area of floral and nesting resources available to pollinators (Ahrné et al., 2009; Berardi et al., 2014; Colla et al., 2009). Additionally, the construction of these habitats on rooftops minimizes the influence of shade from neighboring buildings, which has been negatively linked with bee richness for ground-level urban gardens (Matteson & Langellotto, 2010). These rooftops are commonly known as green roofs, eco-roofs, or living roofs (Berardi et al., 2014).

Green roofs are ecologically engineered rooftops that are partially or completely covered in vegetation and growing media (Oberndorfer et al., 2007). These roofs are constructed on the top of buildings for the ecosystem services they provide (Berardi et al., 2014). These services include storm water management (Mentens et al., 2006; Stovin et al., 2012; Zhang et al., 2015), increased roof albedo (Getter & Rowe, 2006), reductions in heat flux (Getter et al., 2011; Scherba et al., 2011), habitat for biota (Baumann, 2006; Kadas, 2006; MacIvor & Lundholm, 2011), air quality control (Luo et al., 2015; Yang et al., 2008), noise insulation (Van Renterghem & Botteldooren, 2011), and prolonging roof membrane life (Teemusk & Mander, 2009).

Green roofs are commonly classified into two distinct types: extensive and intensive green roofs (Berardi et al., 2014; Oberndorfer et al., 2007). An extensive green roof is defined by a shallow substrate with a depth < 20 cm and intensive green roofs are defined by a deeper substrate at a depth > 20 cm (Berardi et al., 2014). The implementation of one roof type over the other has trade offs. Due to the shallow substrate that defines extensive green roofs, they have a lower construction cost (Berardi et al., 2014). However, they have lower energy performance, storm water management potential, and support lower values of plant diversity (Berardi et al., 2014; Mentens et al., 2006). The shallow substrate exposes plant communities to harsh environmental conditions such as drought and flooding (Oberndorfer et al., 2007). Therefore, only drought tolerant species and low growing plants can endure. The greater depth of intensive green roofs allows for the establishment of a more diverse plant community. Plant communities are only restricted by climate, building height, substrate depth, and irrigation (Oberndorfer et al., 2007). The deeper substrate also allows for greater water retention and increased insulation capabilities (Berardi et al., 2014). The consequence of a deeper substrate is increased weight and cost (Berardi et al., 2014).

Green roofs are commonly adapted into building design for the energy related benefits (Berardi et al., 2014). More recently, researchers have emphasized that green roofs have the potential to provide valuable habitat in urban areas (Benvenuti, 2014; MacIvor & Lundholm, 2011; Oberndorfer et al., 2007). However, the extent to which green roofs can support urban biodiversity conservation remains relatively unknown (Lepczyk et al., 2017; Williams et al., 2014). Organisms are exposed to high levels of solar radiation, high wind speeds, intense drought, and flooding that exceed values associated with adjacent ground-level habitat (Oberndorfer et al., 2007). More research examining urban landscape connectivity, the persistence of fauna and flora populations over extended periods of time, and direct contrasts between green roof and ground level biodiversity is needed (Lepczyk et al., 2017; MacIvor & Lundholm, 2011; Williams et al., 2014).

1.3.1: Green Roof Pollinator Communities

A limited number of studies have directly compared pollinators foraging on rooftops and ground level habitats. These studies are limited to bees (Colla et al., 2009; Ksiazek et al., 2012; Tonietto et al., 2011; Walker, 2016) and butterflies (Lee & Lin, 2015). Colla et al. (2009) indicated that green roofs surveyed in their study were able to support bee communities compositionally similar to ground-level green space. However, green roof bee communities had lower diversity, richness, and abundance (Colla et al., 2009). Tonietto et al. (2011) and Ksiazek et al. (2012) both found fewer bees foraging on Chicago green roofs in comparison to ground level habitat. Results from the Tonietto et al. (2011) study indicated prairie habitat was significantly more species rich in comparison to green roofs. However, no significant difference was observed between green roofs and urban parks. In Tonietto and colleague's (2011) study pollinator communities were significantly different between habitat types. Prairie habitat supported the greatest quantity of native bee species (97% native), urban parks were slightly lower (94% native), and green roof sites had the lowest representation (74% native; Tonietto et al., 2011). Walker (2016) observed green roofs supporting a lower abundance and richness of native bees in comparison to ground level habitats as well. Similar results have been found when examining butterflies on eleven green roofs in Taipei, Taiwan (Lee & Lin, 2015). Butterfly richness and abundance was lower on green roofs in comparison to ground-level city parks. Common butterfly species were very abundant on the studied green roofs. However, some uncommon species were also observed (Lee & Lin, 2015).

These studies demonstrate the general trend that species richness and abundance may be lower on green roof systems in comparison to ground-level habitat (Colla et al., 2009; Ksiazek et al., 2012; Lee & Lin, 2015; Tonietto et al., 2011; Walker, 2016). However, these green roofs systems ecosystems still provide important resources for many pollinator species especially if ground level habitat is not present.

1.3.2: Influence of Site and Landscape Characteristics on Green Roof Pollinator Communities

Several site and landscape characteristics have been documented to influence the species richness and abundance of pollinator communities utilizing green roof habitat (Kratschmer et al., 2018; Lee & Lin, 2015; MacIvor, 2015; Tonietto et al., 2011). These characteristics include adjacent ground level green space quality and quantity (Tonietto et al., 2011), green roof height (MacIvor, 2015), surface area of nectar plants (Kratschmer et al., 2018; Lee & Lin, 2015), substrate type and depth (Kratschmer et al., 2018), age (Kratschmer et al., 2018; Lee & Lin, 2015), and plant richness (Kratschmer et al., 2018; Tonietto et al., 2011).

Landscape Features

Similar to ground level pollinator studies in urban environments, the urban landscape surrounding green roofs can influence pollinator species richness and abundance (Braaker et al., 2014; Braaker et al., 2017; Hennig & Ghazoul, 2011; Tonietto et al., 2011). Connectivity with surrounding habitat may be especially important for pollinating insects such as bees and has a stronger influence on green roof communities in comparison to communities at urban ground level (Braaker et al., 2014; Braaker et al., 2017). In urban environments, it is rare for one small habitat patch to be sufficient to provide both nesting and adequate food resources for pollinators (Hernandez & Frankie, 2009). Surrounding green space can positively influence both richness and abundance of bee communities on green roofs (Tonietto et al., 2011). Additionally, green space quality also has an influence on bee communities (Tonietto et al., 2011). Interestingly, Lee and Lin (2015) found that abundance of butterflies visiting green roofs was not influenced by surrounding ground level green space. Other features of the landscape may have a negative effect on pollinator communities visiting green roofs in urban landscapes. While the availability of water is essential for the survivability of many insect pollinators, large water bodies especially saltwater bodies are devoid of pollinator resources in the landscape (Michener, 2007). However, evidence suggests the presence of large water bodies within the landscape may have no significant influence on the richness of the pollinator community (Power et al., 2012; Tonietto et al., 2011). Nonetheless, it is an important feature to include in landscape analyses. Another feature that may negatively affect pollinator communities is the area of impervious surfaces area and has been shown to reduce bumble bee richness (Ahrné et al., 2009).

Green Roof Abiotic Characteristics (Height, Surface Area, Age, Substrate)

Green roof height may also have an influence on richness and abundance of green roof pollinator communities. Green roofs constructed at greater heights may exhibit vertical isolation from ground-level habitat and limit access to some species of bees (MacIvor, 2015). Only two studies have examined this phenomenon and reported contrasting results (Kratschmer et al., 2018; MacIvor, 2015). MacIvor (2015) examined cavity nesting bees on green roofs in relation to nesting success and found a decrease in nests and an increase in abandoned nests as green roof height increased (MacIvor, 2015). Kratshmer et al. (2018) found building height did not negatively alter the bee community but bee size did decrease with height. Research examining butterflies also indicated green roof height had no statistically significant effect on the abundance of butterflies visiting green roofs (Lee & Lin, 2015). Nonetheless, green roof height must be considered if these systems are to be constructed for pollinator resource provisions.

The size of the green roof can also influence pollinators communities (Madre et al., 2013; Wang et al., 2017). A significant positive correlation between the size of the green roof and species richness has been documented (Madre et al., 2013; Wang et al., 2017). This phenomenon can be explained by the species-area relationship, which states the species richness of a given area tends to increase with increases in area (Connor & McCoy, 1979; Madre et al., 2013)

Green roof substrate may also influence richness and abundance of bee communities present on green roofs due to the requirements of ground nesting species (Kratschmer et al., 2018). In Kratschmer and colleague's (2018) study, green roofs with fine substrate had the highest mean wild bee richness. These fine substrate green roofs had a stronger positive correlation with bee richness and abundance in contrast to coarse substrate green roofs. However, green roofs categorized as having fine substrate also had the highest amount of floral resources. This suggests the relationship may be caused by the improved floral resources rather than the substrate type. This study also examined substrate depth and found a positive relationship with ground nesting wild bee species and increased depth (Kratschmer et al., 2018).

Green roof age has not been found to significantly affect bee communities (Kratschmer et al., 2018). However, green roof age has been found to significantly affect butterfly abundance (Lee & Lin, 2015). As the age of the green roof increased, there was an increase in the number of butterflies surveyed. Butterfly abundance gradually increased until 38 months, after which it remained constant (Lee & Lin, 2015).

Green Roof Floral Community

Quantity and species richness of floral resources can affect green roof pollinator communities (Kratschmer et al., 2018; Lee & Lin, 2015; Tonietto et al., 2011; Wang et al., 2017). Butterfly abundance is positively correlated with area of nectar producing plants on green roofs in Taipei City, Taiwan (Lee & Lin, 2015). Similarly, in Vienna, Austria green roof flower coverage was positively correlated with bee species richness and abundance (Kratschmer et al., 2018). Species richness of entomophilous plant species is believed to positively influence pollinator richness and abundance on green roofs (Kratschmer et al., 2018; Lee & Lin, 2015; MacIvor et al., 2014; Madre et al., 2013; Tonietto et al., 2011; Wang et al., 2017). The number of spontaneously colonized plant species, in particular, may strongly influence species richness and abundance of the green roof pollinator community, as it was found to be the best predictor of green roof butterfly communities (Wang et al., 2017). This study found plant species that spontaneously colonized green roofs were better predictors of the butterfly richness and abundance in comparison to purposively planted species richness (Wang et al., 2017). Spontaneous plant species increases overall floral richness of the plant community and has been determined to provide valuable resources in ground level habitats (Benedek 1972; Lagerlöf et al., 1992; Nicholls & Altieri, 2012; Robinson & Lundholm, 2012; Sivakoff et al., 2018).

In ground level ecosystems it is well understood that pollinator species richness is positively correlated with floral richness (Ebeling et al., 2008; Hegland & Boeke, 2006; Potts et al., 2004). Diverse floral patches provide increased pollen and nectar resources for extended periods of time, compliment pollinator specialism, and provide a greater diversity of pollen and nectar resources for pollinator species seeking multiple or specific plant species (Blüthgen & Klein, 2011; Ebeling et al., 2008; Potts et al., 2004). However, this important relationship has not been exclusively studied on green roofs in North America. While Tonietto et al. (2011) observations stressed the importance of floral species richness on the Chicago pollinator community, the number of green roofs examined was limited to six roofs. It is essential to understand this relationship due to the high proportion of green roofs that are propagated with low diversity *Sedum* monocultures (Oberndorfer et al., 2007). Empirical evidence in North America suggests these roofs may disproportionally benefit exotic bee species in comparison to native species, consequently altering pollinator communities (MacIvor et al., 2014). This stresses the importance to survey the pollinator communities visiting low species rich green roofs such as *Sedum* roofs and comparing these communities to green roofs established with high values of plant species richness.

Thesis Objectives

The influence of green roof characteristics on pollinator richness and abundance is poorly understood. With the increase in green roofs in urban areas, especially those with low levels of floral species richness, it is important to fill these knowledge gaps. One significant gap in knowledge is the influence of entomophilous plant species on pollinator communities. Current evidence suggests that floral resource availability and species richness may be important drivers of green roof pollinator richness and abundance. However, to my knowledge, a study examining this relationship has not been conducted in North America. Additionally, an important group of pollinators, hover flies (Family Syrphidae) have not been examined in a green roof environment. The two main objectives of this thesis were:

(1) Examine the influence and effect size of green roof characteristics on the richness, abundance, and community composition of three different insect pollinator groups (bees, hover flies, and butterflies). Site characteristics examined included the total richness of flowering plant species present on the green roof, spontaneously colonised species richness, planted species richness, surface area of flowering plant species on the green roof, green roof height, and total surface area of the green roof. Landscape features that were examined included the proportion of green space, natural space, and saltwater within a 500 m radius of the green roof. The influence of green roof floral species richness and surface area on insect pollinator communities will be the focal point of this study due to the novelty. The results from this thesis will provide a framework that outlines important green roof characteristics for supporting diverse pollinator communities in urban areas.

I hypothesize that green roofs with greater floral richness will support greater pollinator richness and abundance throughout the study period. The surface area of floral displays should have a positive relationship with pollinator abundance. My third hypothesis is that green roof height will negatively influence the richness and abundance of green roof pollinator communities. I expect that the total green roof area will have a positive relationship with pollinator abundance and pollinator richness. I hypothesize that greater values of adjacent ground level green space and natural space will have a positive effect on pollinator richness and abundance. My final hypothesis is that the area of saltwater within a 500 m radius of the green roof will negatively influence the richness and abundance of the green roof pollinator communities.

I hypothesize that floral characteristics will have the strongest effect on green roof pollinator communities. I also hypothesize that spontaneous floral species richness will be a stronger positive predictor of the pollinator community in contrast to planted species richness.

(2) My second objective is to provide a survey of pollinator communities utilizing green roofs in Halifax and Dartmouth. Additionally, I want to identify what entomophilous plant species are present on these green roofs. A green roof pollinator and plant survey at this scale has not been conducted in this region of Canada. Research examining pollinators on green roofs in Canada is mostly conducted in Toronto. It is important to study Eastern Canadian pollinator communities on green roofs due to the different climatic conditions, different pollinator communities and the large number of green roofs in this region.

2: Methods

2.1: Study Location

Insect pollinators were collected on 18 green roofs located in Halifax Regional Municipality, Nova Scotia, Canada (See Table 1 and Figure 1). Green roofs were chosen to encompass a range of sites with varying levels of plant species richness and building height. Halifax is a port city on the Atlantic Ocean with a population just over 316, 000 (Statistics Canada, 2016). Halifax has an Atlantic Canada/Maritime climate with warm summers and cool winters, a yearly rainfall of 1468 mm, and daily average maximum/minimum temperatures of 19.1 °C and – 4.1°C (Environment Canada, 2019). The average temperature in Halifax during the study's duration was 17.0°C and the total precipitation was 450.1 mm (Environment Canada, 2017).

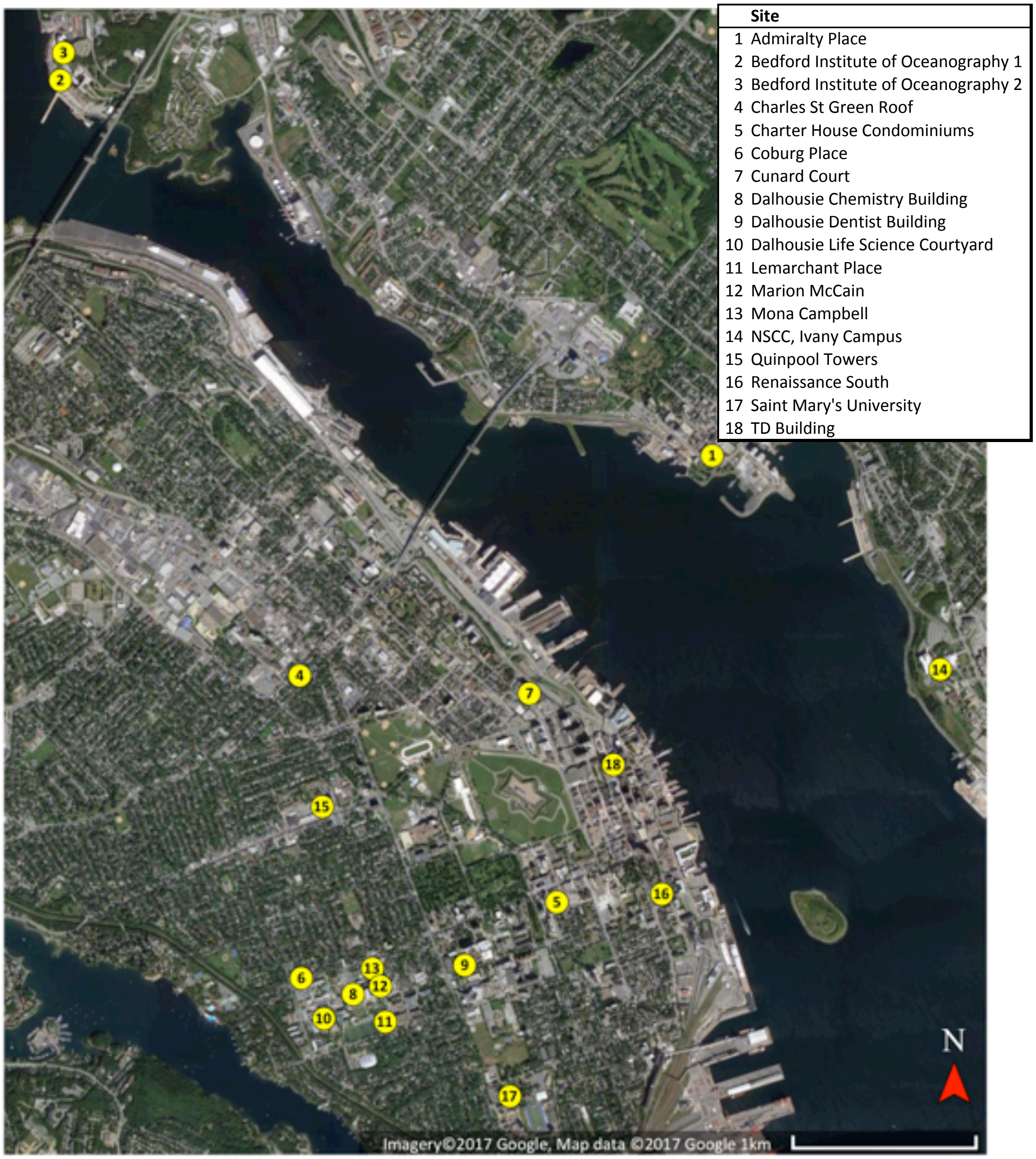

Figure 1. Distribution of green roofs (yellow circles) surveyed in the Halifax Regional Municipality, Nova Scotia, 2017. Map was created using Google Earth.

Table 1. Green roof sites from which pollinator communities were surveyed in and around Halifax, Nova Scotia, 2017. Detailed site location can be found in appendix table A1. Extensive green roofs (E) were defined as roofs with a substrate depth ≤ 20 cm and intensive roofs (I) were defined as > 20 cm. Sun exposure is only related to the duration of bowl surveys (09:30 – 15:30).

Site	**Location**	**Type**	**Age (yrs)**	**Veg. Description**	**Site Features**
Admiralty Place	Prince St.	I	>14	Rooftop ornamental garden	Full sun except early morning, north and east sides protected by building
Bedford Institute of Oceanography1	Baffin Blvd.	E	>14	Dominated by spontaneous veg.	Full sun except late afternoon, west side protected by building
Bedford Institute of Oceanography2	Challenger Dr.	E	3 - 0	Turf roof	Full sun and fully exposed to harbour
Charles St Green Roof	Charles St.	E	4 - 14	Dominated by spontaneous veg	Minimal sun, protected by tree canopy
Charter House Condominiums	Brenton St.	I	>14	Rooftop ornamental garden, small birch trees	Full sun, north side protected by building
Coburg Place	Coburg Rd.	E	>14	Turf roof	Full sun except early morning, east side protected by building
Cunard Court	Brunswick St.	I	>14	Small ornamental gardens, turf, pine trees	Partially shaded, one side at ground level, harbour side exposed
Dalhousie Chemistry Building	Coburg Rd.	I	>14	Dominated by spontaneous veg	Full sun, north side one story above ground level
Dalhousie Dentist Building	University Ave.	I	>14	Small ornamental gardens, turf, deciduous trees	Partially shaded, surrounded by buildings
Dalhousie Life Science Courtyard	Oxford St.	I	>14	Dominated by spontaneous veg., pine tree	Full sun, surrounded by buildings, soil ramp leads to green roof
LeMarchant Place	LeMarchant St.	E	3 - 0	*Sedum* roof	Full sun except early morning, north, east, and south sides surrounded by building
Marion McCain	University Ave.	E	>14	Small ornamental garden and turf, deciduous tree	Full sun, surrounded by buildings
Mona Campbell	LeMarchant St.	E	4 - 14	*Sedum* roof	Full sun except partially shaded early morning, north and east side protected by building
NSCC, Ivany Campus	Mawiomi Pl.	E	4 - 14	Native plantings, ornamental plantings, and *Sedum* mats	Full sun, late afternoon partial shading, north side protected by building.
Quinpool Towers	Quingate Pl.	E	>14	Small vegetable garden and turf	Full sun except early morning, north and east side protected by building
Renaissance South	Barrington St.	E	>14	Rooftop garden	Full sun, north, east, and west sides surrounded by building
Saint Mary's University	Robie St.	E	4 - 14	Native coastal barrens species	Partial shaded, west side protected by building
TD Building	Barrington St.	E	3 - 0	*Sedum* roof	Full sun, north side protected by building

2.2: Pollinator Surveys

Targeted insect pollinators for this study included bees (superfamily Apoidea), hover flies (family Syrphidae), and butterflies (order Lepidoptera). These pollinator assemblages were chosen because they are ecologically important and attractive to the public (Campbell & Hanula, 2007). Green roof pollinator communities were sampled once a month from 2 June 2017, until 29 September 2017. Approximately one week separated each sample month. Green roofs were sampled June 2 – 25, July 4 – 27, August 7 – 29, and September 8 – 29. All study sites except the green roofs located at the Bedford Institute of Oceanography were sampled each month. Sampling at the Bedford Institute of Oceanography green roofs was delayed to the beginning of July because permission to access the property was not granted for the month of June. To maximize pollinator capture and minimize the influence of weather, pollinators were sampled on sunny days with a temperature above 15°C. Green roofs were not surveyed the same day as green roof maintenance. If lawn maintenance occurred during the sample day, samples from that day were omitted from analyses and the green roof was resampled another day.

Two methods were used to collect insect pollinators: hand netting and bowl traps. Use of two methods help correct for sampling biases implicitly associated with each method. That is, bowl traps tend to underrepresent larger pollinators such as bumble bees and hand netting tends to underrepresent smaller insects because they can be difficult to see (Roulston et al., 2007).

At each site, pollinators were hand netted for two 30 - min sessions within a single day. Morning sample sessions occurred between 10:00 – 12:00 and afternoon sessions occurred between 13:30 – 15:30. Weather and temperature at the time of surveying were documented. For every sample session, the same two surveyors patrolled the green roof only capturing insect pollinators that landed on flowers. Sampling effort between the surveys was equal. Captured pollinators were given a unique identifier and the visited flower species was recorded. Pollinators were kept in vials and at the end of the collection day placed in a freezer for euthanization. This sampling regime was followed at each site for every sample month. Pollinators were collected across the entire green roof rather than within plots due to the extreme heterogeneity of some of the roofs examined. Some green roofs included significantly different plant communities such as graminoid dominated lawns and dense floral gardens. Therefore, sampling pollinators within plots that only comprised a portion of these heterogeneous green roofs would have failed to represent the whole pollinator community visiting the green roof.

A cordless Shark™ vacuum with a custom made attachment for capturing pollinators was used instead of hand nets to avoid damaging plants on green roofs with rooftop gardens (Figure 2). The vacuum was used by one surveyor during the hand netting sessions while the other surveyor used a hand net to capture pollinators on plants that did not require additional protection. The original nozzle was removed from the vacuum and a 7/8" (inner radius) chlorinated polyvinyl chloride (CPVC) pipe was used to increase the length of the nozzle. Using epoxy resin the CPVC pipe was mounted to a 3 mm thick polypropylene plate. A sheet of 2 mm ethylene vinyl acetate (EVA) foam was glued to the bottom polypropylene plate to form a seal with the vacuum. The attachment was then secured with screws to the end of the vacuum. To prevent pollinators from being sucked into the vacuum, a clear chamber was inserted into the end of the CPVC pipe. The chamber was constructed from a clear vinyl tube with an outer radius of 7/8". Using epoxy resin, a fine mesh was attached to one end of the tube. The mesh end of the chamber was then inserted into the end of CPVC pipe. No adhesive was used. Friction held the chamber in securely. This allowed the chamber to be easily removed. When the vacuum was turned on the pollinator was sucked to the back of the clear chamber against the mesh. The specimen was immediately transferred to a vial to prevent escape and minimize damage.

Figure 2. Modified cordless vacuum used to collect pollinators visiting ornamental plants that could not be damaged.

Bowl traps were placed on the green roof at 09:30 (± 15 min) and were active for 6 h. Due to limited access and the high residential activity of some of the green roofs leaving the bowl traps for a longer duration was not feasible. Bowl traps were constructed from 3 1/4 oz Solo cups and spray painted satin white, fluorescent yellow, and satin oasis blue. Fifteen bowl traps, five of each color, were placed evenly across the green roof at an equal distance apart. The distance between bowls was dependent on green roof size with some of the larger roofs having bowls separated by ~ 7 m. On smaller green roofs bowls were placed no less than one meter apart to reduce competition between bowls. Different colored bowls were placed to avoid clumps of the same color. Bowls were placed directly on the green roof and in direct sunlight. If the vegetation of a green roof concealed the bowls, metal rods were used to raise the bowls to the same height of the vegetation and into direct sunlight. Once placed on the roof the bowls were filled 3/4 full with soapy water. One squirt of Blue Original Dawn soap (approximately 10 ml) was added to 1 L of water to create the soapy water. Pollinators collected from bowl traps were transferred to vials containing 70% isopropanol and stored at room temperature until pinning.

2.3: Quantifying Green Roof Site and Landscape Characteristics

Green roof site characteristics that were quantified included floral richness, floral resource surface area, green roof surface area, and green roof height. Examined landscape features within a 500 m radius of the green roof included saltwater, natural space, and green space.

Floral Variables

The floral richness and floral area were quantified on the same days as pollinator surveys. To quantify green roof floral richness, the number of all plant species in flower at the time of sampling was recorded. These plants were all identified to species with the exception of a few species that were identified only to genus. Graminoids and conifers were excluded from floral richness because they are mainly wind pollinated. The Go Botany dichotomous key created by New England's Wild Flower Society/ Native Plant Trust and "Roland's Flora of Nova Scotia" written by Zinck (1998) were used to identify the flowering plant species, with additional assistance from Dr. Jeremy Lundholm and Katie Porter. An estimate of the percent cover of floral display was used to provide an approximate quantity of floral resources available to pollinators on the green roof. To quantity floral display area a 1x1 m quadrat was randomly placed on the green roof.

Percent cover of total floral display within the quadrat was then visually estimated. This was replicated ten times at each green roof for every pollinator sample session. Several green roofs encompassed distinctly different plant communities, such as gardens and turf communities. For these green roofs, the number of replicates conducted in each area was determined by the ratio. For example, if a garden comprised approximately 40% of the total green roof area, four replicates were conducted on the garden and the remaining six replicates on the lawn. The quadrat used was divided into equal sections to increase the accuracy of the percent cover estimation. For quadrats with less than 1% but greater than 0% floral cover, the value was reassigned as 0.5%.

Site and Landscape Variables

Green roof surface area was calculated by measuring the dimensions of the green roofs using a tape measure and overlaying these dimensions on images extracted from Google Earth Pro version 7.3.2. If the building manager provided the building plans, they were used instead. Green roof height was visually assessed on site and the number of floors above ground level was determined for each green roof. Green roofs were considered to be zero stories high if one side of the green roof was at ground level.

Some insect pollinators can travel large distances when foraging for food and provisions (Gathmann & Tscharntke, 2002). Due to this mobility, urban pollinator studies have found landscape features such as green space to influence pollinator communities (Hernandez & Frankie, 2009; Tonietto et al., 2011). Therefore, landscape variables were incorporated into this study. Landscape variables examined included percent cover of green space, natural space, and saltwater bodies within a 500 m radius of the green roof. Saltwater bodies were assessed in this study because Halifax is a port city and some green roof sites were in close proximity to the harbor. A radius of 500 m was chosen for landscape variables to accommodate the foraging distances of wild bees (Gathmann & Tscharntke, 2002; Tonietto et al., 2011). The foraging range of bees is species dependent. Smaller species have a more limited foraging range of only a few hundred meters while larger species can forage over greater distances (Gathmann & Tscharntke, 2002). The 500 m radius accommodates both of these foraging distances.

Percent cover of landscape variables was visually calculated using imagery from Google Earth Pro version 7.3.2. Circles with a radius of 500 m were drawn using the ruler function. The surface area of the landscape variables was then visually estimated within the circles. Due to the significant amount of tree cover along the streets in the south end of Halifax, green space within a 500 m radius was difficult to estimate visually. For this landscape variable, smaller circles with a radius of 250 m were placed in upper, lower, right, and left halves of the larger 500 m radius circle. Percent cover was estimated individually for each of these smaller circles and an average was calculated for each green roof. This average represented an estimation of the percent cover of green space within a 500 m radius of the green roof. For the percent cover of saltwater bodies and natural space, the 500 m radius circle was divided into even proportions to allow for a better estimation of the surface area. Natural space was defined as urban grass fields or urban forests that were not heavily managed and excluded turf dominated green space and street tree canopy.

2.4: Pollinator Preparation and Identification

Pollinators captured by net were stored in a freezer and pollinators captured in bowl traps were stored in a 70% isopropanol solution at room temperature until pinning. Butterflies captured in bowl traps were pinned immediately to reduce damage to the specimens. All bee specimens were cleaned following the procedures outlined in Sam

Droege's (2015) "The Very Handy Manual: How to Catch and Identify Bees and Manage a Collection." However, to increase efficiency a vortex mixer was used instead of cleaning the specimens by hand. Bee specimens were placed individually in 50 ml centrifuge tubes containing soap and water. The vial was placed on a vortex mixer for 30 s or until pollen was completely removed. The bee was then transferred to a vial containing water and the procedure was repeated to remove soap residue. Afterwards, the specimen was placed in a clear chamber with a mesh top and bottom, and small balls of paper towel. A hair drier was used to dry the bee until the desired level of fluffiness was reached. Fly specimens belonging to the genus *Eristalis* were constantly covered in pollen due to their significant amount of hair. These specimens were cleaned following the same procedures as the bees.

Specimens that were left in the freezer for over 2 months became too stiff for the cleaning process. To relax specimens, they were placed in a hydration chamber. The hydration chamber was constructed from a large sealed tupperware container that was filled with hot but not boiling water. Specimens were individually inserted into labeled wax paper envelopes, which were then placed into a second Tupperware container. This second container had several holes in the sides and floated on top of the hot water. The second container allowed the moisture to reach the specimens but prevented water from soaking the specimens. Water was replaced every 24 h and specimens were removed once they were relaxed. Hover flies that are stored in isopropanol alcohol for extended periods of time can have their exoskeleton collapse after being air-dried and this can impede identification (OHara, 1994). To prevent exoskeleton collapses hover flies were placed in 100% ethyl acetate for 4 h and larger specimens overnight (OHara, 1994). These specimens were patted dry and then pinned. Some coloration of the exoskeleton was lost from this process.

All bee specimens were identified to species with the exception of some of the more difficult groups. These groups included *Lasioglossum* subgenus *Dialictus*, genus *Nomada,* and genus *Sphecodes.* For each of these groups, specimens were separated into groups by morphological features. Bee specimens were identified using "The Bees of the Eastern United States part I" by Mitchell (1960) and Discover Life keys by Polistes Foundation, Inc. (2018). Dr. Alana Pindar confirmed and assisted with the identification of the more difficult bee species. Hover flies were identified to subgenus using "The Key to the Genera of Nearctic Syrphidae" (Miranda et al., 2013) and "The Butterflies of Nova Scotia" (Linda and Peter Payzant, n.d.) was used to identify all butterflies to species.

2.5: Statistical Analysis

All statistical analyses were conducted in R-Studio version 1.1.453 (R Core Team, 2018). Multiple linear regression was used to analyze the effects of the green roof characteristics on the different pollinator communities. Using the lmtest package in R, a likelihood ratio test of nested models determined what distribution fit the data the best (Hothorn et al., 2017). Out of the three distributions examined – Gaussian, Poisson, and Negative-Binominal – the Gaussian distribution was the best fit for every model. Therefore, the function lm was used for all regression models.

Six models were used to examine the effects of independent variables on dependent variables. Dependent variables examined included bee species richness and abundance, hover fly subgenus richness and abundance, and total pollinator subgenus richness and abundance. Independent variables examined included green roof floral richness, floral structure surface area, green roof height, green roof surface area, green space, saltwater, and natural space. Pollinator species richness for all three insect groups was the total number of species/sub-genera observed at each green roof. Similarly, green roof floral richness was the total number of flowering plant species observed on the green roof. Pollinator abundance was the total number of specimens collected on the green roof for each respective pollinator assemblage. The surface area of floral structures on the green roof was the mean observed throughout the study period. Transformations were applied to independent and dependent variables to meet the assumptions of the multiple linear regression models. A square root transformation was applied to the dependent variables bee abundance, total pollinator richness, and total pollinator abundance. The remaining dependent variables were not transformed. Log transformations were applied to independent variables green roof height, floral display area, green space, natural space, and saltwater space. For all independent variables that were quantified as a percentage, the logit function in R's pack R's car package was used to transform the data (Fox and Weisberg, 2019). The remaining independent variables were not transformed

All independent variables were examined for multicollinearity using the variance inflation factor (function = vif) in R's car package (Fox and Weisberg, 2019). The percentage of saltwater area was deemed to be correlated with the percentage of natural space. A correlation between saltwater and natural space was also observed in the non-metric multidimensional scaling analysis. After running the models, the percentage of natural space was chosen to be used in the models instead of saltwater area. Natural space was used instead of saltwater area because a positive relationship between saltwater area and the richness of pollinator communities was observed. Biologically this does not make sense as saltwater provides no beneficial resources for pollinators. Contrarily, natural space has been observed to be positively correlated with pollinator communities in previous urban studies (Tonietto et al., 2011). Due to this rationale natural space was included and saltwater area was omitted from the analysis.

To simplify the models, meet model assumptions, and reduce overfitting caused by too many independent variables and low sample size, the Akaike Information Criterion (AIC) stepwise algorithm (function = step) was used to remove the independent variables that had no effect on the model. The defined variables were removed from the model and the simplified model was used. Due to the low sample size and the large number of coefficients, model overfitting was a high risk. To make sure overfitting was not an issue a predicted R^2 was calculated and compared to the adjusted R^2. If the predicted R^2 was a notably smaller than the adjusted R^2, outliers with values greater than 0.5 on the Cook's distant plot were removed and the model was run again. If the estimated coefficients in the new regression model's output were not significant different than the complete data set was used. It was assumed the overfitting did not drastically affect the output of the model. Scaled coefficient estimates were used to examine the effect size of independent variables in relation to each other. To visualize the effects of the independent variables on the dependent variables, the R package visreg was used (Breheny and Burchett, 2018).

To determine if the number of spontaneous plant species or the number of planted species had a greater influence on the pollinator community the same set of models with the same independent and response variables were run again. The AIC stepwise algorithm was also applied to these models. However, if the step function advised the removal of planted or spontaneous richness from the model the variable was not removed. For every green roof, the floral richness variable was separated into two distinct variables, spontaneous floral richness and planted floral richness. Spontaneous green roof plant species were considered plant species that could establish on the green roof without human assistance. These species tended to be native or weedy non-native species with well developed dispersal methods. Planted green roof species were plant species that required human intervention for the plants to be present on the green roof. Many of these species were ornamental plant species. Information provided by property managers and gardeners was also used to identify plant species that were initially planted on the green roofs.

To explore the relationships between individual taxon abundances and green roof characteristics, ordinations were carried out using non-metric multidimensional scaling (NMDS) using the abundances of each taxonomic group. Two NMDS analyses were completed, one examined pollinators captured by net and the other examined pollinators captured by bowl. The predictor variables used in NMDS included, date of capture, green roof height, green roof surface area, percentage of green space within a 500 m radius, percentage of saltwater within a 500 m radius, and percentage of natural space within a 500 m radius. These predictor variables were fit to the axis scores using the "envfit" function in R's vegan package (v. 2.5-5, Oksanen et al., 2019).

3: Results

3.1: Pollinators Collected

A total of 3051 pollinator specimens were collected on the green roofs surveyed in Halifax NS. Pollinator specimens were comprised of 2370 bees, 670 hover flies, and 11 butterflies (Table 2). Bees were the most diverse pollinator assemblage with 47 different species identified. Hover flies were the second most diverse group with 14 subgenera identified and butterflies were the least diverse group with only 5 species identified. Bee species native to Nova Scotia comprised 79% of the species observed and only 30.3% of total bee abundance (Table 2). A native ranking was not provided for hover flies because they were not identified to species. For butterflies, 60% of the species observed were native to Nova Scotia and 36% of total butterfly abundance were native. The most common bee species captured on the green roofs was the non-native *Bombus impatiens*. *Toxomerus* was the most common hover fly genus and the most common butterfly species was the non-native *Pieris rapae.* When examining all pollinator assemblages, the most common pollinator genus collected was *Lasioglossum* and was comprised of 1086 individuals. The genus *Bombus* was the second most common genus with a total of 751 individuals collected. The third most common genus was *Toxomerus* with 487 individuals captured.

Of the collected bees, 83.2% were ground nesting species, 7.2% were managed hive species (*Apis mellifera*), 5.0% were cavity nesting species, 4.1% were above or ground nesting species, and 0.5% were parasitic species (Table 2). Bees were observed nesting in green roof substrate on three green roofs. A large number of bees were discovered nesting in a flowerbed on the Cunard Court green roof during the June sample session. This green roof was an intensive green roof with a very deep substrate located at ground level on top of an underground parking garage. Due to the high number of *Andrena miserabilis* captured in June at this site, it is believed this was the species observed nesting in the soil. *Andrena spp.* and *Lasioglossum spp*. were observed nesting at the green roof located at the Renaissance South building. Several *Lasioglossum spp.* individuals and one *Andrena spp.* were observed nesting in the large rectangular planters that were located on the roof. These planters were deeper than the green roof at an average depth of 23.4 cm. A small *Bombus ternarius* nest was found at Bedford Institute of Oceanography 1 green roof. It appeared to have been damaged by birds. This green roof was classified as an extensive green roof with an average soil depth of 15 cm.

Table 2. Pollinator species collected from June – September 2017 from 18 green roofs surveyed in the Halifax Regional Municipality Nova Scotia. Pollinators were collected using hand nets and bowl traps. Native ranking was defined by the Atlantic Canada Conservation Data Center with the exception of *Bombus impatiens* which was defined by Sheffield et al. (2003). *Lasioglossum spp2* all belong the subgenus *Dialictus.*

Family	Sub-Family	Genus/ Sub-Genus	Species	#	Nest Type	Native vs. Non-native
Andrenidae	Andreninae	*Andrena*	*carlini*	1	Ground[1]	Native
			crataegi	5	Ground[1]	Native
			dunningi	1	Ground[1]	Native
			hippotes	10	Ground[1]	Native
			hirticincta	1	Ground[1]	Native
			illinoiensis/salictaria	1	Ground[1]	Native
			miserabilis	26	Ground[1]	Native
			nivalis	3	Ground[1]	Native
			vicina	2	Ground[1]	Native
			wilkella	43	Ground[1]	Non-native
			morphospecies1	1	Ground[1]	N/A
Apidae	Apinae	*Apis*	*mellifera*	170	Managed Hive[1]	Non-native
		Bombus	*bimaculatus*	37	Ground/Surface[2]	Native
			impatiens	563	Ground[2]	Non-native[7]
			perplexus	3	Surface/trees & logs[2]	Native
			rufocinctus	47	Ground/Surface[2]	Native
			ternarius	86	Ground[2]	Native
			terricola	1	Ground[2]	Native
			vagans	14	Ground/Surface[2]	Native
		Melissodes	*illata*	3	Ground[1]	Native
	Xylocopinae	*Ceratina*	*calcarata*	7	Cavity[1]	Native
			dupla	1	Cavity[1]	Native
	Nomadinae	*Nomada*	*morphospecies1*	5	Parasite[1]	N/A
			morphospecies2	1	Parasite[1]	N/A
Colletidae	Colletinae	*Colletes*	*simulans*	1	Ground[1]	Native
	Hylaeinae	*Hylaeus*	*affinis/modestus*	5	Cavity[4]	Native
			annulatus	1	Cavity[4]	Native
			leptocephalus	2	Cavity[3]	Non-native

Family	Sub-Family	Genus/ Sub-Genus	Species	#	Nest Type	Native vs. Non-native
Colletidae	Hylaeinae	*Hylaeus*	*punctatus*	76	Cavity[3]	Non-native
			verticalis	5	Cavity[5]	Native
Halictidae	Augochlorini	*Augochlorella*	*aurata*	4	Ground[1]	Native
	Halictinae	*Agapostemon*	*virescens*	13	Ground[1]	Native
		Halictus	*confusus*	53	Ground[1]	Native
			ligatus	17	Ground[1]	Native
			rubicundus	43	Ground[1]	Native
		Lasioglossum	*coriaceum*	4	Ground[1]	Native
			cressonii	39	Ground[1]	Native
			leucozonium	172	Ground[1]	Non-native
			paraforbesii	3	Ground[1]	Non-native
			versans	10	Ground[1]	Native
			zonulum	5	Ground[1]	Non-native
			morphospecies1	20	Ground[1]	N/A
			*morphospecies2**	833	Ground[1]	N/A
		Sphecodes	*morphospecies1*	6	Parasite[1]	N/A
Megachilidae	Megachilinae	*Anthidium*	*manicatum*	4	Cavity[1]	Non-native
		Megachile	*frigida*	1	Cavity/rotten logs[6]	Native
			inermis	4	Cavity/rotten logs[6]	Native
			melanophaea	7	Ground[6]	Native
			rotundata	10	Cavity/vertical soil banks[6]	Non-native
			Bee total	2370		
Syrphidae	Eristalinae	*Eristalinus*	-	2	-	N/A
		Eoseristalis	-	7	-	N/A
		Eristalis	-	22	-	N/A
		Eumerus	-	1	-	N/A
		Merodon	-	2	-	N/A
		Syritta	-	12	-	N/A
		Xylota	-	1	-	N/A
	Syrphinae	*Allograpta*	-	4	-	N/A
		Eupeodes/Epistrophe	-	27	-	N/A
		Pipiza/Heringia	-	5	-	N/A
		Platycheirus	-	4	-	N/A
		Sphaerophoria	-	78	-	N/A
		Syrphus	-	18	-	N/A
		Toxomerus	-	487	-	N/A
			Hover fly total	670		

Family	Sub-Family	Genus/ Sub-Genus	Species	#	Nest Type	Native vs. Non-native
Pieridae	Pierinae	*Pieris*	*rapae*	5	-	Non-native
Hesperiidae	Hesperiinae	*Poanes*	*hobomok*	2	-	Native
		Thymelicus	*lineola*	2	-	Non-native
Nymphalidae	Nymphalinae	*Vanessa*	*virginiensis*	1	-	Native
			Cardui	1	-	Native
			Butterfly total	11		

[1] (Packer et al., 2007). [2] (Colla et al., 2011), [3] (Sheffield et al., 2011a), [4] (Sheffield et al., 2008), [5] (Scott, 1995), [6] (Sheffield et al., 2011b), [7] (Sheffield et al., 2003)

Average richness for the studied green roofs was 13 bee species, 5 hover fly subgenera, and 1 butterfly species (Table 3). Average abundance observed on the green roofs was 132 bees, 37 hover flies, and 1 butterfly (Table 4). Of the studied green roofs, the Dalhousie Life Science Courtyard green roof had the highest bee richness, bee abundance, butterfly richness, and butterfly abundance. The Nova Scotia Community College (NSCC), Ivany Campus green roof had the highest hover fly richness and the Marion McCain green roof had the highest hover fly abundance. The LeMarchant Place green roof had the lowest bee richness, and bee abundance. The Mona Campbell green roof had the lowest hover fly richness and abundance with no hover flies were captured on this green roof. No butterflies were captured on Admiralty Place, Bedford Institute of Oceanography 1, Charles St., Coburg Place, Cunard Court, Dalhousie Chemistry Building, Dalhousie Dentist Building, LeMarchant Place, Marion McCain, Mona Campbell, Quinpool Towers, and TD Building green roofs.

Table 3. Number of pollinator species collected from June – September 2017 from 18 green roofs surveyed in the Halifax Regional Municipality Nova Scotia. Pollinators were collected using both hand netting and bowl traps.

Site	Bee Species Richness	Hover Fly Subgenera Richness	Butterfly Species Richness	Total Pollinator Subgenera Richness
Admiralty Place	15	4	0	16
Bedford Institute of Oceanography 1	12	3	0	12
Bedford Institute of Oceanography 2	18	4	1	20
Charles St. Green Roof	6	3	0	6
Charter House Condominiums	17	4	1	17
Coburg Place	5	5	0	9
Cunard Court	18	8	0	20
Dalhousie Chemistry Building	22	5	0	23
Dalhousie Dentist Building	15	3	0	13
Dalhousie Life Science Courtyard	25	8	3	29
LeMarchant Place	2	1	0	3
Marion McCain	8	4	0	12
Mona Campbell	16	0	0	12
Nova Scotia Community College, Ivany Campus	22	9	2	28
Quinpool Towers	4	6	0	10
Renaissance South	15	4	1	18
Saint Mary's University	15	7	1	20
TD Building	7	4	0	10
Average with SE	13 ± 1.6	5 ± 0.6	1 ± 0.2	15 ± 1.7

Table 4 Pollinator abundance observed from June – September 2017 on 18 green roofs surveyed in the Halifax Regional Municipality Nova Scotia. Pollinators were collected utilizing both hand netting and bowl traps.

Site	Bee Abundance	Hover Fly Abundance	Butterfly Abundance	Total Pollinator Abundance
Admiralty Place	92	41	0	133
Bedford Institute of Oceanography 1	40	18	0	58
Bedford Institute of Oceanography 2	85	57	1	143
Charles St Green Roof	24	8	0	32
Charter House Condominiums	144	60	1	205
Coburg Place	34	41	0	75
Cunard Court	214	49	0	263
Dalhousie Chemistry Building	164	10	0	174
Dalhousie Dentist Building	250	63	0	313
Dalhousie Life Science Courtyard	337	31	4	372
Lemarchant Place	6	36	0	42
Marion McCain	92	64	0	156
Mona Campbell	146	0	0	146
NSCC, Ivany Campus	175	40	3	218
Quinpool Towers	50	70	0	120
Renaissance South	176	5	1	182
Saint Mary's University	211	49	1	261
TD Building	130	28	0	158
Average with SE	132 ± 20.8	37 ± 5.2	1 ± 0.3	170 ± 21.7

3.2: Green Roof Site and Landscape Characteristics

Green Roof Floral Characteristics

In total 167 plant species were identified green roofs examined. A complete list of all flowering plants surveyed on the green roofs can be found in appendix table 2A & 3A. The Dalhousie Life Science Courtyard green roof the highest floral richness at a value of 50 different flowering species and the Charles Street green roof had the lowest floral richness at a value of 6 (Table 5). Of the studied green roofs the average floral richness was 28 species. Non-native plant species comprised 74.4% of the flowering plant species identified. The most common flowering plant species were the non-native species *Hieracium* x *flagellare* and the native species *Oxalis stricta.* These plant species were found on 16 of the 18 green roofs surveyed. The non-native species *Cerastium fontanum* was the second most common flowering plant species and was found on 15 of the green roofs examined. The non-native species *Trifolium repens* was the third most common flowering and was observed on 14 of the examined green roofs. The average floral area was highest at the TD building green roof with a value of 6.81% and lowest at Charles Street green roof with a value of 0.15%. The average Halifax green roof floral area was 1.9%. See Table 5 for complete list of green roof characteristics.

Table 5. Site and landscape characteristics of the Halifax Regional Municipality green roofs where the pollinators were collected from June – September 2017. Floral richness is the total number of flowering species observed throughout the study period. Floral display cover is the average observed throughout the study period.

Site	Site Characteristics				Landscape Features (500 m radius)		
	Height (Floors)	Size (m^2)	Floral Richness	Floral Display Cover ± SE (%)	Saltwater Cover (%)	Green Space (%)	Natural Space (%)
Admiralty Place	2	564	21	3.03 ± 0.81	44	8	1
Bedford Institute of Oceanography 1	1.5	480	19	0.43 ± 0.031	47	33	20
Bedford Institute of Oceanography 2	0	348	27	1.78 ± 0.61	35	44	27
Charles St Green Roof	0	20	6	0.15 ± 0.037	0	18	0
Charter House Condominiums	5	1012	49	1.30 ± 0.36	0	20	8
Coburg Place	4	122	16	0.39 ± 0.066	0	37	6
Cunard Court	0	854	30	2.13 ± 0.81	13	13	1
Dalhousie Chemistry Building	0	32	24	1.89 ± 0.5	0	29	2
Dalhousie Dentist Building	1	1412	28	2.63 ± 1.2	0	27	3
Dalhousie Life Science Courtyard	1	1171	50	4.02 ± 1.2	3	38	6
Lemarchant Place	2	78	16	0.26 ± 0.04	0	33	3
Marion McCain	1	261	17	1.01 ± 0.18	0	27	0
Mona Campbell	3	175	24	2.69 ± 0.83	0	28	0
NSCC, Ivany Campus	2.5	810	49	1.75 ± 0.43	31	39	23
Quinpool Towers	2	3327	43	0.63 ± 0.19	0	36	0
Renaissance South	2	180	27	2.08 ± 0.92	17	9	0
Saint Mary's University	3	207	37	1.59 ± 0.4	0	55	8
TD Building	6	287	23	6.81 ± 1.7	19	9	0
Average with SE			28.1 ±	1.9 ± 0.38	12 ± 4	28 ± 3	6 ± 2

3.3: Green Roof Pollinator and Floral Interactions

Pollinators were hand netted on the green roofs while visiting 86 different plant species. Non-native plant species represented 64.3% of visitation captures (Table 6). The greatest quantity of pollinators was captured while visiting the non-native plant species *Leontodon autumnalis,* which was found on 10 of the 18 green roofs examined (Table 6). The second largest number of pollinators was caught while visiting the genus *Sedum*. Plant species belonging to the genus *Sedum* were observed on 7 green roofs. The genus *Solidago* was the third most visited plant genus. Nine of the studied green roofs were colonized by the genus *Solidago.* When only considering bee species capture the top five plant genera in order included *Sedum*, *Solidago, Leontodon*, *Symphyotrichum*, and *Hydrangea.* For hover flies, the top five plant genera included *Leontodon, Sedum, Erigeron*, *Hieracium,* and *Medicago.* Butterflies were only collected on five different genera. These genera included *Trifolium, Coreopsis, Leontodon, Solidago,* and *Symphyotrichum*. See appendix table 4A for the complete list of plant species and the associated number of pollinator visits.

Table 6. Number of pollinators captured while visiting floral genera on the 18 studied green roofs located in the Halifax Regional Municipality Nova Scotia. Pollinators were captured using hand nets and bowls from June – September 2017. Native ranking is defined by the Atlantic Canada Conservation Data Center.

Genus	Bee	Hover Fly	Butterfly	Total # of Visits	Native vs. Non-native	Percent Capture (%)
Leontodon	171	92	1	264	Non-native	14.5
Sedum	235	21	0	256	Non-native	14.1
Solidago	210	8	1	219	Native	12.0
Symphyotrichum	123	7	1	131	Native	7.2
Hydrangea	122	1	0	123	Non-native	6.8
Hieracium	79	17	0	96	Non-native	5.3
Dasiphora	76	15	0	91	Native	5.0
Thymus	46	4	0	50	Non-native	2.7
Erigeron	28	17	0	45	Native	2.5
Trifolium	39	0	1	40	Non-native	2.2
Vicia	34	0	0	34	Non-native	1.9
Euthamia	30	3	0	33	Native	1.8
Rhus	29	1	0	30	Native	1.6
Centaurea	26	1	0	27	Non-native	1.5
Medicago	9	17	0	26	Non-native	1.4
Allium	19	4	0	23	Native	1.3
Sibbaldiopsis	17	6	0	23	Native	1.3
Echinacea	16	3	0	19	Non-native	1.0
Prunella	10	9	0	19	Native	1.0
Spiraea	19	0	0	19	Non-native	1.0
Daucus	10	7	0	17	Non-native	0.9
Euonymus	16	1	0	17	Non-native	0.9
Oxalis	8	7	0	15	Native	0.8
Cerastium	2	12	0	14	Non-native	0.8
Lavandula	14	0	0	14	Non-native	0.8
Rudbeckia	12	2	0	14	Non-native	0.8
Veronica	5	9	0	14	Non-native	0.8
Origanum	11	1	0	12	Non-native	0.7
Brassica	10	1	0	11	Non-native	0.6
Coriandrum	8	3	0	11	Non-native	0.6
Taraxacum	3	8	0	11	Non-native	0.6

Genus	Bee	Hover Fly	Butterfly	Total # of Visits	Native vs. Non-native	Percent Capture (%)
Lotus	9	0	0	9	Non-native	0.5
Stellaria	4	5	0	9	Non-native	0.5
Hosta	8	0	0	8	Non-native	0.4
Ranunculus	5	3	0	8	Non-native	0.4
Begonia	7	0	0	7	Non-native	0.4
Coreopsis	6	0	1	7	Non-native	0.4
Crepis	2	5	0	7	Non-native	0.4
Fragaria	5	1	0	6	Native	0.3
Rubus	5	0	0	5	Native	0.3
Leucanthemum	4	0	0	4	Non-native	0.2
Tagetes	4	0	0	4	Non-native	0.2
Ajuga	2	1	0	3	Non-native	0.2
Hesperis	3	0	0	3	Non-native	0.2
Rosa	3	0	0	3	Native	0.2
Phlox	2	0	0	2	Non-native	0.1
Raphanus	1	1	0	2	Non-native	0.1
Solanum	2	0	0	2	Non-native	0.1
Vaccinium	2	0	0	2	Native	0.1
Achillea	1	0	0	1	Native	<0.1
Gaylussacia	1	0	0	1	Native	<0.1
Linum	1	0	0	1	Non-native	<0.1
Malva	1	0	0	1	Non-native	<0.1
Minuartia	0	1	0	1	Native	<0.1
Monarda	1	0	0	1	Non-native	<0.1
Myosotis	1	0	0	1	Non-native	<0.1
Oenothera	1	0	0	1	Native	<0.1
Potentilla	1	0	0	1	Non-native	<0.1
Sonchus	1	0	0	1	Non-native	<0.1
					Total Native	35.7
					Total Non-native	64.3

3.4: Influence of Site and Landscape Variables on Green Roof Pollinator Richness and Abundance

Primary Green Roof Characteristic Models

In general, green roof floral characteristics were the strongest predictors of pollinator richness and abundance (Table 5). When green roof height was determined to have an effect on the response variables, this variable was always a negative predictor. Green space was consistently found to have no effect on any of the pollinator response variables examined.

Both floral display surface area and floral richness were the strongest predictors of bee richness and were comparable in effect size (Appendix Table 5A and Figure 3). Green roof height and surface area were also strong negative predictors of bee richness. Natural space was a weak predictor of bee richness. The best predictor of bee abundance was floral display area, and this was a positive relationship (Appendix Table 6A and Figure 4). Floral richness was also a strong positive predictor of bee abundance. Green roof height was a weak negative predictor of bee abundance. The strongest predictor of hover fly richness was floral richness (Appendix Table 7A and Figure 5). Green roof height was a weak negative predictor of hover fly richness. All other variables examined were found to have no influence on hover fly richness. The only predictor of hover fly abundance was green roof surface area, and this was a positive relationship (Appendix Table 8A and Figure 6). Floral richness was the strongest predictor of total pollinator richness (Appendix Table 9A and Figure 7). Other strong positive predictors included floral display area and natural space. Both green roof height and surface area were negative predictors of total pollinator richness. Floral display area was the best predictor of total pollinator abundance (Appendix Table 10A and Figure 8). Floral richness was also a strong positive predictor. Green roof height was a negative predictor of total pollinator abundance. Natural space and surface area were weak predictors of total pollinator abundance.

Table 5. Scaled coefficient estimates from the multiple regression analysis. Pollinators were captured using hand nets and bowls on 18 green roofs located in the Halifax Regional Municipality, Nova Scotia from June – September 2017. Bold text represents the strongest effect. A "*" denotes a p-value that is less than 0.05. A "×" denotes coefficients that were removed from the model due to their lack of influence on the independent variable. See appendix tables 5A to 10A for complete regression output.

Model	*y*	β_1	β_2	β_3	β_4	β_5	β_6	
		Floral Richness	Floral SA	Green Roof SA	Green Roof Height	Natural Space	Green Space	Adj. R^2
1	Bee Richness	3.84*	**4.09***	- 2.57*	- 2.89*	2.05	×	0.788
2	Bee Abundance	1.60*	**2.78***	×	- 1.05	×	×	0.746
3	Hover Fly Richness	**1.66***	×	×	- 0.708	×	×	0.420
4	Hover Fly Abundance	×	×	**10.6***	×	×	×	0.373
5	All Pollinator Subgen. Rich.	**0.607***	0.515*	- 0.275	- 0.358*	0.255*	×	0.798
6	All Pollinator Abundance	1.97*	**2.11***	0.027	-0.873	-0.239	×	0.744

SA = surface area, Subgen. Rich. = subgenera richness

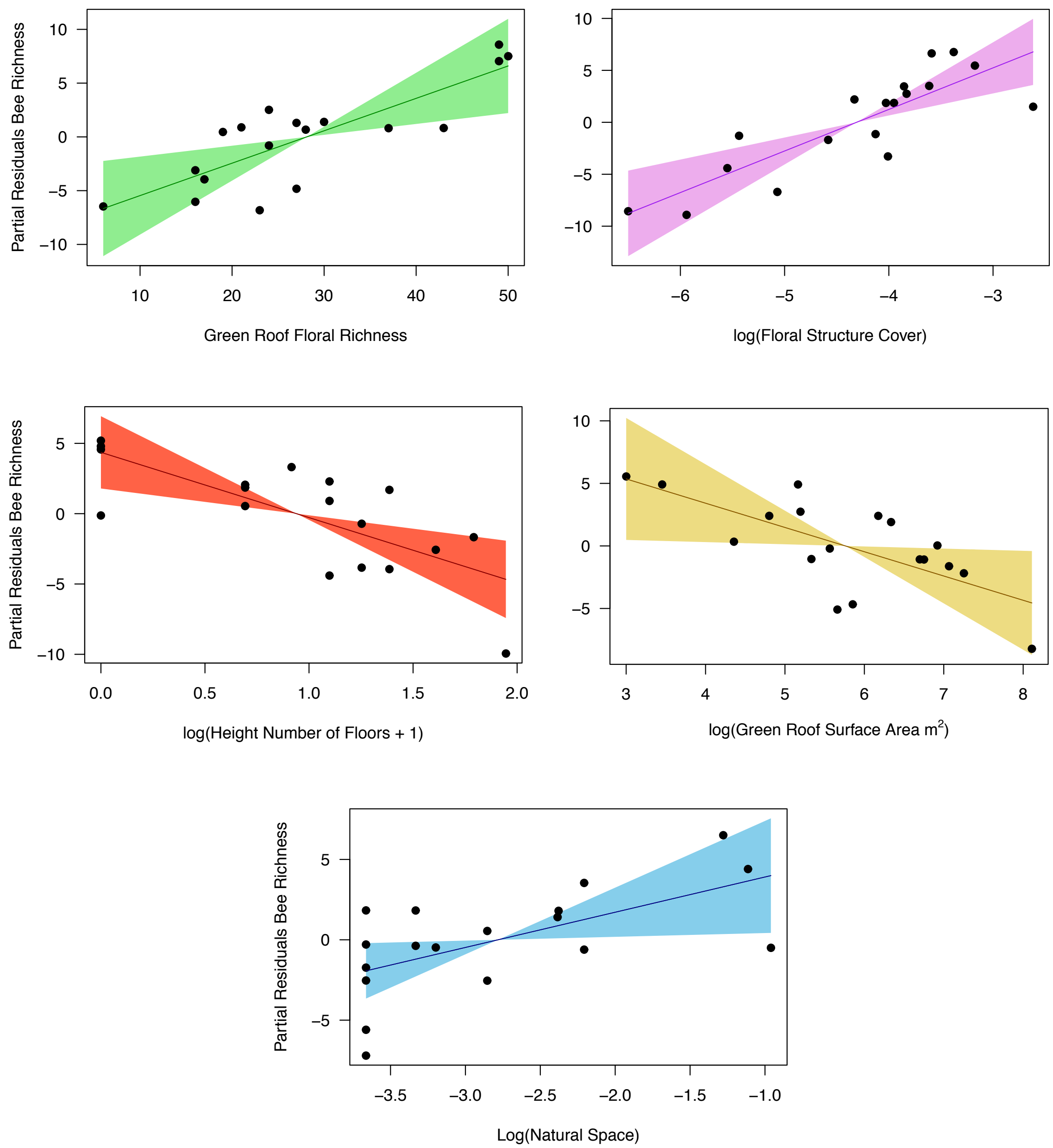

Figure 3. Partial residual plots from the multiple linear regression model the examined the effects of the green roof characteristics on bee species richness. Bee communities were surveyed using hand nets and bowls on 18 green roofs in the Halifax Regional Municipality, Nova Scotia. A total of 47 bee species were collected. See appendix table 5A for multiple linear regression output.

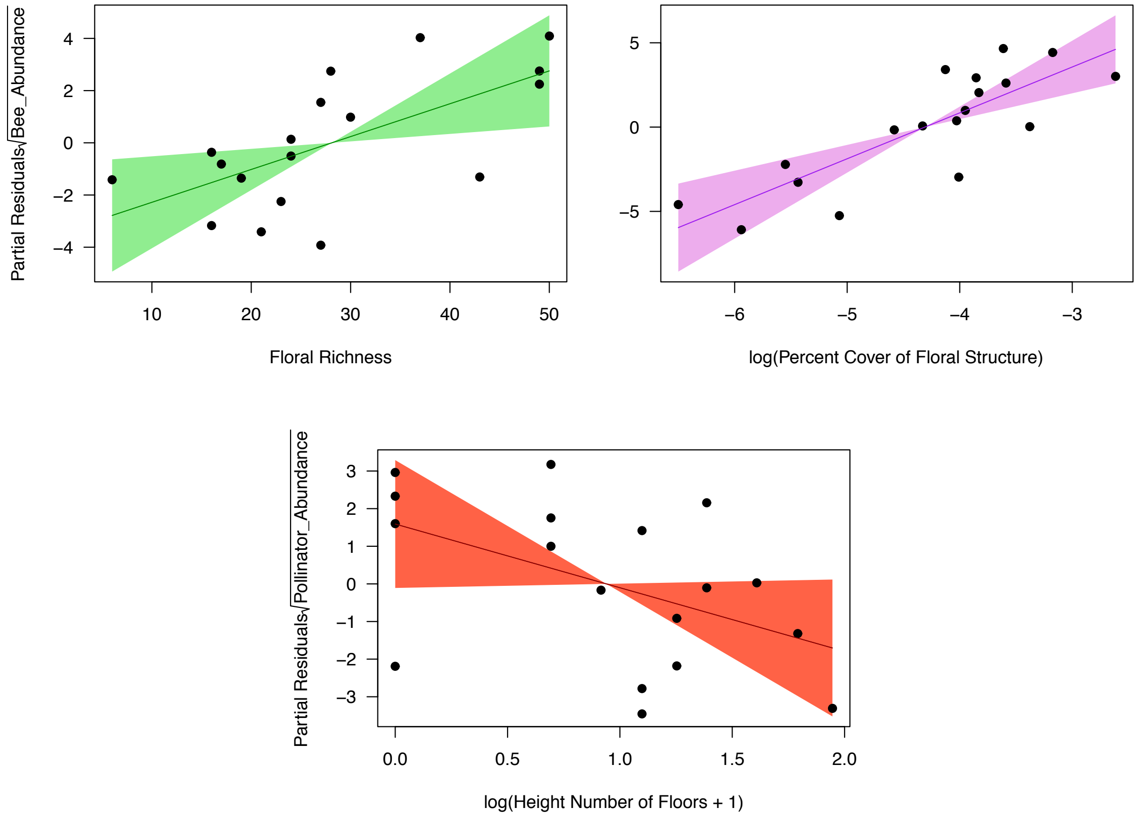

Figure 4. Partial residual plots from the multiple linear regression model that examined the effects of the green roof characteristics on bee abundance. Bee communities were surveyed using hand nets and bowls on 18 green roofs in the Halifax Regional Municipality, Nova Scotia. A total of 2370 bees were collected. See appendix table 6A for multiple linear regression output.

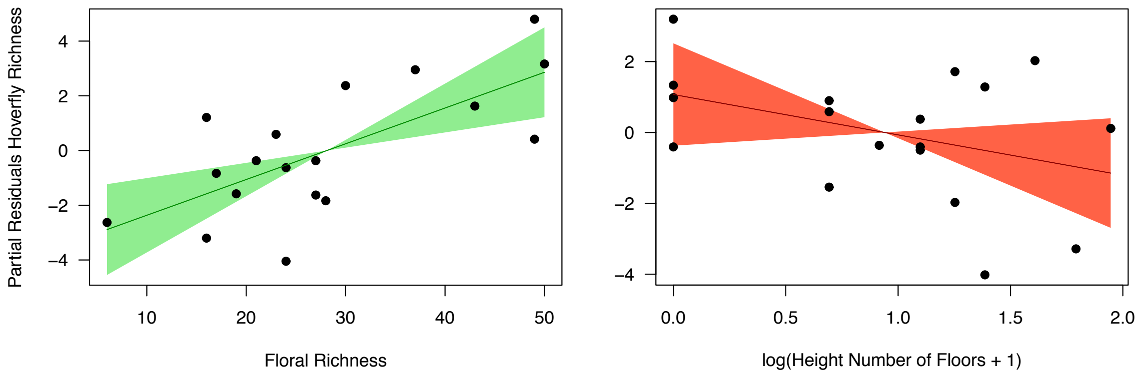

Figure 5. Partial residual plots from the multiple linear regression model that examined the effects of the green roof characteristics on hover fly subgenera richness. Hover fly communities were surveyed using hand nets and bowls on 18 green roofs in the Halifax Regional Municipality, Nova Scotia. A total of 11 hover fly subgenera were collected. See appendix table 7A for multiple linear regression output.

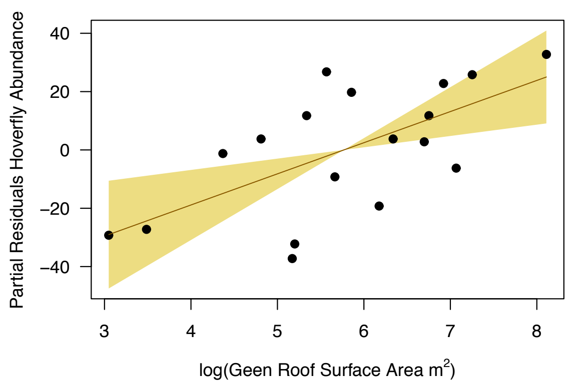

Figure 6. Partial residual plots from the multiple linear regression model that examined the effects of the green roof characteristics on hover fly abundance. Hover fly communities were surveyed using hand nets and bowls on 18 green roofs in the Halifax Regional Municipality, Nova Scotia. A total of 670 hover flies were collected. See appendix table 8A for multiple linear regression output.

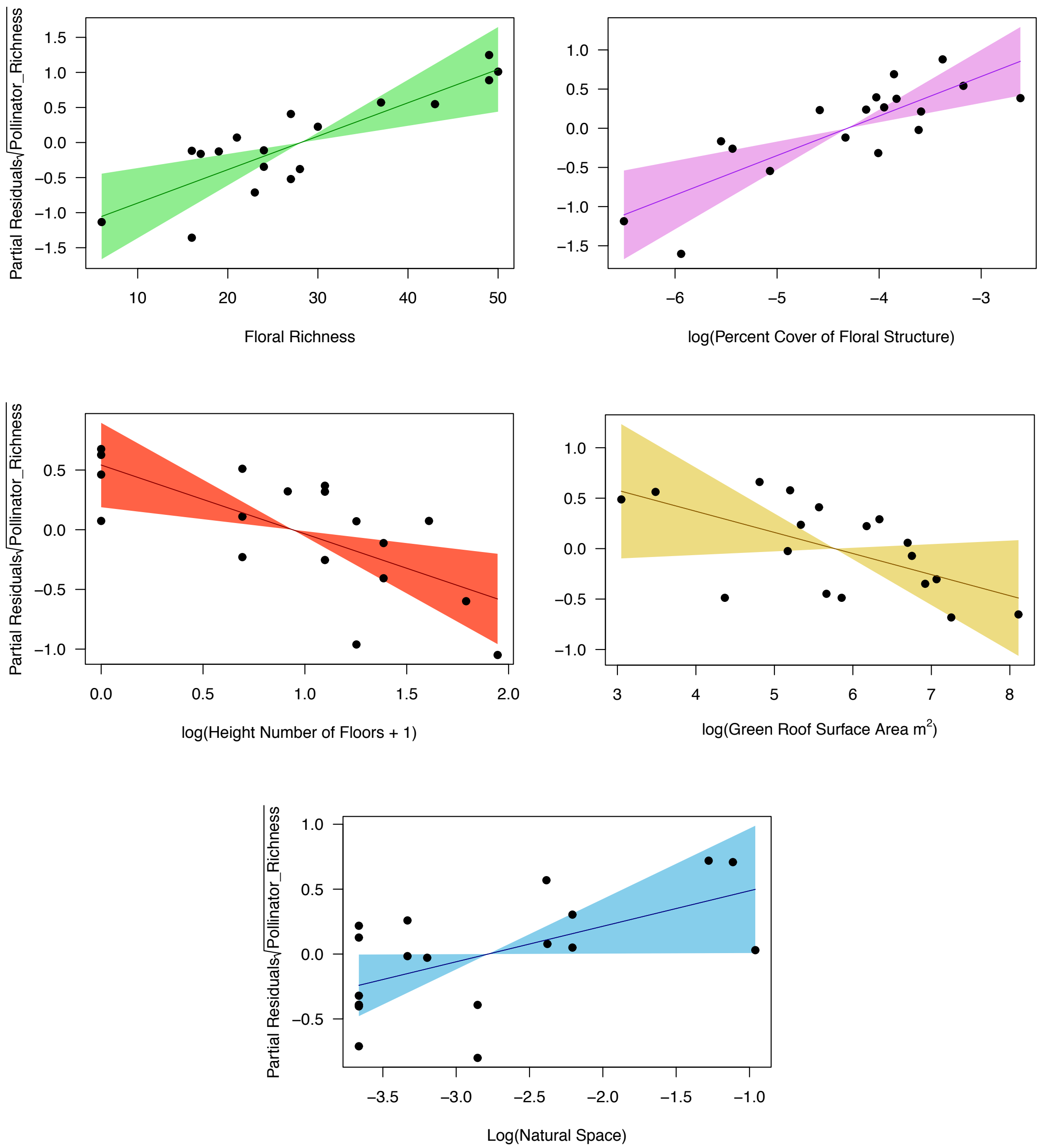

Figure 7. Partial residual plots from the multiple linear regression model that examined examining the effects of the green roof characteristics on total pollinator sub genera richness. Pollinator communities were surveyed using hand nets and bowls on 18 green roofs in the Halifax Regional Municipality, Nova Scotia. A total of 53 subgenera were collected. See appendix table 9A for multiple linear regression output.

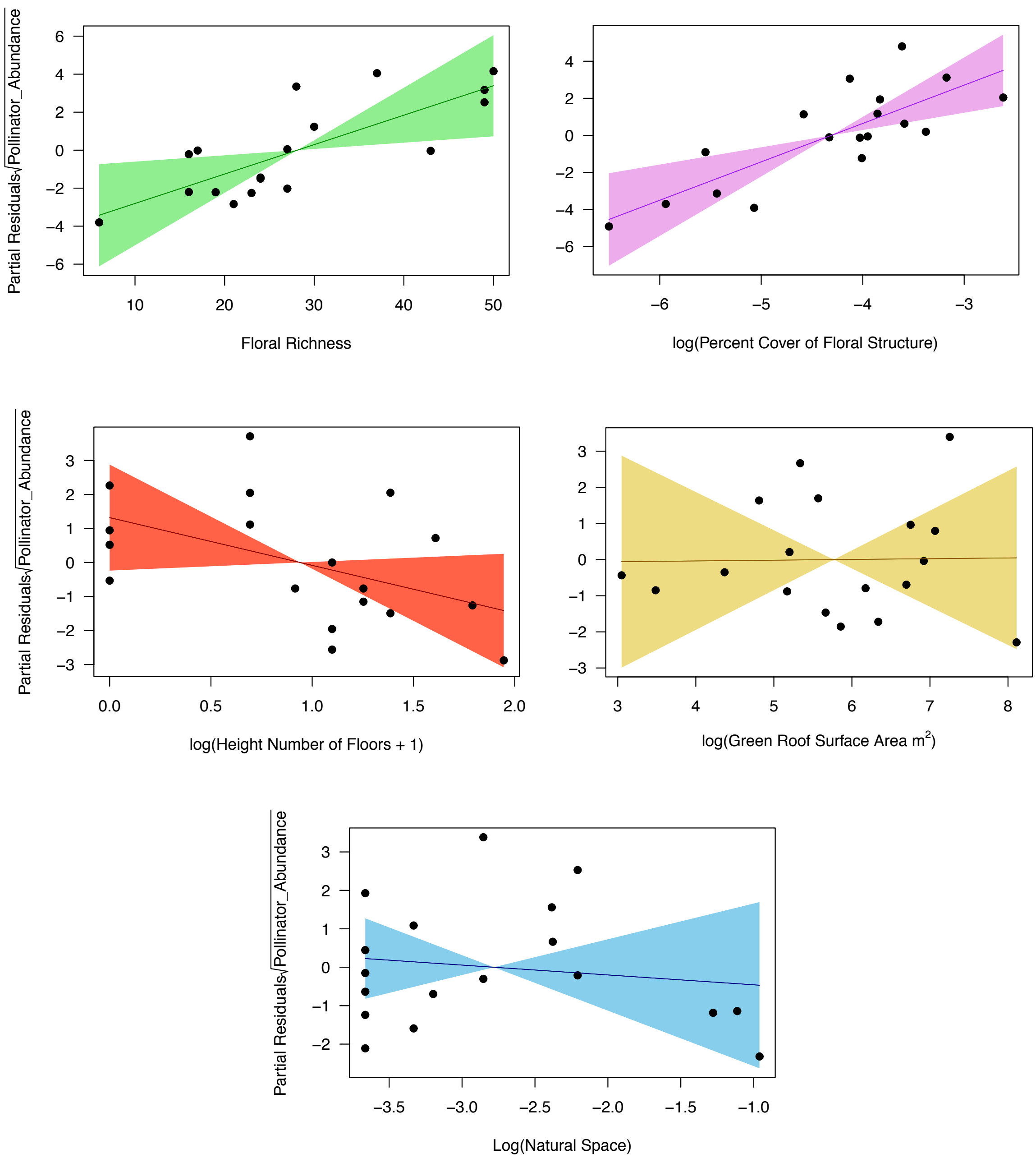

Figure 8. Partial residual plots from the multiple linear regression model that examined the effects of the green roof characteristics on total pollinator abundance. Pollinator communities were surveyed using hand nets and bowls on 18 green roofs in the Halifax Regional Municipality, Nova Scotia. A total of 3051 pollinators were collected. See appendix table 10A for multiple linear regression output.

Spontaneous Vs. Planted Floral Richness Models

Both planted floral richness and spontaneous floral richness were positive predictors of bee richness and were comparable in effect size (Table 6). Spontaneous floral richness was a stronger predictor of hover fly and total pollinator richness. In these two models, spontaneous floral richness was the strongest predictor overall. Planted floral richness had a stronger effect on bee and total pollinator abundance. However, planted floral richness in these models was not the strongest predictor. Please see appendix tables 11A to 16A for regression output.

Table 6. Scaled coefficient estimates from the multiple regression analysis that included floral spontaneous richness and planted floral richness. Pollinators were captured using hand nets and bowls on 18 green roofs located in Halifax Regional Municipality, Nova scotia from June – September 2017. A "*" denotes a p-value that is less than 0.05. Bold text represents the strongest effect. A "×" denotes coefficients that were removed from the model due to their lack of influence on the independent variable.

Model	*y*	β_1	β_2	β_3	β_4	β_5	β_6	β_7	
		Floral Spon. Rich.	Floral Plan. Rich.	Floral SA	Green Roof SA	Green Roof Height	Natural Space	Green Space	Adj. R^2
1	Bee Richness	2.14	2.65*	**3.72***	- 2.80	- 3.27*	2.82*	×	0.74
2	Bee Abundance	1.37	1.72	**2.46***	-0.97	- 1.32*	×	×	0.74
3	Hover Fly Richness	**1.39***	0.18	×	×	×	×	×	0.31
4	Hover Fly Abundance	-10.6	1.13	×	**20.3***	×	×	8.75	0.42
5	All Pollinator Subgen. Rich	**0.62***	0.29	0.34	- 0.39	- 0.35*	0.41*	-0.21	0.75
6	All Pollinator Abundance	0.62	1.65*	**2.25***	0.01	- 1.20*	- 0.14	0.81	0.77

SA = surface area, Spon. = Spontaneous, Plan. = Planted, Rich = Richness, Subgen.= subgenera

3.5: Effects of Green Roof Characteristics on Pollinator Composition

The NMDS ordination indicated environmental conditions that were correlated with variation in pollinator species composition (Figure 9A and 9B). The NMDS analysis had a stress level of 0.169 and 3 dimensions (k=3). See Table 7 for a list of pollinators associated with the different green roof characteristics examined. At a genus level most *Andrena* species were associated with green roofs at a lower height and captured earlier in the collection period. *Andrena hippotes* and *Andrena miserabilis* were associated with lower roofs and captured earlier in the season. *Andrena wilkella* was captured earlier in the season and was not significantly influenced by other environmental variables. Species belonging to the genus *Bombus* were in high abundance in the middle to late periods of the data collection. *Bombus ternarius,* and *Bombus impatiens* were both found in high abundance later in the collection period and associated with green roofs at higher heights. These two species had little to no correlation with the presence of natural space/green space. *Bombus rufocinctus* and *Bombus vagans* appeared to be in abundance in the middle of the season and correlated positively with the presence of natural space and saltwater. *Agapostemon virescens* was highly associated with the presence of natural space and was not correlated with the other environmental variables examined. *Halictus ligatus* was positively correlated with the presence of natural space. The effect of the environmental variables on the genus *Lasioglossum* was inconsistent between species. These species were spread throughout the non-metric multidimensional scaling ordinations. *Lasioglossum leucozonium*, *Lasioglossum versans, Lasioglossum spp1.,* and *Lasioglossum spp2.* abundances were not correlated with the environmental variables examined. *Lasioglossum cressonii* was collected in high abundance early in the collection period. Species belonging to the genus *Megachile* were captured later in the season. The species *Megachile rotundata* was collected on green roofs with greater height. *Apis mellifera* and *Halictus rubicundus* were not affected by the environmental variables examined.

Several of the Syrphidae subgenera were positively correlated with the presence of natural space and green space (Figure 9). The subgenus *Eristalis* was captured in high abundance later in the season and was significantly correlated with the presence of natural space. *Toxomerus* specimens were collected throughout the season and along with the sub genus *Syritta* they were found on green roofs at a greater height.

Table 7. Pollinator species and subgenera associated with green roof environmental conditions. Pollinators were captured using hand nets and bowls on 18 green roofs located in Halifax Regional Municipality, Nova scotia from June – September 2017. Associations with environmental conditions were estimated using non-metric multidimensional scaling (NMDS) ordinations (stress = 0.169). Species were only included in this table if ≥ 5 individuals were included in the NMDS ordination.

Species	**Native vs. Non-native**	**Associated Environmental Condition**
Bombus impatiens	Non-native	High Height
Megachile rotundata	Non-native	High Height
Bombus ternarius	Native	High Height
Toxomerus	N/A	High Height
Syritta	N/A	High Height
Andrena crataegi	Native	Low Height
Nomada spp.	N/A	Low Height
Andrena hippotes	Native	Low Height
Andrena wilkella	Non-native	Low Height
Andrena miserabilis	Native	Low Height

Species	Native vs. Non-native	Associated Environmental Condition
Bombus vagans	Native	Green/Natural Space
Agapostemon virescens	Native	Green/Natural Space
Halictus ligatus	Native	Green/Natural Space
Eristalis	N/A	Green/Natural Space
Bombus rufocinctus	Native	Green/Natural Space
Andrena crataegi	Native	Early Season
Nomada spp.	N/A	Early Season
Andrena wilkella	Non-native	Early Season
Andrena hippotes	Native	Early Season
Megachile melanophaea	Native	Early Season
Andrena miserabilis	Native	Early Season
Lasioglossum cressonii	Native	Early Season
Bombus impatiens	Non-native	Late Season
Megachile rotundata	Non-native	Late Season
Bombus ternarius	Native	Late Season
Eristalis	N/A	Late Season
Syritta	N/A	Late Season
Eupeodes/Epistrophe	N/A	Late Season
Megachile rotundata	Non-native	Late Season
Apis mellifera	Non-native	Minimal Influence
Halictus rubicundus	Native	Minimal Influence
Lasioglossum spp1	N/A	Minimal Influence
*Lasioglossum spp2**	N/A	Minimal Influence
Lasioglossum leucozonium	Non-native	Minimal Influence
Lasioglossum versans	Native	Minimal Influence

**Lasioglossum spp2* all belong the subgenus *Dialictus*.

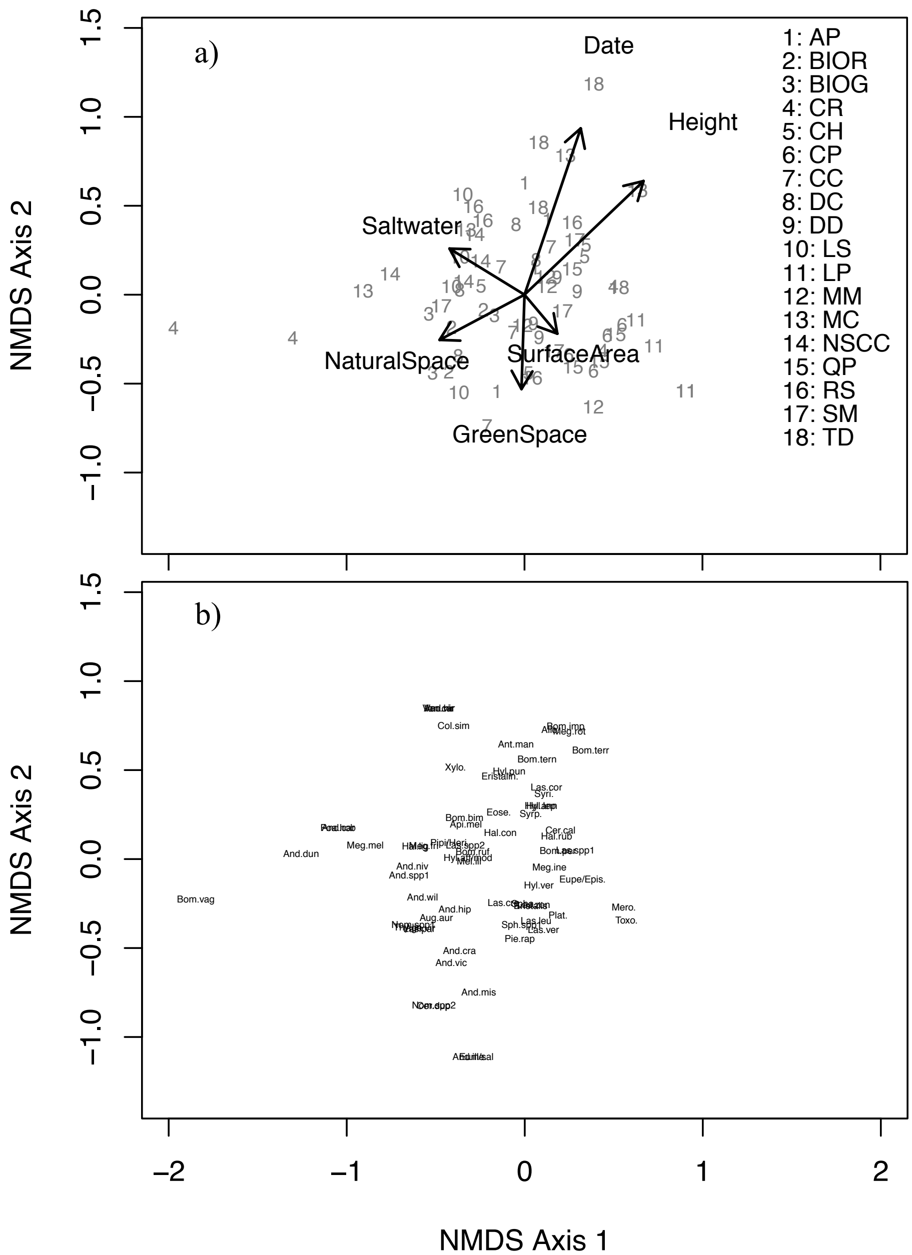

Figure 9A. Non-metric multidimensional scaling ordinations of green roofs located in the Halifax Regional Municipality NS, Canada. Environmental variables are overlain as arrows (stress = 0.169). Arrow length multiplied by two to show effect. Pollinators were captured using hand nets and bowls from June – September 2017. (a) Axes 1 – 2, sites and correlations: (b) Axes 1 – 2, pollinator species: See Table 8 for environmental variables and other correlates.

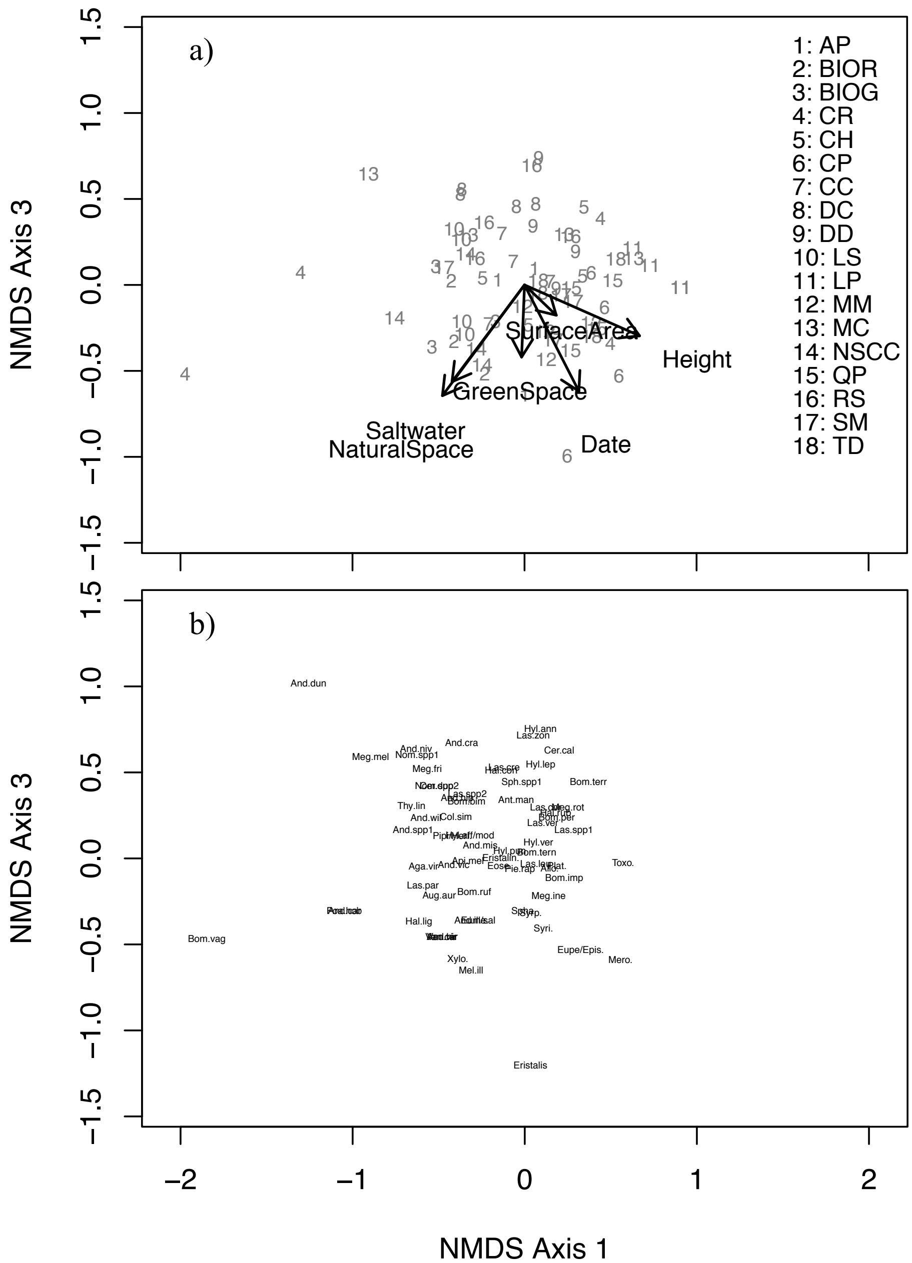

Figure 9B. Non-metric multidimensional scaling ordinations of green roofs sites located in Halifax NS, Canada. Environmental variables are overlain as arrows (stress = 0.169). Arrow length multiplied by two to show effect. Pollinators were captured using hand nets and bowls from June – September 2017. (a) Axes 1 – 3, sites and correlations: (b) Axes 1 – 3, pollinator species: See Table 8 for environmental variables and other correlates.

Table 8. Correlation between environment variables and NMDS axis scores for sites using envfit procedure, stress = 0.169 (Oksanen 2019). Pollinators were captured using hand nets and bowls on 18 green roofs located in the Halifax Regional Municipality, Nova scotia from June – September 2017.

	Axis 1	**Axis 2**	**Axis 3**	**r^2**	**P-value**
Date	0.271	0.803	-0.531	0.339	0.001
Green Roof Height	0.689	0.658	-0.305	0.236	0.002
Green Roof Surface Area	0.548	-0.652	-0.524	0.028	0.586
Saltwater Area	-0.562	0.346	-0.751	0.141	0.015
Green Space Area	-0.025	-0.784	-0.620	0.114	0.055
Natural Space Area	-0.568	-0.302	-0.766	0.177	0.005

4: Discussion

4.1: Green Roof Pollinator Community Richness, Abundance, and Composition

Green Roof Bee Community

Pollinator communities were abundant and species rich on the green roofs surveyed in Halifax Nova Scotia, demonstrating the importance of these habitat patches for urban pollinators. Despite the relatively modest sampling effort 47 bee species were observed on the surveyed green roofs and 2370 individuals collected. Other North American green roof bee studies have identified 51 species (Colla et al., 2009), 24 species (Walker, 2016), 19 species (Tonietto et al., 2011), and 17 species (MacIvor et al., 2014). The number of singletons observed was similar to other green roof bee studies (Tonietto et al., 2011). There were 833 bee specimens not identified to a species due to the difficulty identifying the subgenus *Dialictus* morphologically. When this group is further classified, my estimates of green roof bee species richness are expected to increase as this subgenus is very diverse (Gibbs, 2010).

There were 34 species of the 157 bee species that are known as native to Nova Scotia identified on the Halifax green roofs (Sheffield et al., 2003). This is similar to Walker's (2016) urban bee study also conducted in Halifax, Canada. In this study, native species represented 79% of species observed but only 30.3% of individuals collected were considered to be native. The percentage of native bee species identified in this study is similar to other North American green roof studies (Tonietto et al., 2011; Walker, 2016). However, the percentage of native individuals collected was significantly lower than previous research (Tonietto et al., 2011). In contrast to urban ground level bee communities, the percentage of native specimens collected on the surveyed green roofs was substantially lower as well (Fetridge et al., 2008; Hostetler & McIntyre, 2001;

Matteson et al., 2008). Green roof studies comparing ground level bee communities and green roof communities have previously documented rooftop habitats harboring a higher percentage of non-native bee species and individuals in comparison to ground level urban habitat (Tonietto et al., 2011; Walker, 2016). The high ratio of non-native bee species present on the studied green roofs and in the supportive literature suggests green roofs may provide resources disproportionately in favor of non-native species. It should be noted that 866 specimens that were not identified to species inflated the ratio of non-native species. Unidentified individuals were omitted from the non-native and native species ratio calculation and accounted for 36.5% of the bee specimens collected. If all of these unidentified species were classified as native the percent of natives would increase to 55.8%. Nonetheless, the high proportion of non-native individuals is an important observation that requires further examination if rooftops are to be developed for urban pollinator conservation.

Green Roof Bee Community: Common Genera and Species

The genus *Lasioglossum* was the most abundant bee genus observed on the surveyed green roofs. This genus has been consistently recognized as a common green roof bee genus (Colla et al., 2009; Kratschmer et al., 2018; Tonietto et al., 2011; Walker, 2016) and is common in other systems in Nova Scotia (Cutler et al., 2015). The second most abundant genus in this study was *Bombus* and has been previously described as an abundant green roof genus (MacIvor et al., 2014). The most common species identified in this study was *Bombus impatiens,* a non-native species to Nova Scotia and has been identified as an abundant bumble bee species in urban environments (Matteson et al., 2008) and has significantly increased in population in North America (Colla et al., 2012). One *Bombus terricola* individual was collected on Renaissance South green roof and another was observed visiting *Sedum selskianum* on the TD green roof. Walker (2016) also identified two individuals on a Halifax green roof and one at ground level. The presence of this species is significant because it has been recognized as a species in decline in North America (Colla et al., 2012) and was assigned as a species of Special Concern in 2015 by Committee on the Status of Endangered Wildlife in Canada. The high abundance of both *Lasioglossum* and *Bombus* in this study is noteworthy. Previous research has indicated green roof height may influence the community composition by acting as an environmental filter preventing the access of certain sized species (Kratschmer et al., 2018; MacIvor, 2015). However, the high abundance of these two genera indicate size may not act as a barrier preventing the access of certain sized species. The NMDS analysis also supports this claim. Both medium sized species such as *Megachile rotundata* and larger species such as *Bombus impatiens* and *Bombus ternarius* were associated with green roofs at a greater height. Additionally, *Lasioglossum* species appeared to not be influenced by the height of the green roof. This implies additional factors are influencing the presence of certain species on green roofs. The high abundance of *Bombus* observed in this study and in MacIvor et al. (2014) study may have been caused by the inclusion of *Sedum* green roofs. *Bombus* species have been documented to maximize pollen and nectar collection by prioritizing local abundant homogenous and floral dense displays (Grindeland et al., 2005; Ishii, 2006). While the large size of *Bombus* allow these insects to forage at great distances > 1 km from their nests (Cresswell et al., 2000), the larger body size requires more energy to maintain flight (Heinrich, 2004). Therefore, flying vertically to green roofs with small floral rewards would not be attractive for these species and may explain their lower abundance in other green roof studies (Colla et al., 2009; Tonietto et al., 2011; Walker, 2016). Green roofs with dense floral rewards, especially *Sedum* rooftops, would make these roofs attractive and may have resulted in the high abundance of *Bombus* species observed in this study and in MacIvor et al (2014). The high abundance of *Lasioglossum* in this study and other green roof studies maybe related to its nesting preferences (Tonietto et al., 2011). Tonietto et al (2011) suggested *Lasioglossum* may nest in green roof substrate and depend exclusively on the roof's floral recourses, due to its relatively limited flight range (Gathmann & Tscharntke, 2002; Walker, 2016).

Green Roof Bee Community: Nesting

In this study, ground nesting bee species represented 83.2% of individuals collected and cavity nesting species represented only 5.0%. An association between ground nesting species and green roofs have been observed in previous literature (Braaker et al., 2017; Kratschmer et al., 2018; Tonietto et al., 2011). Braaker et al (2017) observed a higher abundance of ground nesting species on green roofs in contrast to ground level habitat and Kratschmer et al. (2018) identified a positive correlation between fine substrate green roofs and the richness and abundance of bee communities. The high proportion of ground nesting species is abnormal for urban bee communities. Urban habitats have been repeatedly documented to benefit and support a greater abundance of cavity nesting species in contrast to ground nesting species (Cane et al. 2006; Fortel et al., 2014; Hernandez & Frankie, 2009; Matteson et al., 2008; Zanette et al., 2005). There are two potential explanations for this phenomenon. First, urban areas provide a wealth of suitable nesting substrate for cavity nesting species and second, ground nesting species are deterred from urban environments due to the high frequency of soil disturbances (Matteson et al., 2008). Green roofs may attract a high abundance of ground nesting species in contrast to ground level urban habitat due to the sandy and stony undisturbed bare substrate which is favorable for ground nesting species (Braaker et al., 2017).

To date, no research has quantified the feasibility of green roofs to provide nesting habitat for ground nesting bees. However, there have been personal observations of bees nesting in green roof substrate (Braaker et al., 2017). I also noted the presence of three different bee genera nesting in green roof substrate. However, the survivability of these nests is unknown. Rather than providing adequate nesting habitat for bees, these green roofs may act as an ecological trap. Green roof environmental conditions may seem favorable initially but due to the harsh environmental conditions such as drought and flooding commonly associated with these systems, the conditions may become hostile resulting in the abandonment of the nest or death. Additionally, if the female is foraging at ground level the constant energy spent to reach the rooftop from ground level for the provision of the brood may result in a reduction of fitness. Previous research examining cavity nesting bees has shown green roofs may act as ecological traps for individuals nesting in artificial nests (MacIvor, 2015). MacIvor (2015) found the number of abandoned nests increased as the height of the green roofs increased. Further research is needed to know if nesting in green roof substrate is an ecological trap for ground nesting bee species.

Green Roof Hover Fly Community

In total 14 subgenera (e.g. *Toxomerus, Sphaerophoria, Eupeodes/Epistrophe…*) belonging to the family Syrphidae were collected on the Halifax green roofs. Hover flies were the second most abundant pollinator assemblage collected with 670 individuals captured. Over 90% of these specimens belong to the aphidophagous subfamily Syrphinae. The larvae of this subfamily are voracious predators of Homoptera, in particular, aphids, and have been documented to be effective natural controls of aphid populations in agricultural fields (Vockeroth, 1992; Ramsden et al., 2017). The high abundance of this subfamily is significant in relation to green roof infrastructure because plants established in these novel habitats have been documented to be highly infested with aphids (Coffman & Waite, 2011; Grimshaw-Surette, 2016; Kadas, 2006). The high abundance of aphids in green roof systems is of special concern because plants infested with aphids decrease in productivity (Barlow et al., 1977). A decrease in green roof plant productivity could reduce plant cover and consequently a reduction in green roof services (Barlow et al., 1977; Speak et al., 2013). To date, the effectiveness of Syrphinae larvae to reduce aphid populations has not been quantified in green roof habitats. Nonetheless, previous research on the Saint Mary's University green roof noted a reduction in aphids following the appearance of Syrphinae larvae (Grimshaw-Surette, 2016). The high abundance of adult Syrphidae collected while feeding on green roof floral communities and the personal observations of Syrphinae larvae feeding on aphids by Grimshaw-Surette (2016) indicate green roofs can provide adequate habitat for this both life stages of this pollinator assemblage. Additionally, building managers will benefit from the presence of this beneficial insect through the reduction of pests feeding on green roof plants.

Green Roof Butterfly Community

A very small number of butterflies were captured visiting the Halifax green roofs. Only 11 individuals belonging to 5 species were collected on six of the studied 18 green roofs. Species richness and abundance were significantly lower than in other studies examining butterfly communities on green roofs (Lee & Lin, 2015; Wang et al., 2017). Lee and Lin (2015) recorded 514 individuals belonging to 12 species and Wang et al.

(2017) observed 8000 individuals belonging to 57 species (Wang et al., 2017). The differing climatic conditions and species pool between Canada and two Asian countries is the likely cause of the drastic variation in richness and abundance. Green roof butterfly communities observed in this study were comparable to ground level urban spontaneous vegetation (USV) sites previously surveyed in Halifax (Robinson & Lundholm, 2012).

Two factors may have caused the low number of butterflies surveyed on the Halifax green roofs. First, the Halifax urban landscape may not support a diverse and abundant butterfly community. In contrast to urban butterfly studies conducted in other North America cities, the Halifax green roof and USV butterfly communities were substantially lower in richness and abundance (Clark et al., 2007; Matteson & Langellotto, 2010; Robinson & Lundholm, 2012). Secondly, green roofs may provide unfavorable habitat for butterfly species. Previous research has observed a significant reduction in butterflies on green roofs in comparison to ground level park habitat (Lee & Lin, 2015). The presence of high wind speeds that are commonly associated with green roof habitat (Oberndorfer et al., 2007) could explain the reduction in the presence of butterfly species utilizing green roof habitat. The much smaller mass:surface area ratio would make butterflies much more susceptible to wind gusts in contrast to the other pollinators (Klipp & Measure, 2011). Therefore, resulting in the low number of butterflies surveyed on the Halifax green roofs.

4.2: Green Roof Floral Community

The floral communities established on the green roofs examined in this study were very species rich. A total of 168 plant species belonging to 36 different families were recording flowering on the 18 studied green roofs. It is important to note graminoids and other wind pollinated plant species were omitted from this study. The inclusion of these plant species would further increase the plant richness observed on the green roofs. Surveys of green roof plant communities have recorded 176 species on 115 green roofs in France (Madre et al., 2014), 67 species on two green roofs in the United Kingdom (Bates et al., 2013), and 109 species on five green roofs in Canada (MacIvor & Lundholm, 2011).

Green roof floral communities were more species rich than ground level USV and lawn communities previously surveyed in Halifax (Robinson & Lundholm, 2012). After excluding wind pollinated plant species and forest sites, Robinson and Lundholm (2012) identified 110 species at the 16 ground level sites examined. Average site richness ranged from 13 to 22, with an overall average of 14.7 ± 2.8 (Robinson and Lundholm, 2012). Of the 18 studied green roofs, site richness ranged from 6 to 50, with an average of 28.1 ± SE = 3.0. It is important to note for Robinson and Lundholm (2012) study, twelve 1 m^2 quadrats were used to assess vegetation species richness at each of the USV sites. Site richness in this green roof study encompassed the whole roof and was not limited to plot boundaries. Therefore, the higher floral richness on the green roofs could be explained by the species-area relationship. Nonetheless, Halifax green roofs have been documented to support greater plant richness in comparison to ground level sites previously (MacIvor & Lundholm, 2011). In MacIvor and Lundholm's (2011) study, 109 plant species were identified on the green roofs and 89 species were identified at ground level (MacIvor & Lundholm, 2011). Green roofs are commonly associated with lower values of plant richness in contrast to ground level systems due to the extreme environmental conditions caused by the shallow substrate (Berardi et al., 2014; Tonietto et al., 2011). However, when comparing this green roof study to Robinson and Lundholm's (2012) urban ground level study the opposite was observed. One potential reason is due to the functional variety of the green roofs examined in this study. Green roofs surveyed included turf dominated recreational roofs, green roofs with community gardens, rooftop ornamental gardens, native green roofs, spontaneous vegetation green roofs, and sedum mat roofs. Due to the range in roofs surveyed ornamental plants such as *Gladiolus* x *hortulanus* and *Phlox subulata*, agricultural species such as *Vaccinium angustifolium* and *Coriandrum sativum*, coastal barren plant species such as *Rhodiola rosea* and *Solidago sempervirens*, weedy species such as *Ranunculus repens* and *Taraxacum officinale*, stonecrop species such as *Sedum acre* and *Sedum album*, shrub species such as *Rhododendron gloria mundi* and *Gaylussacia baccata*, and tree species such as *Prunus spp*. and *Cydonia oblonga* were recorded on the Halifax green roofs. Photos showing the range of green roofs can be found in Figure 10.

Another potential explanation for the high species richness is the variation in substrate depth and maintenance of the green roofs examined in this study. This study encompassed 12 extensive and 6 intensive green roofs. The average species richness for extensive green roofs was 25 ± SE = 3.6, and 34 ± SE = 5.2 for intensive roofs. Intensive green roofs have been documented to harbour a greater richness of plant species in contrast to intensive green roofs (Berardi et al., 2014; Oberndorfer et al., 2007). Due to the increased soil depth, intensive green roofs have a lower risk of drought and can support a plant community similar to ground level with proper maintenance (Oberndorfer et al., 2007; Olly et al., 2011). The inclusion of these intensive green roofs and others in this study resulted in the observation of drought susceptible species and tree/shrub species that are typically not present on green roof infrastructure.

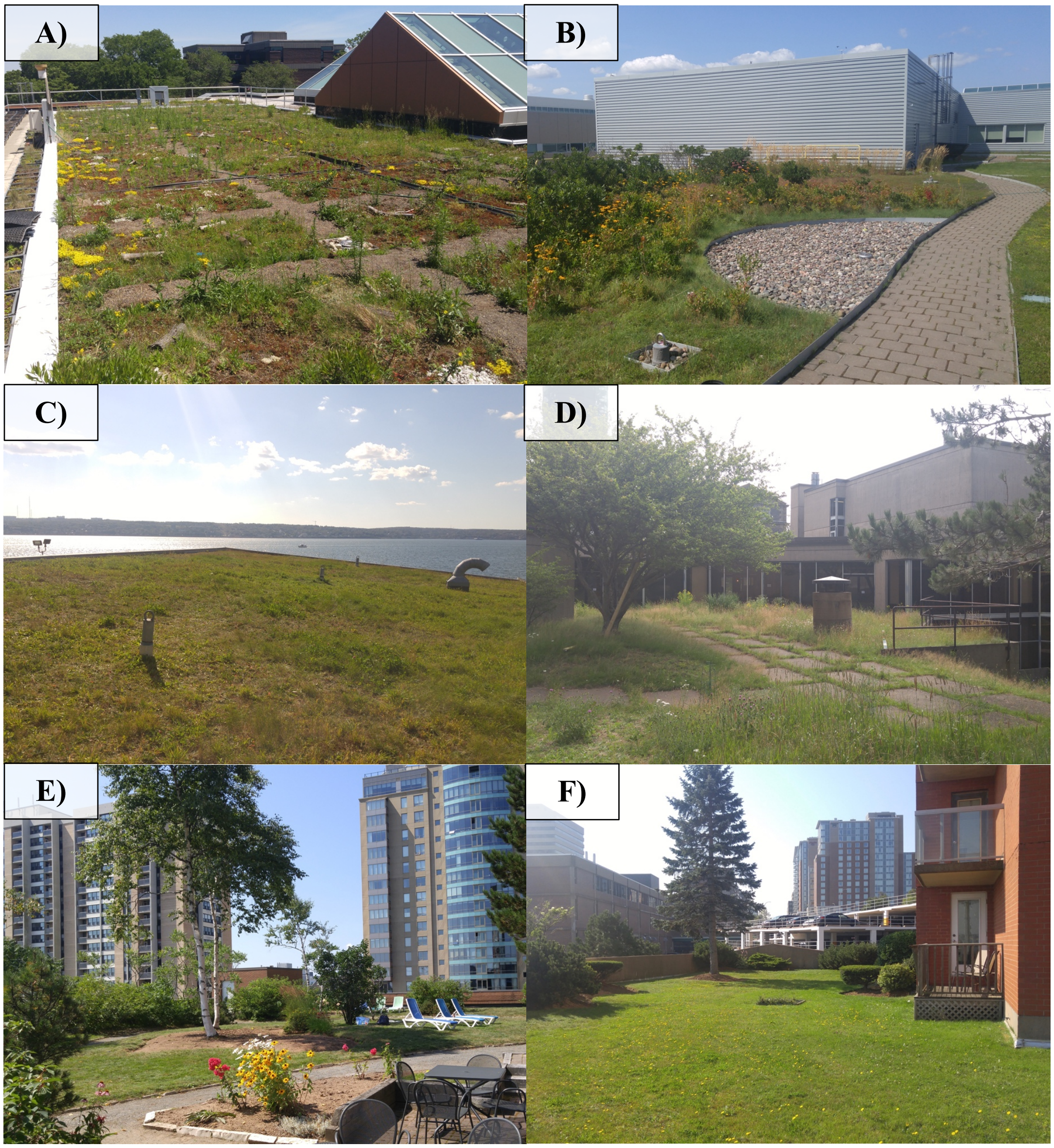

Figure 10. Photos of six of the 18 green roofs in which pollinators were surveyed from June to September 2017 within the Halifax Regional Municipality NS, Canada. A) Saint Mary's University, B) NSCC Ivany Campus, C) Bedford Institute of Oceanography 1, D) Dalhousie Life Science Courtyard, E) Charter House Condominiums, F) Cunard Court

It is important to note the characteristics of the three most florally rich green roofs due to the large number of plant species established. In total, 97 different species (57% of the total number of species observed) were recorded on the three most florally rich green roofs. The Dalhousie Life Science Courtyard (50 species) was an intensive green roof with deep substrate. This green roof was likely less environmentally harsh due to the close proximity to ground level and protection provided by the facades of adjacent buildings that encompassed the majority of the roof. The vegetation on this green roof was not mowed and was left to stabilize naturally. The deep substrate, assumed low environmental stress, and the absence of mowing allowed the establishment of a greater range of floral resources on this green roof (Berardi et al., 2014; Politi et al., 2012). The second most florally rich green roof was the Charter House Condominiums (49 species) an intensive rooftop garden. On a weekly basis, gardeners maintained and watered this green roof garden allowing the establishment of a variety of ornamental species observed. Similarly, the NSCC Ivany Campus extensive green roof, which also had 49 species, required regular watering to permit the survival of several of the species present on the green roof. It is important to note that high levels of management allowed for the persistence of the floral richness recorded on the NSCC Ivany Campus and Charter House Condominiums green roofs. Photos of all three green roofs can be found in Figure 10.

4.3: Pollinator and Floral Interactions

Native and Non-native

The high abundance of non-native bees collected on the studied green roofs may be related to the high percentage of non-native plant species (74.4% non-native) established on the surveyed green roofs. A study examining the pollen loads of bees visiting green roofs discovered the pollen loads of non-native bee species contained significantly more non-native *Sedum* pollen in comparison to native bee species (MacIvor et al., 2014). This implies *Sedum* which is a common non-native green roof plant species may disproportionately benefit non-native bee species and consequently alter bee community composition (MacIvor et al., 2014). Studies conducted in other systems at ground level have also shown native bee species tend to prefer native floral communities and generalist non-native pollinators to be frequent visitors of non-native species (Morandin & Kremen, 2013; Pardee & Philpott, 2014; Richardson et al., 2000). For this study, the top two most visited plant genera, *Leontodon* and *Sedum,* are not native to Nova Scotia and together represent 28.6% of total pollinator capture. The top three most abundant bee species found feeding on the green roof floral communities were also non-native generalist species: *Bombus impatiens* (n = 563), *Lasioglossum leucozonium* (n = 172) and *Apis mellifera* (n = 170) (Vaudo et al., 2016; Zayed, 2006). While pollinator-plant networks were not analyzed in this study, these two observations in conjunction with the supportive literature suggests the high ratio of non-native bee species may be related to the high occurrence of non-native species present on the green roofs.

Spontaneous Vs. Planted Floral Richness

Spontaneous floral richness was the strongest predictor of species richness for hover fly and total pollinator communities. The importance of spontaneous vegetation is also emphasised by the number of pollinators visiting these genera. Six of the top 10 most visited floral genera were categorised as spontaneous colonisers and these six genera were responsible for 43.8% of total capture by nets. The relative importance of spontaneous species observed in this study coincides with prior research in both green roof habitat (Wang et al., 2017) and in ground level habitats (Nicholls & Altieri, 2012; Robinson &

Lundholm, 2012; Sivakoff et al., 2018). Wang et al. (2017) found the best predictor of butterfly diversity, abundance, and richness was the richness of spontaneous plant species that colonised the examined rooftop gardens. In agricultural systems, spontaneous plant species or "weeds" have been long understood to be important factors for promoting pollinator species richness and abundance (Benedek 1972; Lagerlöf et al., 1992; Nicholls & Altieri, 2012). More recently, urban vacant lots colonized by spontaneous vegetation have been recognised as a valuable pollinator habitat and support high values of pollinator species richness (Robinson & Lundholm, 2012; Sivakoff et al., 2018). These vacant/undisturbed lots have been documented to support greater bee species richness and abundance in contrast to other urban habitats such as conventional planted ornamental gardens (Tommasi et al., 2004). Due to their inaccessibility to the general public, green roofs are not subjected to negative social pressures associated with spontaneous vegetation sites in urban areas (Nassauer & Raskin, 2014) and represent an excellent opportunity to provide pollinator habitat that is colonized by spontaneous plant species.

As green roof systems age they will increase in plant richness through spontaneous colonization if these "weedy" species are not removed (Dunnett et al., 2008; Köhler, 2006). The significant effect of spontaneous floral richness on the richness of the green roof pollinator communities emphasizes these floral species should be allowed to become established on green roofs unless the species can outcompete other species present or damage the rooftop lining (Köhler, 2006). For turf dominated green roofs reductions in mowing frequencies is one method to increase the spontaneous floral resources (Lerman et al., 2018). This will not only increase beneficial food resources for pollinators but also decrease the cost associated with green roof management. The Dalhousie Life Science Courtyard green roof is a great example of this. The absence of mowing over the previous years allowed this green roof to flourish with floral richness and consequently pollinator richness and abundance. I did not observe the perceived improvement of the pollinator community due to the study's limited duration. However, reductions in mowing frequencies have been shown to increases pollinator habitat and improve pollinator communities in ground level urban systems (Garbuzov et al., 2015; Lerman et al., 2018; Wastian et al., 2016). Spontaneous plant genera observed in this study such as *Solidago, Symphyotrichum, Trifolium*, *Centaurea,* and *Daucus* have been recognised as attractive pollinator species in other studies (Fründ et al., 2010; Garbuzov & Ratnieks, 2014; Hennig & Ghazoul, 2011; Sivakoff et al., 2018). These genera in addition to the other popular spontaneous genera observed in this study, are important genera that should be allowed to establish on green roofs for the floral resources they provide pollinator communities.

In contrast to the other pollinator communities, bee richness was more highly influenced by the presence of planted species richness. However, the surface area of the floral display was still the strongest predictor of bee richness. Four of the top 10 most visited species were categorised as planted in this study. The genus *Sedum* was the second most visited genus overall and was the most visited genus by bees. This common green roof plant genus has been previously documented as a valuable floral resource for bees (Garbuzov & Ratnieks, 2014; Kratschmer et al., 2018; MacIvor et al., 2014). Due to its drought resistance, this genus is an excellent green roof plant that can provide valuable floral resources especially, when mixed with other floral species (Kratschmer et al., 2018; MacIvor et al., 2014). Many other attractive planted species were observed on the studied green roofs. Planted genera such as *Thymus, Allium, Hydrangea, Echinacea,* and

Rudbeckia, have been repeatedly acknowledged as pollinator friendly entomophilous plants (Garbuzov & Ratnieks, 2014; Martins et al., 2017; Sivakoff et al., 2018).

4.4: Influence of Green Roof Characteristics on Pollinator Communities

Overall Green Roof Pollinator Community

Several green roof characteristics were identified to influence species richness and abundance of pollinator communities. These characteristics can be used to develop more pollinator friendly green roofs. Green roof floral characteristics such as the number of flowering plant species, floral display surface area, and percent of natural space within a 500 m radius were all identified as strong positive predictors of green roof pollinator communities. Green roof height was identified as a strong negative predictor of pollinator communities. Not all green roof characteristics were strong predictors of pollinator communities. Green roof surface area was a weak predictor and green space had no influence on pollinator communities. There were some variations in the influence of green roof characteristics on the different pollinator assemblages examined.

Due to limited site selection there was a cluster of sites located in the South End of Halifax. The site characteristics of these green roofs were diverse and despite being in close proximity, the richness and abundance of the green roof pollinator communities varied drastically in response to the independent variables. The results from the NMDS analysis supports this.

Green Roof Bee Community

Green roof floral richness and floral surface area were both positive and the strongest predictors of richness and abundance of the bee communities visiting the green roofs. Similar findings have been concluded in other green roof studies (Kratschmer et al., 2018; Tonietto et al., 2011) and in ground level studies (Ebeling et al., 2008; Grindeland et al., 2005; Sih & Baltus, 1987). Kratschmer et al (2018) found a positive relationship between green roof forage availability and the richness and abundance of green roof bee communities in Austria. Tonietto et al (2011) observed that the most florally rich green roofs supported the greatest number of bee species. The positive influence of site level green roof floral richness and display area on bee species richness and abundance observed in this study and others supports the notion that urban pollinator species richness could be increased with small scale plantings of rich floral communities (Blackmore & Goulson, 2014; Hülsmann et al., 2015).

Another positive predictor of the green roof bee community was the percent area of natural space within a 500 m radius of the green roof. Other studies have also documented a positive relationship between pollinator communities and the proportion of vegetated surfaces within urban landscapes (Braaker et al., 2014; Braaker et al., 2017; Hennig & Ghazoul, 2011; Tonietto et al., 2011). However, many studies do not distinguish green space and natural space (Hernandez & Frankie, 2009; Tonietto et al., 2011). This study provides further evidence that urban bee studies should differentiate green space into naturalized space and overall green space (Hernandez & Frankie, 2009; Tonietto et al., 2011). Without this differentiation, the proportion of vegetated surfaces within a 500 m radius would not have been identified as a positive predictor of bee richness or total pollinator subgenera richness. Similar findings were observed by Tonietto et al (2011). They concluded if green space was not differentiated, a negative relationship would have been observed for their urban park sites. It was believed that the large surface area of frequently mowed turf grass which provides minimal resources for bees was the cause of the negative relationship (Tonietto et al., 2011). Likewise, the absence of a relationship between green space and pollinator communities observed in this study may have been caused by the large amount of urban green space dominated by turf grass (Lerman et al., 2018). Another possible factor responsible for the lack of a relationship between green space and the pollinator communities is the high proportion of street tree canopy that compromises Halifax's green space. The percent cover of tree canopy in Halifax is neighborhood dependent and ranges from 4 to 27%, with the majority of these values exceeding 20% of the total land coverage (Halifax Regional Municipality, 2013). The tree canopy in Halifax is dominated by three species, Norway Maple (*Acer platanoides*), American Elm (*Ulmus americana*), and Silver Linden (*Tilia tomentosa*) (Halifax Regional Municipality, 2013). *Ulmus americana* is typically wind pollinated (Marks, 2017). Therefore, this species would provide little floral resource for pollinator communities. In contrast, both *Tilia tomentosa* and *Acer platanoides* provide high quality and abundant floral resources when in flower (Hausmann et al., 2016; Jacquemart et al., 2018; Koch & Stevenson, 2017). However, the capacity for these tree species to provide floral resources is limited to the flowering duration and the remainder of the year these abundant street tree canopy species would provide no food resources for pollinators. Therefore, the large amount of turf grass green space and street tree canopy may have been the cause for the absence of a relationship between green space and pollinator community variables. This study demonstrates the importance of natural space for overall pollinator and bee richness in urban areas and the need to differentiate urban green space when examining urban pollinator communities.

Two green roof characteristics, green roof height and surface area, were identified as negative predictors of the bee community (richness and abundance). The negative relationship between height and bee communities indicates that as green roofs increase in height, they become isolated from ground level habitat (MacIvor, 2015). A negative relationship between green roof height and bee communities has been previously described for cavity nesting bee species in Toronto (MacIvor, 2015). As the building height increased the abundance of brood cells decreased in artificial nesting boxes (MacIvor, 2015). However, other research has concluded height had no negative influence on the bee community in Vienna (Kratschmer et al., 2018). Nonetheless, this study indicates as green roofs increase in height their ability to provide habitat for bee communities is reduced.

Interestingly, green roof total surface area was a strong negative predictor of bee richness and had no influence on bee abundance. This opposes the species-area relationship, which states the number of species tends to increase with area (Connor & McCoy, 1979; Madre et al., 2013). Contrary to the results of this study, other studies have found the size of a green roof had a positive effect on hymenopteran species richness (Madre et al., 2013) and neutral effect on bee richness (Braaker et al., 2017). The negative relationship observed in this study may be due to the limited site selection of green roofs in Halifax. The two largest green roofs examined, Quinpool Tower (3328 m^2) and Dalhousie Dentistry green roof (1412 m^2) were both turf dominated green roofs. These roofs were substantially larger than the average green roof size (630 m^2). While floral richness was relatively average for these roofs, the majority of floral richness was attributed to individual plants and with limited floral availability. This was especially evident for the Quinpool Tower green roof. To test if these two roofs caused the observed negative relationship, these two sites were removed from the multiple linear regression analysis. When these green roofs were removed, green roof surface area was deemed to have no influence on bee species richness. Therefore, the inclusion of these two significantly larger green roofs with low floral richness and availability of floral resources were the probable cause of the negative relationship observed.

Hover Fly Community

Only three of six green roof characteristics were determined to have an influence on hover fly communities. Identical to the bee communities, floral richness was a positive and the strongest predictor of hover fly species richness. Studies examining hover flies in other systems at ground level have also observed a positive relationship (Fründ et al., 2010; Meyer et al., 2009) and a neutral relationship (Ebeling et al., 2008). This study observed no relationship between floral richness and hoverfly abundance. Additionally, hover fly abundance was not influenced by floral richness or floral display surface area. These findings contradict several studies that observed that number of hover fly visitations was positively influenced by the floral richness and the availability of floral resources (Blaauw & Isaacs, 2014; Ebeling et al., 2008; Hegland & Boeke, 2006). The lower influence of the floral community on hover fly community in comparison to the bee communities examined is intriguing and may be explained by the different habitat requirements of the larval stage of hover flies. Meyer et al. (2009) found floral resources and adequate habitat directly influenced the presence of hover fly density for the larval stage of hover flies. This study did not consider the requirements of the larval stage of hover flies. With such a high abundance of aphidophagous species, their presence is probably more strongly influenced by the presence of aphids for the larval stage of their life cycle. The high abundance of aphidophagous species may also explain the why the surface area of green roofs was the strongest and only predictor of hoverfly abundance. Larger green roofs would be able to provide more adequate prey for the larval stage of these hover flies.

Butterfly Community

The influence of green roof characteristics on butterfly communities were not examined due to the small number of specimens collected. While this study did not statistically test the influence of floral species, this green roof characteristic appeared to have an important influence on the presence of butterflies. The three most floral diverse green roofs had the greatest butterfly richness and abundance. A positive relationship between green roof floral species richness and butterfly species richness and abundance has been documented in other studies (Lee & Lin, 2015; Wang et al., 2017).

Future Green Roof Characteristics to Examine

The age of a green roof is an important green roof characteristic that was omitted from this study due to the limited site selection. Previous studies have documented that the age of a green roof had no influence on the bee communities visiting green roofs (Braaker et al., 2017; Kratschmer et al., 2018) and a positive influence on butterfly abundance (Lee & Lin, 2015). The significant influence of spontaneous plant species richness on the pollinator communities observed in this study indicates this green roof characteristic should be analyzed in the future. The increase in spontaneous colonization of floral species associated with increases in age (Dunnett et al., 2008; Köhler, 2006) may be the underlining cause of the observed positive influence of green roof age on butterflies (Lee & Lin, 2015). In Lee and Lin's (2015) study, they observed green roofs older than 38 months plateaued and butterfly abundance stabilized. A green roof study that controls for site maintenance and an emphasis on newly constructed sites would be essential to determine the optimal green roof age for bee and hover fly communities.

4.5: Importance of Floral Communities on Green Roof Pollinator Communities

Green roof floral characteristics were the strongest predictors of all the pollinator response variables examined, with the exception of the hover fly abundance. This provides empirical evidence that expresses the importance to design green roof floral communities with both high values of floral species richness and floral display area. This finding is the most important result of this study because industrial standard green roofs are commonly propagated with monocultures belonging to the genus *Sedum* and green roof bylaws that mandate the construction of green roofs on new buildings typically do not set a minimum number of plant species. A green roof floral community with high species richness is important for supporting diverse pollinator communities for the following three reasons. First, a greater diversity of flowering plants has more flowering morphology variation and can meet the requirements of differing pollinator feeding appendages (Goulson, 1999). Second, bee species require different quantities of nutrients for the rearing of their young and a greater diverse floral community can provide pollen and nectar nutritional needs of multiple bee species (Blüthgen & Klein, 2011; Ebeling et al., 2008; Potts et al., 2004). Finally, bee species forage as adults at different times of the year and a more diverse floral community with differing flowering phenologies will provide more food resources throughout time, providing food resources for multiple bee species (Ebeling et al., 2008). In regards to green roof floral display area, a more floral abundant community would be able to provide more resources and would sequentially be more attractive to pollinators, resulting in a higher number of visitations (Grindeland et al., 2005; Sih & Baltus, 1987).

The habitat value of the industrial standard green roof, *Sedum* mat roofs, can be drastically improved by increasing their floral richness. *Sedum* roofs are typically florally dense but due to the homogeneity of the floral resources, these roofs would not be able to support as rich of a pollinator community. This relationship was observed on the TD building green roof. This relatively low florally rich *Sedum* green roof had the highest average floral display surface area of all the studied green roofs and had the second highest capture of pollinators during a single sample session when *Sedum selskianum* was flowering. However, only 7 bee species were collected on this green roof throughout the entire study. In addition, *Sedum spp.* typically have narrow flowering phenology. When these species are not in flower, these roofs would provide very little floral resources for pollinators. This could be detrimental for pollinators because the NMDS analysis indicated significant changes in the abundance of species during the summer months. Several species were in high abundance in the early part of the season when *Sedum spp.* would not be in flower. Similarly, Kratschmer et al (2018) found that *Sedum spp.* provided a wealth of floral resources in midseason, but earlier season bee species relied exclusively on green roof herbaceous garden plant species and spontaneous flora that colonized the surveyed green roofs. The need for floral resources outside of *Sedum spp.* flowering phenologies observed in this study and in Kratschmer et al. (2018) study stresses the importance that green roofs should be not propagated exclusively with *Sedum* monocultures. Rather a mixture of *Sedum* and other flowering plant species with a variety of blooming phenologies is needed to optimize the green roof's ability to support pollinator communities in the urban environment.

Designing green roofs that are floral species rich and resource abundant, especially on extensive green roof systems, presents many challenges. Plants selected for extensive green roof propagation must be able to survive the harsh environmental stresses associated with green roofs (Oberndorfer et al., 2007). Plants established on green roofs experience extreme drought and flooding conditions, as well as high solar radiation and wind speeds (Oberndorfer et al., 2007). One potential approach to increase plant species richness on extensive green roofs is the alteration of green roof substrate. This method proposes the addition of pebble piles, logs, and redistribution of the substrate to alter microsite conditions (Walker & Lundholm, 2018). Another method is the habitat template approach, which can be used to increase plant species pools for extensive green roof propagation (Lundholm, 2006; Lundholm & Walker, 2018). This concept suggests examining local habitats with similar environmental stressors as green roofs and utilizing these habitats as a source for green roof plant section (Lundholm, 2006). For the studied Halifax green roofs, coastal heathlands represents an excellent local source for plant selection (Lundholm & Walker, 2018). A recent review of the habitat approach has determined that this method has shown success for some plant species and represents a successful method to sift out potential local green roof plant species (Lundholm & Walker, 2018).

5: Conclusions

As human populations increasingly become urbanized and pollinator friendly rural environments are becoming threatened, providing pollinator habitat in urban areas is becoming increasingly important. The high values of species richness and abundance observed in this study and others indicate green roof infrastructure can provide valuable floral and nesting resources for insect pollinators. Green roof infrastructure can be complemented with ground level naturalized areas to further improve urban pollinator communities. The development of vegetated roof tops provides a unique opportunity for public engagement with the provision of valuable pollinator resources in urban areas. The development of the green roofs will not only benefit pollinators, as a wide range of ecosystem services will also be the consequence of increasing green roof infrastructure in urban areas.

This study identified several green roof characteristics that influence green roof pollinator habitat value. Green roof floral species richness was identified as a positive and the strongest predictor of hoverfly richness and total pollinator richness, and floral display surface area was determined as a positive and the strongest predictor of bee richness, bee abundance, and total pollinator abundance. The strongest predictor of hoverfly abundance was the total green roof surface area. Green roof height was a negative predictor of bee richness, bee abundance, hoverfly richness, total pollinator richness, and total pollinator abundance. Features of the urban landscape were also found to influence pollinator communities. While overall green space was deemed to have no effect on the pollinator communities, the percent cover of natural space was a positive predictor of bee and total pollinator richness.

These green roof characteristics should be implemented into green roof policies to insure green roofs are optimized to support pollinator communities in urban environments. This study proves that green roof bylaws mandating green roof construction need to include a minimum standard of floral species richness and floral abundance. The industrial standard green roofs, *Sedum* roofs are not sufficient to support a species rich pollinator community and these roofs can be significantly improved with the addition of other drought tolerant plant species. These green roof plant communities must include species with early and late flowering phonologies to provide pollinators with consistent floral resources outside *Sedum* flowering times. Modifications to green roof substrate and selecting plant species from local habitats with similar environmental stressors is one potential way to increase green roof floral richness. In this study's region, rearing coastal heathland plant species for green roof propagation is a promising option. Additionally, allowing spontaneously colonized floral species to establish on green roof systems can also significantly improve green roof pollinator communities. Plant species belonging to the genera, *Solidago, Trifolium,* and *Leontodon* are attractive entomophilous plants and are great examples of genera that should be left to establish. Green roof policies should also emphasize the construction of green roofs at lower heights. These lower height green roofs will be able to support a more species rich and abundant pollinator communities in contrast to green roofs at greater heights. In addition, it is important to include a variety of early flowering species on these low height green roofs due to the high abundance of individuals belonging to the genus *Andrena* that were associated with these roofs. Following these outlined characteristics will allow green roofs to be developed that are more pollinator friendly and sequentially resulting in a more pollinator diverse urban landscape.

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Appendix

Table A1. Detailed location of the green roof sites in which the pollinator communities were surveyed from June – September, 2017.

Site	Address	Latitude/Longitude
Admiralty Place	1 Prince St, Dartmouth	44°39'50.2", 63°34'00.7"
Bedford Institute of Oceanography 1	399 Baffin Blvd, Dartmouth	44°41'01.9", 63°36'47.7"
Bedford Institute of Oceanography 2	1 Challenger Dr, Dartmouth	44°41'05.8", 63°36'45.8"
Charles St green roof	6033 Charles St, Halifax	44°39'11.0", 63°35'41.4"
Charter House Condominiums	1465 Brenton St, Halifax	44°38'30.5", 63°34'40.1"
Coburg Place	6369 Coburg Rd, Halifax	44°38'17.0", 63°35'46.5"
Cunard Court	2065 Brunswick St, Halifax	44°39'09.6", 63°34'47.4"
Dalhousie Chemistry Building	6274 Coburg Rd, Halifax	44°38'15.1", 63°35'30.5"
Dalhousie Dentist Building	5981 University Ave, Halifax	44°38'20.3", 63°35'06.8"
Dalhousie Life Science Courtyard	1355 Oxford St, Halifax	44°38'09.2", 63°35'39.3"
LeMarchant Place	1246 LeMarchant St, Halifax	44°38'09.2", 63°35'23.8"
Marion McCain	6135 University Ave, Halifax	44°38'15.6", 63°35'23.0"
Mona Campbell	1457 LeMarchant St, Halifax	44°38'19.6", 63°35'26.2"
Nova Scotia Community College, Ivany Campus	80 Mawiomi Pl, Dartmouth	44°39'13.1", 63°33'03.7"
Quinpool Towers	2060 Quingate Pl, Halifax	44°38'48.2", 63°35'39.0"
Renaissance South	1313 Barrington St, Halifax	44°38'31.7", 63°34'13.8"
Saint Mary's University	923 Robie St, Halifax	44°37'56.1", 63°34'53.3"
TD Building	1785 Barrington St, Halifax	44°38'54.3", 63°34'27.6"

Table 2A. List of all flowering plant species observed on the 18 green roofs surveyed in Halifax Nova Scotia, 2017. List excludes graminoids and conifers. Native ranking is defined by the Atlantic Canada Conservation Data Center.

Family	**Genus**	**Species**	**Native vs. Non-native**
Anacardiaceae	*Rhus*	*typhina*	Native
Apiaceae	*Coriandrum*	*sativum*	Non-native
	Daucus	*carota*	Non-native
Asparagaceae	*Hosta*	*spp. 1*	Non-native
		spp. 2	Non-native
Asteraceae	*Achillea*	*millefolium*	Native
	Anaphalis	*margaritacea*	Native
	Centaurea	*nigra*	Non-native
	Coreopsis	*lanceolata*	Non-native
	Crepis	*capillaris*	Non-native
		tectorum	Non-native
	Echinacea	*purpurea*	Non-native
	Erigeron	*annuus*	Native
		canadensis	Native
		strigosus	Native
	Euthamia	*graminifolia*	Native
	Galinsoga	*quadriradiata*	Non-native
	Hieracium	*caespitosum*	Non-native
		x flagellare	Non-native
		kalmii	Native
		lachenalii	Non-native
		pilosella	Non-native
		piloselloides	Non-native
		sabaudum	Non-native
		spp. AP	N/A
		spp. BIOG	N/A
		spp. LS	N/A
		spp. NSCC	N/A
		spp. SM	N/A
	Lactuca	*serriola*	Non-native
	Leontodon	*autumnalis*	Non-native
	Leucanthemum	*vulgare*	Non-native
	Leucanthemum	*x superbum*	Non-native
	Monarda	*didyma*	Non-native
	Rudbeckia	*hirta*	Non-native

Family	Genus	Species	Native vs. Non-native
Asteraceae	*Senecio*	*viscosus*	Non-native
		vulgaris	Non-native
	Solidago	*bicolor*	Native
		canadensis	Native
		juncea	Native
		nemoralis	Native
		rugosa	Native
		sempervirens	Native
		spp.	N/A
	Sonchus	*arvensis*	Non-native
		asper	Non-native
		oleraceus	Non-native
		spp.	Non-native
	Symphyotrichum	*lateriflorum*	Native
		novi-belgii	Native
	Tagetes	*erecta*	Non-native
	Taraxacum	*officinale*	Non-native
Begoniaceae	*Begonia*	*x semperflorens-cultorum*	Non-native
Berberidaceae	*Berberis*	*thunbergii*	Non-native
Boraginaceae	*Myosotis*	*discolor*	Non-native
	Myosotis	*spp. LS*	N/A
	Myosotis	*stricta*	Non-native
	Pulmonaria	*saccharata*	Non-native
Brassicaceae	*Arabidopsis*	*thaliana*	Non-native
	Barbarea	*vulgaris*	Non-native
	Brassica	*rapa*	Non-native
	Capsella	*bursa-pastoris*	Non-native
	Erysimum	*cheiranthoides*	Non-native
		hieraciifolium	Non-native
	Hesperis	*matronalis*	Non-native
	Raphanus	*sativus*	Non-native
	Rorippa	*palustris*	Native
Campanulaceae	*Campanula*	*rotundifolia*	Native
Caprifoliaceae	*Viburnum*	*plicatum ssp. tomentosum*	Non-native
Caryophyllaceae	*Cerastium*	*fontanum*	Non-native
		tomentosum	Non-native
	Minuartia	*groenlandica*	Native
Caryophyllaceae	*Sagina*	*procumbens*	Native
	Stellaria	*graminea*	Non-native
Celastraceae	*Euonymus*	*europaeus*	Non-native

Family	Genus	Species	Native vs. Non-native
Clusiaceae	*Hypericum*	*perforatum*	Non-native
Crassulaceae	*Hylotelephium*	*spectabile*	Non-native
	Rhodiola	*rosea*	Native
	Sedum	*acre*	Non-native
		album	Non-native
		floriferum	Non-native
		forsterianum	Non-native
		kamtschaticum var. ellacombianum	Non-native
		selskianum	Non-native
		sexangulare	Non-native
		spurium	Non-native
Ericaceae	*Gaylussacia*	*baccata*	Native
	Rhododendron	*gloria mundi*	Non-native
	Vaccinium	*angustifolium*	Native
Fabaceae	*Lotus*	*corniculatus*	Non-native
	Medicago	*lupulina*	Non-native
	Trifolium	*arvense*	Non-native
		campestre	Non-native
		hybridum	Non-native
		pratense	Non-native
		repens	Non-native
	Vicia	*cracca*	Non-native
Geraniaceae	*Erodium*	*cicutarium*	Non-native
	Geranium	*robertianum*	Native
		spp.	Non-native
Hydrangeaceae	*Hydrangea*	*paniculata*	Non-native
Iridaceae	*Gladiolus*	x *hortulanus*	Non-native
	Iris	*germanica*	Non-native
	Sisyrinchium	*montanum*	Native
		spp.	N/A
Lamiaceae	*Ajuga*	*reptans*	Non-native
	Lamium	*maculatum*	Non-native
	Lavandula	*angustifolia*	Non-native
	Mentha	*arvensis*	Native
	Origanum	*vulgare*	Non-native
	Prunella	*vulgaris*	Native
	Salvia	*spp.*	Non-native
	Thymus	*praecox*	Non-native
Liliaceae	*Allium*	*schoenoprasum*	Native

Family	Genus	Species	Native vs. Non-native
Liliaceae	*Hemerocallis*	*lilioasphodelus*	Non-native
	Hemerocallis	*spp. 1*	Non-native
	Hemerocallis	*spp. 2*	Non-native
	Hemerocallis	*spp. 2*	Non-native
	Tulipa	*spp.*	Non-native
Linaceae	*Linum*	*catharticum*	Non-native
Malvaceae	*Malva*	*moschata*	Non-native
Oleaceae	*Forsythia*	*spp.*	Non-native
	Syringa	*vulgaris*	Non-native
Onagraceae	*Epilobium*	*ciliatum*	Native
	Oenothera	*biennis*	Native
Orchidaceae	*Spiranthes*	*cernua*	Native
Oxalidaceae	*Oxalis*	*stricta*	Native
Polemoniaceae	*Phlox*	*subulata*	Non-native
	Phlox	*spp.*	Non-native
Polygonaceae	*Polygonum*	*persicaria*	Non-native
Portulacaceae	*Portulaca*	*oleracea*	Non-native
Ranunculaceae	*Aquilegia*	*canadensis*	Non-native
	Ranunculus	*repens*	Non-native
Rosaceae	*Alchemila*	*spp.*	Non-native
	Cotoneaster	*spp.*	Non-native
	Cydonia	*oblonga*	Non-native
	Dasiphora	*fruticosa*	Native
	Fragaria	*virginiana*	Native
	Potentilla	*argentea*	Non-native
		canadensis	Native
		norvegica	Native
		recta	Non-native
		simplex	Native
	Prunus	*spp. 1*	Non-native
		spp. 2	Non-native
	Rosa	*multiflora*	Non-native
		rugosa	Non-native
		spp.	Non-native
		virginiana	Native
	Rubus	*idaeus*	Native
	Sibbaldiopsis	*tridentata*	Native
	Spiraea	*japonica*	Non-native
Saxifragaceae	*Heuchera*	*spp.*	Non-native
Scrophulariaceae	*Buddleja*	*davidii*	Non-native

Family	Genus	Species	Native vs. Non-native
Scrophulariaceae	*Euphrasia*	*stricta*	Non-native
	Linaria	*vulgaris*	Non-native
	Nuttallanthus	*canadensis*	Non-native
	Veronica	*arvensis*	Non-native
		chamaedrys	Non-native
Scrophulariaceae	*Veronica*	*officinalis*	Non-native
		peregrina	Non-native
		serpyllifolia	Non-native
Solanaceae	*Petunia*	*x hybrida*	Non-native
	Solanum	*dulcamara*	Non-native
		ptychanthum	Non-native
Violaceae	*Viola*	*tricolor*	Non-native
Unknown	*Unknown*	*spp.*	N/A

Table 3A. Floral species richness on 18 green roofs located in Halifax Nova Scotia, 2017. List excludes graminoids and conifers. Admiralty Place (AP), Bedford Institute of Oceanography 1 (BIO1), Bedford Institute of Oceanography 2 (BIO2), Charles St. Roof (CR), Charterhouse Condominium (CH), Coburg Place (CP), Cunard Court (CC), Dalhousie Chemistry Building (DC), Dalhousie Dentistry (DD), Dalhousie Life Science Courtyard (LS), LeMarchant Place (LP), Marion McCain (MM), Mona Campbell (MC), Nova Scotia Community College, (NSCC), Quinpool Towers (QP), Renaissance South (RS), Saint Mary's University (SM), TD Building (TD)

Genus	Species	AP	BIO1	BIO2	CR	CH	CP	CC	DC	DD	LS	LP	MM	MC	NSCC	QP	RS	SM	TD
Achillea	*millefolium*					×				×	×					×			
Ajuga	*reptans*										×								
Alchemilla	*spp.*														×				
Allium	*schoenoprasum*														×			×	×
Anaphalis	*margaritacea*																	×	
Aquilegia	*canadensis*																	×	
Arabidopsis	*thaliana*																	×	
Barbarea	*vulgaris*				×														
Begonia	*x semperflorens-cultorum*	×																	
Berberis	*thunbergii*										×						×		
Brassica	*rapa*								×										
Buddleja	*davidii*												×						
Campanula	*rotundifolia*																	×	
Capsella	*bursa-pastoris*					×			×							×			
Centaurea	*nigra*			×							×					×			
Cerastium	*fontanum*	×		×		×	×	×		×	×	×	×	×	×	×	×	×	×
	tomentosum					×									×				
Coreopsis	*lanceolata*										×								
Coriandrum	*sativum*															×			
Cotoneaster	*spp.*																×		
Crepis	*capillaris*														×				
	tectorum											×							
	spp.																		×
Cydonia	*oblonga*									×									

Genus	**Species**	**AP**	**BIO1**	**BIO2**	**CR**	**CH**	**CP**	**CC**	**DC**	**DD**	**LS**	**LP**	**MM**	**MC**	**NSCC**	**QP**	**RS**	**SM**	**TD**
Dasiphora	*fruticosa*	×				×													
Daucus	*carota*			×					×	×	×	×			×				×
Echinacea	*purpurea*					×									×				
Epilobium	*ciliatum*			×						×	×	×				×		×	×
Erigeron	*annuus*											×		×					
	canadensis			×		×	×	×	×	×	×	×		×	×	×		×	×
	strigosus		×	×		×			×	×	×	×	×	×	×			×	
Erodium	*cicutarium*															×			
Erysimum	*cheiranthoides*								×			×				×		×	
	hieraciifolium										×								
Euonymus	*europaeus*							×		×									
Euphrasia	*stricta*			×				×											
Euthamia	*graminifolia*										×								
Forsythia	*spp.*							×											
Fragaria	*virginiana*							×		×					×	×		×	
Galinsoga	*quadriradiata*								×										
Gaylussacia	*baccata*	×																	
Geranium	*robertianum*										×								
	spp.														×				
Gladiolus	*x hortulanus*												×						
Hemerocallis	*lilioasphodelus*					×					×								
	spp. 1					×													
	spp. 2					×													
	spp. 2							×											
Hesperis	*matronalis*								×										
Heuchera	*spp.*							×											
Hieracium	*caespitosum*		×												×				
	x flagellare	×	×	×		×	×	×	×	×	×		×	×	×	×	×	×	×
	kalmii										×								
	lachenalii		×	×		×				×	×				×	×			
	pilosella						×												
	piloselloides		×								×				×			×	×
	sabaudum	×				×					×				×		×		
	spp. 1	×																	
	spp. 2			×															
	spp. 3										×								
	spp. 4																	×	
	spp. 5														×				
Hosta	*spp. 1*	×						×		×									

Genus	Species	AP	BIO1	BIO2	CR	CH	CP	CC	DC	DD	LS	LP	MM	MC	NSCC	QP	RS	SM	TD
Hosta	*spp. 2*					×													
Hydrangea	*paniculata*							×		×									
Hypericum	*perforatum*										×				×				
Hylotelephium	*spectabile*														×				
Iris	*germanica*					×													
Lactuca	*serriola*													×					×
Lamium	*maculatum*					×													
Lavandula	*angustifolia*					×													
Leontodon	*autumnalis*			×				×		×	×		×	×	×	×	×		×
Leucanthemum	*vulgare*		×			×		×	×	×	×		×			×			
	x superbum					×													
Linaria	*vulgaris*		×												×	×			
Linum	*catharticum*														×				
Lotus	*corniculatus*		×											×					
Malva	*moschata*															×			
Medicago	*lupulina*	×	×	×		×	×	×			×		×	×	×	×	×	×	
Mentha	*arvensis*								×										
Minuartia	*groenlandica*																	×	
Monarda	*didyma*					×													
Myosotis	*discolor*															×			
	spp.										×								
	stricta								×							×			
Nuttallanthus	*canadensis*					×													
Oenothera	*biennis*										×					×		×	×
Origanum	*vulgare*										×								
Oxalis	*stricta*	×		×		×	×	×	×	×	×	×	×	×	×	×	×	×	×
Petunia	*x hybrida*	×																	
Phlox	*subulata*					×													
	spp.					×													
Polygonum	*persicaria*															×		×	
Portulaca	*oleracea*															×			
Potentilla	*argentea*					×									×	×			
	canadensis				×						×				×				
	norvegica													×					
	recta																×		
	simplex						×	×											
Prunella	*vulgaris*	×		×		×	×	×		×	×		×			×	×		
Prunus	*spp. 1*							×											
	spp. 2										×								

Genus	Species	AP	BIO1	BIO2	CR	CH	CP	CC	DC	DD	LS	LP	MM	MC	NSCC	QP	RS	SM	TD
Pulmonaria	*saccharata*					×													
Ranunculus	*repens*	×		×		×	×	×	×	×	×		×		×	×	×		
Raphanus	*sativus*															×			
Rhodiola	*rosea*																	×	
Rhododendron	*gloria mundi*									×									
Rhus	*typhina*					×											×		
Rorippa	*palustris*								×									×	
Rosa	*multiflora*																×		
Rosa	*rugosa*					×													
	spp.					×													
	virginiana														×				
Rubus	*idaeus*				×				×										
Rudbeckia	*hirta*					×					×				×				×
Sagina	*procumbens*																×		
Salvia	*spp.*					×													
Sedum	*acre*					×						×				×		×	
	album											×		×	×				
	floriferum													×	×				
	forsterianum													×					
	kamtschaticum var. ellacombianum													×	×				
	selskianum																		×
	sexangulare											×		×	×				×
	spurium											×		×	×			×	×
Senecio	*viscosus*		×	×			×	×		×		×				×		×	×
	vulgaris								×			×						×	
Sibbaldiopsis	*tridentata*																	×	
Sisyrinchium	*montanum*			×							×				×			×	
	spp.	×																	
Solanum	*dulcamara*										×					×	×		
	ptychanthum															×			
Solidago	*bicolor*																	×	
	canadensis										×			×	×		×		
	juncea		×																
	nemoralis										×								
	rugosa				×	×			×		×				×		×		
	sempervirens																	×	
	spp.																	×	
Sonchus	*arvensis*		×	×							×			×					

Genus	Species	AP	BIO1	BIO2	CR	CH	CP	CC	DC	DD	LS	LP	MM	MC	NSCC	QP	RS	SM	TD
Sonchus	*asper*			×												×			
	oleraceus						×			×	×						×		
	spp.																		×
Spiraea	*japonica*							×		×							×		
Spiranthes	*cernua*														×				
Stellaria	*graminea*	×	×	×	×	×	×	×	×		×		×		×	×		×	
Symphyotrichum	*lateriflorum*						×		×	×	×		×	×	×	×			
Symphyotrichum	*novi-belgii*	×				×					×			×	×	×	×	×	×
Syringa	*vulgaris*					×													
Tagetes	*erecta*	×																	
Taraxacum	*officinale*	×		×		×	×	×			×		×			×			×
Thymus	*praecox*														×				
Trifolium	*arvense*		×	×				×		×	×	×			×	×		×	×
	campestre		×	×				×		×					×		×	×	
	hybridum										×			×					×
	pratense		×			×			×		×			×	×				
	repens	×	×	×		×	×	×	×	×	×		×		×	×	×	×	
Tulipa	*spp.*					×													
Vaccinium	*angustifolium*								×						×			×	
Veronica	*arvensis*			×		×		×			×		×			×	×		
	chamaedrys					×													
	officinalis			×			×	×								×	×	×	
	peregrina					×													
	serpyllifolia	×	×	×		×		×		×			×		×	×	×		
Viburnum	*plicatum ssp. tomentosum*							×											
Vicia	*cracca*	×	×		×	×			×	×	×			×	×	×	×		×
Viola	*tricolor*																×		
Unknown	*spp.*															×			

Table 4A. Number of insect pollinators collected on each green roof plant species. Pollinators were collected on 18 green roofs, June – September, 2017. Pollinators were only collected if they feeding on the floral resource. Native ranking is defined by the Atlantic Canada Conservation Data Center.

Genus	**Species**	**Visits**	**Native vs. Non-native**	**Visits per Genus**
Leontodon	*autumnalis*	264	Non-native	**264**
Hydrangea	*paniculata*	123	Non-native	123
Sedum	*selskianum*	117	Non-native	**256**
Solidago	*rugosa*	107	Native	**219**
Symphyotrichum	*lateriflorum*	105	Native	**131**
Dasiphora	*fruticosa*	91	Native	91
Hieracium	*x flagellare*	73	Non-native	96
Solidago	*canadensis*	56	Native	**219**
Solidago	*bicolor*	53	Native	**219**
Sedum	*spurium*	52	Non-native	**256**
Thymus	*praecox*	50	Non-native	50
Erigeron	*strigosus*	42	Native	42
Vicia	*cracca*	34	Non-native	34
Euthamia	*graminifolia*	33	Native	33
Rhus	*typhina*	30	Native	30
Sedum	*acre*	29	Non-native	**256**
Trifolium	*repens*	29	Non-native	40
Centaurea	*nigra*	27	Non-native	27
Medicago	*lupulina*	26	Non-native	26
Symphyotrichum	*novi-belgii*	26	Native	**131**
Allium	*schoenoprasum*	23	Native	23
Sedum	*floriferum*	23	Non-native	**256**
Sibbaldiopsis	*tridentata*	23	Native	23
Sedum	*sexangulare*	21	Non-native	**256**
Echinacea	*purpurea*	19	Non-native	19
Prunella	*vulgaris*	19	Native	19
Spiraea	*japonica*	19	Non-native	19
Daucus	*carota*	17	Non-native	17
Euonymus	*europaeus*	17	Non-native	17
Oxalis	*stricta*	15	Native	15
Cerastium	*fontanum*	14	Non-native	14
Lavandula	*angustifolia*	14	Non-native	14
Rudbeckia	*hirta*	14	Non-native	14

Genus	**Species**	**Visits**	**Native vs. Non-native**	**Visits per Genus**
Origanum	*vulgare*	12	Non-native	12
Brassica	*rapa*	11	Non-native	11
Coriandrum	*sativum*	11	Non-native	11
Taraxacum	*officinale*	11	Non-native	11
Hieracium	*lachenalii*	10	Non-native	96
Lotus	*corniculatus*	9	Non-native	9
Stellaria	*graminea*	9	Non-native	9
Hieracium	*spp.*	8	N/A	96
Ranunculus	*repens*	8	Non-native	8
Sedum	*fosterianum*	8	Non-native	**256**
Begonia	*x semperflorens-cultorum*	7	Non-native	7
Coreopsis	*lanceolata*	7	Non-native	7
Crepis	*tectorum*	7	Non-native	7
Veronica	*serpyllifolia*	7	Non-native	14
Fragaria	*virginiana*	6	Native	6
Trifolium	*pratense*	6	Non-native	40
Veronica	*chamaedrys*	6	Non-native	14
Rubus	*idaeus*	5	Native	5
Hosta	*lancifolia*	4	Non-native	8
Hosta	*spp.*	4	Non-native	8
Sedum	*kamtschaticum var. ellacombianum*	4	Non-native	**256**
Tagetes	*erecta*	4	Non-native	4
Trifolium	*hybridum*	4	Non-native	40
Ajuga	*reptans*	3	Non-native	3
Erigeron	*canadensis*	3	Native	45
Hesperis	*matronalis*	3	Non-native	3
Hieracium	*sabaudum*	3	Non-native	96
Leucanthemum	*x superbum*	3	Non-native	4
Rosa	*virginiana*	3	Native	3
Raphanus	*sativus*	2	Non-native	2
Solanum	*dulcamara*	2	Non-native	2
Vacuumcinium	*angustifolium*	2	Native	2
Achillea	*millefolium*	1	Native	1
Gaylussacia	*baccata*	1	Native	1
Hieracium	*caespitosum*	1	Non-native	96
Hieracium	*pilosella*	1	Non-native	96
Leucanthemum	*vulgare*	1	Non-native	4
Linum	*catharticum*	1	Non-native	1
Malva	*moschata*	1	Non-native	1

Genus	**Species**	**Visits**	**Native vs. Non-native**	**Visits per Genus**
Minuartia	*groenlandica*	1	Native	1
Monarda	*spp.*	1	Non-native	1
Myosotis	*stricta*	1	Non-native	1
Oenothera	*biennis*	1	Native	1
Phlox	*spp.*	1	Non-native	2
Phlox	*subulata*	1	Non-native	2
Potentilla	*argentea*	1	Non-native	1
Sedum	*album*	1	Non-native	**256**
Sedum	*spectabile*	1	Non-native	**256**
Solidago	*juncea*	1	Native	**219**
Solidago	*nemoralis*	1	Native	**219**
Sonchus	*arvensis*	1	Non-native	1
Trifolium	*arvense*	1	Non-native	40
Veronica	*arvensis*	1	Non-native	14

Table 5A. Scaled multiple linear regression output for both the bee richness model. Bees were collected on 18 green roofs located in the Halifax Regional Municipality Nova Scotia from June – September 2017. Bolded text denotes statistically significant effects (p-value < 0.05). "N/A" denotes coefficients that were removed from the model using the step function. These coefficients were removed due to their insignificant influence on the independent variable.

Coefficient	**Estimates**	**Std. Error**	**p-value**
(Intercept)	13.4444	0.7314	**3.73e-10**
Floral Richness	3.8389	1.1702	**0.00657**
Floral Structure Area	4.0852	0.8803	**0.00057**
Green Roof Surface Area	-2.5729	1.0750	**0.03393**
Green Roof Height	-2.8857	0.7805	**0.00305**
Natural Space	2.0450	0.8379	**0.03112**
Green Space	N/A		
Adjusted R^2	0.7875		
F-Statistic	13.6		
p-value	0.000136		

Table 6A. Scaled multiple linear regression output for both the bee abundance model. Bees were collected on 18 green roofs located in the Halifax Regional Municipality Nova Scotia from June – September 2017. Bolded text denotes statistically significant effects (p-value < 0.05). "N/A" denotes coefficients that were removed from the model using the step function. These coefficients were removed due to their insignificant influence on the independent variable.

Coefficient	**Estimates**	**Std. Error**	**p-value**
(Intercept)	10.7859	0.4942	**3.28e-12**
Floral Richness	1.6037	0.5776	**0.014852**
Floral Structure Area	2.7781	0.5671	**0.000235**
Green Roof Surface Area	N/A		
Green Roof Height	-1.0526	0.5240	0.064264
Natural Space	N/A		
Green Space	N/A		
Adjusted R^2	0.7458		
F-Statistic	17.63		
p-value	4.999e-05		

Table 7A. Scaled multiple linear regression output for the hoverfly richness model. Hoverflies were collected on 18 green roofs located in the Halifax Regional Municipality Nova Scotia from June – September 2017. Bolded text denotes statistically significant effects (p-value < 0.05). "N/A" denotes coefficients that were removed from the model using the step function. These coefficients were removed due to their insignificant influence on the independent variable.

Coefficient	Estimates	Std. Error	p-value
(Intercept)	4.5556	0.4232	**1.88e-08**
Floral Richness	1.6641	0.4483	**0.00209**
Floral Structure Area	N/A		
Green Roof Surface Area	N/A		
Green Roof Height	-0.7083	0.4483	0.13495
Natural Space	N/A		
Green Space	N/A		
Adjusted R^2	0.4197		
F-Statistic	7.148		
p-value	0.006601		

Table 8A. Scaled multiple linear regression output for the hoverfly abundance model. Hoverflies were collected on 18 green roofs located in the Halifax Regional Municipality Regional Municipality, Nova Scotia from June – September 2017. Bolded text denotes statistically significant effects (p-value < 0.05). "N/A" denotes coefficients that were removed from the model using the step function. These coefficients were removed due to their insignificant influence on the independent variable.

Coefficient	**Estimates**	**Std. Error**	**p-value**
(Intercept)	-42.642	21.817	0.0695
Floral Richness	N/A		
Floral Structure Area	N/A		
Green Roof Surface Area	10.677	3.205	**0.00423**
Green Roof Height	N/A		
Natural Space	N/A		
Green Space	N/A		
Adjusted R^2	0.3726		
F-Statistic	11.1		
p-value	0.004233		

Table 9A. Scaled multiple linear regression output for the total pollinator subgenera richness model. Pollinators were collected on 18 green roofs located in the Halifax Regional Municipality Nova Scotia from June – September 2017. Bolded text denotes statistically significant effects (p-value < 0.05). "N/A" denotes coefficients that were removed from the model using the step function. These coefficients were removed due to their insignificant influence on the independent variable.

Coefficient	**Estimates**	**Std. Error**	**p-value**
(Intercept)	3.8199	0.1006	**7.16e-14**
Floral Richness	0.6072	0.1612	**0.00269**
Floral Structure Area	0.5151	0.1210	**0.00112**
Green Roof Surface Area	-0.2751	0.1478	0.08740
Green Roof Height	-0.3584	0.1073	**0.00589**
Natural Space	0.2552	0.1152	**0.04691**
Green Space	N/A		
Adjusted R^2	0.7982		
F-Statistic	14.45		
p-value	0.0001007		

Table 10A. Scaled multiple linear regression output for the total pollinator abundance model. Pollinators were collected on 18 green roofs located in the Halifax Regional Municipality Nova Scotia from June – September 2017. Bolded text denotes statistically significant effects (p-value < 0.05). "N/A" denotes coefficients that were removed from the model using the step function. These coefficients were removed due to their insignificant influence on the independent variable.

Coefficient	**Estimates**	**Std. Error**	**p-value**
(Intercept)	12.50655	0.44358	**2.46e-12**
Floral Richness	1.97286	0.71086	**0.01680**
Floral Structure Area	2.11458	0.53364	**0.00188**
Green Roof Surface Area	0.02723	0.65186	0.96737
Green Roof Height	-0.87319	0.47320	0.08980
Natural Space	-0.23928	0.50814	0.64616
Green Space	N/A		
Adjusted R^2	0.7444		
F-Statistic	10.9		
p-value	0.000393		

Table 11A. Scaled multiple linear regression output for the bee richness model. Bees were collected on 18 green roofs located in the Halifax Regional Municipality Nova Scotia from June – September 2017. Green roof floral richness was separated into spontaneous and planted floral richness for this model. Bolded text denotes statistically significant effects (p-value < 0.05). "N/A" denotes coefficients that were removed from the model using the step function. These coefficients were removed due to their insignificant influence on the independent variable

Coefficient	Estimates	Std. Error	p-value
(Intercept)	13.4444	0.8024	**3.53e-09**
Spontaneous Floral Richness	2.1432	1.3308	0.13560
Planted Floral Richness	2.6454	1.1814	**0.04677**
Floral Structure Area	3.7203	1.0396	0.00433
Green Roof Surface Area	-2.7956	1.2838	0.05208
Green Roof Height	-3.2723	0.9540	**0.00562**
Natural Space	2.8190	0.9431	**0.01232**
Green Space	N/A		
Adjusted R^2	0.7443		
F-Statistic	9.248		
p-value	0.0009096		

Table 12A. Scaled multiple linear regression output for the bee abundance model. Bees were collected on 18 green roofs located in the Halifax Regional Municipality Nova Scotia from June – September 2017. Green roof floral richness was separated into spontaneous and planted floral richness for this model. Bolded text denotes statistically significant effects (p-value < 0.05). "N/A" denotes coefficients that were removed from the model using the step function. These coefficients were removed due to their insignificant influence on the independent variable.

Coefficient	Estimates	Std. Error	p-value
(Intercept)	10.7859	0.4954	**5.16e-11**
Spontaneous Floral Richness	1.3670	0.7642	0.09889
Planted Floral Richness	1.7196	0.7164	**0.03350**
Floral Structure Area	2.4624	0.6213	**0.00188**
Green Roof Surface Area	-0.9683	0.7911	0.24444
Green Roof Height	-1.3204	0.5863	**0.04383**
Natural Space	N/A		
Green Space	N/A		
Adjusted R^2	0.7446		
F-Statistic	10.91		
p-value	0.0003917		

Table 13A. Scaled multiple linear regression output for the hoverfly richness model. Hoverflies were collected on 18 green roofs located in the Halifax Regional Municipality Nova Scotia from June – September 2017. Green roof floral richness was separated into spontaneous and planted floral richness for this model. Bolded text denotes statistically significant effects (p-value < 0.05). "N/A" denotes coefficients that were removed from the model using the step function. These coefficients were removed due to their insignificant influence on the independent variable.

Coefficient	Estimates	Std. Error	p-value
(Intercept)	4.5556	0.4604	5.74e-08
Spontaneous Floral Richness	1.3983	0.5170	**0.0163**
Planted Floral Richness	0.1802	0.5170	0.7323
Floral Structure Area	N/A		
Green Roof Surface Area	N/A		
Green Roof Height	N/A		
Natural Space	N/A		
Green Space	N/A		
Adjusted R^2	0.3133		
F-Statistic	4.878		
p-value	0.02334		

Table 14A. Scaled multiple linear regression output for the hoverfly abundance model. Hoverflies were collected on 18 green roofs located in the Halifax Regional Municipality Nova Scotia from June – September 2017. Green roof floral richness was separated into spontaneous and planted floral richness for this model. Bolded text denotes statistically significant effects (p-value < 0.05). "N/A" denotes coefficients that were removed from the model using the step function. These coefficients were removed due to their insignificant influence on the independent variable.

Coefficient	**Estimates**	**Std. Error**	**p-value**
(Intercept)	37.222	3.932	3.38e-07
Spontaneous Floral Richness	-10.607	6.362	0.1194
Planted Floral Richness	1.128	5.009	0.8254
Floral Structure Area	N/A		
Green Roof Surface Area	20.284	6.373	**0.0072**
Green Roof Height	N/A		
Natural Space	N/A		
Green Space	8.746	4.644	0.0822
Adjusted R^2	0.4227		
F-Statistic	4.112		
p-value	0.02277		

Table 15A. Multiple linear regression output for the total pollinator subgenera richness model. Pollinators were collected on 18 green roofs located in the Halifax Regional Municipality Nova Scotia from June – September 2017. Green roof floral richness was separated into spontaneous and planted floral richness for this model. Bolded text denotes statistically significant effects (p-value < 0.05).

Coefficient	Estimates	Std. Error	p-value
(Intercept)	3.8199	0.1116	**1.08e-11**
Spontaneous Floral Richness	0.6235	0.2259	**0.0201**
Planted Floral Richness	0.2896	0.1645	0.1088
Floral Structure Area	0.3356	0.1718	0.0793
Green Roof Surface Area	-0.3947	0.1888	0.0631
Green Roof Height	-0.3540	0.1328	**0.0237**
Natural Space	0.4072	0.1502	**0.0219**
Green Space	-0.211	0.1853	0.2809
Adjusted R^2	0.752		
F-Statistic	8.344		
p-value	0.0017		

Table 16A. Scaled multiple linear regression output for total pollinator abundance model. Pollinators were collected on 18 green roofs located in the Halifax Regional Municipality Nova Scotia from June – September 2017. Green roof floral richness was separated into spontaneous and planted floral richness for this model. Bolded text denotes statistically significant effects (p-value < 0.05).

Coefficient	**Estimates**	**Std. Error**	**p-value**
(Intercept)	12.506550	0.421590	**4.43e-11**
Spontaneous Floral Richness	0.615768	0.853192	0.48700
Planted Floral Richness	1.647149	0.621210	**0.02425**
Floral Structure Area	2.242503	0.648803	**0.00616**
Green Roof Surface Area	0.007236	0.712845	0.99210
Green Roof Height	-1.195327	0.501605	**0.03841**
Natural Space	-0.142501	0.567218	0.80672
Green Space	0.814814	0.699595	0.27118
Adjusted R^2	0.769		
F-Statistic	9.089		
p-value	0.001206		