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**URBAN GREEN ROOF VEGETATION ASSEMBLAGE DEMOGRAPHY,
CLASSIFICATION, AND DESIGN RECOMMENDATIONS**

**By
Kristen Elizabeth Hahn
BSch, Queen's University, 2007**

**A thesis
presented to Ryerson University

in partial fulfillment of the
requirements for the degree of
Master of Applied Science
in the program of
Environmental Applied Science and Management

Toronto, Ontario, Canada, 2009**

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Title: Urban Green Roof Vegetation Assemblage Demography, Classification and Design Recommendations
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ABSTRACT

Green roofs offer exciting potential as a technology that is capable of ameliorating environmental problems in urban areas. Little is known about the vegetative communities on existing installations and systematic design procedures for green roofs are currently lacking. The current research has performed a vegetation census on eight installations in downtown Toronto and has considered relationships between vegetation demography, installation physical parameters, and maintenance activities. The frequency and abundance of planted and colonist species are examined to quantify variation in vegetation assemblages. The use of an installation classification scheme based on dominant photosynthetic pathway is examined. This study provides recommendations for the construction of recommended species lists and highlights several areas for future research.

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CHAPTER 1

Green Roof Vegetation and Design General Background

1.1 Introduction

Green roofs are meant to work. They are purposefully built, engineered systems designed to ameliorate environmental problems associated with traditional construction practices and materials. Green roofs consist of many different functional layers as summarized in the definitive book, 'Planting Green Roofs and Living Walls', by Dunnett and Kingsbury (2008) (Figure 1.1). Support and insulation layers are covered by a waterproofing layer that is designed to prevent leaks and plant root penetration. On top of the waterproofing layer, a drainage layer is installed. Filter membranes may also be included to prevent green roof media from being washed down and clogging draining systems. Finally, growing media and a layer of vegetation are installed. Since plants are the workhorses of green roofs, plant choice is an important consideration in the overall design process.

Figure 1.1: General composition of green roofs. Source: *Green Roofs for Healthy Cities*, 2005.

Green roofs are a technology that has the potential to provide a multitude of environmental benefits for both the community and the individual building owner. An expanding body of literature exists outlining how current development planning strategies are unsustainable and detrimental to human health (McKinney 2002; Bradford and

Gharabaghi 2004; Palmer *et al.* 2004; Yang *et al.* 2007; Lawson *et al.* 2008). In contemporary building practices, heat-trapping, impermeable building materials such as asphalt, tar, concrete, and stone replace 'undeveloped' areas of grass, plants and soil. This results in the loss of the ecosystem functions that 'natural' vegetated areas provided. When buildings, roads, and other structures are built in dense stands, such as those found in urban cores, the problem is compounded.

1.2 Environmental Problems in Urban Areas

During rain events, stormwater – having nowhere to infiltrate – collects on city surfaces and then runs over the impermeable city, picking up grit, grease and contaminants. Large pulses of contaminated water then flow down into sewer systems, sometimes overwhelming their capacity, as well as that of water treatment plants. This leads to sewer overflows wherein untreated water is discharged into local water bodies (Alp and Melching 2009). The city fares no better in fairer weather. Dark, hard building materials conduct the sun's heat into the building's interior, necessitating the use of artificial cooling systems. Heat also re-radiates out of these materials, leading to the urban heat island effect that causes ambient temperatures in urban centres to be several degrees higher than temperatures in surrounding, more 'rural' areas (Oke 1982). In the winter, heat is lost through these same materials and further synthetic conditioning for interior comfort may be required.

Even though environmental problems associated with urbanization are numerous, people still need to live and work. Society still needs to build. It is not logical to recommend literally trying to undo urbanization, knocking down buildings and digging up roads to allow meadows to return. Urbanization and modern building practices have

also allowed humankind to prosper. Innovative solutions are needed in order to strike a balance between progress and environmental degradation.

1.3 History of Green Roofs

One of the most woefully underused areas within the urban sphere is the roof (Brenneisen 2005). This leaves large parcels of bitumen, tar, and gravel that do little else than direct water away from the rest of the building, while perhaps housing some building mechanical equipment. Sometimes, new solutions arise from re-examining old practices. People have been planting vegetation on roofs for centuries. The hanging gardens of Babylon can be considered to be ancient examples of such a technology (Grant 2007). Sod roofs have been prolific in Europe for centuries, and plants have been historically reported to be used in roof reinforcement in China and Japan as well (Dunnett and Kingsbury 2008). Green roofs, in the more contemporary sense, can be traced to early 20th century Germany. Thanks to publicly buoyed environmentalism in the 1960s and 1970s, multi-layered, engineered green roof systems were widely installed across Germany and the enthusiasm for this building practice remains today (Dunnett and Kingsbury 2008).

In North America, green roofs are a more recent phenomenon. The technology has only gained popularity and prominence within the last 10 to 15 years, although there are some examples of earlier installations such as on the Rockefeller Centre in New York, which was installed in 1938 (Greenroofs.com 2009) and on the Manulife Centre in Toronto, which has been in place for approximately thirty years (City of Toronto 2009). In the city of Toronto, at least one hundred different buildings have installed green roofs

and municipal and private interest in the technology continues to increase (City of Toronto 2009).

1.4 Green Roof Benefits and Initial Costs

Much of the current green roof literature focuses on the potential for this technology to provide benefits to the community and to the individual. The benefits of green roofs have been reviewed extensively (Peck *et al.* 1999; Goya 2004; Banting *et al.* 2005; Dunnett and Kingsbury 2008). Green roofs have been shown to reduce building energy use for heating and cooling since they have a moderating effect on ambient temperatures. In general, plants are able to modulate ambient temperatures by shading, insulating, and using heat energy for evapotranspiration (Kolb and Schwartz 1986; Palomo Del Barrio 1998). This can contribute to the reduction of peak and absolute energy demands, as well as aid in mitigating the urban heat island effect. Stormwater runoff quality and quantity have also been demonstrated to be improved by green roofs as the plants and media absorb and filter incoming stormwater (Snodgrass and Snodgrass 2006; Berndtsson *et al.* 2009). It has been shown that the filtering actions of the living components of green roofs also improve air quality (Okano *et al.* 1988; Winner 1994; Currie and Bass 2005). This technology is thought to provide many other less-tangible benefits such as potential for increased biodiversity, aesthetic value, and amenity space (Snodgrass and Snodgrass 2006; Dunnett and Kingsbury 2008). It suffices to say that the multitude of benefits that may be derived from the use of this technology make it an appealing alternative to traditional roofing practices.

The costs of implementing this technology must also be considered. Currently, green roofs have a higher initial cost than traditional roofing systems (Wong *et al.* 2003;

Lee 2004; Saiz *et al.* 2006; Kosareo and Ries 2007; Carter and Keeler 2008). Carter and Keeler (2008) estimated that a green roof with a media depth of 7.62 cm and simple planting design would cost \$75.04 / m² more than a conventional roof. The cost of the green roof system was based on an average of quotes from manufacturers in the study area (Athens, GA). Wong *et al.* 2003 calculated that green roofs in Singapore had initial costs that were between \$40.61 / m² and \$179.83 / m² higher than traditional roofs, depending on the depth of the media, the complexity of the planting design, and whether or not the roof was built to be accessible. It is postulated that the higher initial costs of green roofs are likely to be offset in the long term as savings from benefits accrue (Wong *et al.* 2003; Saiz *et al.* 2006; Kosareo and Ries 2007). Green roof initial costs will also likely decrease as use of the technology becomes more widespread (Carter and Keeler 2008). As people recognize the exciting potential of this technology, there is a growing demand to know how one can go about building a green roof for their own property. The question of how to plan, design, and build a green roof, however, is much more complex than it may seem.

1.5 Influence of Green Roof Benefits on Construction

A closer examination of green roof benefits reveals one of the fundamental issues that complicate green roof design. Firstly, it is important to recognize that that no roof is able to perform maximally for all benefits mentioned above. There are inherent tradeoffs between benefits that make green roof design an optimization problem. For example, in order for a green roof to provide building cooling, it must be able to release or reflect incoming heat. In order for a green roof to provide building heating savings, it must be able to retain and insulate building heat, preventing its escape. It would be impossible to

design a roof that both maximizes heat release, while maximizing building heat retention. The individual building owners must decide which benefits are most important to their particular situation and design a roof based on these priorities. This means that there is no such thing as a 'one size fits all' green roof design.

Another source of the variation inherent in green roof design arises from the individualistic nature of their construction. It has been established that some green roof benefits act at the community level, while others benefit the individual building owner (Peck and Kuhn 2000). Since community-level benefits rely on the synergistic effects of multiple green roofs, many installations must be present in an area for these macro-scale benefits to exist. Because these structures are built on discrete property, it is the individual building owner that must take financial and practical responsibility for installing a green roof. Though many cost-benefit studies exist for green roof implementation, it is still somewhat questionable as to what degree the costs of installation and maintenance are outweighed by direct financial gain of the building owner (Wong *et al.* 2003; Banting *et al.* 2005; Clark *et al.* 2008).

As Hardin (1968) so famously expounded in his 'Tragedy of the Commons' argument, an individual always weighs the costs and the benefits of his or her actions, and his or her eventual course is determined by which way the scale tips. Hardin (1968) illustrated that over-consumption and resource exploitation occur because for the individual who takes more than his or her share from a common pot, the benefits are all personally reaped while the cost is defrayed vaguely across society. Green roofs as a solution to this detrimental natural tendency present the reverse situation wherein much of the benefits are hazily dispersed throughout the community, while the individual

directly feels the costs. All of this does not make for an easy argument in favour of green roofs. It also strengthens the idea that green roof design is intrinsically variable, since an individual is likely to be influenced by personal values when deciding in which design to invest to maximize personal benefits. The individual is also expected to demand direct demonstration of performance from green roofs before committing to this 'new' building practice. Because of these considerations, it must be accepted that encouraging green roofs in urban centres will likely lead to a patchwork of different designs, each emphasizing particular areas of perceived importance.

1.6 Standardization of Green Roof Design

However, this must be reconciled with knowledge that some design choices are inherently better than others as evidence emerges from empirical studies indicating how different aspects of green roof design improve performance in different realms. One of the most significant roadblocks preventing widespread adoption of green roof technology is a lack of standardization in the vegetation design process. The question of how to build a green roof becomes refined as, "How can a green roof be designed that will best achieve a certain portfolio of goals?" Currently, no thorough, standardized vegetation design system exists for green roofs.

The development of a standardized green roof vegetation design procedure is no simple task. Knowledge from all facets of the green roof industry must somehow be compiled and combined. Academic researchers, installers, suppliers, horticulturalists, municipal policy makers, urban planners, engineers, and ecologists are just some of the various stakeholders that must engage in discourse in order for green roof design standardization to move forward. This standardization requires a framework whereupon

this harvested bounty of interdisciplinary expertise can be hung. A framework has been proposed in order to put into context the contribution of the current research (Figure 1.2). Given the complexity of the task at hand, as well as the vast gaps in current knowledge, a standardized green roof vegetation design tool must be built deliberately, one piece at a time.

Figure 1.2: Flow diagram of systematic green roof design tool. Concepts in bold italics have been examined in the current project.

A performance-focused standardized vegetation design tool for green roofs should consider design goals as well as the feasibility restrictions of a particular installation. The systematic tool would then provide suggestions for appropriate plant species, using an understanding of the relationships between various plant characteristics and installation performance in light of specified priorities. The list of plant recommendations would be paired with further understanding of how the physical parameters of the roof (size, height, media depth etc.), and the maintenance regime interact with the plant community.

1.7 Establishing Green Roof Population Demographics

In order to begin to understand, compare, and contrast the functioning of different green roof plant communities, the demographics of these communities must first be examined. Although the history of the use of this technology spans centuries, rigorous

scientific exploration of green roofs is still in its infancy (Dunnett and Kingsbury 2008). A great deal of research is needed before a standardized design procedure can be developed. One of the first steps in this process is to gather baseline information about existing green roof vegetation community demographics to provide a foundation for the design and execution of future studies. Information such as the identity and relative abundances of species present on existing green roofs is currently lacking. Once these factors have been quantified, methodology for describing green roof vegetation communities must also be developed. Standardized classification and description is needed in order to effectively track how these communities change over time and space.

CHAPTER 2

Green Roof Vegetation Demography and Standardization of Green Roof Vegetation Design

2.1 The Green Roof Design Process

The design of a green roof involves the consideration of a multitude of factors. As with many green building technologies, it is easier to design and install a green roof for a new building, since the physical requirements of the system can be incorporated into the greater design of the building (Dunnett and Kingsbury 2008). Retrofitting older buildings is possible, although additional support may need to be constructed (Dunnett and Kingsbury 2008). In the pre-design phase of green roof construction, a feasibility assessment must first be performed. There are several ultimate limiting factors that will decide whether green roofing is appropriate for a given building. The load bearing capacity of a roof must be known, and both green roof media and vegetation must be chosen with this restriction in mind (Dunnett and Kingsbury 2008). This primarily constrains media depth, which in turn limits the potential species pool for planting.

The substrate used on green roofs is referred to as 'growing media' as opposed to 'soil' since it varies markedly from substrate found at ground level (Friedrich 2005). In fact, growing media may not contain 'soil' in an earth-science sense at all (Friedrich 2005). Many different types and compositions of media are available and the appropriate media choice must be made such that the media is not too heavy for the roof to support, nor too light to stay where it is put (Beatty and Berghage 2004). Although fantastic advances in substrate engineering have occurred, it is not just the weight of the substrate itself that is constraining. The substrate must be able to hold water for the vegetation, and the weight of water is constant at approximately 1 kg / L (XeroFlor 2009). This means that the media depth restraint due to load bearing capacity cannot be overcome by simply engineering the lightest possible substrate.

Once it has been determined that the installation of a green roof is structurally feasible, the components of the system must be designed. Green roof systems consist of much more than just media and vegetation. Insulation, roof deck support systems, waterproofing membranes, root protection barriers, drainage layers, and filter mats must all be designed to accommodate the proposed system (Dunnett and Kingsbury 2008). Installations may also include irrigation systems such as sprinklers, drip and tube systems, capillary systems, or standing water systems (Dunnett and Kingsbury 2008). Reviews of the design considerations of these components can be found in green roof design books (Dunnett and Kingsbury 2008; Snodgrass and Snodgrass 2005) and in green roof standards (FLL 2002). The focus of the current research is on the design of the vegetative component of green roofs.

2.2 Green Roof Vegetation Design Resources

Current resources that provide information about green roof vegetation assemblage design include plant selection guides, plant recommendations from various stakeholders, and standards published from third party associations. Automated, interactive plant selection programs are in their infancy, but some encouraging work in this area has also been recognized.

2.2.1 Plant Selection Guides

Two of the most prominent green roof plant selection guides come from Snodgrass and Snodgrass (2006), and Dunnett and Kingsbury (2008). Both books are authored for the North American market, and provide a broad overview of the general issues associated with plant choice. Dunnett and Kingsbury's (2008) guide has a stronger focus on plant choice as it relates to green roof benefits, and provides a more extensive

review of green roof construction. Snodgrass and Snodgrass (2006) have a greater concentration on factors affecting plant establishment and survival. Both guides offer extensive lists of potentially suitable green roof plants, organized alphabetically by species name. Dunnett and Kingsbury (2008) organize their recommendations further by providing separate lists for different depths of growing media and types of plants (perennials vs. grasses vs. bulbs, etc.). While these guides provide a good starting point for someone who is interested in designing a green roof system, there is a large volume of information to digest. Readers must weigh the characteristics of each plant species against each other, and no standardized scale for suitability ranking is provided. Species-specific differences in benefit-related performance levels are also not discussed, likely because these differences have not yet been exhaustively and reliably quantified (Grant 2007).

2.2.2 Plant List Recommendations

Many green roof supply and design companies provide lists of recommended plants on their websites. These recommendations are generally based on the experiences of professionals who have tried these species in their local field conditions. For example, a Toronto-based company called 'Green Garage' provides a list of plants they recommend based on media depth (Green Garage 2007). Emory Knoll Farms, based in Maryland, is run by Snodgrass and Snodgrass, who authored the previously discussed guide. They also offer a list of suggested plants broken down by aesthetic categories such as 'yellow flowers', 'blue foliage', and 'winter interest' (Emory Knoll Farms 2008). Other stakeholders with an interest in encouraging green roofs have developed lists of recommended plants. For example, the City of Toronto developed such a list in

conjunction with the Toronto and Region Conservation Authority (City of Toronto 2007). This list focuses heavily on native species, although it does not include much information regarding the selection process for the final list of recommended plants (City of Toronto 2007). It also does not specify the criteria for plants to be considered 'native', nor why being 'native' leads to particular suggested species being advantageous. The list does, however, specify that it is preliminary in nature and likely to be expanded as systematic knowledge of green roof plants grows.

2.2.3 Plant Selection Standards

Several guidelines have been developed that address green roof planting design. The American Society for Testing and Materials (ASTM) has released a guideline for plant selection, but this guideline is very general in nature and identifies desirable plant characteristics rather than making specific recommendations (ASTM 2006). The Landscaping and Landscape Development Research Society (FLL), a German Standards organization, has developed a similar guideline which provides standardized procedures for testing characteristics of green roof media (FLL 2002). Neither guideline offers explicit suggestions for plant-media pairing. Currently, no systematic, objective-based procedure exists to aid in the problem of green roof vegetation design.

2.2.4 Plant Selection Programs

Systematic vegetation design software has been developed for other ecosystems. For example, the U.S. Department of Agriculture (2008) has developed an online interface known as VegSpec to aid professionals in choosing appropriate plants for re-vegetation of ground-level disturbed ecosystems. This tool is available free online and takes in to consideration site characteristics, as well as the goals of re-vegetation (USDA

2008). The database includes over 2000 plant species, but does not include horticultural or 'gardening' plants (USDA 2008).

Some researchers are working towards green roof-specific design tools. For example, Grant (2007) developed the framework for a decision-making tool that took weighted design goals into account in order to recommend suitable plantings. It was concluded from this work that many of the relationships between green roof benefits and vegetation characteristics have not been adequately quantified, which leaves the true functional potential of specific assemblages unclear (Grant 2007). Furthermore, this tool only considered coarse-scale vegetation differentiation, since there is a lack of information as to the performance of various plant taxa beyond simplistic estimations. This work divided design recommendations based on design types recognized by the FLL (Grant 2007). The output of this tool would recommend, for example, a 'sedum' type roof over a 'lawn-perennial-shrub' roof, depending on the user-specified prioritization of benefits. These design types do not provide information about the relative proportions of each plant category and underline the need to further refine our knowledge regarding the optimization of plant composition on green roofs.

2.3 Development of a Systematic Green Roof Vegetation Design Procedure

Each of the previously mentioned tools available for green roof design contributes important information to the overall challenge of how to deliberately design green roofs that work. However, it is apparent that a great deal more knowledge is necessary in order to move forward toward a systematic green roof vegetation design procedure. It is proposed that green roof vegetation should be chosen such that the design assemblage is optimized in order to maximize performance. Quantitative green roof benefits generally

arise from the way a plant uses resources such as water and carbon dioxide to invest in structural growth and reproduction. Qualitative and aesthetic benefits also can depend on plant growth and reproduction, since these contribute to the 'look' of a plant.

It is not appropriate to simply seek out the highest-performing plants, as certain species will be disqualified if they are not able to establish and thrive on green roofs, since this is the obvious first criterion for plant selection. For example, a laboratory study examining the ability of two hundred seventeen different plant species to assimilate nitrogen dioxide identified *Eucalyptus viminalis* as the species with the highest capacity (Morikawa *et al.* 1998). Nitrogen dioxide metabolism by plants contributes to improvement in air quality. However, Clark (2005) acknowledged that this species is inappropriate for green roof use, as it can grow to over ninety feet in height and would surely cause undue point load stress on a rooftop. It is therefore important to design experiments to represent the appropriate population of plants for green roof application. Controlled lab experiments and field experiments each make important contributions to the body of knowledge. Some initial studies of these types have already been carried out (Kolb and Schwartz 1986; Palomo Del Barrio 1998; Clark 2005). A great deal of further research is needed for this area in order to better resolve performance relationships.

The benefits of green roofs have traditionally been established by comparing their performance to conventional roofing materials and potential savings have been calculated in this way (Peck *et al.* 1999; Goya 2004; Banting *et al.* 2005). This baseline for comparison is less useful for a tool that strives to compare advantages between designs. Currently, no studies have focused on comparing green roof vegetation assemblages

between multiple roofs in one area and this information would be useful in order to establish the nature of variation that exists between designs.

2.4 Quantification of Green Roof Vegetative Assemblages

In order to compare between designs, methodology must be developed to describe and quantify assemblages as a whole. Green roof vegetation design requires the synthesis of expertise from a plethora of disciplines. It is difficult to properly integrate all perspectives and this leads to approaches that negate or under-represent certain disciplines. Ecological perspectives on the vegetative component of green roof design are currently lacking (Dunnett *et al.* 2008). Green roof plant species function as a community and must be studied as such. Proportions and numbers of species are currently decided based on landscape design principles or aesthetic factors (Dunnett and Kingsbury 2008). Planting assemblage design could benefit greatly by integrating ecological knowledge of plant community demographics. This knowledge could be used to recommend species assemblages that are realistic and will achieve greater stability over the long-term.

Since literature regarding green roof vegetation assemblages suggests they are rarely tracked, vital information regarding the fate of these communities remains uncollected and unanalyzed. One of the most glaring weaknesses of current design approaches is the assumption that once planted, the vegetation assemblage on a green roof will remain the same in perpetuity. Many calculations of the costs and benefits of green roofs versus conventional roofs have long-term components wherein savings are assumed to accrue over time (Peck *et al.* 1999; Banting *et al.* 2005; Dunnett and Kingsbury 2008). Projections of these savings assume that initial design vegetation

composition remains stable over time, or that change in green roof species assemblage will not significantly affect installation performance. However, like any living system, green roofs are dynamic and are subject to various abiotic and biotic pressures that lead to competition and succession. An adaptive management approach to green roof design would integrate information regarding vegetation demographic changes from year to year and further studies are needed in order to gather this information. Since there is a lack of a standardized design procedure, each currently existing North American green roof has been designed somewhat *de novo* and in relative isolation of others without synthesis and analysis of green roof vegetation community demographic data.

2.5 Existing Green Roof Vegetation Surveys

Few surveys have been published detailing the dynamics of green roof vegetation assemblages. An initial survey of the success of planted species and the incidence of colonizing plants was performed on Carleton University's green roof (Langton-Yanowitz *et al.* 2005). The installation consisted of a 665 sq. ft. extensive green roof, with media depths ranging between 6" and 2" (Langton-Yanowitz *et al.* 2005). A mixture of seventy-five 'prairie plant' species was initially planted and this survey determined that only nine species established (Langton-Yanowitz *et al.* 2005). A further twenty-eight non-planted species were identified. This survey was carried out using the Daubenmeyer vegetation plot survey method, which included visual estimation of the percentage cover provided by particular species over the roof (Langton-Yanowitz *et al.* 2005). The results of this survey were only superficially analyzed, and the current status of this monitoring project is unknown. This field survey has not been formally published, although it

provides an interesting example of how initial green roof design can change under the forces of nature (Langton-Yanowitz *et al.* 2005).

A similar vegetation census was performed on York University's green roof (TRCA 2004). This installation was surveyed four years after initial planting. The investigation involved the compilation of a list of all species observed on the roof over three visits from July through October. The green roof consisted of several different areas, including some containers, and was found to contain a total of 91 vascular plant species (TRCA 2004). Roughly a third of these species were determined to be natives, while the rest were considered to be exotic species. For each species observed, researchers also reported the coefficient of conservatism, which is a score that indicates the degree to which a species is constrained to high-quality, low-disturbance habitats. The coefficients for all species were used, along with the species richness of the community to calculate the floristic quality index (FQI) of the assemblage. It was determined that the green roof had a lower FQI and fewer native species than a natural prairie habitat. However, it was noted that the roof was relatively young and that FQI and the proportion of native species might improve over time (TRCA 2004).

Two longer-term vegetation surveys have been published. The results of one long-term vegetation demographic monitoring program were reported by Kohler (2006). This study monitored two green roofs in Berlin; one for twenty years and one for thirteen years (Kohler 2006). Both roofs showed variation in the proportion of planted species from year to year. Over one hundred different colonist species were recorded throughout the twenty year monitoring period of the first roof, although only 10% of these species persisted with any dominance (Kohler 2006).

In Sheffield, UK, Dunnett and colleagues (2008) tracked an experimental installation consisting of panels with two different depths planted with the same vegetation assemblage over a six-year period. This study reported changes in proportions of planted species over time, as some species increased in numbers while others decreased due to competition (Dunnett *et al.* 2008). This study also recorded thirty-five non-planted colonizing species that were able to establish on their experimental green roofs over a two-year period (Dunnett *et al.* 2008). The changes in vegetation assemblages observed by these studies demonstrate the need for long-term vegetation monitoring. However, these studies only followed one or two particular roofs, and the application of their findings to green roofs outside of Europe is unknown.

One multi-roof, North American survey of colonizing species on traditional roofs was carried out at the University of Saskatchewan (Archibold and Wagner 2007). Seven tar-and-gravel roofs were surveyed across the campus using a transect sampling method (Archibold and Wagner 2007). These roofs were not intended to be green roofs, but it was found that thirty-two plant species were able to establish and survive (Archibold and Wagner 2007). This study found that the most abundant species were common 'ruderals' which is a term that refers to plants that are typically found colonizing abandoned sites such as *Lactuca serriola* (Prickly lettuce) and *Sonchus arvensis* (Sow thistle) (Archibold and Wagner 2007). This study suggests that even traditional roofs encourage spontaneous colonization, although it is not known what effect green roofing has on this phenomenon. It is also not known how spontaneous colonization contributes to the overall community dynamics of green roofs in North America.

Existing green roof vegetation censuses provide important first steps towards a greater understanding of the variation present between and within existing green roof installations (TRCA 2004; Langton-Yanowitz *et al.* 2005; Kohler 2006; Dunnett *et al.* 2008). However, it is difficult to compare and contrast the findings from the aforementioned studies in order to draw a clearer picture of the demography of green roof vegetation assemblages. Most of these studies do not describe and classify the installation holistically. Reporting the presence and relative abundances of species is important, although this information alone does not indicate much about the greater functioning of a roof. Indexes such as FQI begin to capture characteristics of the green roof ecosystem (TRCA 2004), but have relatively specialized application. A more systematic approach could be established in order to gather demographic information in a useful way that can then be applied to the development of an automated design tool for green roofs.

2.6 Developing a Functional Green Roof Vegetation Classification Scheme

Several standardized vegetation classification systems exist for terrestrial landscapes in Canada including Ecological Land Classification (Ontario Ministry of Natural Resources 2007), the Canadian National Vegetation Classification Initiative (Nature Serve Canada 2007), and Canadian Forest Ecosystem Classification (Natural Resources Canada 2007). All of these systems record plant species identity and abundances and use hierarchical classification systems to describe differentiated vegetation communities based on associations between species (Environment Canada 2005; Nature Serve Canada 2007; Natural Resources Canada 2007). Researchers

currently do not have an analogue of such systematic, vegetation-based classification systems to describe green roof communities.

2.6.1 The Extensive-Intensive Classification System

Instead, most literature currently utilizes a classification system based on green roof physical parameters wherein low-maintenance roofs having shallow media are classified as 'extensive' while roofs with deep media and higher maintenance requirements are classified as 'intensive' (Kohler 2003; Getter and Rowe 2006; Grant 2006; Kohler 2006; Schrader and Boning 2006). The extensive/intensive classification system does not have standardized parameters for determining the distinction between 'shallow' and 'deep' substrate, although the cut-off for extensive roofs is typically reported as approximately 15 cm (Dunnett and Kingsbury 2008; Snodgrass and Snodgrass 2006). Descriptions of this classification system largely ignore the vegetation component of green roofs, only going so far as to mention that intensive roofs have the potential to support a greater variety of species than extensive roofs, since fewer species are able to live in shallow soils (Dunnett and Kingsbury 2008; Snodgrass and Snodgrass 2006).

2.6.2 Vegetation-Based Assemblage Classification

In plant demography, classifications based on species' physiognomy have traditionally been used to differentiate between functional groups (Shimwell 1971). The term 'physiognomy' traditionally refers to the gross form of the plant, such as classifying a species as being 'woody' or 'herbaceous' (Kenoyer 1929). Physiognomic classification is based on the idea that form leads to function (Shimwell 1971). Several such classification systems have been developed, the most widely recognized of which is arguably Raunkiaer's life form classification system which considers the relative position

of a plant's meristems during times of harsh ecological conditions (Shimwell 1971). This classification system is still used in contemporary literature to describe ecological communities (Gago *et al.* 2007; Yoshie 2008; Naqinezhad *et al.* 2009; Odland 2009). However, this classification system is more useful for studies that examine the relationship between plant community composition and changing ecological gradients or conditions. Green roofs are a unique situation in that environmental conditions are designed and managed in order to support desired assemblages. The characteristics that are utilized in Raunkiaer's system are not easily and directly related to species performance in green roof benefits and would thus not be the best choice for use in a systematic green roof vegetation design procedure. Also, comprehensive databases listing species and assignment into life-form categories are currently lacking, which would make it difficult for green roof researchers to use this as a standardized classification system.

Since traditional physiognomic classification systems were developed long before contemporary green roofs, using ecological understanding outside of the realm of the engineered construction of 'living machines', there would seem to be a need to develop a green roof-specific system. Some rudimentary vegetation-based classification systems have been used in green roof research. The Landscaping and Landscape Development Research Society (FLL), a German Standards organization, utilizes the extensive/intensive system but breaks down these categories further and recognizes several different vegetation assemblage types (Table 2.1) (FLL 2002). This classification system was utilized by Grant (2007) in the development of a prototype for an automated green roof design tool.

Table 2.1: Green roof vegetation design types as recognized by FLL (Grant 2007).

Type of Greening	System Type S _x	Substrate depth (cm)	Substrate depth (in)	Plant type
Extensive greening	1	2.0 to 4.0	0.8 to 1.6	moss-sedum
	2	>4.0 to 6.0	>1.6 to 2.4	sedum-moss
	3	>6.0 to 10.0	>2.4 to 4.0	sedum-moss-herb
	4	>10.0 to 15.0	>4.0 to 6.0	sedum-herb-grass
	5	>15.0 to 20.0	>6.0 to 8.0	grass-herb
Intensive greening	6	15.0 to 25.0	6.0 to 10.0	lawn-perennial-small shrub
	7	>25.0 to 50.0	>10.0 to 20.0	lawn-perennial-shrub
	8	>50.0	>20.0	lawn-perennial-shrub-tree

However, the 'Plant type' categories are somewhat vague and are not all from a common baseline as categories include a plant genus (*Sedum*), a life history trait (perennial), general common name descriptions of plants (moss, grass, herb, shrub, and tree), and a common name description of a vegetation community (lawn). Revision and standardization of terminology is needed.

2.6.3 Installation Classification Based on Photosynthetic Pathway

There are many ways of potentially classifying green roof plant functional types. In the context of a systematic green roof design tool, it makes sense to gear classification categories towards plant attributes that contribute to the benefits provided by the technology. However, a comprehensive understanding of the relative contribution of plant traits to each design goal is currently lacking (Grant 2007). The development of a classification scheme to organize green roof plant diversity encounters the same considerations involved in any general classification. Categories must be established to the appropriate level of distinction that is able to differentiate between discrete categories. Too many categories risks having similar species treated as different groups,

while a scheme with too few categories can lead to over-generalization wherein dissimilar species belong to the same group.

One of the challenges of creating a vegetation-based classification system for green roof communities is the determination of an appropriate taxonomy upon which to develop classification categories. For green roofs, it is proposed that a classification scheme based on photosynthetic pathway may be a useful method for differentiating between different vegetation assemblages. While photosynthetic pathway is not necessarily a visually discernable characteristic, it embodies the same spirit of 'gross form leading to function' as other physiognomic systems. Photosynthetic pathway is also a physiological plant characteristic that is widely documented and reasonably easily determined through a literature search. The process of photosynthesis for most terrestrial vascular plants involves the fixation of carbon dioxide into sugar, utilizing water and the energy of the sun. The metabolic pathway through which a plant achieves this has ramifications on the way the plant obtains, invests, and expends resources. Differences in metabolic pathway also lead to differences in the structure of a plant (Tregunna *et al.* 1970). Certain pathways require specialized structures, and all result in structural optimization that tailors the form of the plant to the pathway (Tregunna *et al.* 1970). There are three recognized photosynthetic pathways: C3, C4, and Crassulacean Acid Metabolism (CAM) (Solomon *et al.* 2002).

Photosynthesis involves the intake of carbon dioxide through small openings on the leaf surface called stomata. The carbon dioxide then goes through a series of reactions to be finally converted in to carbohydrates. The C3 pathway is the most common in terrestrial vascular plants (Solomon *et al.* 2002). It is the most energy

efficient of the three pathways, but also loses the most water through evapotranspiration. The name 'C3' refers to the three-carbon compound 3-phosphoglycerate that results from the reaction between CO_2 and Ribulose biphosphate (RuBisCo), which is the first enzyme of the carbon fixation (Calvin) cycle. Evapotranspiration rates increase with increasing temperature, and plants of hot, dry climates have evolved to minimize water loss. The C4 and CAM pathways arose as drought adaptations, although at the expense of energetic efficiency.

An unfortunate consequence of closing stomata to minimize water loss is that low levels of carbon dioxide will cause RuBisCo to increasingly catalyze reactions using oxygen floating around within the plant instead of carbon dioxide (Solomon *et al.* 2002). This process, called photorespiration, causes a plant to break down carbohydrates rather than produce them. C4 plants overcome this inefficiency by spatially separating reaction steps, keeping RuBisCo in anoxic bundle-sheath cells and ferrying carbon from mesophyll cells via four-carbon organic acid intermediate compounds oxaloacetate and malate. The '4' in C4 refers to the number of carbons in these intermediate compounds. CAM plants have adapted a different means of overcoming this problem. 'CAM' is short for crassulacean acid metabolism and refers to the separation of photosynthetic steps through time. CAM plants only open their stomata at night to let in carbon dioxide. The carbon dioxide is then concentrated and provided to RuBisCo during the day, when the process of carbon fixation continues. CAM and C4 pathways are similar but are distinguished by important differences. The C4 pathway is generally associated with distinctive leaf anatomy to enable the spatial separation of reactions while these specialized structures are not present in CAM plants (Solomon *et al.* 2002). The C4

pathway is also associated with aggressive, rapid growth while the CAM pathway is not (Solomon *et al.* 2002).

Since it has been recognized that rooftop conditions are generally harsher, especially with respect to moisture deficits, than conditions at ground level, green roof plants must have adaptations that allow for survival in this unique environment. The utilization of a classification scheme based on photosynthetic pathway captures differences in these adaptations and is thus an appropriate and informative choice.

2.6.4 Planted versus Colonist Species

A further consideration in the classification of vegetation on a green roof is whether species present have been intentionally planted, or whether they have arrived as colonists. For the purpose of this study, intentionally planted species are considered to be species that were purchased either as seeds, cuttings, plugs or otherwise, and placed into the installation in a deliberate manner. Colonist species are defined as species that have 'inserted themselves' into installations, without any anthropogenic mediation. Although colonist species may be 'unintentional', they may be considered desirable or undesirable depending on the opinions of the specific building owner and the impacts the species has on other wanted species.

In green roof literature, studies that focus on planted taxa dynamics generally focus on their survival and establishment. For example, a study by Durhman and colleagues (2004) planted three species of Sedum, a forb (*Coreopsis lanceolata*), and a species of grass (*Schizachyrium scoparium*) on an installation in Michigan. This study subjected plantings to a variety of watering regimes and measured the survival and success of these taxa, recording such characteristics as rate of establishment, amount of

coverage, persistence, and evidence of stress. It was determined that the *Sedum* species out-performed other experimental taxa in this regard. This study was expanded to evaluate the survival responses of additional species to irrigation regimes, substrate depths and types (Monterusso *et al.* 2005; Rowe *et al.* 2006; Rowe *et al.* 2007; Durhman *et al.* 2007). Similar studies that consider species survival and give recommendations for potentially useful green roof plants have been carried out in other localities such as Portland (Hauth and Liptan 2003), Malmo, Sweden (Emilsson 2003) and Nova Scotia (Licht and Lundholm 2006).

Studies that consider colonist taxa generally examine spontaneous colonization as a planting method, or consider colonists as a nuisance to planted species. As a planting method, spontaneous colonization is characteristic of green roofs in Europe, sometimes referred to as 'brown roofs' (Dunnett and Kingsbury 2008). These 'brown roofs' relocate substrate material from surrounding terrestrial locations onto roofs, and allow the existing seed bank and incoming propagules to vegetate the installation (Dunnett and Kingsbury 2008). This method of vegetation establishment has been used in London as a means of restoring lost habitat for rare avian species such as *Phoenicurus ochruros* (Black Redstart) (Gedge 2003). Spontaneous colonization has not been widely used as a planting method outside of 'brown roof' applications since these roofs can have an undesirable aesthetic similar to that of an 'abandoned site' (Dunnett and Kingsbury 2008). The previously reviewed vegetation surveys that considered colonist species (Langton-Yanowitz *et al.* 2005; Kohler 2006; Archibold and Wagner 2007; Dunnett *et al.* 2008) are among the few studies that have included this component of green roof vegetation communities. All of these studies cast colonist species in a somewhat negative light,

considering them in the context of detracting from planted assemblages, or acting as a 'weed' on traditional roofs.

No studies to date have considered planted and colonist species holistically as an entire assemblage. An examination of all species found on green roofs, regardless of origin, may reveal important trends that cannot be found when looking at planted and colonist communities in exclusion of each other. The distinction between planted and colonist species can also be used to examine areas where planting designs may have fallen short.

2.7 Ecological Factors Influencing Vegetation Assemblages

Description and census of green roof vegetation are inadequate in and of themselves. Similar to human sociology, when gathering information regarding plant communities, one must also gather information regarding the 'stage' on which demography plays itself out. A multitude of ecological research has shown that the diversity of vegetation assemblages plays a large role in determining ecosystem functional properties (For a review, see Tilman *et al.* 2002). Species richness (number of species) is one of the most fundamental measures of diversity. At a regional scale, species richness depends on the rate of species immigration, as well as the rate of species extinction (Molles 2004). The success of individual species depends on a balance between resource availability as it favors proliferation, and disturbance as it hinders propagation (Molles 2004).

For green roofs, these factors may depend on the physical parameters of the roof itself. There are a multitude of physical parameters that create unique microclimatic circumstances for each individual installation (Hole 2004). Some of the most basic of

these physical parameters are roof height, size, age, and media depth (Dunnett and Kingsbury 2008). All of these may affect the success of individual plant species on green roofs as they may be related to the available resource pool and they may also alter species immigration and extinction patterns. However, very little research exists that examines the effect of varying these parameters on green roof vegetative community composition. The development of a thorough, systematic design tool would require the specification of appropriate physical parameters of a roof in addition to a species list in order to ensure the success of particular vegetation assemblages. A few studies exist that have attempted to examine the effects of varying physical parameters on vegetative communities.

2.7.1 Roof height

Island biogeography theory was developed by MacArthur and Wilson (1967) to explain the relationships between species immigration and extinction as they relate to the stability of an ecosystem. MacArthur and Wilson (1967) used the concept of islands as a metaphor for different, isolated, and initially unpopulated habitats where species arrived from some mainland source population. This theory states that the rates of immigration and extinction depend on factors such as the distance to the mainland, and size of the island. Green roof height above ground could potentially provide a barrier for immigration of new species that might lead to lower diversity on higher roofs in that two roofs of the same size, distance from source pool, and having the same extinction rates would be hypothesized to have different species diversity if their rates of immigration differed (MacArthur and Wilson 1967). To date, no published studies are known to have examined roof height as it relates to the diversity of plants found on a green roof.

2.7.2 Roof size

Island biogeography theory also states that all other things being equal (immigration and extinction rates, distance to source pool), larger islands should have more species since they represent a bigger target for potential colonist seeds and spores (MacArthur and Wilson 1967). However, this relationship depends on the dispersal abilities of the species in question for distance to source pool to not be a limiting factor (Molles 2004). Larger islands (roofs) may also have higher habitat heterogeneity, which would mean that they could potentially have more available niche spaces, also leading to higher diversity (Molles 2004). However, Kohler's (2006) observations of green roofs in Berlin over a twenty-year period revealed little correlation between species diversity and roof size. Kohler (2006) studied one building's installation which consisted of sub-roofs of various sizes. It is not known whether roof size is correlated with plant diversity when green roofs are viewed at a larger scale (between installations vs. within installation).

2.7.3 Roof Age

Age is related to the physical properties of an ecosystem somewhat indirectly. Roof age is most closely tied to resource availability since all organisms alter their environments as they grow, utilize resources, and dispose of waste over time (Molles 2004). Even in death, organisms leave behind their physical structures which are decomposed, liberating chemical components into the nutrient cycle (Molles 2004). The cumulative effects of all species within an ecosystem on the system itself accrue with age. Ecological theory states that the trajectory of species diversity within an assemblage will depend on "whether the increase in potential niches resulting from increased biomass, stratification ... and other consequences of biological organization exceeds the

counter effects of increasing size and competition" (Odum 1969). The relationships between these antagonistic processes will thus differ from ecosystem to ecosystem. Kohler (2006) examined green roof vegetation dynamics over a twenty-year period and considered the effects of roof age on species diversity. It was determined that installation species diversity initially increased over the first few years as colonist species arrived. In later years, the number of species present on the roof varied without predictable trend. The association between species number and installation age has not been further clarified since the study by Kohler (2006). Further research is needed in order to quantify the nature of this association to direct future studies which may disentangle influencing factors.

2.7.4 Media depth

Media depth is another physical parameter of green roofs that is related to resource availability. The media stores water, nutrients, as well as microbes and fungi which play critical roles in resource cycling (Moles 2004). Dunnett and colleagues (2008) examined the effect of varying media depths on plant diversity. Two different media depths (10 cm vs. 20 cm) were utilized in the experiment. It was determined that species richness decreased with depth. This is consistent with traditional ecological theory which explains that habitats that have an abundance of resources tend to be dominated by a small number of species that are able to maximally exploit these resources (Grime 2002). In the experiment performed by Dunnett and colleagues (2008), further explanation for the observed trend was provided, stating that a lack of resources in shallower depths caused planted species to under-perform, leaving more bare ground for potential colonists to exploit. More research is needed to clarify the mechanism behind

this relationship, and further studies examining the effects of a more continuous range of media depths may aid in this regard.

2.8 Maintenance

Green roof maintenance also may affect species richness since the application of fertilizer and supplementary irrigation affects the resources available to plants while weeding activities and the use of pesticides act as a 'disturbance'. Green roofs are a unique ecosystem in that they are generally much more intensively managed and maintained than 'natural' habitats (Dunnett and Kingsbury 2008). However, the aforementioned lack of understanding of the fate of green roof vegetation design over time also means that current design practices do not include systematic, tailored maintenance regime recommendations. Since green roofs are dynamic living systems, maintenance is required in order to control (or at least better predict) the trajectory of the assemblage. Currently, various green roof design approaches, including plant selection guides and third party standards, provide vague maintenance recommendations at best. Most design approaches agree that a roof may need fertilizing, weeding, and protection from pests and disease (FLL 2002; ASTM 2006; Dunnett and Kingsbury 2008). A green roof design tool cannot be properly developed without better understanding of the interplay between green roof plant assemblage demography and maintenance activities.

The majority of studies that consider green roof maintenance do so as part of a cost-benefit analysis. Quantification of maintenance costs and activities has differed considerably between studies. For example, a case study of an installation in Pittsburgh performed a life cycle impact analysis of a *Sedum*-dominated green roof versus a bare roof (Kosareo and Ries 2007). This study stated that maintenance for the two roof types

was not assumed to be significantly different and so this factor was not included in calculating cost differences (Kosareo and Ries 2007). A study by Carter and Keeler (2008) also did not factor in maintenance costs in a cost-benefit analysis as they stated that both green roofs and traditional roofs simply required visual inspection twice yearly.

Other studies have considered maintenance based on estimates of theoretical costs provided by landscaping companies. A study by the City of Waterloo (2004) quoted an annual maintenance cost of \$2000.00 for a 1600 m² green roof, which was \$1000.00 more than the estimate for a comparable conventional roof. A study by Wong and colleagues (2003) stated that extensive roof maintenance was minimal, requiring watering, weeding, and plant material replacement twice a month. The same study quoted the maintenance needs of an intensive installation consisting of 80% shrubs to include the employment of a full or part-time gardener for \$650 / month. An intensive roof with trees was quoted as requiring \$15,000 in annual maintenance, once the pruning needs of trees was added on top of other activities (Wong *et al.* 2003). Clearly, great differences in opinion concerning the maintenance commitment for a green roof exist. Research is needed to quantify, describe, and synthesize actual maintenance activities experienced by existing installations.

2.9 Objectives of Current Research

The overarching goal of the current study was to contribute knowledge that will aid in the creation of a standard for green roof vegetation design. A census of the vegetation present on eight green roofs in downtown Toronto in 2008 was expected to reveal critical information needed to assess the influence of roof physical parameters and

maintenance activities on green roof vegetation assemblages. The objectives of the current research were as follows:

1. Quantify the variation in vegetative communities present on green roofs in downtown Toronto by recording identity and abundance of all vascular plant species present on each installation through field observation.
2. Classify assemblages in a functional manner by determining the photosynthetic pathway for each species through a literature search.
3. Identify areas for improvement of current vegetation design practices by examining the method of arrival for plant species (planted versus colonist) through the comparison of field observations with original planting lists.
4. Determine the variation present in roof physical parameters by quantifying roof height, size, age, and media depth for all installations through field observation and interviews with building owners.
5. Clarify variation in operational needs between installations by identifying maintenance activities performed on each installation through interviews with building owners.
6. Contribute information about vegetation design considerations by determining whether relationships exist between installation species richness, physical parameters, and maintenance activities.

CHAPTER 3

Methodology

3.1 Research Approach and Scope

This research examines eight case studies of green roofs in the downtown Toronto area. A case-study approach was the most appropriate methodology due to the immaturity of existing green roof vegetation knowledge as discussed in the previous chapter. Before experimental assemblages can be used to determine more exact relationships among green roof vegetation, physical parameters, and maintenance activities, a better understanding of the demography of realistic vegetation assemblages is needed. The existing roofs examined for this project were not designed in the systematic way that has been previously outlined, since such a system does not yet exist. However, these roofs exhibit the outcome of the effects of physical parameters and maintenance on green roof plant assemblage because they exist under actual operating conditions. Surveys of existing green roof conditions are necessary to identify important avenues of inquiry to properly focus and guide future work.

The results from the current research are most applicable to the Toronto area and further research utilizing the general methodology of this study is needed to determine the nature of green roof vegetative communities in other areas. Toronto has shown great interest in, and enthusiasm for, encouraging this roofing technology. More than one hundred green roofs currently exist in Toronto (City of Toronto 2009). This number is increasing due to the City's policies such as their green roof financial incentive program which provides a grant to interested building owners to help offset the initial cost of installation (DiGironimo 2007). Recently, Toronto passed a by-law that will actually require green roofs on new buildings with a footprint larger than 2000 m², and higher

than six storeys (Lewington 2009). All of this makes Toronto an ideal venue for studying green roofs.

3.2 Study Area Conditions

All sites were located in downtown Toronto, Ontario, Canada (43°40'0 N, 79°25'0 W). The average temperature for the 2008 growing season (May to November) was 15°C and the total precipitation during that time was 668 mm (Environment Canada 2009a). Normal average temperature calculated from 1971 to 2000 for May to November is approximately 16°C, and normal precipitation during this period is approximately 504 mm (Environment Canada 2009b).

3.3 Site Selection

A list of all known green roofs in Toronto was obtained (Alex Alkoury and Doug Banting, personal communication, August 1st, 2008). All sites were contacted to request access for a vegetation survey. Of those sites that replied, eight sites were chosen to be surveyed. Each site was given a three letter abbreviation for identification based on the name of the building (Table 3.0).

Table 3.1: Green roof study site identification codes

Identification Code	Site
SPA	215 Spadina Ave.
MEC	Mountain Equipment Co-op (MEC)
RYE	Ryerson University
HAZ	Hazelton Place
ROM	Royal Ontario Museum
RIC	401 Richmond St. West
JAZ	Jazz Condos
NOW	NOW Magazine

These eight sites were geographically constrained within a radius of approximately 1.5 kilometers in order to examine roofs that experienced largely similar climatic conditions (Figure 3.1).

Figure 3.1: Green roof study site locations

All roofs were selected such that they would typically be classified as 'extensive' (*sensu* Dunnett and Kingsbury 2008) installations, meaning that they all had media depths between 2 cm and 15 cm, had limited access, and were continuous, permanent installations. This is as opposed to rooftop gardens, which consist of vegetation in discrete planters, or 'intensive' (*sensu* Dunnett and Kingsbury 2008) installations that are characterized by deeper media and function similar to traditional ground-level gardens. The sample was constrained so as to exclude any installations that did not fall under the 'extensive' description to ensure that the case studies were not so disparate that they could not reasonably be compared to one another.

3.4 Site Descriptions

Building owners and operators were interviewed. They were asked to provide a list or otherwise describe the initial planting plan of the installation. They were also asked why and how they went about choosing the particular plant species that were a part of the original design.

3.5 Plant Species in Ontario

In order to contextualize findings from a census of vegetation on green roofs in Toronto, a list of plant species in Ontario was obtained (NHIC 2008). This list included both terrestrial and aquatic plants. The list of species was cross-referenced with a list of aquatic species of northeastern North America (Crow and Hellquist 2000) and aquatic species were removed in order to obtain a list of terrestrial species of vascular plants known to occur in Ontario. The list also contained taxa classified down to the level of subspecies for certain plants. The list was edited to include taxa at the species level of

resolution. The family distribution of Ontario species was then calculated based on this modified list.

3.6 Vegetation Census

Each site was visited once during the period of September to October, 2008. The sampling period was constrained in order to control for seasonal variation in floristic composition. The same two surveyors performed all vegetation censuses. Access time was a limiting factor since these roofs were generally not accessible to the public and can typically only be viewed from afar. A quick, but thorough, survey method was developed. Instead of using time-consuming subplots as representations of the vegetative community, the entire roof was surveyed by both surveyors. Surveys were performed over periods of roughly two hours each. Surveyors walked systematically around the roof, and through the vegetation where possible. All observed species were recorded. Any unidentifiable specimens were recorded photographically and a sample was collected and pressed to be identified at a later time. Species were identified using expert guidance which involved pre-sampling training (Sam Benvie, personal communication, June 23, 2008) and post-sampling verification (Sam Benvie, personal communication, November 24, 2008). Botanical keys and other references were also used (Alex 1992; Chambers *et al.* 1996; Dickinson *et al.* 2004). If plants could not be identified to the species level, they were identified to the most detailed taxonomic resolution possible.

When dealing with such ephemeral things as percentage cover, a high degree of precision is unnecessary and probably misleading. Since roofs were only surveyed once during the growing season, species abundance was expressed as a range using the percentage cover categories of the Braun-Blaunquet cover scale (as described by

Shimwell 1971). This figure was estimated by considering the percentage of the roof that would be occupied by the species (in isolation of all other species) if one was to observe the species from directly above. The abundance of each species was determined visually and percentage cover categories were assigned to each species and recorded independently by each surveyor. The two cover estimates for each species were then compared. When estimates were not in agreement, the lower percentage cover score was used to provide the most conservative estimate of plant abundance. Because of vertical stratification, the sum of cover values for all species on an installation may total more than 100%. This method of visually estimating percentage cover is commonly used in vegetation research (e.g. Clarkson 1984; Carni and Ladislav 1998; Yoshihara *et al.* 2009) and has been shown to provide accurate, repeatable data (Dethier *et al.* 1993).

Sedum spp. represented a special circumstance. Since many of the *Sedum*-based roofs are sold as complete patented systems, proprietary concerns were raised with regard to reporting the exact identity of species used. *Sedum* species identities were conveyed to surveyors in confidence. Therefore, the number of different sedum species used was reported, but not species identity. It is also noteworthy that percentage cover values for *Sedum* were recorded at the genus level. For the purposes of this work, the term 'physiognomy' has been adopted in order to refer to the 'face' or 'outward appearance' of green roof vegetation assemblages. Any examination of 'dominance' of particular plant species over another is carried out in the physiognomic sense, meaning that one species appears qualitatively in greater abundance than another, as opposed to indicating something deeper about the competitive interactions between species.

3.6.1 Representativeness of Census Visits

Site RYE allowed access over the entire 2008 growing season and was visited approximately once every two weeks, in addition to the formal census survey visit in September 2008. A running total of all species observed was kept for the period from May 2008 until November 2008. This was done to assess the extent to which a fall survey could identify the spectrum of species present.

3.6.2 Classification into Photosynthetic Pathway Type

Once all species from all sites had been identified, information regarding photosynthetic pathways for species was obtained from the published literature (See Appendix A). Specimens that were unable to be identified to the species level were assigned the photosynthetic pathway recognized for similar species within the same genus. Percentage cover in relation to roof area of C3, C4 and CAM plants for each roof was determined by adding together individual species percentage covers within each group.

3.6.3 Classification of Planted and Colonist Species

Interviews were conducted with building owners and operators for all study sites. Owners and operators were asked to provide a list of planted species and this list was compared to the list of species determined by the vegetation survey. Species not appearing on the planted list were designated as colonist species.

3.7 Quantification of Installation Physical Parameters

Roof age and media depth were determined during interviews with building owners and operators. Roof size was measured using 2005 orthophotos (First Base

Solutions 2005) and ESRI'S ArcGIS 9.x. To correct for error in measurement from orthophotos, the schematics for site RYE were known and the actual installation size was compared to the orthophoto measured area for the site. A correction factor was applied to the rest of the site measurements. For roofs that were not built in 2005, size estimates were taken from the building or installer website. Roof height was recorded as standard storeys (10 ft). If the building itself did not consist of standard storeys, a height estimate was taken based on adjacent buildings.

3.8 Maintenance Survey

The building owners and operators for all eight sites were interviewed to quantify the nature of maintenance carried out at the site in 2008. A survey was developed based on maintenance activities suggested by the ASTM standard (ASTM 2006) (Appendix B). Interview subjects were asked whether the roof was fertilized, irrigated, or weeded in 2008. If the roof was weeded, interview subjects were asked to indicate the frequency with which weeding took place. Interview subjects were also asked whether additional media, plants or pesticides were added in 2008.

3.9 Data Analysis

Modal class was calculated for percentage cover categories. For all sites where each species was present, the mode of percentage cover category was calculated as the most frequently occurring category. If multiple modes existed, the lowest value modal class was taken in order to provide a conservative estimate. Given the small sample size of eight sites and the resulting lack of normal distribution of results, non-parametric statistics were used to probe for exploratory data analysis. Spearman's rank order correlation was used to probe for relationships between the number of species present at a

site and roof age, roof height, roof size and media depth. Mann-Whitney U tests were used to test for difference in the number of species present at sites under different maintenance regimes. Differences between the number of species present at a site and dominant photosynthetic pathway type were also evaluated using a Mann-Whitney U test.

CHAPTER 4

Results

4.1 Site Descriptions

4.1.1 215 Spadina (SPA)

Site SPA was planted with a mixture of forbs and grasses, many of which were perennials native to Ontario. A total of 13 different species were included in the original planting design, such as *Rudbeckia hirata* (Black-Eyed Susan), *Solidago bicolor* (Silver Goldenrod), and *Panicum virgatum* (Switch Grass). These species were planted in a clumped distribution, with thirteen areas, each containing a unique species except for one clump along the edge that blended two visually similar species, *Helianthus tuberosa* (Woodland Sunflower) and *Rudbeckia lacinata* (Green-Headed Coneflower).

The building owners and operators at site SPA were particularly interested in the increased amenity space provided by green roof installation (Young 2006). An accessible viewing deck allows tenants to visit and enjoy the garden, although vegetation-level access is limited to maintenance personnel. Plants with varying heights and flowering times were chosen to give seasonal interest to the assemblage. The owners and operators were also interested in using this installation as a vehicle to showcase their awareness of and enthusiasm for environmental issues (Young 2006). These goals were communicated to the suppliers and designers involved in the green roof construction, and the specific species list was chosen to satisfy these aims.

4.1.2 Mountain Equipment Co-op (MEC)

Site MEC was originally planted with more than 40 different species of perennials, annuals and grasses. The original plant community included species of *Allium* (chives), *Linum* (Flax), *Festuca* (Fescue), *Sedum* (stone crop), and *Pteridophyta* (ferns). Broadleaf species such as *Papaver rhoeas* (corn poppy), *Iris pumila* (dwarf

bearded iris), *Lavandula angustifolia* (lavender), and unspecified species of sunflower were planted in clumped distributions around the roof. Grass species were planted in a more uniform distribution throughout the roof, and sedum species were focused around the corners of the installation. Since the time of installation, many of these originally planted species have died out, while new species have migrated in. Overall, the installation was most strongly meant to resemble a meadow-type habitat and was dominated by broadleaf species and grasses.

The design priorities of the building owners and operators were to include species that would "do well" under the physical constraints of the installation environment and also attract songbirds. The building owners and operators were also influenced to emphasize native species during the collaborative design process with the installers. These design goals were communicated to the installers without specific species preferences from the building owners and operators. Ultimately, it was the installers who chose the specific types and abundances of species that would comprise the original design.

4.1.3 Ryerson University (RYE)

The green roof at Ryerson University (RYE) that was considered is located on the George Vari Engineering and Computing Centre. This installation was planted as a monoculture of *Hemerocallis* var. *Catharine Woodbery* (Daylilies). Vegetative material was installed with a uniform distribution, planted in rows with the intention of having the species' natural rhizomatous growth fill the roof in with a continuous cover of daylilies.

This assemblage was chosen for aesthetic reasons. *Hemerocallis* was viewed as a tough, resilient plant that is self-spreading and easy to maintain. The personal experience

of the designer working with this species also led to the final choice of vegetation assemblage.

4.1.4 Hazelton Place (HAZ)

Site HAZ was originally planted with a mixture of eight different *Sedum* (stone crop) species and grasses such as *Bouteloua gracilis* (Blue grama) and *Selseria caerulea* (Blue moor grass). Vegetative material was planted in plugs with a regular distribution. Sections of grass alternate with sections of *Sedum* and plugs are expected to grow to achieve full coverage.

The final design assemblage was chosen based on the type of green roof system desired by the building owners and operators as ordered from the green roof supplier. Media depth was a constraining factor in species choice, as well as the climatic circumstances of the roof.

4.1.5 Royal Ontario Museum (ROM)

Site ROM was originally planted with a mixture of *Sempervivum* (hens & chicks), *Allium* (chives), and *Equisetum* (horsetails) and ten different species of *Sedum* (stone crop). More than half of planted species were succulents (*Sedum* and *Sempervivum*) and all species were planted in plugs. This installation also included several tree species including *Amelanchier canadensis* (Serviceberry), *Cladastris lutea* (Yellow Wood), *Populus tremuloides* (Trembling Aspen), and *Cercidiphyllum japonicum* (Katura), which were planted strategically over underlying building support columns in subterranean planters containing much deeper substrate. These planters surficially lined up with the rest of the installation, so as to give a continuous appearance.

During the design phase, the initial priority of the building owners and operators was to select native species for use in the installation. The shallow depth of media excluded many native species and so the owners and operators then decided to focus on species that were suited to available soil depth and environmental conditions. This installation is overlooked through the windows of other portions of the building so it was also a priority to choose species that would be highly aesthetic and provide interest across seasons. The owners and operators chose species to vary height characteristics to maximize relief. They wanted the final effect to be reminiscent of a painting or garden scene. At the same time, the owners and operators wanted a vegetation assemblage that provided potential for education and research, since these priorities reflect the institution's mandate. The final installation design reflects the influence of all of these preferences and goals.

4.1.6 Richmond St. W (RIC)

The green roof at 401 Richmond St. west (RIC) consists of two separate installations; much of the roof is covered with a 'roof top garden' that consists of various species planted in pots interspersed among outdoor furniture and architectural features. This study chose to focus on the other section of the green roof which is planted with a *Sedum*-mat for aforementioned reasons. The installation consisted of a mat of eight to twelve species of *Sedum* that was laid over existing roof structure. This part of the roof can be seen from the rooftop garden area, but is not accessed except for maintenance purposes.

The building owners and operators decided to install this particular type of green roof because they wanted to add on to the existing green roof, having been pleased with

the results obtained from their initial investment. However, they did not want to greatly increase the amount of maintenance and "commitment" from what they already were experiencing. The desire was to expand roof green area without the budget expanding out of reach. Structural loading was not a limiting factor. The building owners and operators expressed environmental focus in their operations and were interested in experimenting with different applications of green roof technology, so they decided to install sedum-mat type vegetation.

4.1.7 Jazz Condos (JAZ)

Site JAZ installed a sedum-mat type green roof, containing eight to twelve species of *Sedum*. This installation is visible for residents in their condos from above the green roof. The building owners and operators decided to choose this particular type of green roof because of their history working with the installation company on other properties. The owners and operators had undertaken similar projects in the past and installed the sedum-mat because of their own experience with its performance. This roof also has limited access, so a low-maintenance system was desired.

4.1.8 NOW Magazine (NOW)

Site NOW was installed with a sedum-mat type roof that consisted of two species of *Sedum*. The potential vegetation that could be used for this installation was limited by structural loading considerations. The building owners and operators also installed the roof as a way of demonstrating their commitment to environmental and sustainability issues.

4.2 Representativeness of Census Visits

The list of total species observed at site RYE from May to November, 2008, was compared to the list of species recorded during the single census visit that occurred in September of the same year. It was determined that 82% of all species observed were captured during the single visit (Appendix C).

4.3 Terrestrial Plant Species in Ontario

It was determined that a total of 2515 terrestrial plant species belonging to 123 families has been recorded in Ontario. The most species-rich family was *Asteraceae*, which contains approximately 12% of Ontario species (Figure 4.1). Families *Poaceae*, *Rosaceae*, and *Cyperaceae* were the next most species-rich families, containing 9%, 7%, and 6% of Ontario species. These were used as a benchmark for determining the distinctiveness of the species assemblages found on green roofs.

4.4 Results of Vegetation Survey

4.4.1 Green Roof Plant Species in Toronto

In total, 112 species belonging to 30 families were observed (Figure 4.2) (See Appendix D for detailed species listing). This represents approximately 4.5% of species in Ontario. More than a quarter of all species observed belonged to the family *Asteraceae*. The family *Crassulaceae* had the second highest species richness, with 12% of observations. Representatives from families *Poaceae*, *Fabaceae*, and *Lamiaceae* made up 10%, 7%, and 5% of observed species. The remaining 39% were scattered among twenty-five different families.

Figure 4.1: Family distribution of terrestrial plant species in Ontario. Families comprising less than 1% of species are omitted.
(Based on information provided by NHIC 2008).

Figure 4.2: Family distribution of observed species on eight green roofs in downtown Toronto.

The most frequently observed species were *Taraxacum officinale* (dandelion), *Plantago major* (common plantain), *Ailanthus altissima* (tree of heaven), *Ulmus americana* (American elm), and *Poa annua* (annual bluegrass) as each appeared on more than half of the roofs surveyed (Figure 4.3) (See Appendix D for detailed species listing). A further thirty-nine species appeared at multiple sites, though on half the roofs or less. Sixty-eight species appeared only once on multiple roofs. *Sedum spp.* appeared on six of eight roofs, but the actual species composition varied from roof to roof.

Figure 4.3: Percentage of observed plant species found at various frequencies on eight green roofs in downtown Toronto.

In terms of modal percentage cover, *Sedum spp.* were the most physiognomically dominant (Figure 4.4), covering an average of 76-100% of the roofs where they were present (See Appendix D for detailed species listing). *Hemerocallis* var. Catharine Woodberry covered the second largest proportion of the roof where it was found, with a modal percentage cover of 51-75%. Eight additional species covered 6-25% of roofs, while twenty-eight other species covered 1-5%. Sixty-three species were observed to be present at various sites, but covered less than 1% of roofs on average.

Figure 4.4: Percentage of observed plant species occurring at various modal percentage cover classes. Percentage cover classes are based on the Braun-Blanquet scale (Shimwell 1971) as follows: + = < 1%; 1 = 1-5%, 2 = 6-25%; 3 = 26-50%; 4 = 51-75%; 5 = 76-90%.

4.4.2 Species Variation between Roofs

The eight study sites varied in terms of number of species present per site (Figure 4.5) (See Appendix D for detailed species listing). Site RYE had the most species, with thirty-nine unique species observed. Sites ROM, MEC, HAZ, and SPA had moderate species diversity, with between twenty-seven and thirty-five recorded at each site. Sites RIC, NOW, and JAZ had the fewest species, with six to fifteen species recorded. The average number of species observed per site was twenty-five, with a standard deviation of twelve species.

Figure 4.5: Number of plant species observed at each site.

4.4.3 Photosynthetic Pathway Type of Green Roof Plant Species in Toronto

Eighty-one per cent of species were determined to utilize the C3 photosynthetic pathway (Figure 4.6) (See Appendix A for detailed species listing). CAM was the second most frequent photosynthetic pathway, as it was found to be employed by twelve per cent of species. The remaining seven per cent of species utilized the C4 photosynthetic pathway.

Figure 4.6: Percentage of observed species utilizing various photosynthetic pathways.

4.4.4 Variation in Photosynthetic Pathway Dominance between Roofs

Sites SPA, MEC, and RYE were physiognomically dominated by C3 plants, as 75-100% of these roofs were covered by species utilizing this pathway (Table 4.1). The remaining five sites each had coverage of 6-25% by C3 species.

No site was physiognomically dominated by C4 plants (Table 4.1). Sites HAZ and SPA had the largest proportions of C4 plants, with 6-25% coverage. Sites MEC, RYE, ROM and NOW had minor patches (<5% cover) of C4 plants, while sites RIC and JAZ contained no C4 species.

CAM physiognomic dominance was observed on sites RIC, JAZ and NOW with 76-100% of these sites being covered by CAM species (Table 4.1). Site ROM was also physiognomically dominated by CAM species, although these species only comprised 26-50% of cover at this site. Site MEC had 6-25% coverage by CAM species. Sites SPA and RYE contained no CAM species.

Site HAZ was the only site to have bimodal photosynthetic pathway physiognomic dominance, with C3 and CAM plants each comprising 6-25% of the roof (Table 4.1).

Table 4.1: Percentage cover category by species of various photosynthetic functional types on eight green roofs in downtown Toronto. Percentage cover classes are based on the Braun-Blanquet scale (Shimwell 1971) as follows: + = < 1%; 1 = 1-5%, 2 = 6-25%; 3 = 26-50%; 4 = 51-75%; 5 = 76-100%.

Site	C3	C4	CAM
SPA	5	2	N/A
MEC	5	1	2
RYE	5	1	N/A
HAZ	2	2	3
ROM	2	+	2
RIC	2	N/A	5
JAZ	2	N/A	5
NOW	2	+	5

4.4.5 Planted Species versus Colonist Species

Overall, forty-three species were intentionally planted and sixty-six species appeared only as colonists (Figure 4.7). Only three species, *Asclepias syriaca* (common milkweed), *Mondarda fistulosa* (wild bergamot), and *Symphyotrichum novae-angliae* (New England aster), were planted intentionally at some sites and appeared as colonists at others.

Figure 4.7: Percentage of species originating as either planted, colonizing, or both.

The number of species planted at each site varied between one species (RYE) and seventeen species (ROM) (Figure 4.8). The average number of species planted per site was 10. The number of colonist species at each site varied between six species (JAZ) and thirty-eight species (RYE). The average number of colonist species per site was 17.

Figure 4.8: Number of planted and colonist species per site.

In terms of cumulative roof cover, the modal class for all combined planted species was 5 (75 - 100%), with half of all sites observed to have this value (Table 4.2). The lowest cover provided by all planted species was 6-25% (class 2) at site ROM. For all roofs, planted cover was physiognomically dominant over colonist cover. Total cover by colonists was mostly 6-25% (class 2) as six sites were observed to have this value. The modal class for bare ground was + (<1%) with five sites observed to have this value. One site (ROM) was physiognomically dominated by bare ground. Site HAZ was equally physiognomically dominated by planted species and bare ground.

Table 4.2: Percentage cover category by planted and colonist species as well as bare ground on eight green roofs in downtown Toronto. Percentage cover classes are based on the Braun-Blanquet scale (Shimwell 1971) as follows: + = < 1%; 1 = 1-5%, 2 = 6-25%; 3 = 26-50%; 4 = 51-75%; 5 = 76-50%.

Site	Planted Species Cover Class	Colonist Species Cover Class	Bare Ground Cover Class
RIC	5	2	+
JAZ	5	2	+
NOW	5	2	+
SPA	5	2	+
RYE	4	3	2
MEC	3	3	+
HAZ	3	2	3
ROM	2	2	4

On a per-species basis, most colonist species were observed to have low modal class percentage cover values (Figure 4.9). Only planted species occurred with percentage cover above 26%.

Figure 4.9: Distribution of observed species occurring at various percentage cover classes on eight green roofs in downtown Toronto. Percentage cover classes are based on the Braun-Blanquet scale (Shimwell 1971) as follows: + = < 1%; 1 = 1-5%, 2 = 6-25%; 3 = 26-50%; 4 = 51-75%; 5 = 76-50%.

4.5 Physical Parameters Results

Installations varied in size between 291 m² and 1098 m² (Table 4.3). Roof height varied between two storeys and six storeys. Media depth varied between 2 cm and 15.24 cm. Roofs varied in age between 0 years (constructed in 2008) and 10 years.

Table 4.3: Green roof study site physical parameters.

Site	Roof Size (m ²)	Roof Height (storeys)	Media Depth (cm)	Roof Age in 2008 (years)
SPA	430	5	15.24	4
MEC	846	2	12.7	10
RYE	820	5	15.24	4
HAZ	410	4	6.35	0
ROM	1098	6	12.7	0
RIC	242	5	2	3
JAZ	291	7	2	3
NOW	474	4	5.2	2

4.6 Maintenance Survey Results

None of the interview subjects reported adding fertilizer, media, or pesticides to their roof in 2008. Five sites reported using irrigation, while three did not (Table 4.4). All sites reported weeding, though sites differed in the frequency of this activity. Half the sites weeded regularly while the other half weeded as needed. Only one site (MEC) reported planting additional species in 2008.

Table 4.4: Maintenance activities reported for 2008 for eight green roofs in downtown Toronto.

Site	Supplemental Irrigation (Y/N)	Weeding Frequency	Additional Planting (Y/N)	Addition of Fertilizer (Y/N)	Addition of Media (Y/N)	Addition of Pesticides (Y/N)
SPA	Y	As Needed	N	N	N	N
MEC	Y	Regular	Y	N	N	N
RYE	N	Regular	N	N	N	N
HAZ	Y	Regular	N	N	N	N
ROM	Y	As Needed	N	N	N	N
RIC	N	As Needed	N	N	N	N
JAZ	N	As Needed	N	N	N	N
NOW	Y	Regular	N	N	N	N

4.7 Relationships between Vegetation and Physical Parameters

4.7.1 Roof Height

The number of plant species observed per site was not found to be correlated with the height of the installation ($r_s = -0.2846$, $p = 0.4945$) (Figure 4.10).

Figure 4.10: Number of plant species observed versus roof height for eight green roofs in downtown Toronto. One standard storey is equal to 10 ft.

4.7.2 Roof Size

The number of plant species observed on roofs tended to increase as roof size increased, although this correlation was only found to be marginally significant ($r_s = 0.6980$, $p = 0.0542$) (Figure 4.11)

Figure 4.11: Number of plant species observed versus roof size for eight green roofs in downtown Toronto.

4.7.3 Roof Age

Roof age was not found to be correlated with the number of plant species found per site ($r_s = 0.2144$, $p = 0.6102$) (Figure 4.12).

Figure 4.12: Number of plant species observed versus roof age in 2008 for eight green roofs in downtown Toronto.

4.7.4 Media Depth

A statistically significant positive relationship was found between the number of plant species and the depth of media ($r_s = 0.7493$, $p = 0.0324$) (Figure 4.13).

Figure 4.13: Number of plant species versus media depth for eight green roofs in downtown Toronto.

4.8 Relationship between Vegetation and Photosynthetic Pathway Dominance

Sites dominated by C3 species tended to have a different number of species than sites dominated by CAM plants, although this difference was not statistically significant ($U = 11.0$, $p = 0.114$) (Figure 4.14). The data point for site ROM which was equally dominated by C3 and CAM species was not included in statistical analysis since it is only one point and comparisons between multiple categories require more than one point per category, but is included in Figure 4.14 for comparison.

Figure 4.14: Comparison of the number of species observed on roofs with different photosynthetic pathway physiognomic dominance. The boundaries of the box represent the 25th and 75th percentiles respectively. The thin solid line represents the median and the bold dashed line represents the mean value.

4.9 Relationships between Vegetation and Maintenance Activities

4.9.1 Irrigation

No difference in species numbers was observed between sites that irrigated and sites that did not ($U = 8.0$, $p = 1$) (Figure 4.15).

Figure 4.15: Comparison of the number of species recorded at irrigated and non-irrigated sites. The boundaries of the box represent the 25th and 75th percentiles respectively. The thin solid line represents the median and the bold dashed line represents the mean value.

4.9.2 Frequency of Weeding Activities

Sites that weeded regularly and sites that weeded on an as-needed basis did not have statistically different numbers of species present ($U = 10.5$, $p = 0.485714$) (Figure 4.16).

Figure 4.16: Comparison of the number of species observed at sites reporting weeding as needed versus those reporting weeding with regular frequency. The boundaries of the box represent the 25th and 75th percentiles respectively. The thin solid line represents the median and the bold dashed line represents the mean value.

CHAPTER 5

Green Roof Vegetation Demography and Relationships with Physical Parameters and Maintenance

5.1 Representativeness of Vegetation Survey

The high percentage of species occurring throughout the 2008 growing season that were captured during a single visit to site RYE suggests that much of the variation present was likely captured at the study sites through the single-visit methodology utilized. The true demography of plants on green roofs would be better resolved if surveying was done throughout the growing season, but access to buildings often limited the possibility of this. In order to truly understand the population of plants present on green roofs, surveys must be conducted on multiple buildings. Research findings of this work indicate that valuable information concerning species richness may be gleaned from single sampling visits. This suggests that the current methodology may be useful for application to wider scales as surveying a larger number of buildings may further refine understanding.

5.2 Toronto Green Roof Plant Species in Context

The diversity of plants found on green roofs in Toronto suggests that many different species can be used in this technology. The family distribution of Toronto green roof species is quite similar to the distribution found in Ontario in general. One important point of difference is the prominence of species from the family *Crassulaceae*. This was the second most species rich family found on green roofs although less than one percentage of Ontario species belong to this group. Although this may not be surprising, since the popularity of utilizing *Crassulaceae* for green roof applications is widely documented, this study is the first to quantify the degree to which this favoritism is demonstrated in existing applications.

It should also be noted that more than half of the *Sedum* species utilized on green roofs in Toronto do not appear on the Ontario list. This was somewhat expected as many North American installations are likely to utilize designs created in other localities, such as in Europe, due to the current lack of standardization in the North American market. It has been stated that green roofs present a unique habitat that is not entirely like any existing terrestrial counterpart (Koehler 2003; Dunnett and Kingsbury 2004), therefore, it makes sense that new and under-represented species may come to characterize these habitats. This also indicates that green roofs have the potential to increase the overall plant species diversity in Ontario.

5.3 Prolific Green Roof Species

The most frequently observed species on Toronto green roofs were all common ruderal plants. This is consistent with the findings of Kohler (2006), Dunnett and colleagues (2008), and Archibold and Wagner (2007). These species are ubiquitous and have adaptations that allow them to establish almost anywhere in the urban sphere, growing on bare roofs (Archibold and Wagner 2007), in sidewalk cracks, along roadsides, *etc.* (Alex 1992). This finding speaks to the limitations present in green roof design. While the green roof design process can be standardized such that optimal species mixes are recommended, it is unlikely that any species mix will persist without colonization from aggressive, hardy species such as *Taraxacum officinale*. Effective management regimes are still necessary, even with optimized green roof vegetation design, in order to prevent competitive exclusion of desirable species by these aggressive species.

5.4 Dominant Green Roof Species

The findings of this study suggest that while all installations consisted of a variety of species, a few species tended to become physiognomically dominant. This is consistent with fundamental ecological principles dealing with intra-species competitive interactions (Oberndorfer *et al.* 2007). Species utilize and invest resources in differing proportions depending on their life histories and characteristics. Species that have competitive advantages over others will be able to grow and reproduce more, leading to dominance (Oberndorfer *et al.* 2007). Other green roof vegetation censuses have also determined that green roof installations tend to consist of a few dominant species and many subordinate species (Kohler 2006; Dunnett *et al.* 2008). This suggests that certain species are better adapted to perform on green roofs, which is supported by many studies that have demonstrated differential species survival (Hauth and Liptan 2003; Durman *et al.* 2004; Rowe *et al.* 2007).

5.5 Species Diversity of Installations

Although the number of species present at each site varied, installations in Toronto show considerable diversity of plant species. Previous green roof vegetation censuses have found similar numbers of species. Langton-Yanowitz and colleagues (2005) found 37 species on a single installation at Carleton College in Minnesota.

Dunnett and colleagues (2008) found approximately 50 species among their various experimental plots in the UK. These plots had different substrate depths and irrigation regimes, but were placed side-by-side, so that they could effectively be considered a single installation. The study carried out by Kohler (2006) observed an average of 52 species on ten sub-roofs of the same installation, although this number is cumulative,

taking into account all of the species observed over several years, without indicating how many were present in any given year. The TRCA (2004) found 91 species on York University's green roof, but the actual installation consisted of multiple levels, as well as separate containers which may be considered sub-plots. All of this indicates that there may be some consistency in the number of species expected to occur on a green roof, independent of location. However, these findings also underline the importance of defining what comprises a discreet green roof plot. Further research is needed in order to clarify under which circumstances an installation could be considered to consist of multiple sub-roofs, versus one continuous plot. The interaction between sub-plots in terms of species immigration, extinction, establishment, and competition could also be considered in future studies.

It is interesting to note that Archibold and Wagner (2007) found an average of 12 species on seven non-green roof sites in Saskatchewan, which is consistent with the lower end of species numbers observed in this study. Although the diversity of bare roofs measured in that study is similar to that measured on green roofs in this study, it should be noted that the cover provided by species on green roofs is much greater. The species found by the Archibold and Wagner (2007) study did not cover significant portions of the roofs studied. This suggests that there may be a minimum level of diversity expected for green roofs and that planning to plant a monoculture is unrealistic.

Findings from this study highlight the unique characteristics of each roof. Although *Sedum* dominated many roofs, the exact species of *Sedum* differed between installations. These findings suggest that green roof design is highly malleable and that designs emphasizing species of perceived importance currently exist.

5.6 Functional Classification of Green Roofs in Toronto

After exploring various aspects of green roof plant species demography, it is desirable to consider similarities and differences between installations in a more applied way. Green roofs offer an interesting challenge for researchers since the technology is still so much in its infancy in North America. Basic information regarding the actual plant populations on green roofs is lacking. In order for the technology to progress, a great deal more empirical research is required. This research must be built upon an understanding of the parameters of the system within which it seeks to determine relationships. Given the paradigm that has been previously illustrated, how should research begin to compile the seemingly disparate data that comes from each individual installation? The current research has proposed that it may be useful to classify green roof vegetation based on gross physiological traits such as the photosynthetic pathway. This moves beyond traditional means of classification based on the physical parameters of the system (Dunnett and Kingsbury 2008) or based on general vegetation types (FLL 2002).

Although all of the roofs that have been considered in this study would have been typically classified as 'extensive', the current research reveals two distinct classes of installations based on photosynthetic pathway: C3-dominated roofs and CAM-dominated roofs. Conversely, under the FLL system, the roofs in the study would be broken up as follows: two 'sedum-moss', one 'moss-sedum', three 'sedum-herb-grass', and two 'grass-herb'. The current study proposes that the utilization of photosynthetic pathway dominance is a more informative classification system with a more appropriate level of resolution than currently existing classification systems offer.

This study has determined that C3 photosynthesis is characteristic of most species of plants found on green roofs in Toronto. This was expected, since C3 is the most common photosynthetic pathway utilized by plants (Solomon *et al.* 2002). The unusually high proportion of species utilizing CAM photosynthesis is a direct result, in this study, of the high occurrence of species from the family *Crassulaceae*. This study has also determined that on green roofs in Toronto, C4 species play a subordinate role. This is not to say that a roof could not be dominated by C4 species, since several C4 species were found to be established as colonizers. Instead, these findings indicate that C4 species are not currently widely used as intentional components of green roof vegetation design in Toronto. Since C4 species have drought adaptations comparable to CAM species, this may suggest an opportunity to further investigate them for more widespread use on green roofs. The functional differences that will arise from roofs dominated by each photosynthetic pathway type are as of yet incompletely known.

5.7 Planted and Colonist Species

This study has provided important basic information regarding the diversity and dominance of plant species currently in use in downtown Toronto green roofs. After quantifying 'what' grows on green roofs, it is important to consider 'how' the current assemblages came to be. Most of the species on Toronto green roofs arrived independently as colonists that were able to exploit a newly provided habitat. Less than half of species observed were intentionally planted on the roofs. This finding adds support to the increasing calls to treat green roofs as dynamic, living systems (Kohler 2006; Oberndorfer *et al.* 2007). Importantly, findings from this study demonstrate that all installations have experienced changes in their community composition since initial

planting, since all sites had colonists. The current research provides important foundational information that will allow future researchers to build upon.

Of the intentionally planted species, *Sedum* was the most prolific and dominant, occurring on six of eight roofs, with a modal percentage cover class of 76-100%. In spite of this prominence and the relatively close proximity of study sites, *Sedum* never occurred as a colonist. This is probably due to the fact that *Sedum* seeds are primarily water-dispersed instead of being wind-dispersed (Encyclopedia Britannica 2009). *Sedum* species were not found to act invasively in the current study, but as more and more green roofs are installed, the potential for between-installation migration may increase. All other reviewed green roof vegetation surveys (TRCA 2004; Langton-Yanowitz *et al.* 2005; Kohler 2006; Dunnett *et al.* 2008) had similar findings, in that none reported observing *Sedum* species to have arrived as colonists.

Another interesting finding was the existence of species that appear both intentionally and as colonists. This highlights the relationship between natural and anthropogenic selective regimes. The goal in green roof design is to be able to construct a system that supports the community of plants necessary to achieve design goals. Although humans control design specifications and deliberately choose plants to use, it is the workings of nature that will ultimately decide the biotic community composition. Focusing on areas where humans and nature seem to have made the same decision can increase understanding of the underlying mechanisms that drive the community. While not all colonists are appropriate choices to be intentionally planted due to their aggressive nature and negative connotations ('weeds'), some species that would naturally find their

way on to a roof can successfully be incorporated into the intentional design of installations.

Although colonist species have been shown to exist on all roofs, this study has demonstrated that all installations were physiognomically dominated by planted species, regardless of age, media depth, height, etc. The degree of dominance did vary between sites, but planted species were always covered more of the roof than colonists. This suggests that although roofs are currently being designed without standardized methodology or clear understanding of vegetation dynamics, these installations have been successful in directing community composition toward the intentional. The serendipitous success of planted species on current roofs may derive from a trial-and-error approach, but compiling this type of information can lead to greater understanding of the mechanisms driving the system. The end-goal of a systematic design tool is likely to be greatly aided by an adaptive management approach. Further research is needed to understand why successful plants are 'successful' so that a systematic tool can be created.

Although all of the design assemblages can be generally considered 'successful', since they have persisted in greater abundances than colonist species, an important contribution of this research is the quantification of the amount of each roof that is covered by colonists. Although each site was constructed and designed with reasonable independence, they all had nearly the same fraction (6-25%) of roof claimed by unintentional species. This indicates that current approaches to design may be incomplete.

Specifically, current green roof designs seem to stop short of filling all available niche space. It is understandable why green roof designers would tend to focus on the

dominant species of a roof, and those are the species that will make the largest contribution to the roof's performance (Oberndorfer *et al.* 2007). It is not likely that low-frequency, low-cover species will significantly impact the level of benefits achieved by a roof, although the true impacts of these species remain unknown. The real issue with these unintentional species is likely the operational costs associated with keeping their numbers in check and replacing desirable species that may be out-competed.

This shortcoming of current approaches to green roof design is also supported by the finding that green roofs seem to have minimum levels of plant diversity and that most roofs in the study had approximately twenty five species present. The processes that were used to design some sites seem to have resulted in an inappropriate level of planted species diversity, such as site RYE which initially planted only one species and actually ended up having the greatest number of species overall of all sites.

5.8 Relationships between Site Vegetation and Physical Parameters

The current research has quantified and described green roof vegetation dynamics, physical site parameters, and maintenance regimes for eight green roofs in downtown Toronto. This investigation has generated data that can be built upon by future studies. An examination of correlations between site physical parameters and the number of species present has revealed that certain parameters are more strongly associated with site diversity than others at this point in time, for the sites in central Toronto.

Roof height was not found to be associated with species number. This is in contrast with predictions that species number would decline as roof height increased. It is possible that the difference in height between buildings was not yet significant enough

to provide a barrier to negatively impact immigration rates of new species. Each site also planted various numbers of species, regardless of the height of the installation. While taller buildings may incur harsher conditions, planting can be tailored such that hardier species are chosen. An interesting path for future research would be to examine whether species present on installations of different height exhibit different degrees of hardiness.

Roof size showed a positive correlation with species number. This correlation was found to be marginally significant (i.e. $0.10 > p > 0.05$) (Utts and Heckard 2004). This could either be due to the larger 'target' area or increased habitat heterogeneity provided by larger installations. It is interesting to note that a post-hoc Spearman's rank order analysis showed that the number of planted species was not associated with roof size ($r_s = 0.38$, $p < 0.05$). This means that the observed trend cannot be explained by designers planting a larger number of species on larger roofs. A better understanding of the mechanisms at work is needed to determine whether larger roofs actually provide a greater diversity and number of niche spaces than smaller roofs, since this is not yet fully understood. (Utts and Heckard et al. 2008). Although the study by Utts and Heckard

Roof age was not found to be associated with the number of species that occur at a given site. This finding is in agreement with previous studies that have also shown a lack of trend over time (Kohler 2006). Green roofs differ from natural bare sites in that they are all initially planted with a number of species from the beginning. Maintenance is performed annually on green roof sites which is likely partially responsible for the number of species appearing at a site in any given year. Competitive interactions between plants will also change as climatic and microclimatic factors oscillate. Annual precipitation, temperature and other factors do not remain constant and so the stage upon

which competitive interactions play out is constantly changing. In urban centres such as Toronto, constant construction and renovation of adjacent buildings is also likely to change microclimatic factors such as shading. This indicates that the number of species present at a green roof site may not vary in a predictable manner. Although the oldest roof in the study (MEC) is one of the oldest green roofs in Toronto, all of the study sites are relatively 'young' in age in the context of plant successional time periods. The dynamics of North American green roof vegetation assemblages over large time periods is unknown, given the relative newness of this technology in this location.

The strongest relationship was found between media depth and number of species present at a given site. A post-hoc Spearman's rank order correlation analysis determined that the number of planted species was not correlated to media depth, so the observed trend cannot be explained based on planted species alone ($r_s = 0.19$, $p < 0.05$). The finding that total community species richness increases with media depth is in contrast with findings from previous vegetation censuses which found higher species diversity at shallower media depths (Dunnett *et al.* 2008). Although the study by Dunnett and colleagues (2008) represented a controlled experiment that manipulated media depth, it is possible that their results also could be interpreted as a test of the competitive abilities of their chosen assemblage.

Dunnett and colleagues (2008) explained the higher species diversity at shallower depths by postulating that poorer performance of planted species led to unfilled niches which were then exploited by colonizers in greater numbers. This is a reasonable explanation. However, the authors do not adequately clarify the role of media depth in dictating species number due to the confounding factor of using a constant planted

species assemblage. While such experimental controls are necessary for scientific studies, the effect of media depth on species number could be better elucidated by comparing the results of multiple parallel controlled experiments utilizing different species assemblages.

The findings in this study of an increase in species number with media depth is also in contrast to ecological theory stating that sites with lower fertility tend to have higher diversity since resource limitation constrains a species' ability to dominate others (Grime 2002). It is possible that media depth alone is actually not the best proxy for site fertility, but the relationships between media parameters and fertility has not yet been adequately documented. It is also possible that a critical threshold exists for media depth wherein very shallow media is so infertile that accepted ecological theory no longer applies. However, such a trend would more likely reveal a convex, parabola-shaped relationship where moderate media depths are associated with higher diversity than very deep or very shallow media. This is in contrast with the linear relationship observed in the current research, although it could also be that the range of media depths studied is insufficient to reveal the whole relationship. It should be noted that saturation in species richness was not observed in the current study. As media depth increases past the observed range, eventually species richness would be expected to at least level-off (if not decrease), since infinite diversity is not possible.

5.9 Relationships between Species Number and Photosynthetic Pathway Dominance

Another interesting relationship found as part of this research is that C3-dominated roofs tended to have more species than CAM-dominated roofs, though the difference was only marginally significant. This could be due to fundamental functional

differences between CAM species and C3 species. Some CAM plants such as various species of *Sedum* are thought to be allelopathic, meaning they produce and excrete chemicals that discourage other species from colonizing (Weston 2005, Benvie, personal communication, June 23, 2008). However, this observed difference also reveals a confounding factor of the current research. CAM-dominated roofs tended to be roofs with shallow media and *vice versa*. The larger number of species found on some roofs versus others could then be due to the effects of media depth, photosynthetic pathway dominance, or a combination of both.

5.10 Green Roof Maintenance

A critical component of the current investigation was the quantification of maintenance activities performed on green roofs. This acknowledges that answering the question of 'how' species assemblages came to be is far more complicated than simply explaining the method by which species arrived. The quantification of maintenance activities adds information regarding the factors that have encouraged existing species to stay and prosper. It has been established that the exact nature of maintenance activities performed on green roofs has remained widely speculative in existing literature. Cost-benefit studies are important tools for encouraging the widespread implementation of green roofs, but these studies are incomplete without direct knowledge of the maintenance tasks actually occurring on installations. This study provides baseline information that can be used in future studies to more accurately capture maintenance commitments.

All of the building owners and operators in this study managed their roofs without deciding to add fertilizer, additional media, or pesticides and only one interview subject

reported adding additional plant material to their site in 2008. This suggests that costs for the addition of such inputs have been minimal for these sites. However, green roofs have not been shown to be completely maintenance-free, which is a sentiment agreed upon in much of the literature (Luckett 2008; Dunnett and Kingsbury 2008; XeroFlor 2009). One of the main differences between green roof site maintenance was determined to be whether sites were irrigated or not as most installations (5 of 8) included some form of irrigation, while some sites (3 of 8) did not. Sites also differed in the frequency with which they performed weeding activities, as some weeded regularly and others weeded as needed. This indicates that the specifics of maintenance regimes will differ from roof to roof and can (and should) be tailored on an individual basis. A clearer understanding of the actual maintenance commitments associated with green roofs will aid in more informed green roof stakeholders that can then design more realistic plans for green roofs. Knowledge of, and commitment to, realistic maintenance plans will also aid in increasing the reliability and performance of green roof systems in general.

5.11 Relationships between Species Richness and Maintenance Activities

The presence of irrigation was not found to influence the number of species present on green roofs in Toronto. This could be due to the unusually high volume or frequency of precipitation events experienced in the 2008 growing season, narrowing the resource pool gap between irrigated and non-irrigated roofs. This could also be due to differences in drought adaptations by species on either type of roof. Drought-tolerant species are likely to survive and thrive on non-irrigated green roofs, while species, which require more water may establish on irrigated installations which would lead to different assemblages, but not necessarily different species number.

All sites performed weeding activities in 2008, which strengthens the conclusion from this study that green roofs will invariably experience some degree of colonization. The frequency of weeding did not translate to any appreciable trend in species richness. It is likely that the thoroughness of weeding is more important than the frequency with which the activity is carried out, although documenting this was beyond the scope of the current study. Whether weeding is scheduled based on a regular time period or based on other cues that incite the need to weed, the number of plant species present does not seem to be affected. This finding indicates that maintenance regimes tailored to the specific building owner and operator preferences and capabilities can be equally successful in affecting species number.

CHAPTER 6

Conclusions and Recommendations

6.1 Future Vegetation Surveys

Future vegetation surveys are needed to compile more data that can be used to further refine conclusions from this study. These future surveys should consider both planted and colonist species, as well as the cumulative vegetative community since all levels of resolution offer important information. Green roof vegetation dynamics remain woefully understudied and many knowledge gaps exist that suggest exciting potential for future research projects.

6.1.1 Changes in Green Roof Assemblages over Time

To fully capture the nature of dynamic community composition changes, censuses should be carried out over several years. The current research offers a snapshot of vegetation demography over a one year period and findings can be enhanced by future studies that revisit roofs over many growing seasons. Information from long-term studies also has applications for cost-benefit studies. Projections of green roof benefit savings assume that initial design vegetation remains stable over time, or that change in green roof species assemblage will not significantly affect installation performance. However, like any living system, green roofs are dynamic and are subject to various abiotic and biotic pressures that lead to competition and succession. The nature of such changes remains unknown and is vital to understanding the advantages of green roof technology.

6.2 Assemblage Classification

Based on the results from the current research, it is recommended that assemblages of green roof species be classified in a functional manner, and that classification based on dominant photosynthetic pathway type may be useful. This new classification scheme can be used to standardize comparisons between multiple

assemblages in future research projects. This classification scheme can replace current schemes that can be vague such as the 'intensive/extensive' classification, or the design types recognized by the FLL (2002). Classification by photosynthetic pathway dominance removes the biasing influence of interpretation since it is a characteristic of plant species that allows for discrete categorization.

The functional differences provided by green roof species require a great deal of further research. The critical characteristics of plant species that contribute to benefit functioning must be determined using controlled experimental studies that vary one characteristic at a time. Findings from experimental studies must then be verified in a field setting. The results from all of these studies then need to be compiled in order to develop a clear picture of how green roof vegetation assemblages actually work to provide environmental benefits. This study has used photosynthetic pathway as a characteristic that is likely to result in functional differences between species. However, the actual performance differences that will arise from roofs dominated by each photosynthetic pathway type are as of yet incompletely known. Photosynthetic pathway offers a good starting point for future green roof performance studies. Once plants are compared based on this characteristic, further studies can tease apart which aspects of the differences between photosynthetic pathways are the most important in determining function.

6.3 Vegetation Design Recommendations

Conclusions deriving from the current research aid in better refining what a recommended species list for green roof plants may look like. A systematic procedure for designing green roofs is needed in order to standardize the design process so that

system performance can be optimized. Once a user indicates the goals of a particular installation, as well as any feasibility restrictions, a systematic tool would compute a list (or several lists) of recommended species. The creation of such lists would require consideration of both the performance of individual species and the compatibility between species. Findings from this study regarding the demography of existing green roof vegetation assemblages have resulted in several recommendations.

This study has demonstrated that all assemblages consist of multiple species, even those that only planted one or two species to begin with. This indicates that plant list recommendations should include a mix of species. Monocultures are unlikely to remain true monocultures, based on the findings from the current research. In terms of the end goal of enhancing green roof performance, it also makes sense to recommend a mixture of species since the different strengths and weaknesses of species within an assemblage may have the potential to act in a complementary fashion, increasing function in multiple benefit realms simultaneously. The current study has demonstrated that installations in downtown Toronto consist of an average of twenty-five species. This number represents a good starting point for species number recommendations for installations in this area, but the optimal number of species for a particular list likely varies from installation to installation and depends on many factors which can be better resolved with further research.

Beyond the number of species, the abundance of species within a vegetation assemblage must also be considered in constructing design plant lists. Results from the current research indicate that these lists may benefit from including recommendation for low-frequency low-cover species which occurred at all sites, but were not included in the

intentional plans of any particular site. This will hopefully work to pre-empt colonization by undesirable species which will in turn help reduce maintenance and should improve success and predictability of design assemblages. A plant list should recommend greater quantities of species found to provide the greatest level of specified benefits since dominant species will play the greatest role in determining the functioning of the installation. The current research recommends that low abundance species be recommended not necessarily based on function, but rather compatibility with dominant species if this low-abundance planting is to have the desired niche-filling effect.

Besides the identity and characteristics of a species, the abundance with which the species appears on the roof is also likely to impact its contribution to green roof performance. The current study underlines the importance of including multiple species at various abundances with the assumption that the dominant species will be mostly responsible for the functioning of the installation. It is not thought to be likely that low-frequency, low-cover species will significantly impact the level of benefits achieved by a roof, but the true impacts of these species remain unknown and future research may choose to examine this. Performance relationships of species must also be examined under different abiotic conditions since a species function will not be constant in all environments. Future research should also examine species performance for different climates, as well as at the microclimate level.

6.4 Assemblage Relationships with Roof Physical Parameters and Maintenance Activities

Once a list of species to be utilized in an installation is compiled, further information is required in order to ensure the success of the green roof. The plant list should be paired with recommendations of installation physical parameters and

maintenance regimes. These are the specifications necessary to ensure that the vegetation assemblage will function as predicted. The current research has determined that roof size, media depth, and photosynthetic pathway dominance have stronger associations with species composition than other factors such as roof age, roof height, irrigation, and frequency of weeding. Assemblages with greater species richness may require larger roofs and / or deeper media to persist. In terms of the relationship between vegetation demography and photosynthetic pathway dominance, it is possible that CAM-dominated species recommendations will require fewer species than C3-dominated species recommendations. The determination of causality between physical parameters, maintenance and vegetation demography will require further study, but the current research has shown which factors seem to be more important than others.

6.5 Effect of Physical parameters

The current research has begun to reveal some of the possible abiotic factors that may influence vegetation dynamics. This study has demonstrated that media depth seems to be tied to the number of species present at an installation. However, it is not known why exactly this is. Further research is needed to determine what media characteristics are most important in determining site fertility. Media depth, composition, and physical properties could all contribute to this. Investigations examining wider ranges of media depth in multiple, parallel controlled experiments would ultimately aid in understanding the relationships between media depth and species number. Furthermore, this study has demonstrated that photosynthetic pathway dominance has also been correlated with media depth at the study sites considered. CAM species are being planted on installations with shallow depths while C3 species occur more dominantly on roofs with

deeper media. Further study is necessary to determine the degree to which abiotic factors such as media characteristics versus biotic factors such as species competition are responsible for the demography of vegetation assemblages on roofs.

Another area for future research is the examination of microclimatic variation that occurs within an installation. In this study, physical parameters were assumed to be constant across an installation, but this is likely not the case. Differences in shading, compaction, wind exposure and other factors likely occur at different areas of the same installation. Studies that measure and characterize the degree of microclimatic variation as well as the effects this variation may have on species dynamics will provide valuable information that will lead to better planning, design and persistence of installations.

6.6 Effect of Maintenance

Findings from the current study indicate that differences between maintenance activities carried out on study sites did not seem to be associated with variation in vegetation demographics. It was postulated that factors such as differences in irrigation may not affect species number, but may affect the characteristics of plants found on different roofs. Further research is needed to reveal whether roofs with different maintenance regimes are characterized by species with different traits and adaptations. Maintenance activities also need to be tracked over several years to gain a clearer understanding of the operational requirements of installations. The maintenance regimes reported in the current study only consider activities carried out in the 2008 season. The frequency and nature of maintenance activities is likely to change over time as different years will provide different challenges. Tracking activities over many years will provide a better average picture of the maintenance that owners and operators can expect.

Combining this knowledge with information from ongoing studies of vegetation demography will provide further understanding of the interplay between green roof maintenance and green roof species assemblages.

6.7 Summary of Conclusions

This study has demonstrated that knowledge concerning vegetation demography on green roofs can reveal important information that can be contributed to a systematic design procedure. Such a systematic procedure also requires understanding of the interplay between installation physical parameters and maintenance activities. Green roofs should be viewed as living, dynamic systems that are influenced by both natural and anthropogenic factors. This technology provides exciting potential to ameliorate many of the environmental problems faced by urban centres, but a great deal of further research is needed to fully understand and optimize the functioning of these systems.

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APPENDIX A

Characteristics of observed species

Species	Common Name	Family	Photosynthetic Pathway	Reference
<i>Acer negundo</i>	Manitoba maple	<i>Aceraceae</i>	c3	(2), (4*)
<i>Acer platanoides</i>	Norway maple	<i>Aceraceae</i>	c3	(12)
<i>Agrostis sp. (gigantea?)</i>	Bentgrass	<i>Poaceae</i>	c3	(1*), (5*), (12*)
<i>Ailanthus altissima</i>	Tree of heaven	<i>Simaroubaceae</i>	c3	(3)
<i>Allium schoenoprasum</i>	Chives	<i>Liliaceae</i>	c3	(1*), (2*), (5*), (12)
<i>Alyssum saxatile compactum</i>	Basket of gold	<i>Brassicaceae</i>	c3	(12)
<i>Ambrosia artemisiifolia</i>	Annual ragweed	<i>Asteraceae</i>	c3	(4), (10)
<i>Amelanchier canadensis</i>	Serviceberry	<i>Rosaceae</i>	c3	(2*), (12*)
<i>Anaphalis margaritacea</i>	Pearly everlasting	<i>Asteraceae</i>	c3	(12)
<i>Andropogon scoparius 'The Blues'</i>	Little bluestem	<i>Poaceae</i>	c4	(2), (5)
<i>Asclepias incarnata</i>	Swamp Milkweed	<i>Asclepiadaceae</i>	c3	(5*), (12)
<i>Asclepias syriaca</i>	Common milkweed	<i>Asclepiadaceae</i>	c3	(5), (12)
<i>Aster (fleabane like - philadelphia fleabaneish)</i>	N/A	<i>Asteraceae</i>	c3	(2*), (5*), (10)
<i>aster (tiny multi)</i>	N/A	<i>Asteraceae</i>	c3	(2*), (5*), (10)
<i>Aster 'big fleabane'</i>	N/A	<i>Asteraceae</i>	c3	(2*), (5*), (10)
<i>Aster 'blue'</i>	N/A	<i>Asteraceae</i>	c3	(2*), (5*), (10)
<i>Aster larger flowers lancelike leaves</i>	N/A	<i>Asteraceae</i>	c3	(2*), (5*), (10)
<i>Aster little multi daisy (panicled / ericoides?)</i>	N/A	<i>Asteraceae</i>	c3	(2*), (5*), (10)
<i>Bidens cernua</i>	Nodding beggar-ticks	<i>Asteraceae</i>	c3	(1)
<i>Bouteloua gracilis</i>	Blue grama	<i>Poaceae</i>	c4	(2), (5)
<i>Cardamine hirsuta</i>	Hairy bittercress	<i>Brassicaceae</i>	c3	(12)
<i>Cerastium fontanum</i>	Mouse-ear chickweed	<i>Caryophyllaceae</i>	c3	(2*), (5*)
<i>Cercidiphyllum japonicum</i>	Katsura	<i>Cercidiphyllaceae</i>	c3	(11)
<i>Chenopodium album</i>	Lamb's quarters	<i>Chenopodiaceae</i>	c3	(3), (10)
<i>Chenopodium glaucum</i>	Oakleaf goosefoot	<i>Chenopodiaceae</i>	c3	(12)
<i>Cichorium intybus</i>	Chicory	<i>Asteraceae</i>	c3	(3)
<i>Cirsium arvense</i>	Canada thistle	<i>Asteraceae</i>	c3	(5*), (12)
<i>Cirsium vulgare</i>	Bull thistle	<i>Asteraceae</i>	c3	(5*), (7), (10)
<i>Cladastis lutea (kentukea?)</i>	Yellow wood	<i>Fabaceae</i>	c3	(11)
<i>Convolvulus arvensis</i>	Field bindweed	<i>Convolvulaceae</i>	c3	(3)
<i>Conyza canadensis</i>	Horseweed	<i>Asteraceae</i>	c3	(10*)
<i>Coreopsis tripteris</i>	Tall tickseed	<i>Asteraceae</i>	c3	(12*)
<i>Crepis tectorum</i>	Narrow leaved hawk's beard	<i>Asteraceae</i>	c3	A
<i>Cyperus esculentus</i>	Yellownutsedge	<i>Cyperaceae</i>	c4	(6), (10)
<i>Dacus carota</i>	Queen Anne's Lace	<i>Apiaceae</i>	c3	(7), (10)
<i>Desmodium paniculatum</i>	Panicledleaf ticktrefoil	<i>Fabaceae</i>	c3	12
<i>Digitaria sp.</i>	Crabgrass	<i>Poaceae</i>	c4	(1*), (10*)
<i>Epilobium sp.</i>	Willowherb	<i>Onagraceae</i>	c3	(12*)
<i>Equisetum hymale</i>	Scouringrush horsetail	<i>Equisetaceae</i>	c3	(5*), (12)
<i>Euphorbia sp.</i>	Spurge	<i>Euphorbiaceae</i>	c4	(2*), (3*), (10*)
<i>Fabaceae (fam) (1 sp.) vertical multi bean</i>		<i>Fabaceae</i>	c3	A
<i>Festuca glauca</i>	Blue fescue	<i>Poaceae</i>	c3	(5*), (12*)
<i>Festuca sp.</i>	Fescue	<i>Poaceae</i>	c3	(1*), (2*), (5*)

<i>Galinsoga quadriradiata</i>	Hairy galinsoga	Asteraceae	c3	(7)
<i>Geum triflorum</i>	Prairie smoke	Rosaceae	c3	(2), (5*)
<i>Helenium autumnale</i>	Common sneezeweed	Asteraceae	c3	(5)
<i>Hemerocallis Catharine Woodbery</i>	Daylily	Liliaceae	c3	(1*)
<i>Hemerocallis Sammy Russel</i>	Daylily	Liliaceae	c3	(1*)
<i>Hypericum perforatum</i>	St. John's Wort	Hypericaceae	c3	(3*), (12)
<i>Hyssopus officinalis ssp. Aristatus</i>	Hyssop	Lamiaceae	c3	A
<i>Lactuca serriola</i>	Prickly lettuce	Asteraceae	c3	(2*), (3*), (12)
<i>Lamiaceae (fam) (1 sp.) (plain alt leaves)</i>		Lamiaceae	c3	A
<i>Lamiaceae (fam) (1sp.) (pink flower)</i>		Lamiaceae	c3	A
<i>Lamiaceae (spearmint?)</i>		Lamiaceae	c3	A
<i>Lepidium densiflorum</i>	Common pepperweed	brassicaceae	c3	(12)
<i>Liatris cylindracea</i>	Ontario blazing star	Asteraceae	c3	(12*)
<i>Liatris spicata</i>	Dense blazing star	Asteraceae	c3	(5*), (12*)
<i>Linaria vulgaris</i>	Toadflax	Scrophulariaceae	c3	(1)
<i>Lupinus perennis</i>	Sundial lupine	Fabaceae	c3	(5*), (12)
<i>Lysimachia vulgaris</i>	Yellow loosestrife	Primulaceae	c3	(12)
<i>Medicago lupulina</i>	Black medick	Fabaceae	c3	(4), (10)
<i>Monarda fistulosa</i>	Wild bergamot	Lamiaceae	c3	(2)
<i>Nepeta cataria</i>	Catnip	Lamiaceae	c3	(12)
<i>Oenothera biennis</i>	Evening primrose	Onagraceae	c3	(2*), (5*), (7)
<i>Oxalis dillenii</i>	Yellow woodsorrel	Oxalidaceae	c3	(10*), (12)
<i>Panicum sp. (miliaceum / dichotomiflorum?)</i>	Switchgrass	Poaceae	c4	(12*)
<i>Panicum virgatum</i>	Cloud nine switchgrass	Poaceae	c4	(5), (12)
<i>Pantago major</i>	Common plantain	Plantaginaceae	c3	(2), (10*)
<i>Poa annua</i>	Annual bluegrass	Poaceae	c3	(1) (5*)
<i>Polygonum sp. (pennsylvanicum / persicaria?)</i>	Knotweed	Polygonaceae	c3	(1*) (4*), (10*), (12*)
<i>Populus sp.</i>	Poplar	Salicaceae	c3	(3*), (7*)
<i>Populus tremuloides</i>	Trembling aspen	Salicaceae	C3	(2), (3*)
<i>Rhus sp. (copallina?)</i>	Sumac	Anacardiaceae	c3	(2*), (12*)
<i>Rosa sp.</i>	Rose	Rosaceae	c3	(2*), (3*), (7*)
<i>Rubus occidentalis</i>	Black raspberry	Rosaceae	c3	(12)
<i>Rudbeckia hirta</i>	Black-eyed susan	Asteraceae	c3	(8)
<i>Rudbeckia laciniata</i>	Cutleaf coneflower	Asteraceae	c3	(12*)
<i>Salix sp.(petiolaris?)</i>	Willow	Salicaceae	c3	(2*), (12*)
<i>Saponaria ocymoides</i>	Rock soapwort	Caryophyllaceae	c3	A
<i>Sedum spp.</i>	Stonecrop	Crassulaceae	CAM	(1*), (12)
<i>Sempervivum sp.</i>	Houseleek	Crassulaceae	CAM	(1*), (12)
<i>Senecio vulgaris</i>	Common groundsel	Asteraceae	c3	A
<i>Sesleria caerulea</i>	Blue moor grass	Poaceae	c3	(13*)
<i>Setaria viridis</i>	Green foxtail	Poaceae	c4	(1*), (4*), (10*)
<i>Silene uniflora compacta</i>	Double bladder campion	Caryophyllaceae	c3	(3*), (12*)
<i>Solanum lycopersicum</i>	Tomato	Solanaceae	c3	(3*), (7*)
<i>Solanum nigrum sensu lato</i>	Black nightshade	Solanaceae	c3	12
<i>Solidago bicolor</i>	Silverrod	Asteraceae	c3	(10*)
<i>Solidago canadensis</i>	Canada goldenrod	Asteraceae	c3	(2), (10)
<i>Sonchus arvensis</i>	Sow thistle	Asteraceae	c3	(10*), (12*)
<i>Stellaria media</i>	Common chickweed	Caryophyllaceae	c3	(9)
<i>Symphyotrichum novae-</i>	New England aster	Asteraceae	c3	see aster

<i>angliae</i>				
<i>Tanacetum vulgare</i>	Common tansy	<i>Asteraceae</i>	c3	(12)
<i>Taraxacum officinale</i>	Dandelion	<i>Asteraceae</i>	c3	(2), (10)
<i>Thlaspi arvense</i>	Field penny-cress	<i>Brassicaceae</i>	c3	(10)
<i>Trifolium pratense</i>	Red clover	<i>Fabaceae</i>	c3	(3*), (4), (10)
<i>Trifolium repens</i>	White clover	<i>Fabaceae</i>	c3	(3*), (10)
<i>Tussilago farfara</i>	Colt's foot	<i>Asteraceae</i>	c3	(12)
<i>Ulmus Americana</i>	American elm	<i>Ulmaceae</i>	c3	(12)
<i>Verbascum sp.</i>	Mullein	<i>Scrophulariaceae</i>	c3	(12*)
<i>Vicia cracca</i>	Tufted vetch	<i>Fabaceae</i>	c3	(1), (3*)

*Indicates that reference refers to species of same genera

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 - (13) Grace, J. 1987. Climatic tolerance and the distribution of plants. *New Phytologist* 106s: 113-130.
- (A) Photosynthetic pathway is assumed as c3 since species was not listed as c4 or CAM by any other reference and since c3 is the most common photosynthetic pathway for vascular plants.

APPENDIX B

Maintenance Survey

1. Name of the building: _____

2. Address: _____

3. City: _____

4. State: _____

5. Zip: _____

6. How long has the building been in use? _____

7. How long has the roof been in use? _____

8. How long has the roof been in use? _____

9. How long has the roof been in use? _____

10. How long has the roof been in use? _____

11. How long has the roof been in use? _____

12. How long has the roof been in use? _____

13. How long has the roof been in use? _____

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16. How long has the roof been in use? _____

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18. How long has the roof been in use? _____

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21. How long has the roof been in use? _____

22. How long has the roof been in use? _____

23. How long has the roof been in use? _____

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25. How long has the roof been in use? _____

26. How long has the roof been in use? _____

27. How long has the roof been in use? _____

28. How long has the roof been in use? _____

29. How long has the roof been in use? _____

30. How long has the roof been in use? _____

31. How long has the roof been in use? _____

32. How long has the roof been in use? _____

33. How long has the roof been in use? _____

34. How long has the roof been in use? _____

35. How long has the roof been in use? _____

36. How long has the roof been in use? _____

37. How long has the roof been in use? _____

38. How long has the roof been in use? _____

39. How long has the roof been in use? _____

40. How long has the roof been in use? _____

Appendix B– Maintenance survey

1). CONTACT INFORMATION

- a) Name:
- b) Address:
- c) Telephone Number/Extension:
- d) Email address:

2). BUILDING PHYSICAL PARAMETERS

- a) Building Location:
- b) Building name of main function:
- c) Building type (commercial, institutional, industrial, residential, mixed etc.):
- d) Roof Area (m² or sq. ft):
- e) Green roof height (stories or m):
- f) Date of Green Roof Construction:
- g) Media depth:
- h) Installation type:
- i) How is the roof accessed?

3). INITIAL PLANTING

- a) Species initially planted on roof (list or attach separate document) Identity
- b) How did you decide on the design species assemblage?

4). MAINTENANCE REGIME

- a) Was the roof fertilized in 2008? Y/N
- b) Was the roof irrigated in 2008? Y/N
- c) Was the roof weeded in 2008? Y/N
 - a. What best describes the frequency of weeding regime?
 - i. Weeded with regular frequency (weekly, monthly, annually, etc.)
Indicate frequency:
 - ii. Weeded as needed
Indicate cues for weeding (presence of particular species, weeds reach certain height, etc.):
 - iii. Other (please indicate)
- d) Were additional desirable plants added to the roof on an ongoing basis in 2008? Y/N
- e) Were additional media added to the roof on an ongoing basis in 2008? Y/N

Were pesticides used on the roof in 2008? Y/N

5). ADDITIONAL COMMENTS

APPENDIX C **Species Observed at Site RYE:** **May 2008 to November 2008**

were observed on September 23, 2008

APPENDIX C – Species observed at site RYE – May 2008 to November 2008

All Species Observed May 2008 - November 2008	Species observed during census visit (Y/N) September 23, 2008
<i>Acer negundo</i>	Y
<i>Acer sp.</i>	Y
<i>Agrostis sp. (gigantea ?)</i>	Y
<i>Ailanthus altissima</i>	Y
<i>Ambrosia artemisiifolia</i>	Y
<i>Asclepias syriaca</i>	Y
<i>Aster sp. A</i>	Y
<i>Aster sp. B</i>	Y
<i>Bidens cernua</i>	Y
<i>Capsella bursa-pastoris</i>	N
<i>Chenopodium album</i>	N
<i>Cirsium arvense</i>	Y
<i>Cirsium vulgare</i>	Y
<i>Conyza canadensis</i>	Y
<i>Coreopsis tripteris</i>	Y
<i>Crepis tectorum</i>	Y
<i>Cyperus esculentus</i>	Y
<i>Epilobium sp.</i>	Y
<i>Festuca sp.</i>	Y
<i>Hordeum jubatum</i>	N
<i>Lactuca serriola</i>	Y
<i>Liatris spicata</i>	Y
<i>Linaria vulgaris</i>	Y
<i>Oxalis dillenii</i>	Y
<i>Panicum sp. (miliaceum / dichotomiflorum)</i>	Y
<i>Plantago major</i>	Y
<i>Poa annua</i>	Y
<i>Polygonum sp. (pensylvanicum / persicaria)</i>	Y
<i>Populus sp.</i>	Y
<i>Rubus occidentalis</i>	Y
<i>Senecio vulgaris</i>	N
<i>Setaria viridis</i>	Y
<i>Solidago canadensis</i>	Y
<i>Sonchus arvensis</i>	Y
<i>Stellaria media</i>	Y
<i>Symphyotrichum novae-angliae</i>	Y
<i>Taraxacum officinale</i>	Y
<i>Thymus vulgaris</i>	N
<i>Tragopogon sp.</i>	N
<i>Trandescantia sp.</i>	N
<i>Trifolium pratense</i>	N
<i>Trifolium repens</i>	Y
<i>Tusilago farfara</i>	N
<i>Ulmus americana</i>	Y
<i>Vicia cracca</i>	Y

Total: 36/44 = 82% species were observed on September 23, 2008

Appendix D -All species observed for all sites

All species observed for all study sites. Percentage cover categories correspond to the following ranges (Braun-Blanquet as reported by Shimwell 1971): + = <1% cover; 1 = 1-5% cover; 2 = 6-25% cover; 3 = 26-50%; 4 = 51-75%; 5 = 76-100%.

Species	SPA	MEC	RYE	HAZ	ROM	RIC	JAZ	NOW	Modal class
<i>Acer negundo</i>			+						+
<i>Acer platanoides</i>			+						+
<i>Agrostis sp. (gigantea?)</i>	+	2	1						+
<i>Ailanthus altissima</i>		+	+	+		2	+	1	+
<i>Allium schoenoprasum</i>		3			1				1
<i>Alyssum saxatile compactum</i>		+							+
<i>Ambrosia artemisiifolia</i>			1		+				+
<i>Amelanchier canadensis</i>					1				1
<i>Anaphalis margaritacea</i>	1								1
<i>Andropogon scoparius 'The Blues'</i>	1			1					1
<i>Asclepias incarnata</i>	2								2
<i>Asclepias syriaca</i>		1	+						+
<i>Aster (fleabane like - philadelphia fleabaneish)</i>			+						+
<i>aster (tiny multi)</i>					+				+
<i>aster 'big fleabane'</i>			+						+
<i>Aster 'blue'</i>			+						+
<i>Aster larger flowers lancelike leaves</i>		+							+
<i>Aster little multi daisy (panicled / ericoides?)</i>		+							+
<i>Bidens cernua</i>			1		+				+
<i>Bouteloua gracilis</i>				1					1
<i>Cardamine hirsuta</i>				+					+
<i>Cerastium fontanum</i>				+		+			+
<i>Cercidiphyllum japonicum</i>					1				1
<i>Chenopodium glaucum</i>					+				+
<i>Chenopodium album</i>	+								+
<i>Cichorium intybus</i>		+							+
<i>Cirsium arvense</i>			1	1			1		1
<i>Cirsium vulgare</i>			+						+
<i>Cladastria lutea (kentukea?)</i>					1				1
<i>Convolvulus arvensis</i>						+			+
<i>Conyza canadensis</i>			2						2
<i>Coreopsis tripteris</i>		+	+						+
<i>Crepis tectorum</i>	+		+						+
<i>Cyperus esculentus</i>			+					+	+
<i>Dacus carota</i>				+					+
<i>Desmodium paniculatum</i>		2							2
<i>Digitaria sp.</i>	+	1							+
<i>Epilobium sp.</i>	+		+						+
<i>Equisetum hymale</i>					1				1
<i>Euphorbia sp.</i>				+					+
<i>Fabaceae (fam) (1 sp.) vertical multi bean</i>						+			+
<i>Festuca glauca</i>				1					1
<i>Festuca sp.</i>		3	1						1
<i>Galinsoga quadriradiata</i>								+	+
<i>Geum triflorum</i>		+							+
<i>Helenium autumnale</i>	2								2
<i>Hemerocallis Catharine Woodbery</i>			4						4

<i>Hemerocallis Sammy Russel</i>	1								1
<i>Hypericum perforatum</i>		1							1
<i>Hyssopus officinalis</i> ssp. <i>Aristatus</i>		+							+
<i>Lactuca serriola</i>			1						1
<i>Lamiaceae</i> (fam) (1 sp.) (plain alt leaves)								+	+
<i>Lamiaceae</i> (fam) (1 sp.) (pink flower)	+								+
<i>Lamiaceae</i> (spearmint?)				+					+
<i>Lepidium densiflorum</i>						+			+
<i>Liatris cylindracea</i>		+							+
<i>Liatris spicata</i>			+						+
<i>Linaria vulgaris</i>	+		1						+
<i>Lupinus perennis</i>		+							+
<i>Lysimachia vulgaris</i>	1								1
<i>Medicago lupulina</i>		2			1				1
<i>Monarda fistulosa</i>	1	2							1
<i>Nepeta cataria</i>				1					1
<i>Oenothera biennis</i>		+							+
<i>Oxalis dillenii</i>			+	+	+	+			+
<i>Panicum</i> sp. (<i>miliaceum</i> / <i>dichotomiflorum</i> ?)	+		1		+				+
<i>Panicum virgatum</i>	2								2
<i>Plantago major</i>		+	1	+	+	1		+	+
<i>Poa annua</i>			1	+	1		1	2	1
<i>Polygonum</i> sp. (<i>pensylvanicum</i> / <i>persicaria</i> ?)			+	+	+				+
<i>Populus</i> sp.			1	1	+			+	+
<i>Populus tremuloides</i>					1				1
<i>Rhus</i> sp. (<i>copallina</i> ?)					1				1
<i>Rosa</i> sp.		+							+
<i>Rubus occidentalis</i>	+		+						+
<i>Rudbeckia hirta</i>	2								2
<i>Rudbeckia laciniata</i>	2								2
<i>Salix</i> sp. (<i>petiolaris</i> ?)	1								1
<i>Saponaria ocymoides</i>		+							+
<i>Sedum</i> spp.		2		3	2	5	5	5	5
<i>Sempervivum</i> sp.					1				1
<i>Senecio vulgaris</i>				1	+		+		+
<i>Sesleria caerulea</i>				1					1
<i>Setaria viridis</i>			+	+	+				+
<i>Silene uniflora compacta</i>		+							+
<i>Solanum lycopersicum</i>						+			+
<i>Solanum nigrum sensu lato</i>						+			+
<i>Solidago bicolor</i>	2								2
<i>Solidago canadensis</i>		1	2						1
<i>Sonchus arvensis</i>			2	+		2	+		+
<i>Stellaria media</i>			+	1		+			+
<i>Symphotrichum novae-angliae</i>	2	1	1						1
<i>Tanacetum vulgare</i>	+								+
<i>Taraxacum officinale</i>	1		2	1	+	2	+	1	1
<i>Thlaspi arvense</i>						+			+
<i>Trifolium pratense</i>					+				+
<i>Trifolium repens</i>	+	1	+	+					+
<i>Tussilago farfara</i>			+						+
<i>Ulmus Americana</i>			+	1	+	+		+	+
<i>Verbascum</i> sp.	1					+			1
<i>Vicia cracca</i>	1	1	2		1				1