EXPANDING THE PLANT PALETTE FOR GREEN ROOFS

By

Drew Anthony Vandegrift

A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

Horticulture – Master of Science

2018

ABSTRACT

EXPANDING THE PLANT PALETTE FOR GREEN ROOFS

By

Drew Anthony Vandegrift

Fifty-four percent of the world's population lives in urban areas and this number continues to grow (United Nations, 2014). Dense development along with the accompanying increase in impervious surfaces can have harmful effects on humans, wildlife, and the earth. Green infrastructure such as green roofs can improve urban areas by introducing plant life to otherwise barren rooftops, thus reducing the negative impact humans may have on the environment. While green roofs are a historically old practice, they are relatively new to North America. Because of their novelty, we are still developing best management practices and discovering what plants are best suited to rooftop environments. If the green roof industry is to grow, the list of suitable plant species must be expanded and this information must be disseminated to green roof practitioners and the general public. Because climate differs from one region to the next, data on plant performance for each climatic region is needed to properly specify green roofs within that region. A rooftop experiment was conducted on the Molecular Plant Sciences Building at Michigan State University in East Lansing, Michigan, USA, to test the suitability of several succulents, herbaceous perennials, and grasses in varying depths of green roof substrate over a seven-year period. Forty-five percent of the species were no longer preset on the roof by the end of the study. Still, several species emerged as successful, as defined by their ability to establish themselves on a green

roof and long term survival. A reference guide to green roof plants was also compiled based on research from 11 studies conducted in the Great Lakes Region that tested plant performance. The result is a database of 80 plant species that have been successfully grown on green roofs in the region and lists traits such as plant growth habit, size, hardiness, drought tolerance, wildlife attractiveness, and other attributes. The reference guide is mostly composed of herbaceous perennials (65%) and succulents (17%). Based on the 11 studies used to compile the plant database, the average minimum depth required for survival of all species tested was 13 cm. Required minimum depth was less for succulent species alone. In addition to plant performance, I also explain why certain groups of plants performed well and how plant selection influences the desired benefits of the green roof. This reference guide can be used by green roof professionals in the Great Lakes region and in other parts of the world with a similar climate (Köppen climate types 'Dfa' (hot summer humid continental) or 'Dfb' (warm summer humid continental)).

ACKNOWLEDGEMENTS

This research was supported by a grant from the Horticultural Research Institute (HRI). Its contents are solely the responsibility of the authors and do not necessarily represent the views of HRI. Additional funding was provided by the USDA National Institute of Food and Agriculture and by AgBioResearch at Michigan State University.

My time in the Horticulture Department during the past few years was made enjoyable by a number of people. I would like to thank Dr. Brad Rowe, my major advisor for making my life easy. Dr. Henry Campa III for his guidance during my graduate and undergraduate degree. Dr. Bert Cregg for his patience and conversation. Sherry Mulvaney for being my guide. The Horticulture Department for assisting me financially. Finally, I would like to thank my wife, Stason Vandegrift.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

Fifty-four percent of the world's population live in cities (80% in the United States, (United States Census Bureau, 2010)) and by 2050 this number will be closer to 66% (United Nations, 2014). Coinciding with an increasing population is the preponderance of impervious surfaces and a decline in green space that results in negative human health, excess stormwater and other consequences. Planting trees and flower beds along streets, covering walls with climbing vines, and replacing traditional roofs with vegetation can alleviate some of these problems.

One of the major contributors to impervious surface in cities are rooftops. For example, rooftops account for 14% of all the impervious surface in New York City (Scott, 2006). Likewise, in downtown Sacramento California, 26% of the total land area is covered with rooftops (Akbari et al., 2003). Many of these roofs are viewed daily from office windows and apartments and could be greened. Just as a homeowner might place plants around their home, plants can be placed on rooftops. A roof with plants on it is called a green roof.

Germany is the exemplar for green roofs, having vegetated roofs that are over 100 years old. Originally gravel was placed on the tops of buildings in Germany to reduce the severity of fires. Over time plants colonized theses rooftops and became green roofs. During the 1980's, Germany began taking advantage of the positive environmental impacts that green roofs provide and today green roofs are part of Germany's building code in many municipalities (Köhler and Poll, 2010).

Below I describe the multitude of benefits that green roof provide and the need for improved plant selection. I conclude by identifying current gaps in green roof research including a lack of long-term studies.

Benefits of green roofs

Stormwater. As urban areas expand, green space is converted to living or working space and the amount of impervious surface increases. Impervious surface results in near instantaneous stormwater runoff that can cause numerous problems. Municipal sewer systems built to move water can be overwhelmed by large storm events. This is especially true for aged municipalities that do not have separate systems for stormwater and sewage. When stormwater and sewage run through the same pipes even a medium sized rain event can result in an overflow (combined sewage overflow). Thus, raw sewage bypasses proper treatment and is discharged directly into rivers, ponds, and lakes. Approximately 772 communities in the United States do not have separate stormwater and sewer systems (Calhoun et al., 2007). In New York City, where the average rainfall is 117cm (Your Weather Service, 2017), 0.13 cm of rain overloads the stormwater system and the resulting overflow makes the beaches unsafe for recreation after the rain (Seggos and Plumb, 2006).

Green roofs can mitigate this problem by reducing the overall runoff and decreasing the peak flow of water off a roof and into the stormwater system. A green roof substrate can act as a sponge and absorb rainfall until the roof reaches its water holding capacity. Whittinghill et al. (2014) found that approximately 92% of rainfall was absorbed by prairie green roofs for rain events greater than 10 mm. In the same study, sedum roofs retained more than 74% of rainfall under the same conditions (Whittinghill et al., 2014). This study demonstrates the relief a green roof can provide to overwhelmed drain systems.

Green roofs are not able to absorb all water that falls on them and the amount of rain fall that is absorbed is dependent on how the green roof is constructed and the intensity and duration of the rain event. Factors that contribute to rain water retention include; deeper growing media, highly absorptive media, fully vegetated roofs and slope.

Human health. The preponderance of concrete and polluted air in urban areas is unhealthy for humans. One reason is a lack of green space (Hartig and Kahn, 2016). People that live in green areas, be it agricultural fields or natural landscapes, report feeling healthier than those in cities (Maas et al., 2006).

Green space reduces stress and can improve human health (Ulrich, 1984). A view of plants is beneficial to those occupying the room as well as the building owner. Trees, grass, and flowers are all pleasing to view, and research shows that nature provides many benefits to those occupying the room. Hospital patients in rooms that view green spaces heal faster than others without such view (Ulrich, 1984). Benefits do not stop with the patients; employees reap the benefits of green space.

In 1993, a study was conducted on job satisfaction and window views. Participants (n=615) were asked to rate their job satisfaction on a scale of 1 to 5, with 5 being very satisfied. The average rating from those with no view of nature from their window (i.e. just streets and parking lots) was 2.22. Participants who could see multiple natural features such as trees, grass and flowers had an average satisfaction rating of 3.58 (Kaplan, 1993). In a survey of workers in Chicago (n=29) and Toronto (n=26), participants reported that working in a building with a view of a green roof as a positive experience. Participants reported shifting to meditative thinking over the busy and constant calculative thinking when viewing the roof (Loder, 2014). Roofs provide a platform for nature where it usually is excluded.

Air pollution. In a study on perception of green roof benefits, most participants thought positively of green roofs because of the plants ability to mitigate air pollution (Loder, 2014). Indeed, green roofs aid in the cleansing of city air. Particles settle on plant surfaces and are washed down to the soil during a rain event. At the soil level, many of the particles get trapped as the water filters through the soil and off the roof. Plants atop green roofs also take up pollutants through their roots and absorb air pollutants through their stomata on leaves. Larger plants such as grasses, shrubs, and trees are most effective at cleansing city air because of their greater leaf surface area (Rowe, 2011).

Noise. Buildings near airports and other noise generating locations can benefit from the noise buffering green roofs provide. The substrate and plants act as a sound diffuser, muffling loud noises (Van Renterghem and Botteldooren, 2008; Rowe, 2011).

Biodiversity. In many places, land that consisted of forests, grasslands, and otherwise functioning ecosystems have been developed into urban space that has reduced habitat for wildlife. For city residents who wish to welcome wildlife that previously inhabited the area, a green roof can be a solution. Green roofs have been shown to attract birds, bats, butterflies, and other insects (Coffman, 2007; Madre et al., 2013; Parkins & Clark, 2015). Eakin et al. (2015) investigated bird communities across 12 green roofs located in the Midwest region of the United States. An average of 10-21 species were found on each roof over the sampling periods. American robin (*Turdus migratorius*) and American goldfinch (*Spinus tristis*), both native to the study area, were found on 75% and 50% of the roofs, respectively. If bird activity is desired on a roof, the green roof design must include habitat conditions that will attract the desired species. Logs and branches are attractive to a variety of birds for perching while areas of exposed soil are advantageous for ground foraging birds (Dunnett and Kingsbury, 2008).

In addition to animal habitat, green roofs can provide space for plant diversity, including rare species (Brenneisen, 2004). Surveys of a 90 year old green roof in Switzerland found 175 species present including several rare species (Brenneisen, 2004). If the diversity of plants, insects, birds, and other wildlife are a goal then a variation in growing substrate depths on the roof can be a key component (Monsma, 2011). Each plant will grow best at certain substrate depths. Having a variety of substrate depths across the roof enables a diverse plant community to exist. Therefore, the diversity of plant structure will create habitat components for a larger variety of wildlife. Madre et al. (2013) demonstrated this in a study of over 100 green roofs in France. Using arthropods (spiders, beetles, etc.) as an indicator of species richness, they found arthropod abundance increased with plant species diversity.

Simply growing plants on a roof will attract more wildlife than a bare roof. Wildlife gardens give opportunities to experience these plants and creatures in an area where they otherwise would not exist.

Urban heat island. As described by Murray (1961), temperature tends to increase as one moves from suburbs to the city center. This “urban heat island” can be reduced with plants (Santamouris, 2014). The vegetation component of green roofs contributes the most to lowering the temperature above a building. Substituting vegetation for paved surfaces reduces temperature above a building by an average of 2 °C (Susca et al., 2011). By converting many roofs to green roofs, the heat island in cities can be reduced.

Energy Savings. For building owners, an attractive feature of green roofs is the long-term energy savings. During the summer, heat radiates into a building through the roof during the day, thus increasing the energy required for air conditioning. During the winter, heat moves in the opposite direction and can increase the cost for heating the building. A green roof can curb this heat flux by insulating the room beneath the roof. This insulating effect is highly dependent on the substrate depth and planting material (Eksi et al., 2017).

A study comparing a green roof to a gravel roof found that the green roof reduced heat flux into the building by 13% in the winter and 167% in the summer (Getter et al., 2011). Reduced heat flux in the summer decreases temperature inside a building up to 4°C during the summer (Peck et al., 1999). A reduction of heat flux can result in huge savings when considering a 0.5 °C decrease in internal building temperature results in an 8% reduction in cooling electricity (Dunnett and Kingsbury, 2008). Over a year, a well-insulated roof keeps the building warmer in the winter and cooler in the summer resulting in less heating and cooling costs. Energy savings are realized in single story buildings or the top floor of a multistory building.

Other cost savings. In addition to energy savings, green roofs extend the lifespan of the waterproofing membrane relative to a conventional roof. Reducing the costs associated with roof replacement and disposal of the old roofing materials. Traditional building roofs generally need to be replaced every 15-25 years. Vegetated roofs last up to twice as long as traditional roofs (Peck and Kuhn, 2003). Green roofs last longer because the waterproofing layer is exposed to less UV radiation and to the daily heat fluctuations that cause the membranes to expand and contract (Liu and Baskaran, 2003). Less expanding and contracting results in less fatigue on the membrane, thus increasing longevity of the roof. Cost savings can be realized in the long term.

The initial installation cost of a green roof is almost always greater than a conventional tar roof. Because of this, most green roofs do not get installed unless the building owner is seeking more than one of the benefits that a green roof offers. Another popular reason to install green roofs are to create a LEED™ certified building or if a city requires the roof to be vegetated. Many cities provide economic incentives for installing green roofs. Portland OR, Chicago IL, and Washington DC are a few cities with green roof policies for buildings (Carter and Fowler, 2008).

For the building owner, green space can result in higher room values. Green space, such as parks, increase property values in cities (Crompton, 2005). A study in Oregon found that street trees add several thousands of dollars to the sale price of a home and a house with street trees sells quicker (Donovan and Butry, 2010).

Aesthetics. As discussed above, people are willing to pay more for areas with more green space thus implying a benefit gained from viewing green space. A hypothesis to explain this is the phenomenon of biophilia. E.O. Wilson described biophilia as humans innate attraction towards nature (Wilson, 1984). Green roofs introduce nature to cities and may fulfil this attraction and inspire curiosity.

Food production. An intriguing and emerging topic is urban agriculture on rooftops. Not agriculture in the sense of large, tractor harvested farms, rather, small hand-tended gardens. The practice of gardens on roofs is attractive where space is limited and food deserts are a concern. Rooftop gardens have appeared in several unique situations. A handful of restaurants, including Fairmont Hotel in Vancouver, Canada, grow herbs and vegetables to implement a fresh factor and a unique flair to their menu (Whittinghill and Rowe, 2012). Apartments have adopted rooftop gardening to attract residents, renting out garden plots. One example is Ecohouse, which provides jobs and fresh food to those in St. Petersburg, Russia (Whittinghill and Rowe, 2012).

Plant selection matters

A roof top is a harsh environment. Typically, wind speeds are higher, temperatures are more extreme, and conditions are dryer on roofs compared to ground level (Boivin et al., 2001). These environmental factors make rooftops difficult places to grow plants and consequently plant selection is crucial. Compounding the difficulty, are climatic differences among regions and variations in microclimates that may occur on an individual roof. Thus, there is no set of plants that work on all roofs. A plant that thrives in a cold northern climate will likely die in a hotter environment and vice versa. A list of suggested or recommended plant species for each geographic region would be helpful to green roof practitioners. In Germany, the FLL (Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau) has developed a guideline for green roof practices (FLL, 2008), but they do not have specific plant guides for all locations in their country. In the United States, the Great Lakes Region has many plants that have been tested on roofs, however a formal guide has not been developed.

Green roof species should have low water use, be adapted to temperature extremes, have low nutrient requirements and need little maintenance. When selecting species for green roofs, a good place to begin searching is high elevation and arid environments, such as mountains or bluffs (Dunnett and Kingsbury, 2008). If the plants are cold hardy, species from hot and dry microclimates do well on roofs since the two locations can be similar climatically (Dunnett and Kingsbury, 2008). Sedum is a highly utilized green roof plant because of its high drought tolerance mechanisms such as water storage, shallow root systems, and CAM photosynthesis (Rowe et al., 2012).

Other than the typical considerations for selecting plants such as, hardiness zone, sunlight exposure, rainfall, a few unique factors to green roofs must be considered. These include:

Substrate depth. Intensive roofs are those with more than 15 cm of growing media and can support a variety of plants such as herbaceous perennials and grasses. If the roof has the proper support, shrubs and trees can be grown. A media depth of 15 cm or less is an extensive roof. The depth of the growing substrate determines what types of plants can be grown. Generally, as substrate depth increases; moisture retention increases, plant survivability increases, and the number of species of plants available increases.

Shallow substrates exclude most plants except for those particularly adapted to drought and temperature extremes. Perhaps the greatest benefit of shallow substrates is exclusion of unwanted plant species. A few plants perform best in the shallowest of substrates. Rowe et al. (2012) demonstrated the importance of depth in the study of 25 succulent species. In a shallow media depth of 2.5 cm, *S. album* and *S. acre* outperformed all other species. However, when tested in deeper media (5.0 cm and 7.5 cm), these two species were intermediate in their growth rate and *S. middendorfianum* had the highest cover.

A deeper media (greater than 15cm) can protect against freezing of plant roots. Boivin et al. (2001) tested how frost impacted green roofs in Quebec. In the cold months when outdoor temperatures were below freezing, temperatures in deeper green roofs remain above freezing. In green roof plots 10 and 15 cm deep, the temperature in the root zone remained above freezing, protecting roots. However, plots with 5cm of substrate dropped below freezing, harming the plants roots.

Substrate composition. Soil is crucial for the success of any plant. In the case of green roofs, the conventional growing substrates are composed of inorganic aggregates such as heat-expanded slate and shale in combination with organic matter (Ampim et al., 2010). Numerous other inorganic components such as crushed brick, volcanic pumice, crushed porcelain, and foamed glass have also been utilized or tested (Ampim et al., 2010; Eksi and Rowe, 2016; Matlock and Rowe, 2016). Components can be mixed in different proportions to alter water holding capacity.

Wind. Consistent wind can be a major problem on roofs as it hastens evapotranspiration and dries out the plants and media. Wind speed is normally higher with increasing height above the surface of the ground and if there are no trees or other buildings to buffer the wind then some plants may not survive.

Irrigation. Without irrigation on a green roof, plant selection is limited. Irrigation may be necessary until the plants become established. Once established, irrigation can be helpful during extreme drought conditions unless there is ample substrate depth to retain sufficient moisture for the selected species. Many plants can survive without; however, irrigation expands the plant palette to include many typical garden species. Rowe et al. (2014)

experimented with irrigation on green roofs. Of three irrigation methods; overhead, drip, and sub-irrigation, overhead was the most effective likely due to the course nature of green roof substrates (Rowe et al., 2014). If sheltered from the wind, irrigated, and provided with sufficient substrate, any plant theoretically can grow on a green roof.

Slope. The pitch, or slope, of a roof is a large factor in what plants will grow on a given roof. Given a typical sloped house roof, a gradient of moisture occurs. The highest point of the roof tends to be the driest and the lowest point the wettest. Getter et al. (2007) found that as slope increased, retention of rainwater decreased. A 25% slope resulted in a mean retention of 75.3% of the rainfall. A 2% slope, typical of most flat-roofed buildings retained 85.2% of the rainfall. Thus, a sloped roof will have a drier substrate compared to a flatter roof.

Current gaps in green roof research regarding plant selection

Long-Term Studies. Green roofs are composed of plant communities and these communities are dynamic. Therefore, the plants present and the quantity of each fluctuates over time. A green roof just after installation may be sparse with few plants. Establishment, defined by full cover, may not be reached until a few years after installation. Many green roof studies are conducted for less than two years (Dvorak and Volder, 2010). Conclusions from these studies may have misleading recommendations and green roofs designed from these studies may have delayed establishment and perform sub-optimally. Thus, the need for long-term studies. If green roofs are to be successful, long-term studies should be conducted where the benefits are demonstrated 10, 20 or even 50 years later. For example, in 2007 a study was conducted on the survivability of 25 green roof plants (Durhman et al., 2007). Twelve of the plants were deemed recommendable after two seasons. This same study was continued for seven years and ended with very different results. Of the 12 recommended plants, 5 were no longer present anywhere and thus not recommended (Rowe et al., 2012). For more examples, see Table 1.1.

Bates et al. (2015a) says it well in the study on recycled aggregate:

> "Vegetation on green roofs takes time to establish, and many vegetation characteristics alter from year to year due to successional processes and drought disturbances (Kohler, 2006; Dunnett et al., 2008; Nagase and Dunnett, 2010; Köhler and Poll, 2010; Rowe et al., 2012; Bates et al. 2013; Lundholm et al., 2014), so findings over short term investigations have to be interpreted with caution"

A current Google Scholar search returns 16,000 studies that include 'Green Roof in the title yet only handful of these studies may be considered long-term (Table 1.1). The column "Long-term effects" in Table 1.1 validates why green roof studies should be continued for an extended amount of time. Seasonal fluctuations in temperature and precipitation may not be seen until later years. Plants that survive initially may die in more extreme years or may be outcompeted with introduced species.

Table 1.1 Green roof studies that have continued for 3 years or longer

Author	Length of study (years)	Year published	Paper title	Long-term effects
Emilsson	3	2008	Vegetation development on extensive vegetated green roofs: influence of substrate composition, establishment method and species mix	Moss coverage increased largely from year 1-3. After year 2, *S. acre* declined in coverage.
Monterusso et al.	3	2005	Establishment and persistence of Sedum spp. and native taxa for green roof applications	Demonstrates the effect of extreme weather on length of study. Most Michigan natives died during unusually hot summer in year 2.
Bates et al.	4	2013	Vegetation development over four years on two green roofs in the UK	Demonstrates need for long-term research to capture weathers influence on outdoors study.
Durhman et al.	4	2007	Effect of substrate depth on initial growth, coverage, and survival of 25 succulent green roof plant taxa	Twelve species recommended for green roof application. Later study found 5 species no longer present after 7 yrs. (see Rowe et al. 2012)
Getter and Rowe	4	2009	Substrate depth influences sedum plant community on a green roof	A species found suitable for green roofs in year 1 (Getter and Rowe 2008) had failed by year 4.
Getter et al.	4	2009	Solar radiation intensity influences extensive green roof plant communities	Planted 9 species. Year 4, *Carex flaccea* most abundant. By year 9 only 3 species remained: *A. cernuum, S. album, and S. acre*. [Data from years 5-9 not yet published]

Table 1 (cont'd)…

Dunnett et al.	5	2008	The dynamics of planted and colonizing species on a green roof over six growing seasons 2001–2006: influence of substrate depth.	All planted species survived to end of study. However, species richness decreased over time.
Bates et al. (a)	6	2015	Effects of recycled aggregate growth substrate on green roof vegetation development: A six year experiment	Notes that if study concluded before year 3, all species would have seemed suitable green roof plants when several did not make it through subsequent drought periods.
Bates et al. (b)	6	2015	Effects of varying organic matter content on the development of green roof vegetation: A six year experiment	Found reduced species richness in year 4 and 5 caused by drought.
Skabelund et al.	6	2014	Semi-arid green roof research 2009-2014: Resilience of native species	Of 130 individual grasses and 98 individual forbs planted, 68 and 21, respectively, were present 6 years later.
Rowe et al.	7	2012	Effect of green roof media depth on Crassulacean plant succession over seven years	(See Durhman et al. 2007)
Kohler	20	2006	Long-term vegetation research on two extensive green roofs in Berlin	10 species planted. One species disappeared from roof each of the following years: 3,5,7,8. Weeds persisted until a few years into study.
Kohler and Poll	20	2010	Long-term performance of selected old Berlin green roofs in comparison to younger extensive green roofs in Berlin.	(See Kohler 2006)
Catalano et al.	30	2016	Thirty years unmanaged green roofs: Ecological research and design implications	5 species originally planted. Ended with 80 species from spontaneous colonization.

BIBLIOGRAPHY

BIBLIOGRAPHY

Akbari, H., L. Shea Rose, and H. Taha. 2003. Analyzing the land cover of an urban environment using high-resolution orthophotos. Landscape and Urban Planning 63(1):1–14. doi: 10.1016/S0169-2046(02)00165-2.

Ampim, P. Y., J. J. Sloan, R. I. Cabrera, D. a Harp, and F. H. Jaber. 2010. Green Roof Growing Substrates: Types, Ingredients, Composition and Properties. Journal of Environmental Horticultural 28(4):244–252.

Bates, A.J. et al., 2015a. Effects of recycled aggregate growth substrate on green roof vegetation development: A six year experiment. Landscape and Urban Planning, 135, pp.22–31. doi: 10.1016/j.landurbplan.2014.11.010.

Bates, A.J. et al., 2015. Effects of varying organic matter content on the development of green roof vegetation: A six year experiment. Ecological Engineering, 82, pp.301–310. doi: 10.1016/j.ecoleng.2015.04.102.

Bates, A. J., J. P. Sadler, and R. Mackay. 2013. Vegetation development over four years on two green roofs in the UK. Urban Forestry and Urban Greening. 12(1):98–108. doi: 10.1016/j.ufug.2012.12.003.

Boivin, M.-A., M.-P. Lamy, A. Gosselin, and B. Dansereau. 2001. Effect of Artificial Substrate Depth on Freezing Injury of Six Herbaceous Perennials Grown in a Green Roof System. HortTechnology 11(3):409–412.

Brenneisen, S. 2004. Green Roofs - How Nature Returns to the City. Acta Horticulturae 643(643):289–293. doi: 10.17660/ActaHortic.2004.643.37.

Catalano, C. et al., 2016. Thirty years unmanaged green roofs: Ecological research and design implications. Landscape and Urban Planning, 149, pp.11–19. doi: 10.1016/j.landurbplan.2016.01.003

Calhoun, L. M., M. Avery, L. Jones, K. Gunarto, R. King, J. Roberts, and T. R. Burkot. 2007. Combined sewage overflows (CSO) are major urban breeding sites for Culex quinquefasciatus in Atlanta, Georgia. The American journal of tropical medicine and hygiene 77(3):478–84.

Carter, T. and L. Fowler. 2008. Establishing Green Roof Infrastructure Through Environmental Policy Instruments. Environmental Management 42(1):151–164. doi: 10.1007/s00267-008-9095-5.

Coffman, R. R. 2007. Comparing Wildlife Habitat and Biodiversity Across Green Roof Type. in Fifth Annual Greening Rooftops for Sustainable Communities Conference 1–17.

Crompton, J. L. 2005. The impact of parks on property values: empirical evidence from the past two decades in the United States. Managing Leisure 10(4):203–218. doi: 10.1080/13606710500348060.

Donovan, G. H. and D. T. Butry. 2010. Trees in the city: Valuing street trees in Portland, Oregon. Landscape and Urban Planning 94(2):77–83. doi: 10.1016/j.landurbplan.2009.07.019.

Dunnett, N. and N. Kingsbury. 2008. Planting Green Roofs and Living Walls. 2nd edn. Timber Press. Portland, OR.

Dunnett, N., A. Nagase, and A. Hallam. 2008. The dynamics of planted and colonising species on a green roof over six growing seasons 2001-2006: Influence of substrate depth. Urban Ecosystems 11(4):373–384. doi: 10.1007/s11252-007-0042-7.

Durhman, A.K., Rowe, D.B. & Rugh, C.L., 2007. Effect of Substrate Depth on Initial Growth, Coverage, and Survival of 25 Succulent Green Roof Plant Taxa. Hort Science, 42(3): 588–595.

Dvorak, B. and A. Volder. 2010. Green roof vegetation for North American ecoregions: A literature review. Landscape and Urban Planning 96(4):197–213. doi: 10.1016/j.landurbplan.2010.04.009.

Eakin, C.J. et al., 2015. Avian response to green roofs in urban landscapes in the Midwestern USA. Wildlife Society Bulletin, 39(3), pp.574–582. doi: 10.1002/wsb.566.

Eksi, M. and D. B. Rowe. 2016. Green roof substrates: Effect of recycled crushed porcelain and foamed glass on plant growth and water retention. Urban Forestry & Urban Greening. 20:81–88. doi: 10.1016/j.ufug.2016.08.008.

Eksi, M., D. B. Rowe, I. S. Wichman, and J. A. Andresen. 2017. Effect of substrate depth, vegetation type, and season on green roof thermal properties. Energy and Buildings 145(1):174–187. doi: 10.1016/j.enbuild.2017.04.017.

Emilsson, T., 2008. Vegetation development on extensive vegetated green roofs: Influence of substrate composition, establishment method and species mix. Ecological Engineering, 33(3–4), pp.265–277. doi: 10.1016/j.ecoleng.2008.05.005.

Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau, (FLL), 2008. Guidelines for the Planning, Construction, and Maintenance of Greenroof Sites, Bonn, Germany.

Getter, K. L. and D. B. Rowe. 2007. Effect of Substrate Depth and Planting Season on Sedum Plug Survival on Green Roofs. Journal of Environmental Horticultural 25(June):95–99.

Getter, K.L., Rowe, D.B. & Andresen, J.A., 2007. Quantifying the effect of slope on extensive green roof stormwater retention. Ecological Engineering, 31(4), pp.225–231. doi: 10.1016/j.ecoleng.2007.06.004

Getter, K.L. & Rowe, D.B., 2009. Substrate depth influences sedum plant community on a green roof. HortScience, 44(2), pp.401–407.

Getter, K. L., D. B. Rowe, J. A. Andresen, and I. S. Wichman. 2011. Seasonal heat flux properties of an extensive green roof in a Midwestern U.S. climate. Energy and Buildings 43(12):3548–3557. doi: 10.1016/j.enbuild.2011.09.018.

Graber, D. A. 1990. Seeing is remembering: How visuals contribute to learning from television news. Journal of Communication 40(3):134–155. doi: 10.1111/j.1460-2466.1990.tb02275.x.

Hartig, T. and P. H. Kahn. 2016. Living in cities, naturally. Science 352(6288):.

Kaplan, R. 1993. The role of nature in the context of the workplace. Landscape and Urban Planning 26(1–4):193–201. doi: 10.1016/0169-2046(93)90016-7.

Kohler, M. 2006. Long-term Vegetation Research on Two Extensive Green Roofs in Berlin. Urban Habitats 4(1):3–26.

Köhler, M. and P. H. Poll. 2010. Long-term performance of selected old Berlin greenroofs in comparison to younger extensive greenroofs in Berlin. Ecological Engineering 36(5):722–729. doi: 10.1016/j.ecoleng.2009.12.019.

Liu, K. and B. Baskaran. 2003. Thermal Performance of Green Roofs Through Field Evaluation. in Proceedings of 1st North American Green Roof Conference: Greening Rooftops for Sustainable Communities. Chicago, IL. 29-30 May, 2003. The Cardinal Group. Toronto, Ontario.

Loder, A. 2014. 'There's a meadow outside my workplace': A phenomenological exploration of aesthetics and green roofs in Chicago and Toronto. Landscape and Urban Planning 126(1):94–106. doi: 10.1016/j.landurbplan.2014.01.008.

Lundholm, J., A. Heim, S. Tran, and T. Smith. 2014. Leaf and life history traits predict plant growth in a green roof ecosystem. PLoS ONE 9(6):1–9. doi: 10.1371/journal.pone.0101395.

Maas, J., R. A. Verheij, P. P. Groenewegen, S. de Vries, and P. Spreeuwenberg. 2006. Green space, urbanity, and health: how strong is the relation? Journal of epidemiology and community health. BMJ Publishing Group Ltd 60(7):587–92. doi: 10.1136/jech.2005.043125.

Madre, F., A. Vergnes, N. Machon, and P. Clergeau. 2013. A comparison of 3 types of green roof as habitats for arthropods. Ecological Engineering. 57(1):109–117. doi: 10.1016/j.ecoleng.2013.04.029.

Matlock, J. M. and D. B. Rowe. 2016. The suitability of crushed porcelain and foamed glass as alternatives to heat-expanded shale in green roof substrates: An assessment of plant growth, substrate moisture, and thermal regulation. Ecological Engineering 94(1111):244–254. doi: 10.1016/j.ecoleng.2016.05.044.

Mitchell, J.M., 1961. The Temperature of Cities. Weatherwise, 14(6), pp.224–258. doi: 10.1080/00431672.1961.9930028.

Monsma, Jeremy. 2011. Ecological succession of green roof plants with emphasis on urban wildlife habitat for insect populations. Masters in Environmental Design Thesis, Michigan State University, East Lansing, MI.

Monterusso, M.A., Bradley Rowe, D. & Rugh, C.L., 2005. Establishment and persistence of Sedum spp. and native taxa for green roof applications. HortScience, 40(2), pp.391–396.

Nagase, A. and N. Dunnett. 2010. Drought tolerance in different vegetation types for extensive green roofs: Effects of watering and diversity. Landscape and Urban Planning. 97(4):318–327. doi: 10.1016/j.landurbplan.2010.07.005.

Oberndorfer, E., J. Lundholm, B. Bass, R. R. Coffman, H. Doshi, N. Dunnett, S. Gaffin, M. Köhler, K. K. Y. Liu, and B. Rowe. 2007. Green Roofs as Urban Ecosystems: Ecological Structures, Functions, and Services. BioScience 57(10):823. doi: 10.1641/B571005.

Parkins, K. L. and J. A. Clark. 2015. Green roofs provide habitat for urban bats. Global Ecology and Conservation 4(1):349–357. doi: 10.1016/j.gecco.2015.07.011.

Peck, S. and M. Kuhn. 2003. Design guidelines for green roofs. Ontario Association of Architects.

Peck, S. W., C. Callaghan, M. E. Kuhn, and B. Bass. 1999. Greenbacks from green roofs: Forging a new industry in Canada, status report on benefits, barriers and opportunities for green roof and vertical garden technology diffusion. Canada Mortgage and Housing Corporation. Ottawa, Canada.

Rowe, D. B. 2011. Green roofs as a means of pollution abatement. Environmental Pollution 159(8–9):2100–2110. doi: 10.1016/j.envpol.2010.10.029.

Rowe, D. B., K. L. Getter, and A. K. Durhman. 2012. Effect of green roof media depth on Crassulacean plant succession over seven years. Landscape and Urban Planning 104(3–4):310–319. doi: 10.1016/j.landurbplan.2011.11.010.

Rowe, D. B., M. R. Kolp, S. E. Greer, and K. L. Getter. 2014. Comparison of irrigation efficiency and plant health of overhead, drip, and sub-irrigation for extensive green roofs. Ecological Engineering. 64:306–313. doi: 10.1016/j.ecoleng.2013.12.052.

Sailor, D. J. 2008. A green roof model for building energy simulation programs. Energy and Buildings 40(8):1466–1478. doi: 10.1016/j.enbuild.2008.02.001.

Scott, M. 2006. Beating the Heat in the World’s Big Cities: Feature Articles. NASA Earth Observatory. 13 January 2017 http://earthobservatory.nasa.gov/Features/GreenRoof/greenroof2.php>

Seggos, B. and M. Plumb. 2006. Sustainable Raindrops: Cleaning New York Harbor by Greening the Urban Landscape. New York, New York. 3 April 2017 <https://www.riverkeeper.org/wp-content/uploads/2009/06/Sustainable-Raindrops-Report-1-8-08.pdf>

Skabelund, L. et al., 2014. Semi-arid green roof research 2009-2014: Resilience of native species. In 12th Annual Cities Alive Green Roof and Wall Conference, Nashville, TN.

Susca, T., S. R. Gaffin, and G. R. Dell’Osso. 2011. Positive effects of vegetation: Urban heat island and green roofs. Environmental Pollution 159(8–9):2119–2126. doi: 10.1016/j.envpol.2011.03.007.

Ulrich, R. S. 1984. View through a window may influence recovery from surgery. American Association for the Advancement of Science 224(1):420–422.

United Nations, Department of Economic and Social Affairs. 2014. World Urbanization Prospects: The 2014 Revision, Highlights. 3 January 2017 <https://esa.un.org/unpd/wup/Publications/Files/WUP2014-Highlights.pdf>

Van Renterghem, T. and D. Botteldooren. 2008. Numerical evaluation of sound propagating over green roofs. Journal of Sound and Vibration 317(3–5):781–799. doi: 10.1016/j.jsv.2008.03.025.

Whittinghill, L. J. and D. B. Rowe. 2012. The role of green roof technology in urban agriculture. Renewable Agriculture and Food Systems 27(4):314–322. doi: 10.1017/S174217051100038X.

Whittinghill, L. J., D. B. Rowe, J. A. Andresen, and B. M. Cregg. 2014. Comparison of stormwater runoff from sedum, native prairie, and vegetable producing green roofs. Urban Ecosystems 13–29. doi: 10.1007/s11252-014-0386-8.

Wilson, E. O. 1984. Biophilia. Cambridge, Mass.

Your Weather Service. 2017. Climate New York - temperature, rainfall and average. 2017 US Climate Data. 28 August 2017 <http://www.usclimatedata.com/climate/new-york/united-states/3202>

CHAPTER 1: EFFECT OF SUBSTRATE DEPTH ON GREEN ROOF PLANT COMMUNITY DEVELOPMENT

Abstract

Green roofs are gradually being accepted and implemented across North America. Green roofs mitigate many of the negative effects that urban areas have on humans and the environment. As rooftops are filled with living plants, the individual species need to be tested for longevity and suitability. This study provides further testing on plant species commonly planted on green roofs as well as a few novel species. Twenty-two plant species including herbaceous perennials, grasses, and sedum were observed on a green roof over a seven-year period in East Lansing, Michigan. Plants were irrigated when needed during the first two years, but had to rely on natural rainfall thereafter. No fertilizer was ever applied. All five species of sedum survived until the end of the seven-year period, but only seven of the 17 herbaceous perennials and grasses survived. Substrate moisture was probably the major factor in terms of species survival and a drought during 2016 was likely the cause for the large loss of species. This study emphasizes the fact that if herbaceous perennials and grasses are to be successful on green roofs, then irrigation may be required during drought periods. It also points out the importance of long-term studies and provides the framework for a continuation of the same study in other areas of the world.

Index words: herbaceous perennials, grasses, living roofs, sedum, substrate depth, vegetated roofs

Species used in this study

Allium cernuum (Nodding wild onion), *Anemone virginiana* (Thimbleweed), *Asclepias tuberosa* (Butterfly weed), *Aster laevis* (Smooth aster), *Aster oolentangiensis* (Sky blue aster), *Campanula rotundifolia* (Harebell), *Coreopsis lanceolata* (Lanceleaf coreopsis), *Echinacea purpurea* (Purple coneflower), *Eragrostis spectabilis* (Purple love grass), *Geum triflorum* (Prairie smoke), *Koeleria macrantha* (June grass), *Liatris aspera* (Rough blazing star), *Monarda fistulosa* (Wild bergamot), *Penstemon hirsutus* (Penstemon), *Schizachyrium scoparium* (Little bluestem), *Sedum album* (white stonecrop), *Sedum kamtschaticum* (Orange stonecrop), *Sedum reflexum* (Blue spruce stonecrop), *Sedum sexangulare* (Tasteless stonecrop), *Sedum spurium* (Caucasian stonecrop), *Sporobolus heterolepis* (Prairie dropseed), and *Tradescantia ohiensis* (Spiderwort).

Significance to the Nursery Industry

Species typically used on green roofs are from the family Crassulaceae and usually the genus Sedum. As the green roof industry grows, a larger plant palette is recommended to reduce monocultures and to satisfy client expectations. This is important aesthetically and for functional practicality. This study demonstrates the importance of watering the roof during drought periods. We chose not to water this study for practical purposes, however more species likely would have survived if supplemental water was provided during drought periods. *Allium cernuum*, performed well as demonstrated by it having the highest coverage for all species. This research will aid nursery's and green roof installers in selecting suitable plants and in setting realistic expectations for their client. This research adds to the knowledge of suitable green roof plants.

Introduction

Fifty-four percent of the world's population lives in cities and it is estimated that 2050 this number will be closer to 66% (United Nations, 2014). Although the construction of cities may be considered a major human achievement, these manufacturing and innovation centers can be detrimental to our well-being (Maller et al. 2006). The preponderance of impervious surfaces and the lack of green space negatively effects human health, the environment, and the economy. Planting trees and flower beds along streets, covering walls with climbing vines, and replacing traditional roofs with vegetation can aid in alleviating some of the issues associated with urban development.

One of the major contributors to dead space in cities are rooftops. For example, rooftops account for 14% of all the impervious surface in New York City in the United States (Scott, 2006). In downtown Sacramento, California, 26% of the area is covered with rooftops (Akbari et al., 2003). Many of these roofs are viewed daily from office windows and apartments and many have the potential to be greened. Just as a homeowner places plants around their home, plants can be placed on rooftops, and not just for aesthetic appeal. Green roofs, a form of green infrastructure, have many benefits. These include mitigating stormwater runoff (Czemiel Berndtsson, 2010), air pollution (Rowe, 2011), noise (Van Renterghem and Botteldooren, 2008; Rowe, 2011), and energy use (Castleton et al., 2010; Getter et al., 2011; Eksi et al., 2017). Green roofs can improve human health (Ulrich, 1984; Kaplan, 1993; Loder, 2014), plant and animal diversity (Brenneisen, 2004; Coffman, 2007; Madre et al., 2013; Eakin et al., 2015; Parkins and Clark, 2015), roof lifespan (Liu and Baskaran, 2003; Peck and Kuhn, 2003), aesthetics (Wilson, 1984), and urban food production (Whittinghill and Rowe, 2012; Whittinghill et al., 2013).

Within a given location, the depth of the growing substrate determines what types of plants can be grown. Generally, as substrate depth increases, moisture retention, plant survivability, and the number of potential suitable plants also increases. Besides a reduction in weight, perhaps the most important benefit of a shallow substrate is the exclusion of unwanted plant species. A few plant species will perform best in shallow substrates, but others such as unwanted weeds may not survive. Rowe et al. (2012) demonstrated the importance of depth in the study of 25 sedum species. In a shallow substrate depth of 4.5 cm, *Sedum album* and *Sedum acre* outperformed all other species. However, when tested in deeper substrates (5.0 cm and 7.5 cm), these two species did not achieve the same growth as *Sedum middendorffianum* which obtained the highest absolute cover. This demonstrates the importance of depth.

Species native to the area may be used for a few reasons. Native plants compete evenly with other native plants and are less likely to become invasive and aesthetically, native plants blend and link with the surrounding landscape (Butler et al. (2012). However, a rooftop is not a native environment.

A rooftop does not provide a native environment as the soils are engineered and the environmental conditions are often more severe than what is found at ground level. Typically, wind speeds are higher, temperatures are more extreme, and conditions are dryer on roofs (Boivin et al., 2001). These factors make plant selection complicated. Other than the typical considerations for selecting plants such as, hardiness zone, sunlight exposure, and rainfall; one must also consider substrate depth and composition, wind, natural rainfall or supplemental irrigation, and slope. Compounding the difficulty, are climatic differences among regions and variations in microclimates that may occur on an individual roof. Thus, there is no set list of plants that work on all roofs.

In addition, a very important factor when evaluating green roof plant performance is the length of time that the study is conducted. Most plant evaluation studies of green roof taxa have only been conducted for one or two years (Dvorak and Volder, 2010) which can result in premature conclusions and misleading recommendations. When studies have been conducted for three or more years, conclusions drawn are often dramatically different than what would have been concluded following just one or two growing seasons (Rowe et al., 2012). Plants that initially survive may eventually experience reduced coverage or disappear completely. This is apparent in Durhman et al's (2007) study. Her results presented 12 species that were suitable for green roofs after a few years of trials. The study continued and by year 7, 5 of those species were no longer present on the roof (Rowe et al. 2012). Therefore competition, variability in climate, and other confounding factors should be considered during the design and planning phase of a green roof.

The objective of this study was to evaluate the effect of substrate depth on survival and long-term plant community development of various herbaceous perennials and grasses native to Michigan along with a standard Sedum mix.

Materials and Methods

Experimental set-up. This study was conducted on the roof of the Molecular Plant Sciences Building (MPS) on Michigan State University's campus in East Lansing, Michigan. The roof was planted on the second floor over the atrium of MPS and covers an area of 232 m^2. The roof consists of three substrate depths: 20 cm, 10 cm, and 4.5 cm (Figure 2.1).

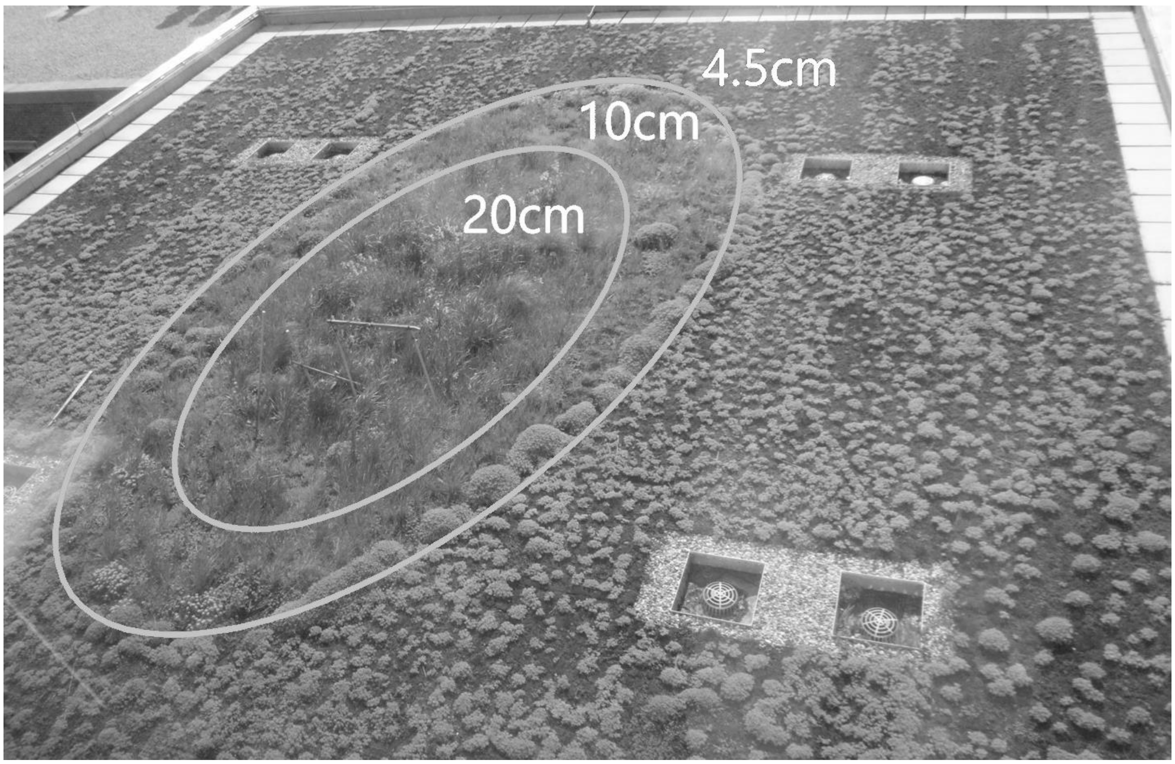

Figure 2.1 The green roof research site located on the Molecular Plant and Soil Sciences Building at Michigan State University.

Substrate consisted of a proprietary mixture of lightweight aggregate and compost (XeroFlor America, LLC, Durham, North Carolina). Substrate was mounded in the middle of the roof in an oval shaped area that was approximately 67 m^2. The mound consists of two sections; a center section that was 20 cm deep covered 20 m^2 and was surrounded by a 10 cm deep section covering 47 m^2. The remainder of the roof covers 165 m^2 and was installed with XF301 pre-grown sedum mats that were 2.5 cm thick. Under the sedum mats were two layers of water retention fabric for a total thickness of 4.5 cm.

Plants were installed October 8-10, 2011. Four grasses and 13 herbaceous perennial species, all native to Michigan and considered drought tolerant, were installed in the 10 cm and 20 cm deep sections. Species planted included the grasses *Eragrostis spectabilis* (Purple love grass), *Koeleria macrantha* (June grass), *Schizachyrium scoparium* (Little bluestem), and *Sporobolus heterolepis* (Prairie dropseed) and the herbaceous perennials *Allium cernuum* (Nodding wild onion), *Anemone virginiana* (Thimbleweed), *Asclepias tuberosa* (Butterfly weed), *Aster laevis* (Smooth aster), *Aster oolentangiensis* (Sky blue aster), *Campanula rotundifolia* (Harebell), *Coreopsis lanceolata* (Lanceleaf coreopsis), *Echinacea purpurea* (Purple coneflower), *Geum triflorum* (Prairie smoke), *Liatris aspera* (Rough blazing star), *Monarda fistulosa* (Wild bergamot), *Penstemon hirsutus* (Penstemon), and *Tradescantia ohiensis* (Spiderwort).

Forty-five and 23 plugs of each species were randomly planted at a spacing of 20 cm apart in the 10 cm and 20 cm deep sections, respectively. All plugs were supplied by a local nursery (Wildtype Nursery, Mason, Michigan), and were 10 cm deep and 5.4 cm wide. There was a total of 765 plugs planted at a depth of 10 cm and 391 planted in 20 cm. Pre-vegetated mats were laid on the remainder of the roof at a depth of 4.5 cm including the water retention fabric and consisted of a mixture of *Sedum album, Sedum kamtschaticum, Sedum reflexum, Sedum sexangulare,* and *Sedum spurium*. Plants were watered immediately after planting and then periodically during the second growing season (2012) to ensure establishment. No supplemental water was supplied thereafter so plants relied on natural rainfall. No fertilizer was applied to the roof. Species not originally planted were removed before data collection once a year, never more than a few individual plants. At the end of each season all plant material was left as is throughout the winter periods and was never cut or removed from the roof.

Data collection. During June 2012, survival of the original plants was recorded. Coverage in August 2012 was estimated from photographs. Thereafter, a linear transect was used to measure community composition and change annually through 2017 (Waite, 2000). A 150 cm long transect was suspended above the plant canopy and plant cover was estimated by placing a rod vertically at each measuring point and recording each species the rod contacted. This was repeated every 10 cm along the transect. The transect was placed randomly at 20 locations within each roof zone to record a total of 300 data points for each substrate depth.

Analysis. Shannon-Weiner Diversity index (H') was calculated for each year to capture the change in diversity over time. This is calculated with the following: $H' = -\sum^{s} p_i * \ln p_i$ where s equals the total number of species in the community and p_i equals the proportion of s made up of the ith species. The calculation considers the number of species (species richness) and the percent cover of each species.

Absolute cover (AC) was analyzed using analysis of variance with species, year, and species-by-year interaction as fixed effects, and transect and species-by-transect interaction as random effects. Species-by-transect interaction was used to test the significance of species effects. Levene's test was performed to test homogeneity of variance. Tukey test was used to assess differences among species within each year. LSD test was used to compare year effects of each species. Multiple comparisons were determined using repeated measures and heterogeneous variance model. A p-value of <0.05 was considered significant. All the statistical analysis were conducted using PROC MIXED and PROC GLIMMIX procedure of SAS (SAS Institute, Chicago, Illinois, USA).

Results

Initial Plant Survival. Eight months after planting survival of most species was higher when grown in 20 cm relative to those in 10 cm (Table 2.1). The herbaceous perennials *A. tuberosa, C. rotundifolia,* and *M. fistulosa,* along with the grasses *S. scoparium* and *S. heterolepis* had higher initial survival rates at the 20 cm depths than any other species. All plants of *A. cernuum, A. virginiana, E. purpurea, P. hirsutus, and T. ohiensis* survived through June 2012 when growing in 20 cm.

Table 2.1 Initial survival rates of individual plugs planted in October 2011 in East Lansing, Michigan, USA, as of June 2012

	Survival (%)	Survival (%)
	10 cm	20 cm
Allium cernuum	100	100
Anemone virginiana	96	100
Asclepias tuberosa	49	82
Aster laevis	100	96
Aster oolentangiensis	93	91
Campanula rotundifolia	26	78
Coreopsis lanceolata	93	96
Echinacea purpurea	91	100
Eragrostis spectabilis	38	23
Geum triflorum	76	74
Koeleria macrantha	100	95
Liatris aspera	91	87
Monarda fistulosa	73	91
Penstemon hirsutus	91	100
Schizachyrium scoparium	44	52
Sporobolus heterolepis	62	87
Tradescantia ohiensis	100	100

Species composition (10 cm). By the second year all species except *C. rotundifolia* and *E. spectabilis* had expanded in coverage. In year three *C. lanceolata,* and the introduced species *S. album* and *S. sexangulare* were the dominant species. By year four, *C. lanceolata* (0.187), *S. scoparium* (0.134), and *S. sexangulare* (0.150) had achieved the highest absolute cover (Table 2.2). Comparatively, mean AC for the year was 0.071. All species were recorded as present except for *T. ohiensis* and *E. spectabilis*. By year six, 13 of the original 17 species were absent. The absolute coverage for *A. cernuum* and *S. heterolepis* increased drastically during this time, from 0.070 to 0.187 and from 0.027 to 0.514, respectively. By year seven, *A. cernuum* (0.660), *C. lanceolata* (0.024), and *P. hirsutus* (0.007) were the remaining species of those originally planted.

By year three, sedum species were encroaching from the 4.5 cm zone. The first to spread from the 4.5 cm zone were *S. album, S. spurium, S. kamtschaticum* and *S. sexangulare*. By the end of the study, the aforementioned species were still present with the addition of *S. reflexum*.

Species composition over time (20 cm). From year one to two, all species increased in absolute cover except for *E. spectabilis*. By August of the third year (2013), *A. laevis, A. oolentangiensis, C. lanceolata,* and *E. purpurea* were the dominant species at the 20 cm depth with absolute cover (AC) values of 0.193, 0.393, 0.237, and 0.250, respectively (Table 2.3). Mean AC for all species was 0.086. By year four, all species were present except for *E. spectabilis* which had completely died off and not re-germinated from seed. *Aster laevis* exhibited the most dramatic increase in cover from year three to four as AC increased from 0.193 to 0.547. By year six, 10 of the 17 original species were absent. Absolute coverage for *A.*

cernuum and *S. heterolepis* increased from year four to year six, from 0.107 to 0.387 and 0.210 to 0.327, respectively, and were the most plentiful species. By year seven, the final year, only seven species remained; *A. cernuum* (AC=0.783), *S. heterolepis* (0.310), *K. macrantha* (0.093), *C. lanceolata* (0.053), *G. triflorum* (0.027), *P. hirsutus* (0.027) and *A. tuberosa* (0.007).

By year three, three sedum species, *S. album, S. sexangulare, and S. spurium*, had been introduced by reseeding themselves from the 4.5 cm section of the roof. All three species, along with *S. kamtschaticum*, persisted until the end of the study.

Species composition (4.5 cm). In the large surrounding zone composed of sedum mats (4.5 cm zone) the original prevegetated mats were installed with 100% coverage with an equal distribution of all sedum species. Transect data for this zone was collected only during years five, six and seven. Coverage in this zone declined over the years to where 14 to 30% of the roof remained bare. *Sedum album, S. kamtschaticum, S. spurium,* and *S. sexangulare* were still present at year seven, whereas *S. reflexum* disappeared by year five. *Sedum kamtschaticum* dominated the zone with a mean AC over 0.4 during years five through seven (Table 2.5). Comparatively, all other species combined never exceeded a mean AC over 0.22.

Table 2.2 Mean absolute cover of plants planted in a green roof in East Lansing, Michigan, USA in 10 cm depth (2013-2017)

Species	Absolute cover			
	2013	2014	2016	2017
Allium cernuum	0.040 c CD	0.070 c ABCD	0.187 b B	0.660 a A
Anemone virginiana	0.010 a CD	0.024 a CD	0.000 a C	0.000 a C
Asclepias tuberosa	0.014 a CD	0.017 a CD	0.000 a C	0.000 a C
Aster laevis	0.084 a CD	0.097 a ABCD	0.000 b C	0.000 b C
Aster oolentangiensis	0.094 a BCD	0.104 a ABCD	0.000 b C	0.000 b C
Campanula rotundifolia	0.000 a D	0.010 a CD	0.000 a C	0.000 a C
Coreopsis lanceolata	0.247 a AB	0.187 a AB	0.000 b C	0.024 b C
Echinacea purpurea	0.060 a CD	0.114 a ABC	0.000 b C	0.000 b C
Eragrostis spectabilis	0.010 a CD	0.000 a D	0.000 a C	0.000 a C
Geum triflorum	0.034 ab CD	0.074 a ABCD	0.000 b C	0.000 b C
Koeleria macrantha	0.117 b BC	0.224 a A	0.000 c C	0.000 c C
Liatris aspera	0.014 a CD	0.034 a CD	0.000 a C	0.000 a C
Monarda fistulosa	0.014 a CD	0.020 a CD	0.000 a C	0.000 a C
Penstemon hirsutus	0.084 a BCD	0.110 a ABC	0.000 b C	0.007 b C
Schizachyrium scoparium	0.044 b CD	0.134 a ABC	0.037 b C	0.000 b C
Sporobolus heterolepis	0.077 b CD	0.027 bc CD	0.514 a A	0.000 c C
Tradescantia ohiensis	0.000 a D	0.000 a D	0.010 a C	0.000 a C
Sedum album	0.267 a A	0.094 b ABCD	0.004 c C	0.004 c C
Sedum kamtschaticum	0.017 bc CD	0.004 c CD	0.084 ab BC	0.100 a BC
Sedum reflexum	0.000 a D	0.000 a D	0.004 a C	0.004 a C
Sedum sexangulare	0.250 a AB	0.150 ab ABC	0.117 b BC	0.224 a B
Sedum spurium	0.084 b BCD	0.064 b BCD	0.107 ab BC	0.167 a B

Mean separation in rows was conducted by LSD test ($p<0.05$). Mean separation in columns was conducted by Tukey test ($p<0.05$). Means followed by the same lowercase letters in rows indicate no significant differences among years. Means followed by the same uppercase letters in columns indicate no significant differences among species.

Table 2.3 Mean absolute cover of plants planted in a green roof in East Lansing, Michigan, USA in 20 cm depth (2013-2017)

Species	Absolute cover			
	2013	2014	2016	2017
Allium cernuum	0.120 c BCD	0.107 c CD	0.387 b A	0.783 a A
Anemone virginiana	0.040 b CD	0.113 a CD	0.000 c B	0.000 c C
Asclepias tuberosa	0.047 a CD	0.060 a CD	0.003 b B	0.007 b C
Aster laevis	0.193 b B	0.547 a A	0.000 c B	0.000 c C
Aster oolentangiensis	0.393 a A	0.133 b BC	0.000 c B	0.000 c C
Campanula rotundifolia	0.000 a D	0.047 b CD	0.000 b B	0.000 b C
Coreopsis lanceolata	0.237 a B	0.117 b CD	0.040 b B	0.053 b C
Echinacea purpurea	0.250 a AB	0.297 a B	0.000 b B	0.000 b C
Eragrostis spectabilis	0.000 a D	0.000 a D	0.000 a B	0.000 a C
Geum triflorum	0.043 a CD	0.020 a CD	0.013 a B	0.027 a C
Koeleria macrantha	0.073 a BCD	0.030 ab CD	0.000 b B	0.093 a C
Liatris aspera	0.013 b D	0.077 a CD	0.000 b B	0.000 b C
Monarda fistulosa	0.033 a CD	0.010 ab CD	0.000 b B	0.000 b C
Penstemon hirsutus	0.087 a BCD	0.050 ab CD	0.000 c B	0.027 bc C
Schizachyrium scoparium	0.133 a BC	0.147 a BC	0.097 a B	0.000 b C
Sporobolus heterolepis	0.070 b BCD	0.210 ab BC	0.327 a A	0.310 a B
Tradescantia ohiensis	0.013 ab D	0.047 a CD	0.027 ab B	0.000 b C
Sedum album	0.083 a BCD	0.063 a CD	0.000 b B	0.003 b C
Sedum kamtschaticum	0.000 a D	0.000 a D	0.017 a B	0.020 a C
Sedum reflexum	0.000 a D	0.000 a D	0.000 a B	0.000 a C
Sedum sexangulare	0.053 ab CD	0.047 ab CD	0.033 b B	0.090 a C
Sedum spurium	0.003 b D	0.023 b CD	0.020 b B	0.080 a C

Mean separation in rows was conducted by LSD test ($p<0.05$). Mean separation in columns was conducted by Tukey test ($p<0.05$). Means followed by the same lowercase letters in rows indicate no significant differences among years. Means followed by the same uppercase letters in columns indicate no significant differences among species.

Table 2.4 Mean absolute cover of plants planted in a green roof in East Lansing, Michigan, USA in 10 cm and 20 cm substrate depths (2017)

Species	Absolute cover	
	10 cm	20 cm
Allium cernuum	0.660 b	0.783 a
Anemone virginiana	0.000 a	0.000 a
Asclepias tuberosa	0.000 a	0.007 a
Aster laevis	0.000 a	0.000 a
Aster oolentangiensis	0.000 a	0.000 a
Campanula rotundifolia	0.000 a	0.000 a
Coreopsis lanceolata	0.024 a	0.053 a
Echinacea purpurea	0.000 a	0.000 a
Eragrostis spectabilis	0.000 a	0.000 a
Geum triflorum	0.000 a	0.027 a
Koeleria macrantha	0.000 b	0.093 a
Liatris aspera	0.000 a	0.000 a
Monarda fistulosa	0.000 a	0.000 a
Penstemon hirsutus	0.007 a	0.027 a
Schizachyrium scoparium	0.000 a	0.000 a
Sporobolus heterolepis	0.000 b	0.310 a
Tradescantia ohiensis	0.000 a	0.000 a
Sedum album	0.004 a	0.003 a
Sedum kamtschaticum	0.100 a	0.020 b
Sedum reflexum	0.004 a	0.000 a
Sedum sexangulare	0.224 a	0.090 b
Sedum spurium	0.167 a	0.080 a

Mean separation in rows was conducted by LSD test ($p<0.05$). Means followed by the same lowercase letters in rows indicate no significant differences between the 10 cm and 20 cm depths.

Table 2.5 Mean absolute cover of plants planted in a green roof in East Lansing, Michigan, USA in 4.5 cm substrate depth (2015-2017)

Species	Absolute cover		
	2015	2016	2017
Sedum album	0.073 a B	0.063 a B	0.093 a B
Sedum kamtschaticum	0.610 a A	0.567 ab A	0.433 b A
Sedum spurium	0.070 a B	0.030 ab BC	0.010 b DC
Sedum reflexum	0.000 a C	0.000 a C	0.000 a D
Sedum sexangulare	0.080 a B	0.033 b B	0.043 ab BC

Mean separation in rows and columns was conducted by LSD test ($p<0.05$). Means followed by the same lowercase letters in rows indicate no significant differences among years. Means followed by the same uppercase letters in columns indicate no significant differences among species.

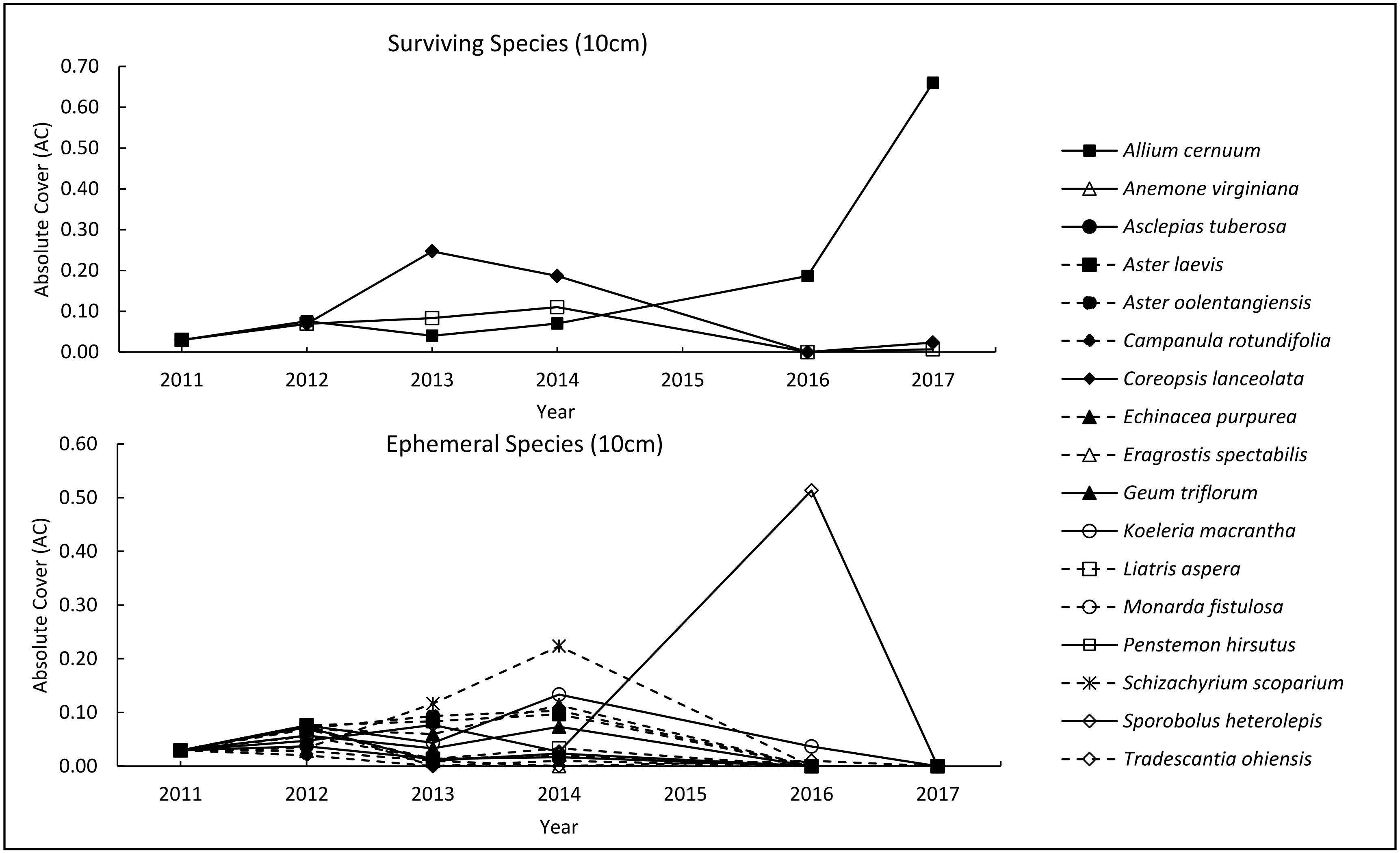

Figure 2.2 Absolute cover of species in 10 cm zone. Ephemeral species are those that did not survive to the end of the study. Individual zone AC was not recorded during 2015. Absolute coverage for 2011 and 2012 estimated from photographs.

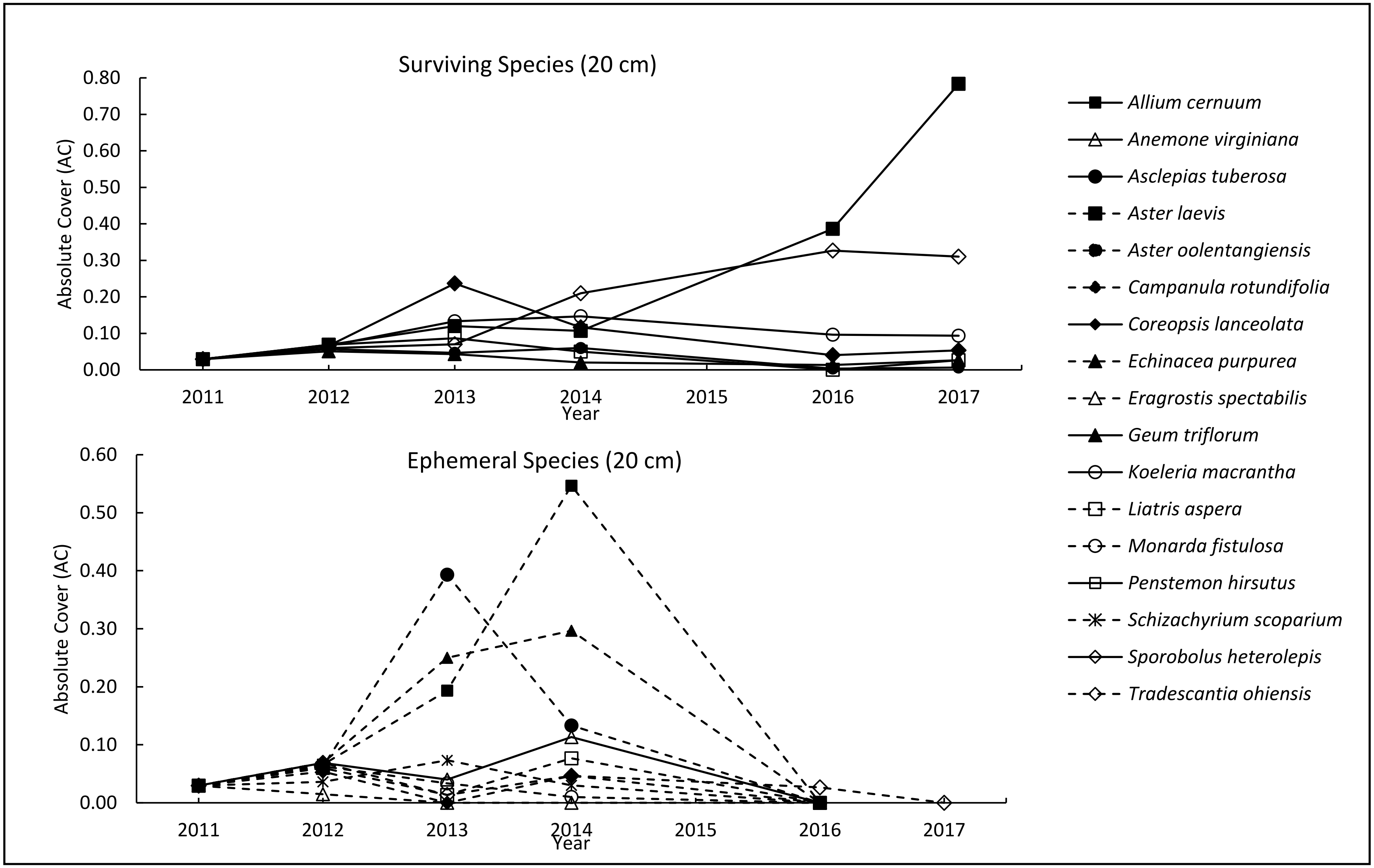

Figure 2.3 Absolute cover of species in 20 cm zone. Ephemeral species are those that did not survive to the end of the study. Individual zone AC was not recorded during 2015. Absolute coverage for 2011 and 2012 estimated from photographs.

Species diversity and richness. Species diversity generally decreased over time (Shannon Diversity Index H')(Figure 2.4). Sedum species that were introduced from the 4.5 cm zone were not included in the diversity analysis due to the edge effect. Diversity would be inflated in the 10 cm zone due to its proximity to the 4.5 cm sedum zone.

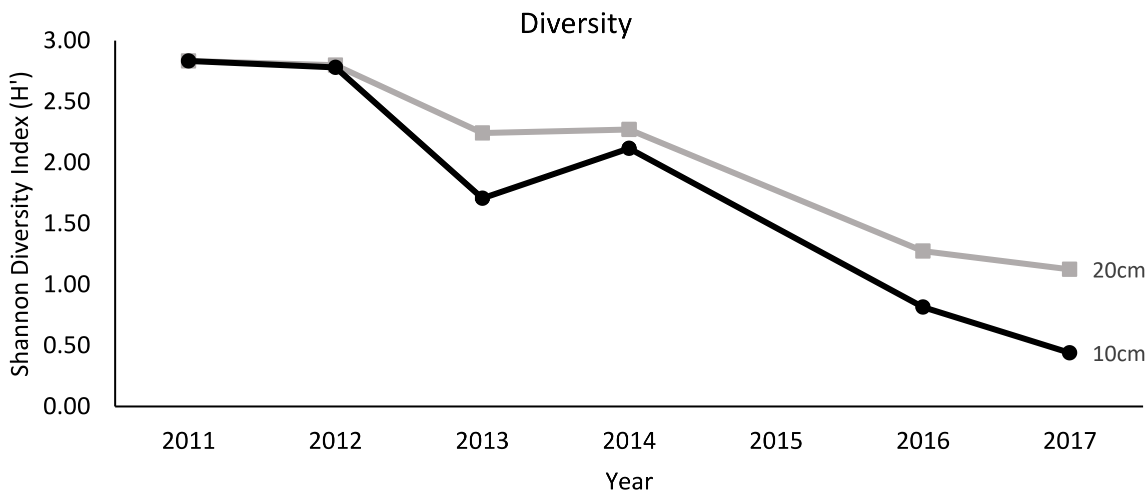

Figure 2.4 Shannon diversity index (H') of original species planted. Diversity does not include introduced sedum species.

Of the species originally planted, seven remained in the 20 cm zone and three remained in the 10 cm zone by the end of the study. If including introduced sedum species, richness is increased to 11 and 8, respectively.

Depth comparison. After 7 years, the 20 cm zone had more than twice the number of original species compared to the 10 cm zone (Table 2.4). Looking at introduced sedums, the 10 cm zone had five sedum species by year seven, while the 20 cm zone had four. This is likely a result of the edge effect discussed previously. The diversity of the 10 cm zone remained less than the 20 cm zone for the entirety of the study.

Discussion

Species diversity and richness. It is likely that initial survival in June 2012 was influenced more by the ability of the plants to establish quickly and withstand the first winter than by moisture content. This is because the roof was irrigated during this time. Plant species composition is expected to change over time as individual plants reseed themselves and compete for water and space. Species richness generally decreased over time. After an extreme drought in year six (2016), species richness was more than halved in both the 10 cm and 20 cm zones. The H' increase in both zones in year four was the result of an increase of abundance of each species by 59% (20 cm) and 76% (10 cm) as well as *C. rotundifolia* reappearing. In this study, substrate depth and plant diversity (H') are directly related. Comparable results were found by Madre et al. (2014) who found that substrate depth had a significant impact on diversity of colonizing species in a survey of 115 green roofs in France.

We observed a constant change in plant presence and a decrease in diversity (H') over the length of this study. This is not surprising as a similar decrease in diversity also occurs on the ground (Millenbah et al. 1996). In the first few years, diversity decrease was likely a result of well-suited species establishing and outcompeting poorer-suited species. For example, G. triflorum, which is relatively short had a difficult time competing against taller plant species. Disturbances, such as the weather event in this study, disrupted this transition and may have provided environmental conditions that favored one species over another. A relatively wet period would favor taller more aggressive plant species. However, questions still arise such as: Is there a steady community of plants that will emerge? If so what is the time necessary for that community to emerge?

As in our study, a similar decrease in diversity was observed on an irrigated roof over five years in Sheffield, UK (Dunnett et al., 2008). While all plant species survived in Dunnett's study, several decreased in abundance, a factor in the Shannon- Weiner Diversity calculation. Species diversity also decreased over two years on an irrigated green roof in Toronto, Ontario (MacIvor et al. 2013). They observed grasses and forbs established from seed. Compared to the first year, diversity (H') had decreased over all treatments. However, diversity does not always decrease over time. Carlisle et al. (2013) conducted a study over 8 years where diversity increased. Located in Ithaca, NY, the roofs were not irrigated, but more importantly, were not weeded. If species diversity is desired, weeding should be avoided. However, leaving colonizing plants is complicated by aggressive species that may overtake desired species and possibly damage waterproofing membranes (Luckett, 2009). In addition, weeds may be looked at unfavorably on the roof and seeds may spread to surrounding landscapes.

In a study on weed establishment on green roofs, Nagase et al. (2013) found that nine species, all native to the area, colonized the green roof platforms in the study. This was within one growing season. All the colonizing species were native dry-open habitats. The study concluded that a higher density of plants excluded more weeds. In the previously mentioned study by Dunnett et al. (2008), 36 species colonized the roof (not included in diversity calculation). The abundance of each species varied from one individual to 138 individuals (average abundance ~ 16).

Weather effects. At some point between years five and six (2015-2016), 41% of the species on the roof disappeared. This major die off occurred during the winter of 2015-16 or summer of 2016. Data collected in August 2015 showed that all species present in 2014 were still present in 2015. Thus, the die-off did not occur in 2015. However, data was not collected as separate zones, so it was not analyzed and presented here. In addition, photographs from year five confirm the presence of these species.

The major die off during 2015-16 was likely due to a drought during the spring and summer of year six (2016). During a 57 day period, May 16, 2016 to July 11, 2016, the total rainfall was 3.28 cm (gray box in Figure 2.5). About a third of that rainfall fell on one day, July 1, 2016. Comparatively, normal rainfall for May, June, and July is 8.5, 8.8, and 7.2 cm, respectively (Andresen et al., 2017). Advice from Dunnett and Kingsbury (2008) regarding cold hardiness and drought on green roofs should be heeded: "…worst case weather scenarios should be assumed."

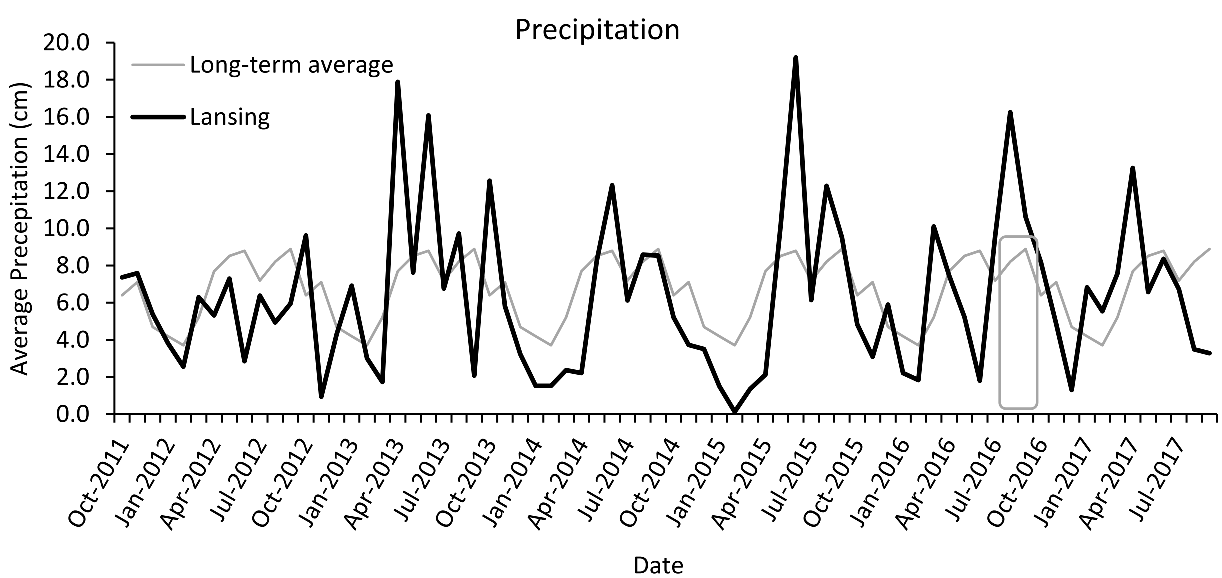

Figure 2.5 Average monthly precipitation in Lansing, Michigan compared to long term average (Andresen et al. 2017).

Another possible explanation for the high plant mortality may be due to the lack of snow cover during the winter of 2013-14 (years 3-4) which also corresponded with the lowest minimum surface and substrate temperatures recorded during that time (Eksi et al., 2017). On

January 28, 2014, the minimum surface temperature reached -20° C. Temperature in the substrate of the sedum dropped to this temperature, however, the substrate temperature in the 20 cm zone only dropped to -9.5° C. Even so, it is more likely that the drought had a greater influence on plant death. In a study on freeze tolerance of herbaceous plants in alpine zones, Larcher et al. (2010) observed that plants survived with less than 50% injury in temperatures as low as -60° C. It is likely that winter temperatures had a negligible effect on plant survival in our study.

It would seem logical that even if the existing plants were killed off due to drought, there would be many species that had produced seeds in previous years that would germinate and take their place. Germination may have occurred during spring 2016, but since the drought period began in May, these young plants likely had not had enough time to form large enough root systems to survive.

After this extreme weather event, all species experienced a decrease in AC, except for *A. cernuum* and *S. heterolepis* which increased in both sections. These two species had a competitive advantage in their ability to withstand and reproduce after the extreme weather where other species died. Sporobolus heterolepis continued to perform through the end of the study in the 20 cm zone but did not survive in the 10 cm zone. In both zones, *A. cernuum* continued to be the best performing species, as measured by the highest absolute coverage, through the final year. Getter et al. (2009) experimented with nine species comparing performance in shade verses sun over a four-year period. *Allium cernuum* covered 31% of the shaded study area (12 cm substrate depth). In the sun it covered 12% of the area. In the 8 cm depth *A. cernuum* survived but did not perform as well.

Plant suitability. Of the original 17 species planted in the 20 cm zone, seven remained at the end of the study. Two of the surviving species were the grasses *K. macrantha* and *S. heterolepis*. The others were the herbaceous perennials *A. cernuum, A. tuberosa, C. lanceolata, G. triflorum*, and *P. hirsutus*. By year 3, sedum from the 4.5 cm and 10 cm zones had entered the 20 cm zone, likely due to seed spreading or a transported cutting. *Sedum kamtschaticum, S. spurium*, and *S. sexangulare* all survived in this zone until the end of the study.

Of the 17 species originally planted in the 10 cm zone, three remained at the end of the study, all herbaceous perennials (*A. cernuum, C. lanceolata, and P. hirsutus*). No grasses survived. By year three, sedum had encroached from the 4.5 cm zone and *S. kamtschaticum, S. spurium,* and *S. sexangulare* all survived until the end of the study. The slight decrease in AC for the sedum species during year four in the 10 cm zone was likely due to the more favorable weather conditions that promoted growth of the taller herbaceous perennials and grasses. Sedum is not likely to compete with C3 plants when ample moisture is available.

In contrast, four of the five species of sedum that were originally planted in the 4.5 cm zone still existed after seven years. The only species that completely disappeared from this zone was *S. reflexum*.

The following is a list of the species that survived and were still present at year seven. Following each are studies from the Midwest, USA, where success was documented: *K. macrantha* (Hawke, 2015), *S. heterolepis* (Hawke, 2015), *A. cernuum* (Monterusso et al., 2005; Getter et al., 2009; Ksiazek et al., 2014; Hawke, 2015; Matlock and Rowe, 2016), *A. tuberosa* (Ksiazek et al., 2014), *C. lanceolata* (Monterusso et al., 2005; Hawke, 2015), *G. triflorum* (Hawke, 2015), and *P. hirsutus* (Hawke, 2015). Sedum species have been extensively tested and proven on green roofs. The following are the sedum species that survived through the end of the study followed by the number of Midwest studies they are proven successful in; *S. album* (5), *S. kamtschaticum* (5), *S. reflexum* (4), *S. spurium* (10), and *S. sexangulare* (4). For further information on the studies mentioned above, see Chapter 2.

Across the roof, *A.* cernuum consistently had the highest survival, growth rate and coverage. This species has several desiccation prevention mechanisms including; glabrous leaves, water storage in bulbs, and minimal leaf area. Allium species are also proficient self-seeders. *Sporobolus heterolepis*, the second best performing species utilizes C4 photosynthesis (Gould and Shaw, 1983). C4 plants operate best at high temperatures (~32 °C) and are more efficient with water than C3 plants. Sedum species have been proven to withstand extreme conditions due to many physiological traits, chief among them CAM photosynthesis (Rowe et al., 2012). Additionally, sedum store large amounts of water in their leaves and reduce water loss through stomata via a waxy leaf coating (Nagase and Dunnett, 2010). Many of the species that did not survive exhibit C3 photosynthesis or normally have deep root systems. These roots were likely limited by the shallow substrate.

Comparison of depths. Interestingly, *S. reflexum* was no longer found in its original zone, but did spread and survive in the 10 cm zone. This suggests that a green roof containing a variety of depths may be beneficial for long-term success as various species will find their environmental niche, thus increasing the plant diversity on a roof. The UK's Green roof guide states: "Substrate depths may vary across the roof deck to promote a diversity of both shallow and deep rooted plants and ones which are more and less drought tolerant." (Allnut et al., 2014). Like in a forest, layers of canopy may exist on green roofs. As time passed in our study, sedum moved into the understory of the deeper zones. This is beneficial as species may co-exist and maximize the resources (Spehn et al., 2000).

Importance of maintenance. Extensive green roofs are typically installed with the intent of minimal maintenance. While these shallow roofs do not require as much maintenance as a home garden, they do still need regular care. In this study, especially in the shallowest zone, bare spots increased over time. This could be mitigated with maintenance such as addition of nutrients and watering during drought.

A similar increase of bareness has been observed in newly planted grasslands in Michigan. For example Millenbah et al. (1996) found an initial increase in live canopy from year one to two. After three years however, live canopy decreased. The mechanism responsible was an increasing litter layer crowding out other species. Part of the reduction in diversity could possibly be explained in our study due to this reason. The stalks and stems of all plant material were left as is throughout the winter periods and was never cut or removed. Maintenance in the form of prescribed burning or mowing would decrease this litter layer and increase live canopy. While burning and mowing may not be an option for most green roofs, maintenance is required if the original look is desired. Green roofs are dynamic, ever changing landscapes. Devoid of maintenance, vegetation will likely change from the original design intent.

Limitations. This study was an observational study of plant changes occurring on one roof. Because of this, any results are specific to this roof and should be extrapolated with caution.

Conclusion

As seen in other research, deeper substrates support a larger variety of species. All substrate depths in this study experienced a decrease in species richness. The 4.5 cm zone only experienced species emigration to the deeper zones. The other two zones experienced species immigration while simultaneously experiencing a decrease in species richness. An increase of species richness may have been observed if we avoided weeding.

Of the 22 species on this green roof, 12 survived across the entire roof. Plants on green roofs must endure daily weather conditions and rare extreme events. This study demonstrates that supplemental irrigation may be critical to maintaining species diversity on a green roof. Because of the length of this study we were able to capture a wide variety of weather events. Future studies on the suitability of plants for any environment should experience a full range of environmental conditions. Thus, the need for long-term studies.

BIBLIOGRAPHY

BIBLIOGRAPHY

Akbari, H., L. Shea Rose, and H. Taha. 2003. Analyzing the land cover of an urban environment using high-resolution orthophotos. Landscape and Urban Planning 63(1):1–14. doi 10.1016/S0169-2046(02)00165-2

Allnut, P., W. Bussey, D. Gedge, M. Harris, I. Henning, S. Poë, N. Ridout, P. Singleton, J. Sorrill, D. A. Tar, and S. Zeller. 2014. The GRO Green Roof Code (Green Roof Code of Best Practice for the UK).

Andresen, J., B. Bishop, T. Aichele, S. Casey, J. Brown, S. Marquie, A. Pollyea, and J. Landis. 2017. Enviroweather Oct 2011 - Sep 2017. 1 September 2017. <https://mawn.geo.msu.edu/station.asp?id=msu&rt=24>

Berndtsson, J.C. 2010. Green roof performance towards management of runoff water quantity and quality: A review. Ecological Engineering 36(4):351–360. doi: 10.1016/j.ecoleng.2009.12.014

Boivin, M.-A., M.-P. Lamy, A. Gosselin, and B. Dansereau. 2001. Effect of Artificial Substrate Depth on Freezing Injury of Six Herbaceous Perennials Grown in a Green Roof System. HortTechnology 11(3):409–412.

Brenneisen, S. 2004. Green Roofs - How Nature Returns to the City. Acta Horticulturae 643(643):289–293. doi: 10.17660/ActaHortic.2004.643.37

Butler, C., E. Butler, and C. M. Orians. 2012. Native plant enthusiasm reaches new heights: Perceptions, evidence, and the future of green roofs. Urban Forestry & Urban Greening 11(1):1–10. doi: 10.1016/j.ufug.2011.11.002

Carlisle, S., M. Piana, and K. Timberlake. 2013. Growing Resilience: Long-term Plant Dynamics and Green Roof Performance. In: Proceedings of Cities Alive: 11th Annual Green Roof and Wall Conference, San Francisco, CA.

Castleton, H.F. et al., 2010. Green roofs; Building energy savings and the potential for retrofit. Energy and Buildings, 42(10), pp.1582–1591. doi: 10.1016/j.enbuild.2010.05.004.

Coffman, R. R. 2007. Comparing Wildlife Habitat and Biodiversity Across Green Roof Type. In: Proceedings of 5th Annual North American Green Roof Conference: Greening Rooftops for Sustainable Communities, Washington, D.C.

Dunnett, N., A. Nagase, and A. Hallam. 2008. The dynamics of planted and colonising species on a green roof over six growing seasons 2001-2006: Influence of substrate depth. Urban Ecosystems 11(4):373–384. doi: 10.1007/s11252-007-0042-7

Durhman, A.K., Rowe, D.B. & Rugh, C.L., 2007. Effect of Substrate Depth on Initial Growth, Coverage, and Survival of 25 Succulent Green Roof Plant Taxa. Hort Science, 42(3): 588–595.

Dvorak, B. and A. Volder. 2010. Green roof vegetation for North American ecoregions: A literature review. Landscape and Urban Planning 96(4):197–213. doi: 10.1016/j.landurbplan.2010.04.009

Eakin, C. J., H. Campa, D. W. Linden, G. J. Roloff, D. Bradley Rowe, and J. Westphal. 2015. Avian response to green roofs in urban landscapes in the Midwestern USA. Wildlife Society Bulletin 39(3):574–582. doi: 10.1002/wsb.566

Eksi, M., D. B. Rowe, I. S. Wichman, and J. A. Andresen. 2017. Effect of substrate depth, vegetation type, and season on green roof thermal properties. Energy and Buildings 145(1):174–187. doi: 10.1016/j.enbuild.2017.04.017

Getter, K. L., D. Bradley Rowe, and B. M. Cregg. 2009. Solar radiation intensity influences extensive green roof plant communities. Urban Forestry and Urban Greening 8(4):269–281. doi: 10.1016/j.ufug.2009.06.005

Getter, K. L., D. B. Rowe, J. A. Andresen, and I. S. Wichman. 2011. Seasonal heat flux properties of an extensive green roof in a Midwestern U.S. climate. Energy and Buildings 43(12):3548–3557. doi: 10.1016/j.enbuild.2011.09.018

Gould, F. W. and R. B. Shaw. 1983. Grass systematics. Brittonia. Texas A & M University Press 35(3):301–301.

Hawke, R. 2015. An evaluation study of plants for use on green roofs. Plant Evaluation Notes 38(1):1–22.

Kaplan, R. 1993. The role of nature in the context of the workplace. Landscape and Urban Planning 26(1–4):193–201. doi: 10.1016/0169-2046(93)90016-7

Ksiazek, K., J. Fant, and K. Skogen. 2014. Native forbs produce high quality seeds on Chicago green roofs. Journal of Living Architecture 1(2):21–33.

Larcher, W., C. Kainmüller, and J. Wagner. 2010. Survival types of high mountain plants under extreme temperatures. Flora - Morphology, Distribution, Functional Ecology of Plants 205(1):3–18. doi: 10.1016/j.flora.2008.12.005

Liu, K. and B. Baskaran. 2003. Thermal Performance of Green Roofs Through Field Evaluation. in Proceedings of 1st North American Green Roof Conference: Greening Rooftops for Sustainable Communities. Chicago, IL.

Loder, A. 2014. 'There's a meadow outside my workplace': A phenomenological exploration of aesthetics and green roofs in Chicago and Toronto. Landscape and Urban Planning 126(1):94–106. doi: 10.1016/j.landurbplan.2014.01.008

Luckett, K. 2009. Green roof construction and maintenance. McGraw-Hill.

MacIvor, J. S., L. Margolis, C. L. Puncher, and B. J. Carver Matthews. 2013. Decoupling factors affecting plant diversity and cover on extensive green roofs. Journal of Environmental Management 130(1):297–305. doi: 10.1016/j.jenvman.2013.09.014

Madre, F., A. Vergnes, N. Machon, and P. Clergeau. 2013. A comparison of 3 types of green roof as habitats for arthropods. Ecological Engineering 57(1):109–117. doi: 10.1016/j.ecoleng.2013.04.029

Madre, F. et al., 2014. Green roofs as habitats for wild plant species in urban landscapes: First insights from a large-scale sampling. Landscape and Urban Planning, 122, pp.100–107. doi: 10.1016/j.landurbplan.2013.11.012

Maller, C., M. Townsend, A. Pryor, P. Brown, and L. St Leger. 2006. Healthy nature healthy people: 'contact with nature' as an upstream health promotion intervention for populations. Health Promotion International 21(1):45–54. doi: 10.1093/heapro/dai032

Matlock, J. M. and D. B. Rowe. 2016. The suitability of crushed porcelain and foamed glass as alternatives to heat-expanded shale in green roof substrates: An assessment of plant growth, substrate moisture, and thermal regulation. Ecological Engineering 94(1111):244–254. doi: 10.1016/j.ecoleng.2016.05.044

Millenbah, K. F., S. R. Winterstein, H. Campa Iii, L. T. Furrow, and R. B. Minnis. 1996. Effects of Conservation Reserve Program Field Age on Avian Relative Abundance, Diversity, and Productivity. The Wilson Bulletin 108(4):760–770.

Monterusso, M. A., D. Bradley Rowe, and C. L. Rugh. 2005. Establishment and persistence of Sedum spp. and native taxa for green roof applications. HortScience 40(2):391–396.

Nagase, A. and N. Dunnett. 2010. Drought tolerance in different vegetation types for extensive green roofs: Effects of watering and diversity. Landscape and Urban Planning 97(4):318–327. doi: 10.1016/j.landurbplan.2010.07.005

Nagase, A., N. Dunnett, and M. S. Choi. 2013. Investigation of weed phenology in an establishing semi-extensive green roof. Ecological Engineering 58(1):156–164. doi: 10.1016/j.ecoleng.2013.06.007

Parkins, K. L. and J. A. Clark. 2015. Green roofs provide habitat for urban bats. Global Ecology and Conservation 4(1):349–357. doi: 10.1016/j.gecco.2015.07.011

Peck, S. and M. Kuhn. 2003. Design guidelines for green roofs. Ontario Association of Architects. Ontario, Canada.

Rowe, D. B. 2011. Green roofs as a means of pollution abatement. Environmental Pollution 159(8–9):2100–2110. doi: 10.1016/j.jsv.2008.03.025

Rowe, D. B., K. L. Getter, and A. K. Durhman. 2012. Effect of green roof media depth on Crassulacean plant succession over seven years. Landscape and Urban Planning 104(3–4):310–319. doi: 10.1016/j.landurbplan.2011.11.010

Scott, M. 2006. Beating the Heat in the World's Big Cities: Feature Articles. NASA Earth Observatory. 13 January 2017.
<http://earthobservatory.nasa.gov/Features/GreenRoof/greenroof2.php>

Spehn, E. M., J. Joshi, B. Schmid, M. Diemer, and C. Korner. 2000. Above-ground resource use increases with plant species richness in experimental grassland ecosystems. Functional Ecology 14(3):326–337. doi: 10.1046/j.1365-2435.2000.00437.x

Ulrich, R. S. 1984. View through a window may influence recovery from surgery. American Association for the Advancement of Science 224(1):420–422.

United Nations, Department of Economic and Social Affairs. 2014. World Urbanization Prospects: The 2014 Revision, Highlights. 3 January 2017.
<https://esa.un.org/unpd/wup/Publications/Files/WUP2014-Highlights.pdf>

United States Census Bureau, 2010. 2010 Census, 4 May 2018.
<https://www.census.gov/geo/reference/ua/urban-rural-2010.html>

Van Renterghem, T. and D. Botteldooren. 2008. Numerical evaluation of sound propagating over green roofs. Journal of Sound and Vibration 317(3–5):781–799. doi: 10.1016/j.jsv.2008.03.025

Waite, S., 2000. Statistical ecology in practice : a guide to analysing environmental and ecological field data, Prentice Hall.

Whittinghill, L. J. and D. B. Rowe. 2012. The role of green roof technology in urban agriculture. Renewable Agriculture and Food Systems 27(4):314–322. do: 10.1017/S174217051100038X

Whittinghill, L. J., D. B. Rowe, and B. M. Cregg. 2013. Evaluation of Vegetable Production on Extensive Green Roofs. Agroecology and Sustainable Food Systems 37(4):465–484. doi: 10.1080/21683565.2012.756847

Wilson, E. O. 1984. Biophilia. Cambridge, Mass.

CHAPTER 2: GREEN ROOF PLANTS FOR THE GREAT LAKES REGION OF NORTH AMERICA

Abstract

Green roofs are still considered relatively new to North America, and we are still learning and implementing best practices. If the green roof industry is to grow and promote diversity, the list of suitable plant species must be expanded and shared with green roof professionals. Because climate differs from one region to the next, data on plant performance for each climatic region is needed to properly specify green roofs within that region. In this paper we collected plant performance data from studies in the Great Lakes region of North America. We have compiled a reference guide that green roof professionals can use in the Great Lakes region and in other parts of the world with a similar climate. The region falls within the Köppen climate types 'Dfa' (hot summer humid continental) or 'Dfb' (warm summer humid continental) characterized by wide seasonal temperature fluctuations with warm to hot (and often humid) summers and cold winters. Information on green roof plant performance was based on peer-reviewed research publications from studies conducted at Michigan State University, the University of Guelph, and plant evaluations conducted by scientists at the Chicago Botanic Garden. A green roof plant community reference guide was constructed that lists traits such as plant growth habit, size, hardiness, drought tolerance, wildlife attractiveness, and other attributes. We then discuss the trends presented in the list including, plant performance, groups of well performing plants, and plant selection and their influence on green roof benefits.

Index words: herbaceous perennials, grasses, Great Lakes region, living roofs

Introduction

Green or living roofs, a form of green infrastructure, can provide many environmental and economic benefits. Stormwater management, both runoff quantity and water quality, is generally considered the leading reason for green roof installation (Czemiel Berndtsson, 2010) followed by their potential to reduce energy use (Castleton et al., 2010; Getter et al., 2011; Eksi et al., 2017). Green roofs can also mitigate the urban heat island (Rowe, 2011), improve air quality (Rowe, 2011), reduce noise (Van Renterghem and Botteldooren, 2008), and extend the lifespan of roofing membranes (Liu and Baskaran, 2003; Peck and Kuhn, 2003). In addition, green roofs can improve the aesthetic appeal of rooftops (Wilson, 1984), improve human health (Ulrich, 1984; Kaplan, 1993; Loder, 2014), provide habitat to increase urban plant and animal diversity (Brenneisen, 2004; Coffman, 2007; Madre et al., 2013; Eakin et al., 2015; Parkins and Clark, 2015), and allow for previously unused space to be used for urban agriculture (Whittinghill and Rowe, 2012; Whittinghill et al., 2013).

Green roofs are classified as either extensive or intensive. Extensive green roofs are usually defined as those with less than 10 to 15 cm of growing substrate. Because of their shallow depth, vegetation is often limited to drought tolerant plants such as succulents unless the green roof is irrigated. In contrast, intensive green roofs are those with more than 15 cm of growing substrate and can support a wider variety of plant types such as herbaceous perennials and grasses. If the roof has the proper support, shrubs and trees can also be grown.

Regardless of the type of green roof, vegetation on rooftops is generally exposed to a harsher environment than what is found at ground level. Temperatures tend to be more extreme, they are often in full sun with stronger drying winds, and substrate depth is often limited due to weight restrictions from structural capacities of the building. The depth of the growing substrate plays a major factor in determining what plant species will be successful. Generally, as substrate depth increases; moisture retention increases, plant survivability increases, and the number of potential suitable plant species increases. Suitable plant palettes can be greatly expanded by providing supplemental irrigation (Van Mechelen et al., 2015).

Each plant species will tend to find its niche on a green roof depending on interdependent variables including substrate depth, moisture content, roof slope, sun exposure, weather conditions, and microclimates. Shallow substrates exclude most plant species except for those with high drought tolerance such as Sedum. Even within relatively shallow depths, species within the same genus will find their niche. Rowe et al. (2012) demonstrated the importance of depth in the study of 25 Sedum species. In a shallow substrate depth of 2.5 cm, *Sedum album* and *Sedum acre* outperformed all other species. However, when tested at depths of 5.0 cm and 7.5 cm, these two species were outperformed by *S. middendorfianum* which obtained the highest absolute cover. One of the benefits of a shallow substrate is that unwanted herbaceous perennials and grasses cannot survive because of limited moisture, thus greatly reducing roof maintenance costs and unwanted plant species.

Herbaceous perennials and grasses are even more dependent on substrate depth than sedums. Dunnett et al., (2008) conducted a 6-year study in the United Kingdom where they evaluated the effect of substrate depth on 15 herbaceous perennials and grasses. While all species survived in both the 10 cm and 20 cm substrate depths, plants growing in the deeper substrate performed better in terms of survival, diversity, size, and flowering. The plants in the 20 cm zone increased in number while those in the 10cm zone decreased. Overall, species richness and diversity were greater in the deeper substrate. Similar results were found in a 6-year study in Michigan (Vandegrift, 2018). Of the two substrate depths tested, 10 cm and 20 cm, the latter retained a larger number of the species that had been originally installed. While not all species survived on the roof, species richness and diversity were higher in the deeper substrate.

Plant evaluation studies have been conducted around the world and many species have been identified that do well on green roofs. Even though green roofs are not as common in North America as they are in Europe, the green roof industry in North America is experiencing steady growth. According to an annual survey conducted by Green Roofs for Healthy Cities, survey respondents reported that 377,281 m^2 of green roofing was installed in the United States and Canada during 2016 (Stand and Peck, 2017). This area is equivalent to the space occupied by 70 American football fields and represents an estimated 10.3% growth over 2015. These numbers continue the double-digit growth the industry has experienced over most of the last decade. Green roofs are still considered relatively new to the United States, and we are still learning and implementing best practices. Because climate differs from one region to the next, data on plant performance for each climatic region is needed to properly specify green roofs within that region. In this paper we have collected plant performance data from those studies that have taken place around the Great Lakes of North America. Our goal is to provide a reference guide that green roof professionals can use in the Great Lakes region and in other parts of the world with a similar climate. The reference guide can be used as is to identify species biased off the traits listed. Additionally, it could be developed into a plant selection tool where users input a few metrics and suitable species are outputted.

Criteria for selection of studies

To be included in this review, studies reported had to be conducted within the Great Lakes region and preferably reported in peer-reviewed scientific journals (Table 3.1). The Great Lakes region falls within the Köppen climate types 'Dfa' (hot summer humid continental) or 'Dfb' (warm summer humid continental) and are characterized by wide seasonal temperature fluctuations with warm to hot (and often humid) summers and cold winters. Precipitation is generally somewhat evenly distributed throughout the year (Arnfield, 2009).

For our purposes, the Great Lakes region is defined as the land area bordering at least one of the Great Lakes and subject to the moderating climate effects due to the presence of the large bodies of water and includes the states of Michigan, northeastern Minnesota, eastern Wisconsin, northeastern Illinois, northern Indiana and Ohio, northwestern Pennsylvania, western New York, and southern Ontario, Canada. Published studies fitting these criteria were conducted in East Lansing, MI, Glencoe, IL, and Princeton, ON. The colder regions bordering Lake Superior are not included because no studies were performed in this geographic area. The United States Department of Agriculture (USDA) and the Natural Resources Canada hardiness maps depict the average annual extreme minimum temperature for various locations. East Lansing, MI (42.7370° N, 84.4839° W) and Glencoe, IL (42.1350° N, 87.7581° W), fall within

USDA hardiness zone 5b (-26.1 to -23.3 °C) and Princeton, Ontario, Canada (43.1700° N, 80.5267° W) falls within hardiness zone 6a (-23.3 to -20.6 °C).

Table 3.1 Summary of green roof plant evaluation studies in the Great Lakes region

Location	Ecoregion (type III)	Plant types*	Study length (years)	Depth (cm)	Summary	Study
East Lansing, MI	Michigan/ North Indiana Drift Plains	S,H,G	7	4.5,10,20	Compared plant survival at the two depths (10 and 20 cm). In 10 cm depth, 3 herbaceous perennials survived to end of study. In 20 cm, 2 grasses and 5 herbaceous perennials survived. All 5 sedum species survived to end of study. Die-off likely due to drought in summer.	Vandegrift (2018)
East Lansing, MI	Michigan/ North Indiana Drift Plains	S,H,G	4	8,10,12	Two studies, both on the effects of sun and shade on green roof plants. The first compared 9 species planted as plugs in two depths, 8 and 12 cm. The second evaluated the establishment of 6 sedum species planted from seed in 10 cm substrate. When sun and shade were compared both studies concluded no difference in absolute cover but there was a difference in percent of each species.	Getter et al. (2009)
East Lansing, MI	Michigan/ North Indiana Drift Plains	S,H,G	2	10	Experimented with foamed glass, crushed glass, and expanded shale as substrates. Nine species were planted and 6 performed well. Plant coverage was the same across all substrates for 5 of 6 of the data collection periods.	Matlock and Rowe (2016)

Table 3.1 (cont'd)…

East Lansing, MI	Michigan/ North Indiana Drift Plains	S	1	4,7,10	Examined effect of substrate depth and planting season on 9 species of sedum. For all depths, found 81% survival in spring planted sedum vs 23% for autumn planted.	Getter and Rowe (2007)
East Lansing, MI	Michigan/ North Indiana Drift Plains	S	1	4,7,10	See Getter and Rowe 2009	Getter and Rowe (2008a)
East Lansing, MI	Michigan/ North Indiana Drift Plains	S	4	4,7,10	Evaluated the effect of depth on initial establishment of 12 species of sedum. Found most species grew best at 7 and 10 cm, relative to 4 cm. Recommended minimum depth of 7 cm.	Getter and Rowe (2009)
East Lansing, MI	Michigan/ North Indiana Drift Plains	S,H,G	4	10	Assessed plant growth in several substrate mixes and fertilizer treatments. Found those with more expanded shale performed poorly and that little fertilizer is needed for sedum tested.	Rowe et al. (2006)
East Lansing, MI	Michigan/ North Indiana Drift Plains	S,H,G	3	10	Evaluated 18 Michigan native species and 9 sedums for suitability on green roofs. Recommended all 9 sedums and 3 MI natives if irrigation is not being used.	Monteruss o et al. (2005)

Table 3.1 (cont'd)…

East Lansing, MI	Michigan/ North Indiana Drift Plains	S	7	2.5,5,7.5	Evaluated 25 species performance in 3 depths over 7 years. Concluded that long term studies are important as species disappear at different times. Six species were present in all depths by the end of the study.	Rowe et al. (2012)
Glencoe, IL	Central Corn Belt Plains	S,H,G	3-4	10,15,20.5	Plant performance study of 216 species with each species evaluated independently. Of the 216 species, 65 received high performance values and we used in our study.	Hawke (2015)
Princeton, ON	Lake Erie Lowland	S	1 year	2.5	Examined the influence of fertilizer on initial establishment of sedum mats. Found that an increase of fertilizer resulted in increased vegetation cover.	Clark and Zheng (2014)

*S=Succulent, H=Herbaceous, G=Grass/sedge

Description of studies

The green roof plant community reference guide (Tables 3.2 and 3.3) is a comprehensive list of plant species that have been documented to perform well on at least one green roof within the Great Lakes region. Performance here is defined as species that survived for several years past the establishment phase (usually the first two years) of green roofs. Plant descriptions came from numerous sources. Information on green roof plant performance was based on peer-reviewed research publications from studies conducted at Michigan State University and the University of Guelph. The extensive plant performance study in Glencoe, IL, was conducted by scientists at the Chicago Botanic Garden. A total of 11 studies were included (Figure 3.1).

Figure 3.1 Locations of the studies used to compile the reference guide include Glencoe, IL, East Lansing, MI, and Princeton, ON.

Studies 1-9 were conducted in East Lansing, MI, which is in the South Michigan/ North Indiana Drift Plains ecoregion (Type III). These studies were only irrigated during establishment and then during the first growing season. Study 10 was conducted in Glencoe, IL, in the Central Corn Belt Plains ecoregion. Study 10 was irrigated the first year for establishment and three individual occasions thereafter when drought was a concern. Study 11 was conducted in Princeton, ON, in the ecoregion Lake Erie Lowland. This last study was watered as needed. Some species have been tested more than others. The column titled "References" lists the publications where each species was tested.

Information on plant performance was obtained from the eleven studies in this review. Information regarding plant details was gleaned from various sources including the Missouri Botanical Garden (Missouri Botanical Garden Plantfinder, 2018), USDA Fire Effects Information System (Gucker, 2007), USDA PLANTS Database (USDA and NRCS, 2017), Habitat Suitability Index (Fish and WIldlife Service, 1985), All About Birds: Bird Guide, (Cornell Lab of Onithology, 2017), Wildtypes' butterfly plant list (Snyder, 2018), a few articles on pollinators (Adamson et al., 2014, 2015; Mädre et al., 2016), and a catalog of plants developed by a Midwest green roof company, LiveRoof (Mackenzie, 2013).

Table 3.2 Plant community reference guide of herbaceous perennials, grasses, and succulents for green roofs in the Great Lakes Region

Plant		Features				Additional information	
Species	Common name	Native to region	Component of Butterfly Habitat	Component of Bird Habitat	Component of Bee Habitat	Notes	Reference
Agastache foeniculum	anise hyssop[15,20]	yes[10,21]	yes[10,20]	yes[10]	yes[20]		10
Allium cernuum	nodding onion[15]	yes[2,8,16,21]	yes[15]	no	no		1,2,3,8,10
Allium senescens	German garlic[15]	no[15]	no	no	no		3
Amorpha canescens	lead plant[15,22,23]	yes[15,21]	yes[15,20,24]	no	yes[20,21,22,23]		10
Andropogon gerardii	big blue stem[10]	yes[15,21]	yes[24]	no	no	Winter interest	10
Antennaria dioica	pussytoes[15]	no[21]	yes[24]	no	no		10
Aquilegia canadensis	columbine[15]	yes[21]	yes[24]	yes[15,21]	yes[21]		10
Armeria maritima	sea thrift[15]	no[21]	no	no	no		10
Artemisia caudata	field sagewort[17]	no[17]	no	no	no		10
Artemisia ludoviciana	white sage[15]	yes[15,21]	no	no	no		10
Asclepias tuberosa	butterfly milkweed[21,23]	yes[21]	yes[15,20,21,23,24]	yes[20]	yes[20,21,23]		1
Aster alpinus	alpine aster[21]	no[21]	yes[24]	no	no	Variety used in study	10
Baptisia alba	false indigo[15]	no[15]	yes[15,20]	no	yes[20]	Variety used in study	10
Bouteloua curtipendula	sideoats grass[15]	yes[15]	no	yes[15]	no		10
Buchloe dactyloides	buffalo grass[15]	no[21]	no	no	no	Cultivar used in study	10
Calamagrostis brachytricha	reed grass[15]	no[15]	no	no	no		10
Calamintha nepeta	calamint[15]	no[15]	no	no	no	Variety used in study	10
Campanula rotundifolia	bluebell[15]	yes[15,21]	no	no	no		10
Carex flacca	blue green sedge[15]	no[15,21]	yes[24]	no	no		2
Ceanothus americanus	New Jersey tea[15,21,23]	yes[15,21]	yes[15,20,21,23,24]	yes[15]	yes[20,21,23]		10
Coreopsis lanceolata	lanceleaf coreopsis[15,23]	yes[8,15]	yes[15,24]	no	yes[20,23]		1,8,10
Coreopsis verticillata	threadleaf coreopsis[15]		yes[15]	no	yes[20]	Cultivar used in study	10
Dalea candida	white prarie clover[15]	part[21]	yes[15,20]	yes[18,21]	yes[20]		10
Dalea purpurea	purple prarie clover[15,21,22,23]	yes[15,21]	yes[15,20,22,24]	yes[18]	yes[20,22,23]		10
Dalea villosa	silky prairie clover[21]	part[21]	yes[20]	yes[18]	yes[20,21]		10
Dianthus gratianopolitanus	cheddar pink[21]	no[21]	no	no	no	Cultivar used in study	10
Festuca amethystina			no	no	no	Cultivar used in study	10

Table 3.2 (cont'd)…

Fragaria virginiana	scarlet strawberry[15]	yes[21]	yes[24]	yes[15]	no		10
Galium verum	yellow spring bedstraw[15,21]	no[15,21]	no	no	no		10
Geum triflorum	old mans whiskers[21]	part[21]	no	no	no		1,10
Helianthus mollis	ashy sunflower[15,21]	part[21]	yes[15,20,21,24]	yes[15,21]	yes[20,21]		10
Heuchera richardsonii	alum root[15]	part[21]	no	no	no		10
Hieracium spilophaeum			no	no	no	Cultivar used in study	10
Hosta lancifolia	narrow-leaved hosta[15]	no[15,21]	no	yes[15]	no		10
Hylotelephium 'Rosy Glow'			no	no	no	Cultivar used in study	10
Koeleria glauca	gray-blue koeleria[15]	no[15]	no	no	no		10
Koeleria macrantha	prarie junegrass[15,21]	yes[15,21]	no	no	no		1,10
Lespedeza capitata	bush clover[15]	yes[15]	yes[24]	no	no		10
Liatris cylindracea	slender blazer star[15]	yes[15,21]	yes[15,20,24]	yes[15]	yes[15,20]		10
Liatris ligulistylis	blazing star[15]	no[21]	yes[15,20,24]	yes[15]	yes[15,20]		10
Monarda fistulosa	wild burgamot[15,21,22,23]	yes[15,21]	yes[15,21,24]	yes[15,20,21,22,23]	yes[20,21,22,23]		10
Monarda punctata	spotted beebalm[21]	yes[15,21]	yes[15,24]	yes[21]	yes[20.23]		3
Nepeta racemosa	nepeta[15]	no[15,21]	yes[15]	no	yes[20]	Cultivar used in study	10
Oligoneuron album	prarie goldenrod[21]	yes[21]	no	yes[18]	no		10
Oligoneuron rigidum (syn: Solidago rigida)	goldenrod[15]	yes[15,21]	yes[15,20]	yes[18]	yes[20]	Cultivar used in study	10
Penstemon digitalis	beardtoungue[15]	part[21]	yes[15,20,22,23]	yes[15]	yes[20,22,23]		10
Penstemon hirsutus	hairy beardtounge[21]	yes[21]	no	no	no		1,10
Perovskia atriplicifolia	Russian sage[15,21]	no[15]	no	no	yes[20]		10
Petrorhagia saxifraga	saxifrage pink[21]	no[21]	no	no	no	Cultivar used in study	10
Phemeranthus calycinus (syn:Talinum calycinum)	fameflower[15]	no[15,21]	no	no	no	Synonym: Talinum calycinum	2
Phlox bifida	sand phlox[15]	part[21]	yes[15]	no	no		10
Phlox subulata	moss phlox[15,21]	yes[21]	yes[15]	no	no	Cultivars used in study	10
Potentilla arguta	tall cinquefoil[21]	yes[21]	no	no	no		10
Pulsatilla vulgaris	pasque flower[15]	no[15]	no	no	no		10
Pycnanthemum virginianum	American mountain mint[15]	yes[15,21]	yes[20,23]	no	yes[20,23]		10
Rhus aromatica	fragrant sumac[15,21]	yes[15,21]	yes[15,24]	yes[15,19,21]	no	Cultivars used in study	10
Rosa carolina	Carolina rose[15,21]	yes[15,21]	yes[15]	yes[15]	yes[20]	Thorns	10
Salvia azurea	blue sage[15]	no[15]	yes[15]	no	no	Variety used in study	10

Table 3.2 (cont'd)…

Schizachyrium scoparium	little bluestem[15,21]	yes[15,21]	yes[24]	yes[21]	no		10
Scilla numidica	autumn squill	no	no	no	no		10
Sedum acre	moss stonecrop[15]	no[15,21]	no	no	no	Evergreen[15], rapid cover[11,15]	2,3,8,9,11
Sedum album	white stonecrop[15,21]	no[15,21]	yes[15]	no	no	Evergreen[15,16], Cultivars used in studies	1,2,3,8,9
Sedum ellacombeanum	ellacombe's sedum[16]	no	no	no	no		8,10
Sedum floriferum		no	no	no	no		4,5,6
Sedum hybridum	hybrid stonecrop[21]	no[21]	no	no	no	Cultivars used in studies	10
Sedum kamtschaticum (syn: Phedimus kamtschaticus)	orange stonecrop[15,21]	no[15,21]	yes[15]	no	no	Evergreen[16]	1,2,3,8,9
Sedum middendorfianum (syn: Phedimus middendorffianus)	diffusum stonecrop[7]	no	no	no	no	Evergreen[16], Cultivars used in studies	7,8,9
Sedum pulchellum	widow's cross[15,21]	no[15,21]	no	no	no		8
Sedum reflexum	blue spruce[16]	no[21]	no	no	no	Evergreen[16]	1,2,8,9
Sedum rupestre	stonecrop[15]	no[15]	no	no	no	Evergreen[15], Cultivars used in studies, Rapid cover[15]	10
Sedum sexangulare	tasteless stonecrop[15,21]	no[15,21]	yes[15]	no	no	Evergreen[15],Rapid cover[15]	1,4,5,6
Sedum spurium (syn: Phedimus spurius)	caucasian stonecrop[15,21]	no[15,21]	yes[15]	no	no	Cultivars used in studys	1,2,4,5,6,7,8,9,10,11
Sedum urvillei			no	no	no		2
Sesleria caerulea	blue moor grass[15]	no[15]	no	no	no		10
Sporobolus heterolepis	prairie dropseed[15,21]	yes[15,21]	no	yes[15]	no	Winter interest	1,10
Symphyotrichum ericoides	heath aster[15]	yes[15,21]	yes[15]	no	no	Cultivar used in study	10
Tetraneuris herbacea	eastern fournerved daisy[21]	part[21]	no	no	no		10
Tradescantia ohiensis	Ohio spiderwort[15]	yes[8,15,21]	no	no	yes[20]		8
Tradescantia tharpii	spider lily[15]	no[15,21]	no	no	yes[20]		10
Viola sagittata	arrowleaf violet[21]	yes[21]	yes[24]	no	no		10

Studies: 1(Vandegrift, 2018), 2(Getter et al., 2009), 3(Matlock and Rowe, 2016), 4(Getter and Rowe, 2007), 5(Getter and Rowe, 2008a), 6(Getter and Rowe, 2009), 7(Rowe et al., 2006), 8(Monterusso et al., 2005), 9(Rowe et al., 2012), 10(Hawke, 2015), 11(Clark and Zheng, 2014), 15(Missouri Botanical Garden Plantfinder, 2018), 16(Mackenzie, 2013), 17(Gucker, 2007), 18(Short, 1985), 19(Cornell Lab of Onithology, 2017), 20(Mäder et al., 2016), 21(USDA and NRCS, 2017), 22(Adamson et al., 2014), 23(Adamson et al., 2015), 24(Snyder, 2018).

Table 3.3 Cultural requirements and attributes of suggested plant species for green roofs in the Great Lakes Region

Plants	Cultural Requirements			Attributes					
Species	Sun (full, part, shade)	Hardiness Zone	Minimum Soil Depth	Flower Color[A]	Flowering Period[A D]	Drought Tolerance (high(H), medium(M), low(L))	Growth Habit (mound, upright, ground cover)	Height[A B C]	Spread[A B C]
Agastache foeniculum	full-part[15]	4-8[10]	15cm[10]	lavender[10]	Jun-Sep[10]	H[10]		60-120cm[15]	45-90cm[15]
Allium cernuum	full-part[10,15,16]	4-8[15]	8cm[2]	pink[15]	Aug-Jun[10,15]	H[15,16]	upright[15]	30-45cm[15]	7.5-15cm[15]
Allium senescens	full-part[15]	4-8[15]	10cm[3]	pink/purple[15]	Jul-Aug[15]	H[15]		30-60cm[15]	15-25cm[15]
Amorpha canescens	full[15]	2-9[15]	15cm[10]	purple/blue[15]	Jul-Sep[10,15]	H[15]	upright[15]	60-90cm[15]	60-75cm[15]
Andropogon gerardii	full[10,15]	4-9[10]	10cm[10]	purple[10,15]	Sep-Feb[15]	M[10,15]	upright[21]	120-180cm[15]	60-90cm[15]
Antennaria dioica		3-8[15]	10cm[10]	white[10]	Jun-Jul[10]	H[10]		7.5-25cm[15]	
Aquilegia canadensis	full-part[10,15]	3-8[15]	10cm[10]	pink/red/yellow[10,15]	Mar-Jul[21]	M[10,15]		60-90cm[15]	30-45cm[15]
Armeria maritima	full[15]	4-8[15]	15cm[10]	purple[21],pink-white[15]	Apr-Jun[10,15]	H[10]	mound[15]	7.5-15cm[15]	15-25cm[15]
Artemisia caudate	full[10,15]		10cm[10]	yellow-green[10]	Aug-Sep[10]	H[10]	mound/ ground cover[17]		
Artemisia ludoviciana	full[15]	4-9[15]	20.5cm[10]	yellowish-gray[15]	Aug-Sep[10,15]	H[10,21]		60-90cm[15]	60-90cm[15]
Asclepias tuberosa	full[15]	3-9[15]	20cm[1]	yellow/orange[15]	Jun-Aug[15]	H[15]	upright[21]	30-75cm[15]	30-45cm[15]
Aster alpinus			15cm[10]	white[10]	Jun[10]	M[21]	mound[21]		
Baptisia alba	full-part[15]	5-8[15]	20.5cm[10]	white[10]	Apr-Jun[10],[15]	H[15]		60-120cm[15]	60-75cm[15]
Bouteloua curtipendula	full[10]	4-9[15]	15cm[10]	purple[10]	Jul-Aug[15]	H[10]	upright[15,21]	45-75cm[15]	45-60cm[15]
Buchloe dactyloides	full[15]	4-8[15]	10cm[10]	green[15]	Jun-Aug[15]	M[10]	ground cover[15]	7.5-25cm[15]	15-30[15]
Calamagrostis brachytricha	full[15]	4-9[15]	20.5cm[10]	green,purple[10]	Sep-Nov[15]	H[10]	upright	90-120cm[15]	60-90cm[15]
Calamintha nepeta	full[15]	5-7[15]	15cm[10]	white[10,15]	Jun-Oct[10,15]	M[15]		30-45cm[15]	30-45cm[15]
Campanula rotundifolia	full[10,15]	3-6[15]	15cm[10]	light purple[10]	Jun-Sep[15]	H[10]		30-45cm[15]	15-30cm[15]
Carex flacca	full-part[15]	4-9[15]	8cm[2]	light green[15]	Jun-Jul[15]	M[15]	mound[15]	15-30cm[15]	30-45cm[15]

Table 3.3 (cont'd)…

Ceanothus americanus	full-part[10,15]	4-8[15]	20.5cm[10]	white[10]	May-Jul[15]	H[10,21]	upright[21]	90-120cm[15]	90-150cm[15]
Coreopsis lanceolata	full[10,15,21]	4-9[15]	10cm[1,8,10]	yellow[10,15,23]	May-Jul[15]	M-H[10,15]		30-60cm[15]	30-45cm[15]
Coreopsis verticillata	full[15]	3-9[15]	10cm[10]	golden-yellow[10,15]	Jun-Sep[15]	H[10]		75-90cm[15]	45-60cm[15]
Dalea candida	full[10]	3-8[15]	10cm[10]	white[10]	May-Jul[15]	M[10]	mound[21]	30-60cm[15]	25-45cm[15]
Dalea purpurea	full[10,15]	3-8[15]	10cm[10]	Rose/Purple[10,15]	Jun-Aug[15]	M-H[10,15,21]		30-90cm[15]	30-45cm[15]
Dalea villosa	full[10]		15cm[10]	magenta[10]		H[10]	upright[21]		
Dianthus gratianopolitanus			10cm[10]	magenta-pink[10]	Jun[10]	H[10]			
Festuca amethystina			15cm[10]	tan[10]	Jun[10]	M[10]			
Fragaria virginiana	full-part[10,15]	5-9[15]	15cm[10]	white[10]	Apr-May[15]	M[15]	ground cover[15]	7.5-25cm[15]	30-60cm[15]
Galium verum	full-part[15]	4-8[15]	10cm[10]	yellow[10,15]	Jul-Sep[15]	H[10,15]		30-75cm[15]	60-90cm[15]
Geum triflorum	full[10]		15cm[10]	pink-red[10],purple[21]	May[10]	H[21]	upright[21]		
Helianthus mollis	full[15]	4-9[15]	20.5cm[10]	golden-yellow[10,15]	Jul-Sep[15]	H[10,15]		60-120cm[15]	30-90cm[15]
Heuchera richardsonii	full-part[15]	3-9[15]	20.5cm[10]	green[10]	Jun-Jul[15]	M[10,15]	mound[15]	30-60cm[15]	30-45cm[15]
Hieracium spilophaeum			10cm[10]	yellow[10]	Jun-Sep[10]	H[10]			
Hosta lancifolia	part-shade[15]	3-8[15]	15cm[10]	light purple[10,15]	Jul-Oct[10,15]	M[15]	mound[15]	25-30cm[15]	30-45cm[15]
Hylotelephium 'Rosy Glow'			10cm[10]	purple[10]	Sep[10]	H[10]			
Koeleria glauca	full[15]	5-9[15]	15cm[10]	tan[10]	May-Jun[15]	H[10,15]	upright[15]	15-60cm[15]	15-30cm[15]
Koeleria macrantha	full[10,15]	3-9[15]	10cm[10]	light green[10,15]	May-Jul[10,15]	H[10,15,21]	upright[21]	30-60cm[15]	25-45cm[15]
Lespedeza capitata	full[10,15]	4-8[15]	10cm[10]	white[10,21]	Jul-Sep[15]	H[10,15,21]	upright[21]	60-120cm[15]	30-60cm[15]
Liatris cylindracea	full[10,15]	4-7[15]	15cm[10]	mauve[10]	Jul-Sep[15]	H[10]		45-60cm[15]	15-30cm[15]
Liatris ligulistylis	full[10,15]	3-8[15]	20.5cm[10]	light purple[10,15]	Jul-Sep[15]	H[10]		30-90cm[15]	15-60cm[15]
Monarda fistulosa	full-part[15]	3-9[15]	15cm[10]	pink/lavender[10,15]	Jul-Sep[15]	M[10,15]	upright[21]	60-120cm[15]	60-90cm[15]
Monarda punctata	full-part[15]	3-8[21]	10cm[3]	Yellow with pink bracts[15]	Jun-Jul[15]		upright[21]	45-60cm[15]	25-30cm[15]
Nepeta racemosa	full-part[15]	4-8[15]	20.5cm[10]	lavender-blue[10,15]	May-Oct[10,15]	H[10,15]	mound[15]	25-30cm[15]	30-45cm[15]
Oligoneuron album	full[10]		20.5cm[10]	white[10]	Jun-Sep[10]	H[10]			
Oligoneuron rigidum (syn: Solidago rigida)	full[15]	3-9[15]	20.5cm[10]	yellow[10,15,21]	Aug-Sep[15]	H[10,21]	upright[21]	90-150cm[15]	45-75cm[15]
Penstemon digitalis	full[10,15]	3-8[15]	15cm[10]	white[10,15,22]	Apr-Jun[15]	H[15,21]	upright[15,21]	90-150cm[15]	45-60cm[15]
Penstemon hirsutus			10cm[1]	light purple[10]	Jun[10]	H[10]			

Table 3.3 (cont'd)…

Perovskia atriplicifolia	full[15]	5-9[15]	20.5cm[10]	lavender[10,15]	Jul-Oct[15]			90-150cm[15]	60-122cm[15]
Petrorhagia saxifraga			10cm[10]	pink[10]	Jun[10]	M[10]			
Phemeranthus calycinus (syn:Talinum calycinum)	full[2,15,16]	5-9[16]	8cm[2]	pink[15,16]	Jul-Sep[16]	H[16]		15-25cm[15]	25-30cm[15]
Phlox bifida	full[10]	4-8[15]	20.5cm[10]	light blue[10,15]	May[15]	H[10,15]		7.5-15cm[15]	15-30cm[15]
Phlox subulata	full[15]	3-9[15]	15cm[10]	purple to pink[15]	Mar-May[15]	H[10]	mound[15]	7.5-15cm[15]	30-60cm[15]
Potentilla arguta	full[10]		20.5cm[10]	white[10]	Jul[10]	H[10]	upright[21]		
Pulsatilla vulgaris	full-part[15]	4-8[15]	15cm[10]	purple[10,15]	Apr-May[15]	H[10]		25-30cm[15]	25-30cm[15]
Pycnanthemum virginianum	full[10,15]	3-7[15]	20.5cm[10]	white[10,15,23]	Jul-Sep[15]	H[10]		60-90cm[15]	30-45cm[15]
Rhus aromatica	full-part[15]	3-9[15]	20.5cm[10]	yellow[10,15]	Apr-Jun[10,15]	H[10]	mound[21]	60-180cm[15]	180-300cm[15]
Rosa carolina	full[15]	4-9[15]	20.5cm[10]	light pink[10,15]	May-Jun[10,15]	H[10,15]	upright[21]	90-180cm[15]	150-300cm[15]
Salvia azurea	full[10,15]	5-9[15]	15cm[10]	blue[10,15]	Jul-Oct[15]	H[10]		90-150cm[15]	60-120cm[15]
Schizachyrium scoparium	full[15]	3-9[15]	20.5cm[10]	purple-red[10]	Aug-Feb[15]	H[10,21]	upright[21]	60-120cm[15]	45-60cm[15]
Scilla numidica			15cm[10]	light purple[10]	Sep-Oct[10]	H[10]			
Sedum acre	full-shade[2]	4-9[15]	2.5cm[9]	yellow[15]	Jun-Jul[15]	H[15]	ground cover[15]	0-7.5cm[15]	
Sedum album	full[2,15,16]	3-8[15]	2.5cm[9]	white[15.16]	Jun-Aug[15]	H[15,16]	ground cover[15,16]	7.5-15cmcm[15]	30-45cm[15]
Sedum ellacombeanum		3[16]	10cm[8]	yellow[10,16]	May-Jul[10,16]	H[10,16]	ground cover[16]	25cm[10]	
Sedum floriferum			7cm[4,5,6]						
Sedum hybridum			15cm[10]	yellow[10]	Jun[10]	H[10]			
Sedum kamtschaticum (syn: Phedimus kamtschaticus)	full-shade[2,15,16]	3-8[15]	4.5cm[1]	yellow[15,16]	Jun-Sep[15,16]	H[15]	ground cover/ mound[15]	7.5-15cm[15]	30-45cm[15]
Sedum middendorfianum (syn: Phedimus middendorffianus)	full-part[16]	3[16]	5cm[9]	yellow[16]	Jun-Jul[16]	H[16]	ground cover[16]		
Sedum pulchellum	full[15]	6-9[15]	10cm[8]	pink[15]	May-Jun[15]	H[15]	ground cover[15]	15-30cm[15]	15-30cm[15]
Sedum reflexum	full-part[16]	3[16]	2.5cm[9]	yellow[16]	Jun-Jul[16]		ground cover[16]		

Table 3.3 (cont'd)…

Sedum rupestre	full[15]	5-8[15]	10cm[10]	yellow[10,15]	Jun-Aug[15]	H[10,15]		7.5-15cm[15]	30-60cm[15]
Sedum sexangulare	full[15]	3-9[15]	4.5cm[1]	yellow[15]	Jun-Aug[15]	H[15]	ground cover[15]	15-30cm[15]	30-60cm[15]
Sedum spurium (syn: Phedimus spurius)	full[15]	4-9[15]	2.5cm[11]	pink-white[10,15]	Jun-Jul[15,16]	H[10,15]	ground cover[15]	7.5-15cm[15]	45-60cm[15]
Sedum urvillei			8cm[2]						
Sesleria caerulea	full-part[15]	5-8[15]	15cm[10]	green[10,15]	Mar-Aug[10,15]	H[10]		15-30cm[15]	25-30cm[15]
Sporobolus heterolepis	full[10,15]	3-9[15]	15cm[10]	green, purple[10]	Aug-Oct[15]	H[10]	upright[15]	60-90cm[15]	60-90cm[15]
Symphyotrichum ericoides	full[15]	3-10[15]	10cm[10]	white[10,15]	Aug-Oct[15]	H[10]		30-90cm[15]	30-45cm[15]
Tetraneuris herbacea			20.5cm[10]	yellow[10]	May-Jun[10]	H[10]			
Tradescantia ohiensis	full-part[15]	4-9[15]	10cm[8]	deep rose-blue[15]	May-Jun[15]	H[15]		60-90cm[15]	45-75cm[15]
Tradescantia tharpii	part-shade[15]	4-9[15]	15cm[10]	rosy purple[10,15]	May-Jul[15]	H[10]		15-30cm[15]	15-30cm[15]
Viola sagittata			10cm[10]	purple[10]	Apr-Jun[10]	M[10]			

Letter key: [Z]Individual species may have several varieties and cultivars that differ slightly. [Y]Numbers rounded. [X]Height and spread are for ground conditions. Plants grown on roof may not reach the height or spread specified. [W]Flower period may be some or all listed months.
Studies: 1(Vandegrift, 2018), 2(Getter et al., 2009), 3(Matlock and Rowe, 2016), 4(Getter and Rowe, 2007), 5(Getter and Rowe, 2008a), 6(Getter and Rowe, 2009), 7(Rowe et al., 2006), 8(Monterusso et al., 2005), 9(Rowe et al., 2012), 10(Hawke, 2015), 11(Clark and Zheng, 2014), 15(Missouri Botanical Garden Plantfinder, 2018), 16(Mackenzie, 2013), 17(Gucker, 2007), 18(Short, 1985), 19(Cornell Lab of Onithology, 2017), 20(Mäder et al., 2016), 21(USDA and NRCS, 2017), 22(Adamson et al., 2014), 23(Adamson et al., 2015), 24(Snyder, 2018).

Description of the green roof plant community reference guide

Previous compilations of green roof plant information for North America were published as an extension bulletin (Getter and Rowe, 2008b) and as a comprehensive review article (Dvorak and Volder, 2010). These reviews focused on studies conducted in the United States and Canada and discussed pertinent literature that was available at the time. Due to the growth of the green roof industry, especially in Chicago and Toronto, and the increase in individual research projects, we can focus our scope to a smaller geographic area. Having a more specific location allows us to create a more specific plant guide. To date, there is no source that compiles the green roof research in the Great Lakes Region. The goal of this review and analysis was to compile a resource guide including all species that have been proven successful on at least one green roof in this geographic region. Success is defined as surviving for several years after the establishment of the green roof (typically the first 2 years).

The green roof plant community reference guide (Tables 3.2 and 3.3) is organized into columns listing common traits that could be useful when selecting plants species. The left column contains the 80 species found suitable for various green roof applications. The remaining columns provide information regarding native status; component to butterfly habitat, bird habitat, and bee habitat; sun preference; hardiness zone; minimum soil depth; flower color; flowering months; drought tolerance; growth habit; and plant height and spread. This information should serve valuable to landscape architects and green roof practitioners as they select plants for their projects. Additionally, this reference guide can be used by do-it-yourself home or business projects in the Great Lakes region and in areas with a similar climate around the world.

Comparison of plant types

The green roof plant community reference guide is composed of herbaceous perennials (65%), succulents (17.5%), and grasses (12.5%). Additionally, there are three woody shrubs, *Ceanothus americanus, Rhus aromatica,* and *Rosa carolina*, and one sedge, *Carex flacca*. Apart from *Hosta*, all species prefer partial or full sun and possess some degree of drought tolerance (Table 3). Drought tolerance is crucial on roofs that are not irrigated. An unirrigated roof in Michigan experienced a loss of half of the species on the roof after a particularly dry summer (Vandegrift, 2018).

A majority of the plants on the reference guide, 52 species, are herbaceous perennials. Ten of the species are grasses. Many of these are North American prairie species that are adapted to environmental conditions similar to what may be found on Midwestern green roofs. These include; frequent cold periods, occasional drought, and limited precipitation (Sutton et al., 2012). Prairie species are often associated with deep root systems that penetrate deep into the soil, a situation seldom found on green roofs. Reeder et al. (2000) reported that prairie plants were able to grow in a variety of soil depths. Suggesting that a deeply rooting prairie species may perform well on a relatively shallow depth green roof. However, that was not found to be the case unless irrigation was provided during drought periods

Fourteen of the species are succulents, a widely used plant group on green roofs. Succulent plants are advantageous for a few reasons. They often exhibit CAM photosynthesis which makes them more water efficient. They are able to store substantial amounts of water in their leaves, stems, and root structures (Dunnett and Kingsbury, 2008). Furthermore, succulents do not rely on deep roots to access water, instead they have shallow roots and store water when it infrequently comes.

It is interesting to note that 39 of the 80 species included in the reference guide are native to the Great Lakes region (Table 2). This could be indicative of the fact that green roofs do not represent native environments. Engineered shallow soils and extreme environmental conditions are conditions unique to city rooftops.

Performance of plant species

The success of individual species depended on a few major factors including plant metabolic photosynthetic processes, substrate depth, and substrate moisture. They are all related as substrate moisture is dependent on depth, sun exposure, and whether supplemental irrigation was provided.

Classification of plant types based on photosynthetic pathway. Photosynthesis is the process where plants convert carbon dioxide into glucose. However, there are three different biochemical pathways in which plants achieve this result: C3, C4, and Crassulacean Acid Metabolism (CAM) photosynthesis (Taiz and Zeiger, 1991). Most plant species exhibit C3 photosynthesis. C3 plants are what is normally found in Michigan and around the Great Lakes as C3 plants thrive under cool and moist conditions found in temperate climates. However, these plants suffer under hot and dry conditions with intense sunlight because they exhibit poor water use efficiency and may undergo photorespiration. C4 plants have a competitive advantage over C3 plants under conditions with high light, high temperatures, or limited water because they do not undergo photorespiration and they use water more efficiently.

Plants that exhibit CAM are physiologically and morphologically adapted to withstand harsh environmental conditions such as drought and thus are ideally suited for shallow extensive green roofs. The CAM photosynthetic pathway enables these plants to adapt to water-stress conditions (Ting, 1985; Sayed, 2001). Because stomata are closed during the day, plant gas exchange occurs at night, thus reducing transpirational water loss. Additionally, CAM plants typically have features such as sunken stomata and thick cuticles and leaves, resulting in high tolerance to drought (Hsiao and Acevedo, 1974).

Substrate depth. Substrate depth has a strong influence on what plants species will survive and perform well on a green roof because deeper substrates can retain more water. Shallow depths also limit rooting depth and are less likely to serve as a buffer against fluctuating temperatures for overwintering survival. Drought can be very stressful and possibly lethal to plants, depending on initial plant selection. If herbaceous perennials and grasses are specified, then deeper substrates or irrigation must be an option during periods of drought.

The species presented here survived in relatively shallow depths (Table 3), but surviving does not equate to thriving. Most of the species tested would likely perform better in a deeper substrate. This was evident on the Molecular Plant Sciences Building at MSU where over 50% of the originally planted species died by the end of seven years (Vandegrift, 2018). Mortality was higher at 10 cm than at 20 cm. By the end of the study, 76% of the species originally planted in the 10 cm zone were absent, while 59% were absent in the 20 cm zone. This roof was not irrigated. Similarly, Hawke (2015) found that most of the species tested at the Chicago Botanic Garden grew more vigorously in the deeper substrate. The success of the few species that performed better in a shallower depth was attributed to plot placement (exposure, rain funneling). Sedum is one exception, where deeper substrates may increase water holding capacity, resulting in root rot. A few species of sedum have been proven to grow in as little as 2.5 cm (Rowe et al., 2012; Clark and Zheng, 2014). However, Table 3 demonstrates that most sedum perform best in 7-10 cm, agreeing with Dvorak et al.'s review (2010). Average minimum depth for all species in the reference guide is ~13 cm.

Numerous studies have concluded that deeper substrate equates to better plant performance (Monterusso et al., 2005; Rowe et al., 2006, 2012; Dunnett et al., 2008; Benvenuti and Bacci, 2010; Lundholm et al., 2010; Thuring and Dunnett, 2014; Heim and Lundholm, 2014; Brown and Lundholm, 2015; Mechelen et al., 2015; Gabrych et al., 2016). Dunnett et al. (2008) reported greater plant survival, diversity, and flowering performance at a depth of 20 cm compared to 10 cm. Species richness also decreased over the six-year study period at both substrate depths, but the rate of decline was greater at 10 cm. Even so, some species performed better in the shallower substrate as the low-growing succulent species were not as competitive at 20 cm. Likewise, the taller perennial plants that possessed greater biomass could not survive as well at 10 cm, but could easily outcompete sedum at 20 cm. Similarly, Gabrych et al. (2016) recorded vegetation on 51 green roofs in Helsinki and found that substrate depth and roof age were predominant in structuring plant communities on green roofs. Shallow substrates maintained sedum and moss species, whereas deeper substrates supported meadow plants.

Despite the cultural limitations of shallow substrate depths, it is often desirable to have shallow depths as buildings must be structurally strong enough to support the added weight of a green roof. If weight is a concern, then options include structurally modifying the roof to increase load capacity or decreasing the bulk density of the substrate. Structural modification is an obvious economic barrier to green roof implementation; thus, it is logical to pursue alternative substrate options.

Combinations of plants

An additional consideration is how plants interact with each other. A study by Lundholm et al. (2010) considered plant life-form and how combinations of plants effected green roof benefits. Test areas containing three to five life-forms cooled the roof and captured water more to a greater degree than those containing just one. Of particular significance was the succulent-grass-tall forb combination. This maximized the most green roof benefits. Flowering time and plant size can be affected by the combination of plants used (Table 2)(Heim and Lundholm, 2016).

Another factor influencing the community of plants on a green roof is the building type. Brown and Lundholm (2015) planted identical species on 2 sections of roof, one directly on the roof and the other with an air gap beneath it. After five years, all species were present on both roofs. However, when the two roofs were compared, the percent species composition were very different. The roof with no air gap contained less succulents and more native and grass species. Thus, the temperature under the roof influences the plant community present.

If the diversity of plant species is important, irrigation should be provided (MacIvor et al., 2013). This is demonstrated in the studies used to compile this reference guide. After establishment, the green roof at the Chicago Botanic Garden was watered once per year during a dry spell during the summer (Hawke, 2015). Eighty-six percent of the species originally planted survived until the end of the trial. However, on the Molecular Plant Sciences roof at MSU the plants were watered during establishment, but irrigation ceased for the remaining years of the study. The roof lost over 50% of the original species planted, likely due to a drought period during the sixth season that saw a large loss of plant life. In addition to irrigation, introduced species should be welcomed if diversity is a goal. Madre et al.'s 2014 study on 115 green roofs found 176 introduced species.

Although succulents may not compete well with taller plants, they can help neighboring plants during stressful periods. Butler and Orians (2011) combined *Sedum album* with herbaceous perennials, observing soil temperature and moisture. The sedum increased the performance of the herbaceous perennials during drought periods in the summer.

Plant selection to provide desired benefits

Green roofs provide many services and benefits. Stormwater management and energy conservation are two of the major benefits. Plant selection is an integral part of the ability of a green roof to provide habitat for wildlife, so it is also given special attention here.

Stormwater management. The success of a green roof in terms of stormwater management is a function of how well a roof retains stormwater. This includes water that is held in the substrate, transpired through the plants, and evaporated from the substrate surface. Many plant related and environmental factors influence water balance. While we cannot control those factors, we can control plant selection, irrigation practices, substrate composition and depth.

In addition to substrate depth, numerous studies have shown that vegetation type can influence stormwater retention. Plants intercept rainwater with foliage which may evaporate before reaching the substrate surface. Additionally, water is removed from the roof through transpiration. A study in England compared grasses, forbs, and sedum, and reported that the grasses were most effective in reducing stormwater runoff followed by the forbs (Nagase and Dunnett, 2012). It was also shown that the size and structure of plants significantly influenced the amount of water runoff. Plant species with larger height, diameter, shoot and root biomass were more effective in reducing water runoff than plant species with smaller height, diameter, shoot and root biomass.

With the current desire to specify more herbaceous perennials and grasses (mostly C3 and C4 plants) for green roofs, there is potential to increase transpiration on rooftops. However, there must be enough substrate moisture for these plants to survive. High transpiration rates are dependent on available moisture and if moisture is not available, these species will be stressed or die. Providing deeper growing substrates or supplemental irrigation could maintain substrate moisture so that high transpiration rates would not be a problem. Overall, a balance must be found between providing enough water to maintain plant health while allowing the substrate to dry out enough to provide stormwater storage capability for the next rain event. As green roof practitioners, the choices we make in these areas will go a long way in determining how well a green roof performs.

Energy conservation. Green roofs can influence the thermal properties of a green roof in three ways: the substrate acts as an additional insulation layer; the plant canopy shades the roof surface; and evapotranspiration cooling (Eksi et al., 2017). In theory, plant species with greater biomass, wider plant canopy for shading, and higher transpiration rates should provide a greater cooling effect. This assumption has been found to be true in some cases, but not all. Eksi et al. (2017) found that a mixture of sedum (depth = 5 cm) resulted in less heat flux into the building during the summer when compared to a roof containing herbaceous perennials and grasses (depth = 20 cm). The deeper substrate acted as a heat sink and continued radiating heat into the building during the night. Even so, the maximum and minimum temperatures, fluctuations in temperature, and heat flux tended to be more stable under the herbaceous roof. It is difficult to determine whether plant species or substrate depth is the more important factor.

Wildlife habitat. Green roofs have been proven to provide habitat for birds, bees, butterflies, invertebrate insects, and other wildlife (Table 2). A study involving 12 green roofs in Michigan and Illinois identified 26 native bird species that visited the roofs, including songbirds and waterfowl (Eakin et al., 2015). The study at the Chicago Botanic Garden (Hawke, 2015) observed nesting *Charadrius vociferous* (killdeer), and visiting *Anas platyrhynchos* (mallard ducks), *Zenaida macroura* (mourning doves), *Turdus migratorius* (American robin), and hummingbirds. Another study conducted on Chicago green roofs demonstrated the value of green roofs for bees (Tonietto et al., 2011). They concluded that an increase in plant diversity resulted in an increase of bee diversity. Green roofs also provide habitat for spiders, true bugs, beetles, and hymenopterans (Madre et al., 2013). Benvenuti (2014) conducted research on green roof platforms at ground level and recorded visits from bees, moths and butterflies.

All of the above studies, except the last, found a greater diversity of the study group on the ground level surrounding the study sites than on the green roofs. Confounding factors include roof height, size, vegetation, and whether the roof is connected to the ground. One must consider the landscape surrounding the green roof. The surrounding landscape has a large influence on what wildlife visits green roofs (Eakin et al., 2015).

Native status and attractiveness to butterflies, birds, and bees seem to be correlated. Most species listed as native have also been noted as attracting birds, bees, or butterflies. Exceptions include *Artemisia ludoviciana, Bouteloua curtipendula, Koeleria macrantha, Penstemon hirsutus, Potentilla arguta*, all of which are native but have yet to be recorded as especially attractive to butterflies, birds, or bees. Granted, these are not the only benefits of these species, just those most noted in the literature.

Conclusion

This manuscript provides a comprehensive reference guide of tested plant species for green roofs in the Great Lakes Region of North America that may be beneficial to green roof practitioners locally and in other parts of the world with a similar climate. We challenge and encourage others to repeat this review and analysis in other parts of the world. This reference guide could be further developed into a plant selection guide.

As with any recommended plants, the reference guide is a work in progress and as further studies are conducted, additional species may prove to be suitable. It should be noted that a specific plant species found to be suitable on one roof may not perform as well on another. As with any environment, local conditions vary. Unique factors such as, wind, irrigation, and slope will alter how a plant performs

BIBLIOGRAPHY

BIBLIOGRAPHY

Adamson, N., B. Borders, J. Cruz, S. Jordan, K. Gill, J. Hopwood, E. Mäder, A. Minnerath, and M. Vaughan. 2014. Pollinator Plants: Midwest Region. 29 March 2017 <www.bringbackthepollinators.org>

Adamson, N., B. Borders, J. Cruz, S. Jordan, K. Gill, J. Hopwood, E. Mäder, A. Minnerath, and M. Vaughan. 2015. Pollinator Plants: Great Lakes Region. 29 March 2017 <http://www.xerces.org/wp-content/uploads/2014/03/GreatLakesPlantList_web.pdf>

Arnfield, A. J. 2009. Koppen climate classification. Encyclopaedia Britannica. 6 April 2018 <https://www.britannica.com/science/Koppen-climate-classification>

Benvenuti, S. 2014. Wildflower green roofs for urban landscaping, ecological sustainability and biodiversity. Landscape and Urban Planning. Elsevier B.V. 124151–161. doi: 10.1016/j.landurbplan.2014.01.004.

Benvenuti, S. and D. Bacci. 2010. Initial agronomic performances of Mediterranean xerophytes in simulated dry green roofs. Urban Ecosystems 13(3):349–363. doi: 10.1007/s11252-010-0124-9.

Berndtsson, J. C. 2010. Green roof performance towards management of runoff water quantity and quality: A review. Ecological Engineering 36(4):351–360. doi: 10.1016/j.ecoleng.2009.12.014.

Brenneisen, S. 2004. Green Roofs - How Nature Returns to the City. Acta Horticulturae 643(643):289–293. doi: 10.17660/ActaHortic.2004.643.37.

Brown, C. and J. Lundholm. 2015. Microclimate and substrate depth influence green roof plant community dynamics. Landscape and Urban Planning. 143:134–142. doi: 10.1016/j.landurbplan.2015.07.009.

Butler, C. and C. M. Orians. 2011. Sedum cools soil and can improve neighboring plant performance during water deficit on a green roof. Ecological Engineering. 37(11):1796–1803. doi: 10.1016/j.ecoleng.2011.06.025.

Castleton, H.F. et al., 2010. Green roofs; Building energy savings and the potential for retrofit. Energy and Buildings, 42(10), pp.1582–1591. doi: 10.1016/j.enbuild.2010.05.004.

Clark, M. J. and Y. Zheng. 2014. Fertilizer rate influences production scheduling of sedum-vegetated green roof mats. Ecological Engineering. 71:644–650. doi: 10.1016/j.ecoleng.2014.08.006.

Coffman, R. R. 2007. Comparing Wildlife Habitat and Biodiversity Across Green Roof Type. in Fifth Annual Greening Rooftops for Sustainable Communities Conference 1–17.

Cornell Lab of Onithology. 2017. All About Birds: Bird Guide. <https://www.allaboutbirds.org/guide/>

Dunnett, N. and N. Kingsbury. 2008. Planting Green Roofs and Living Walls. 2nd edn. Timber Press. Portland, OR.

Dunnett, N., A. Nagase, and A. Hallam. 2008. The dynamics of planted and colonising species on a green roof over six growing seasons 2001-2006: Influence of substrate depth. Urban Ecosystems 11(4):373–384. doi: 10.1007/s11252-007-0042-7.

Dvorak, B. and A. Volder. 2010. Green roof vegetation for North American ecoregions: A literature review. Landscape and Urban Planning 96(4):197–213. doi: 10.1016/j.landurbplan.2010.04.009.

Eakin, C. J., H. Campa, D. W. Linden, G. J. Roloff, D. Bradley Rowe, and J. Westphal. 2015. Avian response to green roofs in urban landscapes in the Midwestern USA. Wildlife Society Bulletin 39(3):574–582. doi: 10.1002/wsb.566.

Eksi, M., D. B. Rowe, I. S. Wichman, and J. A. Andresen. 2017. Effect of substrate depth, vegetation type, and season on green roof thermal properties. Energy and Buildings 145(1):174–187. doi: 10.1016/j.enbuild.2017.04.017.

Fish and WIldlife Service. 1985. Habitat Suitability Index Models: Red-winged blackbird. 23 March 2017 <https://www.nwrc.usgs.gov/wdb/pub/hsi/hsi-095.pdf>

Gabrych, M., D. J. Kotze, and S. Lehvävirta. 2016. Substrate depth and roof age strongly affect plant abundances on sedum-moss and meadow green roofs in Helsinki, Finland. Ecological Engineering. 86:95–104. doi: 10.1016/j.ecoleng.2015.10.022.

Getter, K. L. and D. B. Rowe. 2007. Effect of Substrate Depth and Planting Season on Sedum Plug Survival on Green Roofs. Journal of Environmental Horticultural 25:95–99.

Getter, K. L. and D. B. Rowe. 2008a. Media depth influences Sedum green roof establishment. Urban Ecosystems 11(4):361–372. doi: 10.1007/s11252-008-0052-0.

Getter, K. L. and D. B. Rowe. 2008b. Selecting Plants for Extensive Green Roofs in the United States. Extension Bulletin E-3047, Michigan State University 1–9. <http://www.hrt.msu.edu/greenroof/PDF/08 GetterRoweExtensionBulletin.pdf%5Cr>

Getter, K. L. and D. B. Rowe. 2009. Substrate depth influences sedum plant community on a green roof. HortScience 44(2):401–407.

Getter, K. L., D. B. Rowe, J. A. Andresen, and I. S. Wichman. 2011. Seasonal heat flux properties of an extensive green roof in a Midwestern U.S. climate. Energy and Buildings 43(12):3548–3557. doi: 10.1016/j.enbuild.2011.09.018.

Getter, K. L., D. B. Rowe, and B. M. Cregg. 2009. Solar radiation intensity influences extensive green roof plant communities. Urban Forestry and Urban Greening 8(4):269–281. doi: 10.1016/j.ufug.2009.06.005.

Gucker, C. L. 2007. Artemisia campestris. Fire Effects Information System. 20 April 2017 <https://www.fs.fed.us/database/feis/plants/forb/artcam/all.html>

Hawke, R. 2015. An evaluation study of plants for use on green roofs. Plant Evaluation Notes 38(1):1–22.

Heim, A. and J. Lundholm. 2014. The effects of substrate depth heterogeneity on plant species coexistence on an extensive green roof. Ecological Engineering. (68)184–188. doi: 10.1016/j.ecoleng.2014.03.023.

Heim, A. and J. Lundholm. 2016. Phenological complementarity in plant growth and reproduction in a green roof ecosystem. Ecological Engineering. (94)82–87. doi: 10.1016/j.ecoleng.2016.05.018.

Hsiao C., T. and E. Acevedo. 1974. Plant response to water deficits, water-use efficiency, and drought resistance. Agricultural Meteorology (14)59–84.

Kaplan, R. 1993. The role of nature in the context of the workplace. Landscape and Urban Planning 26(1–4):193–201. doi: 10.1016/0169-2046(93)90016-7.

Liu, K. and B. Baskaran. 2003. Thermal Performance of Green Roofs Through Field Evaluation. in Proceedings of 1st North American Green Roof Conference: Greening Rooftops for Sustainable Communities. Chicago, IL. 29-30 May, 2003. The Cardinal Group. Toronto, Ontario.

Loder, A. 2014. 'There's a meadow outside my workplace': A phenomenological exploration of aesthetics and green roofs in Chicago and Toronto. Landscape and Urban Planning 126(1):94–106. doi: 10.1016/j.landurbplan.2014.01.008.

Lundholm, J., J. S. MacIvor, Z. MacDougall, and M. Ranalli. 2010. Plant Species and Functional Group Combinations Affect Green Roof Ecosystem Functions. PLoS ONE. Edited by H. H. Bruun 5(3):e9677. doi: 10.1371/journal.pone.0009677.

MacIvor, J. S., L. Margolis, C. L. Puncher, and B. J. Carver Matthews. 2013. Decoupling factors affecting plant diversity and cover on extensive green roofs. Journal of Environmental Management 130(1):297–305. doi: 10.1016/j.jenvman.2013.09.014.

MacKenzie, D. 2013. Liveroof green roof plants and mixes 29–57. <www.liveroof.com>

Mäder, E., J. Fowler, J. Vento, and J. Hopwood. 2016. 100 Plants to Feed the Bees: Provide a Healthy Habitat to help Pollinators Thrive. Storey Publishing.

Madre, F., A. Vergnes, N. Machon, and P. Clergeau. 2013. A comparison of 3 types of green roof as habitats for arthropods. Ecological Engineering. 57(1):109–117. doi: 10.1016/j.ecoleng.2013.04.029.

Matlock, J. M. and D. B. Rowe. 2016. The suitability of crushed porcelain and foamed glass as alternatives to heat-expanded shale in green roof substrates: An assessment of plant growth, substrate moisture, and thermal regulation. Ecological Engineering 94(1111):244–254. doi: 10.1016/j.ecoleng.2016.05.044.

Missouri Botanical Garden Plantfinder 2018. <http://www.missouribotanicalgarden.org/plantfinder/plantfindersearch.aspx>

Monterusso, M. A., D. Bradley Rowe, and C. L. Rugh. 2005. Establishment and persistence of Sedum spp. and native taxa for green roof applications. HortScience 40(2):391–396.

Nagase, A. and N. Dunnett. 2012. Amount of water runoff from different vegetation types on extensive green roofs: Effects of plant species, diversity and plant structure. Landscape and Urban Planning 104(3–4):356–363. doi: 10.1016/j.landurbplan.2011.11.001.

Parkins, K. L. and J. A. Clark. 2015. Green roofs provide habitat for urban bats. Global Ecology and Conservation 4(1):349–357. doi: 10.1016/j.gecco.2015.07.011.

Peck, S. and M. Kuhn. 2003. Design guidelines for green roofs. Ontario Association of Architects.

Reeder, J. D., C. D. Franks, and D. G. Milchunas. 2000. 'Root Biomass and Microbial Processes' In, The Potential of U.S. Grazing Lands to Sequester Carbon and Mitigate the Greenhouse Effect. 31 March 2018. <http://eco.ibcas.ac.cn/group/baiyf/pdf/gxzy/9_The_Potential_of_U.S._Grazing_Lands_to_Sequester_Carbon_and_Mitigate_the_Greenhouse_Effect.pdf>

Rowe, D. B. 2011. Green roofs as a means of pollution abatement. Environmental Pollution 159(8–9):2100–2110. doi: 10.1016/j.envpol.2010.10.029.

Rowe, D. B., K. L. Getter, and A. K. Durhman. 2012. Effect of green roof media depth on Crassulacean plant succession over seven years. Landscape and Urban Planning 104(3–4):310–319. doi: 10.1016/j.landurbplan.2011.11.010.

Rowe, D. B., M. A. Monterusso, and C. L. Rugh. 2006. Assessment of heat-expanded slate and fertility requirements in green roof substrates. HortTechnology 16(3):471–477.

Sayed, O. H. 2001. Crassulacean acid metabolism 1975-2000, a checklist. Photosynthetica 39(3):339–359.

Short, H. L. 1985. Habitat Suitability index models: Red-winged Blackbird.

Snyder, B. 2018. Wildtype Native Plant Nursery: Butterfly Plants. 20 December 2016. <http://www.wildtypeplants.com/butterfly.pdf.>

Stand, B. & Peck, S.W., 2017. 2016 Annual Green Roof Industry Survey Executive Summary. March 14, 2018. <https://static1.squarespace.com/static/58e3eecf2994ca997dd56381/t/5967869229687ff1cfbb6ada/1499956889472/GreenRoofIndustrySurvey2016ExecutiveSummary.pdf>

Sutton, R. K., J. A. Harrington, L. Skabelund, P. MacDonagh, R. R. Coffman, and G. Koch. 2012. Prairie-based green roofs: Literature, templates, and analogs. Journal of Green Building 7(1):143–172. doi: 10.3992/jgb.7.1.143.

Taiz, L. and E. Zeiger. 1991. Plant Physiology. Redwood City, CA: Benjamin/Cummings Publishing.

Thuring, C. E. and N. Dunnett. 2014. Vegetation composition of old extensive green roofs (from 1980s Germany). Ecological Processes. 3(1):4. doi: 10.1186/2192-1709-3-4.

Ting, I. P. 1985. Crassulacean Acid Metabolism. Annual Review of Plant Physiology. 36(1):595–622. doi: 10.1146/annurev.pp.36.060185.003115.

Tonietto, R., J. Fant, J. Ascher, K. Ellis, and D. Larkin. 2011. A comparison of bee communities of Chicago green roofs, parks and prairies. Landscape and Urban Planning. 103(1):102–108. doi: 10.1016/J.LANDURBPLAN.2011.07.004.

Ulrich, R. S. 1984. View through a window may influence recovery from surgery. American Association for the Advancement of Science 224(1):420–422.

USDA and NRCS. 2017. The PLANTS Database. Greensboro, NC 27401-4901 USA. 10 August 2016. <http://plants.usda.gov.>

Vandegrift, D. 2018. Performance of succulents, grass, and herbaceous perennials on green roofs. Masters Thesis, Michigan State University.

Van Mechelen, C., T. Dutoit, and M. Hermy. 2015. Adapting green roof irrigation practices for a sustainable future: A review. Sustainable Cities and Society. (19)74–90. doi: 10.1016/J.SCS.2015.07.007.

Van Mechelen, C., T. Dutoit, and M. Hermy. 2015. Vegetation development on different extensive green roof types in a Mediterranean and temperate maritime climate. Ecological Engineering (82)571–582. doi: 10.1016/j.ecoleng.2015.05.011.

Van Renterghem, T. and D. Botteldooren. 2008. Numerical evaluation of sound propagating over green roofs. Journal of Sound and Vibration 317(3–5):781–799. doi: 10.1016/j.jsv.2008.03.025.

Whittinghill, L. J. and D. B. Rowe. 2012. The role of green roof technology in urban agriculture. Renewable Agriculture and Food Systems 27(4):314–322. doi: 10.1017/S174217051100038X.

Whittinghill, L. J., D. B. Rowe, and B. M. Cregg. 2013. Evaluation of Vegetable Production on Extensive Green Roofs. Agroecology and Sustainable Food Systems 37(4):465–484. doi: 10.1080/21683565.2012.756847.

Wilson, E. O. 1984. Biophilia. Cambridge, Mass.