TESTING SUBSTRATES FOR GRANITE OUTCROP PLANT SPECIES VEGETATIVE COVER IN EXTENSIVE VEGETATED ROOF MODULES

by

KELSEY BROOKS

(Under the Direction of Jon Calabria)

ABSTRACT

Currently, non-native sedums dominate vegetated roof landscapes in the Southeastern U.S.; however, interest in native species alternatives is escalating as citizens recognize the benefits native plants offer over non-native species. This research examines the performance of eight granite outcrop plant species in typical extensive vegetated roof conditions, over the course of one growing season, to offer new plant alternatives to conventional roof plantings. Granite outcrop plants are a threatened community occurring in the Georgia Piedmont. Species from this community may be uniquely adaptable to extensive vegetated roof conditions because of similar conditions between vegetated roofs and granite outcrop habitat. Findings suggest granite outcrop plant species may be good alternatives to non-native sedums in extensive vegetated roof plantings in the Georgia Piedmont. Four-inch depth substrate with 10% organic matter produced the most vegetation cover $F(3,396) = 2.89$, $p = .035$, and offers optimal conditions for granite outcrop planted extensive vegetated roofs.

INDEX WORDS: granite outcrop, green infrastructure, landscape architecture, native plants, vegetated roof

TESTING SUBSTRATES FOR GRANITE OUTCROP PLANT SPECIES

VEGETATIVE COVER IN EXTENSIVE VEGETATED ROOF MODULES

by

KELSEY BROOKS

BA, The University of Georgia, 2009

A Thesis Submitted to the Graduate Faculty of The University of Georgia in Partial

Fulfillment of the Requirements for the Degree

MASTER OF LANDSCAPE ARCHITECTURE

ATHENS, GEORGIA

2019

TESTING SUBSTRATES FOR GRANITE OUTCROP PLANT SPECIES

VEGETATIVE COVER IN EXTENSIVE VEGETATED ROOF MODULES

by

KELSEY BROOKS

Major Professor:	Jon Calabria
Committee:	Eric Macdonald
	David Berle
	Heather Alley

Electronic Version Approved:

Suzanne Barbour
Dean of the Graduate School
The University of Georgia
May 2019

DEDICATION

This thesis is dedicated to Clancy, world’s most lovable man.

ACKNOWLEDGEMENTS

Many thanks are owed to the very special people that nurtured this project, especially Professor Jon Calabria, who was always patient and generous with his time and knowledge. Heather Alley at the Mimsie Lanier Center for Native Plant Studies was unbelievably supportive, providing the granite outcrop plants needed for the trial, guidance, the physical space for the experiment and serving on the thesis defense committee. This project surely would never have happened without her. Thank you to Henning von Schmeling at the Chattahoochee Nature Center for donating many granite outcrop plants and for being an inspiring force in plant conservation. Professor David Berle also generously offered his space at the UGArden as a location for the plant trial and to him I am very grateful. The support of the University of Georgia's Office of Sustainability set this whole project in motion. The funding provided through their Campus Sustainability Grant Program covered all the expenses of this research project, and we are so lucky for their generosity and the work they do to advance a culture of sustainability on campus.

My classmates, Jacque Menke and Keely McDonald generously dedicated an entire day to hand-mixing substrates and filling extensive vegetated roof trays. Their brute strength and companionship, along with June's wacky antics, made for one of the most memorable days of graduate school, and I very much appreciate their friendship and support in this project.

Finally, Michael Clancy deserves an award for his role serving as field assistant at each plant monitoring event, substrate-mixing, and every out-of-town errand to haul rocks or sand, or to pick up plant babies. He is a wonderful partner in all of life's adventures, none of which would be nearly as fun without him.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

This thesis examines the performance of a Piedmont-native, vulnerable plant community under typical extensive vegetated roof conditions. Granite outcrop plant species exhibit characteristics that would suggest a unique adaptability to the rooftop environment, an environment characterized by wind, drought, sun, and temperature extremes, and shallow, rocky substrate (Klein and Coffman, 2015). These environmental conditions are remarkably similar to those experienced by plant species growing atop granite outcrops, where plants have evolved with adaptations that allow them to survive under exposure to high light intensity and extreme fluctuations in soil moisture levels (Burbanck and Platt, 1964).

Vegetated Roof History

Vegetated roofs are relatively uncommon in the Southeast, when compared to Europe, which has a much longer history with the practice. They are still evolving in Southeastern North America as regional research on vegetated roofs is just beginning. Their history can be traced back for thousands of years, however, the earliest reported example is the mythical Hanging Gardens of Babylon, one of the seven wonders of the ancient world (Reade, 2000). Historians cite ancient writings and illustrations describing a magnificent, terraced palace built with lush gardens spilling over the building's rooftop edges and draping over the palace facade. King Nebuchadnezzar II of Babylon built the palace around 600 BC to ease the depression of his homesick wife, Amytis. Legend states that she missed deeply the landscape of the Persian mountains she left behind when joining the king at his palace in Babylon. Illustrations depict the rooftop gardens, which were not technically “hanging,” as spilling over with mature shrubs, flowers and trees originally found in Amytis’ Persian homeland (Osmundson, 1999). Interestingly, this early example reinforces one of the major social benefits of vegetated roofs that research today has only recently begun to explore: the scenic nature of vegetated roofs offers psychological benefits in the form of stress reduction, increased life-satisfaction and decreases in the frequency and duration of illness (Kahn, 1997).

Hundreds of years later, green roofs spread throughout Europe and Scandinavia, where homes were insulated with soil coverings, and then planted with grasses and flowers to affix the insulating material (Getter and Rowe, 2006). In North America, settlers moving onto the Great Plains brought vegetated roofs in the late 1800s. Here, timber was scarce, though soil was plentiful. Thus, early green roofs were substituted in place of timber for roof coverings.

Vegetated roof technology as we know it today can be linked back to Germany prior to WWI, when the nation was undergoing a period of rapid industrialization. Highly flammable tar roofs were used atop inexpensive housing projects being built throughout their cities. In order to protect these vulnerable roofs and minimize fire risks, H. Koch developed a method of covering rooftops in gravel and sand (Getter and Rowe, 2006). Wind-dispersed seeds inevitably colonized these new environments, forming unanticipated rooftop meadows. Impressively, many of these early vegetated roofs remain functional to this day (Kohler and Keeley, 2005).

The Great Depression witnessed a decline in the burgeoning vegetated roof industry, which was further hastened by the start of WWII. Although these events temporarily stalled the progress of roof greening, Germany eventually picked up where it left off, and now adds an estimated 86 million square feet of new vegetated roofing per year (Velazquez, 2011). This progress has been supported by federal-level policies established by Germany and the European Union that incentivize green infrastructure and renewable energy projects, particularly in the form of energy tax reform. In contrast, the United States predominantly relies on short-term policy strategies (Buehler et al., 2011). These state and municipal level policies periodically expire, leading to steep declines in small-scale renewable energy projects, market uncertainty, and a resulting reluctance among investors to contribute to large-scale green infrastructure projects. Implementing federal-level policies, like those found in Germany and the rest of Europe, may help build confidence in the U.S. renewable energy sector, which could support more sustained industry-growth, technological advancement and vegetated roof research.

Ecosystem Services

Vegetated roofs are an especially important tool in urban development because they have the potential to simultaneously address multiple objectives. Often, common urban design strategies fall short on efficiency by addressing one problem, even when development is known to cause multiple problems (Snodgrass and Snodgrass, 2006). Detention areas for instance, a strategy mandated by many municipal development codes, often addresses the singular goal of managing peak stormwater runoff from the site. On the other hand, vegetated roofs reduce stormwater runoff by encouraging evaporation, while concurrently addressing additional consequences of development such as the urban heat island effect and habitat loss. Additionally, stormwater absorption by vegetated roofs is shown to increase in tandem with substrate depth, as well as in correlation with the transpiration rate of the plant species that populate it (Nawaz, McDonald and Postoyko, 2015). This provides vegetated roof designers with an opportunity to address multiple, site-specific levels of runoff through adjustments in substrate and plant species specifications (Farrell et al., 2013). Moreover, vegetated roofs potentially offer numerous advantages in the form of social, economic and environmental benefits. Ultimately, the intersectionality of the public and private benefits that vegetated roofs offer to urban development is possibly the strongest case for their increased adoption across North America and the world, and the primary reason why more regionally-specific vegetated roof research is necessary.

Human Health

"Biophilia" is a hypothesis popularized by E.O. Wilson in his 1984 book of the same name. The biophilia hypothesis potentially explains many of the social benefits vegetated roofs may provide to people living in urban areas. In sum, it theorizes that either consciously or unconsciously, human beings have evolved possessing an innate desire for meaningful connections with nature and other life forms (Wilson, 1984). The theory further states that humans require daily contact with nature for maintenance of their psychological wellbeing. There is ample scientific evidence to support this hypothesis. Individuals and groups with direct access to natural areas have been found to be healthier, happier and more satisfied with their lives, homes and careers (Kaplan and Kaplan, 1995). Aesthetically speaking, even something as simple as looking at natural areas through a window has been shown to decrease the rate of illness in prison inmates, increase the pace of healing in hospitalized patients, and increase productivity in workers (Kahn, 1997). Hospitals are increasingly designed to provide this contact with nature through scenic views of vegetated roof plantings, interior courtyards and therapeutic gardens to facilitate a more healing atmosphere (Marcus and Barnes, 1999).

Urbanization, or the gradual population shift from rural to urban areas, has steadily increased throughout history. In North America, roughly 82% of the population currently lives in urban areas, and projections predict an urban population increase of 2.5 billion people worldwide by 2050 (U.N., 2018). As North American cities continue to densify, the biodiversity of urban environments will grow increasingly important in facilitating the important connections between humans and nature and offering an introduction to other life forms for many residents, particularly young people who may spend all their lives in these urban environments. Research shows that exposure to nature in everyday life is a major determinant to the level of sensitivity to environmental issues children feel as they grow up (Sebba, 1991; Rohde and Kendle, 1994). It is said that "Knowledge generates interest, and interest generates concern" (Tallamy, 2007). The ecological concern of future generations depends on the connections they make with nature today. Vegetated roofs provide one useful strategy to facilitate this human-nature relationship and raise awareness of important ecological concerns in our dense urban environment.

There is a growing recognition among scientists and residents surrounding the issue of urban noise pollution (Eriksson, 2017). In the past, urban noise was considered a sometimes annoying, but inescapable and ultimately harmless feature of city-living. Regulations and legislations to control noise from aircraft, car traffic, industrial processes, construction and loud neighbors are routinely discussed across the country. However, the World Health Organization urges communities to take the threat of noise pollution more seriously, as studies routinely conclude that excess noise can lead to elevated anxiety levels and stress responses (Novotney, 2011). Vegetated roofs offer a barrier between the outside city-soundscape and building interior for residents living within these buildings, and quiet city streets by absorbing noise that would otherwise echo off hard surfaces like traditional building roofs and walls. One study demonstrates that thicker substrates can increase the sound insulating properties of vegetated roofs (Connelly and Hodgson, 2015). This research suggests that vegetated roofs have the potential to mitigate the problem of urban noise pollution and alleviate some of the anxieties and stress hormones that result for individuals in communities embracing this infrastructure.

The environmental advantages offered by vegetated roofs are perhaps their most publicized and promoted. As urban areas continue to densify, it becomes increasingly clear that new strategies to re-green cities are necessary to offset some of the damages wrought by large swaths of impervious area. With little opportunity for parks or green space at ground level, where real estate is at a premium and plant and animal habitat has likely already been replaced by roads or buildings, vegetated roofs offer an especially practical and appealing alternative.

In healthy ecosystems, stormwater is filtered and absorbed through the soil. Impervious surfaces, which are ubiquitous in the urban environment, hinder this process. When water flows off these impervious surfaces during rain events they contribute to flash flooding, water pollution and the exhaustion of ground water reserves. The runoff issue appears most acute when one considers that as much as 95% of rainfall is absorbed into the ground in a healthy forest, while urban areas only average roughly 25% stormwater absorption (Scholz-Barth, 2001). Unabsorbed rainfall rushes through streets and parking lots, where it picks up trash and contaminants on the way to streams, rivers and ultimately oceans. Vegetated roofs may alleviate some of the burden of a city's stormwater concerns as they replace the impervious roof surface and building footprint with pervious substrate and plant material. The substrate holds rainwater, which is then absorbed through plant roots or evaporated back into the atmosphere. Vegetated roofs have the potential to recycle between 60 and 100 percent of rainwater, depending on the system type (Denardo et al., 2005). Furthermore, water uptake and transpiration are higher in granite outcrop plant species than the commonly planted vegetated roof sedum, *Sedum pachyphylum* (Wolf and Lundholm, 2008). Granite outcrop plant species also exhibit more plasticity in water absorption than sedums chosen exclusively for their drought tolerance. This means that granite outcrop plants are not only able to withstand long periods of drought, but also absorb more water during rain events, in turn, lessening the urban stormwater burden more efficiently than a conventionally planted vegetated roof (Farrell et al., 2013).

Vegetated Roof Challenges

For all their many benefits, vegetated roofs may pose an equal amount of challenges. Most of these challenges can be alleviated over time, through research at the regional and site-specific level. North American vegetated roofs are relatively young compared to those in Europe. Thus, long-term studies in Southeastern North America have not had sufficient time to thoroughly quantify landscape performance or data on plant mortality (Dvorak and Volder, 2010). Further research on native plant alternatives will increase confidence in regional vegetated roof industries and assist in the initiation and spread of vegetated roofs in our area.

Vegetated Roof Components

Engineered systems are necessary for the proper functioning of vegetated roof systems. Conceptually speaking, vegetated roofs are a rather simple configuration of a building with plants growing in some sort of substrate atop them, however, certain precautions to protect buildings from water and plant roots are necessary to insure long-term vegetated roof success. The failure of any of these precautionary elements may necessitate costly repairs due to the limitations in accessibility that the rooftop environment presents. Therefore, it is of utmost importance to properly plan and engineer vegetated roof systems in advance of installation. While vegetated roofs may be categorized as *extensive* or *intensive* regarding their growing medium and vegetation, both systems share several common, basic components in the form of waterproofing, insulation, filtration and drainage layers, as well as root barriers, planting medium and plant material (Snodgrass et al., 2006). Due to the relatively high maintenance and installation costs of intensive vegetated roofs, extensive roofs make up the most vegetated roof systems in use today and hold the most potential for building retrofits and increased adoption (Dunnett and Kingsbury, 2010). For this reason, as well as the environmental preferences of granite outcrop plant species, this study focuses only on the potential adaptability of these plants to the extensive vegetated roof environment.

An important determinant of plant suitability to extensive vegetated roof growing conditions is the level of maintenance required over time. Extensive vegetated green roofs differ from intensive vegetated roofs, and for that matter, plants growing on the ground, by several factors, most importantly: the depth of growing medium, cost, complexity, and the required maintenance and accessibility. Intensive vegetated roofs are so named due to their relatively intense maintenance and construction needs. They possess a much deeper, more organic substrate and can create and support park-like settings similar to those one would find on the ground (Snodgrass et al., 2006). Intensive roofs are also typically limited to flat roofs as they are meant to be visited by the public.

Extensive green roofs are simpler, less expensive to install and maintain, and allow for limited human access. The growing medium is typically only two to four inches in depth, and it is more sensitive to disturbance from foot traffic than a deeper medium with more extensive root proliferation. With restricted accessibility, extensive green roof planting design must consider the long-term viability of plant communities without considerable human assistance. Findings on pollen limitation on green roofs in Chicago demonstrated that while the overall number of honeybees that visited green roofs was lower than on the ground, those insects that were present provided more pollination services, resulting in higher overall seed set between the two populations (Ksiazek, Fant and Skogen 2012.) This demonstrates that habitats created on vegetated roofs have the potential to function sustainably in the long-term.

The Georgia Piedmont

The Piedmont Plateau sits between the Atlantic Coastal plain to the east and the Appalachian Mountains to the west. It stretches from New Jersey in the North to central Alabama in the South. With approximately 80,000 miles of land, the Piedmont consists of comparatively low, rolling hills composed of many different types and ages of rock formations (Hanley, 2006). The Georgia Piedmont is a remnant of an ancient mountain chain that broke apart with the separation of Pangea some 175 million years ago, and which has since eroded. It extends west to east between the foothills of the Blue Ridge Mountains and the coastal plain.

The rock deposits that characterize the Piedmont are some of the most economically important raw materials for the state. This has contributed to the long history of mining operations in the region. Large granite blocks used for construction are quarried from east Georgia batholiths, which are large masses of rock formed from magma deep within the earth's crust. Crushed granite stone, used mainly for roads, is quarried from areas of western Georgia.

The climate of the Georgia Piedmont, and most of the surrounding states from Oklahoma in the west to Virginia in the east and stretching southward into south-central Florida is characterized as humid subtropical (Godfrey 2012). This climatic zone has hot and humid summers with mild winters. Summer average highs are generally in the mid 90 to lower 90°F, while lows are right around mid to high 70°F. The warm summer temperatures, combined with moist, tropical air, create the notoriously humid and uncomfortable summer weather. Winter highs can reach into the 50°F and lows dip into the 30°F. Maximum precipitation generally falls during winter and spring (December, March and April), in the form of rain, when cold, dry air from Canada clashes with warm, moist air from the Gulf of Mexico. These environmental conditions are a unique hallmark of the Piedmont, but they also impose heavy burdens on non-native plant species, especially in the form of fungus and disease, to which plants adapted to less humid environments are more susceptible (Sutton, 2008).

Granite Outcrops

Southeastern granite outcrops are large expanses of mostly exposed Precambrian metamorphic rock that occur throughout the Piedmont Plateau (McVaugh, 1943). They result when the most resistant granite rocks withstand erosion, while surrounding areas of more easily weathered material is simultaneously covered over by soils. The resulting granite outcrops may appear as domes towering high above the surrounding landscape, such as Stone Mountain, or as exposed flat rocks. Geographically speaking, outcrops may be clustered in groups, or protrude in isolation (Murdy and Carter, 2000). These rock expanses are interspersed with pockets of vegetation that form within the rock's surface, and entire outcrops can vary in size from only a few square feet to hundreds of acres.

The Piedmont region of Georgia is completely underlaid with Precambrian rock (Murdy et al., 2000). While most of the Piedmont's rock layer is topped by variable depths of soil, granite outcrops are exposed areas of this bedrock appearing above the land's surface. They are known as "micro-environmental deserts," due to the harsh environmental conditions and dramatic differences in plant species composition observed between them and the surrounding temperate environments (Shure, 1999). Summer temperatures on rock outcrop surfaces can reach between 122-131° F. The thin soils that accumulate in pockets on the rock's surface dry rapidly during heat and drought, but winter rains can leave these areas saturated for prolonged periods due to the absence of cracks through which rainwater can drain away. Granite outcrops represent an environment of extremes.

Over millennia, shallow depressions form within granite outcrops from weathering, which slowly fill with soil as lichens and mosses colonize, die and break down within these depressions. Acidic rainwater trapped in these pockets erodes the rock further, through a process known as hydrolysis, allowing space for more plant species to colonize. Soil forms when these plants shed leaves, die and break down or when rock erodes. The deepening soil pockets trap more rainwater, beginning the cycle anew. This cycle may continue for long periods of time, although heavy rains have been known to periodically slough off the accumulated soils and vegetation, setting the process back to an earlier successional state.

Plant Community Development

Four successional stages of development are categorized on rock outcrops, with the transition from bare rock to the fourth stage, Oak-Pine-Hickory forest, lasting some 1,000 years (Shure, 1999). Exposed rock surfaces are colonized by lichens and mosses. Even those rocks that appear lifeless are in fact covered by fragile, microscopic lichen colonies that darken the rock's face. Long-term weathering leads to the development of pits on the rock surface. The successional progression initiates as the depressions accumulate soil, which are quickly colonized by a community of lichens, annuals and herbs. Eventually, soil deepens, allowing pits to support perennials, shrub communities and more diverse plant life. Temperature and moisture level fluctuations stabilize as substrates deepen, allowing for the colonization of more shrubs and small trees. With each differing soil depth characterized by its own highly specialized plants, granite outcrop plant species have evolved specializations that mean they are often found nowhere else in the world. These are known as endemic plant species. Endemic plant species, or those plants that are native and restricted to a particular area, distinguish granite outcrops from other ecological areas. They evolved due to the extreme micro environmental characteristics, as well as the disjointed geographical occurrence of rock outcrops (Shure, 1999). Endemic plants make these environments special and sensitive. Georgia has the highest amount of granite outcrops in all the U.S., with the highest abundance in the upper Piedmont region just east of Atlanta (McVaugh, 1943). Georgia also boasts the highest concentration of granite outcrop endemic plant species, which allows Georgia a rare opportunity and distinct responsibility to preserve these species (Shure, 1999).

Atop granite outcrops, seasonal displays are vibrant and striking. Species are clustered in serpentine patterns that spiral depressions which are surrounded by rocky expanse. Winter, spring, summer and fall offer uniquely beautiful displays of annual and perennial flowers. Pools that form in depressions during the early spring witness rare blooms of short-lived pool-sprites which lay dormant the rest of the year. The textures of granite outcrop plant species add interest and depth to these seasonal displays, with trails of delicate mosses juxtaposed by swaths of large-flowered coreopsis blooms, the stout, hairy stems of ragwort, the fine textures of grasses and the vibrant leaves of succulents. Each season offers new interest and beauty.

Threats to Granite Outcrop Plant Species

Granite outcrops are not well known or understood by most people who live in Georgia, even though approximately ninety percent of all the Piedmont's estimated twelve thousand acres of outcrops occur in Georgia (Murdy et al., 2000). Unfortunately, these fragile communities have been unappreciated and destroyed or abused (Murdy et al., 2000). Their destructive uses may manifest in the form of dumping grounds, off-road vehicle trails, and parking lots, among others. Perhaps the lack of agricultural potential of granite outcrops, in a state dominated by agricultural land-use, has contributed to their undervaluing. Furthermore, many granite outcrops have been disturbed or destroyed through a long history of mining practices, with mining evidence apparent on most of today's remaining outcrops (Ambrose et al., 2013).

Our region of Georgia has a unique responsibility to protect and promote these beautiful, fragile and misunderstood landscapes. We theorize that vegetated roofs offer one opportunity to safeguard some of these plant species while regenerating displaced green space in our urban areas and providing habitat connectivity for the birds and insects that rely on these plants for food and shelter.

Conservation Status

Research suggest that the fragile, endemic plant communities of granite outcrops are an especially old biotic community, where species evolved in isolation rather than as remnants of other more widespread species that evolved elsewhere (Shure, 1999). The scientific significance of this suggests that granite outcrop plant species are locally-adapted on a highly specific scale. It is therefore incredibly important to conserve those remaining granite outcrops, as future losses will inevitably mean species extinction, and to develop new strategies to assist in the conservation process.

Currently, most granite outcrops have been protected by chance, due to their generally inaccessible locations, or the efforts of well-informed landowners (Murdy and Carter, 2000). Ten Georgia outcrops have current protection status, six of which reside in the Atlanta metropolitan area, with each individually managed by different regional offices (Murdy and Carter, 2000).

Historically, quarrying has caused the most destruction of granite outcrop ecology. There are twenty-two active commercial quarrying operations in the Atlanta area alone (Shure, 1999). However, due to the high proportion of granite outcrops in the Atlanta metropolitan area, which has a population just below six million people, according to 2017 U.S. Census data, damage due to human use and development is also high. The fragile nature of plant populations evolving in isolation means they are especially susceptible to human-induced disturbance. Lichens, which grow directly on the rock surface, show greatly reduced growth and increased stress responses where there is trampling from foot traffic (Shure and Ragsdale, 1977).

State and county parks offer some protection for granite outcrops in the Atlanta area, with a small staff working to educate the public about these fragile landscapes. It is also recommended that conservation efforts be expanded to local efforts by purchasing and setting aside parcels of land that contain granite outcrops (Shure 1999). Education and awareness surrounding the unique evolutionary history and ecology of granite outcrops is also an important step in the conservation process, one that may be extended into urban areas with granite outcrop vegetated roofs serving as that vital first step in the introductory process.

Plant Safeguarding

Research also reveals that vegetated roofs offer an opportunity for safeguarding threatened plant species (Bennett and Arcese 2013). The isolation offered by rooftop patches that exist in otherwise ecologically stark landscapes (i.e. urban areas), may be beneficial for the persistence of threatened species at risk of disturbance or competition from non-native species. Extensive vegetated roofs, which consist of a comparatively thin substrate (in contrast to *intensive* vegetated roofs), remain particularly isolated as their composition is not suitable for foot traffic from maintenance or public access, which could damage the thin, sensitive growing medium and plants. Lack of maintenance access is traditionally seen as a hindrance to plant success on conventional vegetated roofs because many sedum-dominated roofs require upkeep on components like supplemental irrigation systems. However, what is perhaps an obstacle to one plant community may benefit the sensitive, threatened plant species of granite outcrops. Should the results of this study prove granite outcrop plants suitable for use in extensive vegetated roof planting plans, future granite outcrop vegetated roofs have the potential to provide multiple benefits in addition to those already offered by traditional green roofs, such as safeguarding a Piedmont-native, threatened plant community and new, research-backed plant alternatives to non-native sedums.

Plant Selection

This research project gathered data on the performance of eight granite outcrop plant species over the course of one growing season atop extensive vegetated roof modules in Athens, Georgia. Each species: *Opuntia mesacantha* (Eastern Prickly-pear), *Helianthus porteri* (Confederate Daisy), *Sedum glaucophyllum* (Cliff Stonecrop), *Coreopsis grandiflora* (Large-flowered oreopsis), *Phemeranthus teretifolius* (Appalachian Rock-portulaca), *Oenothera fruticosa* (Narrow-leaved Sundrops), *Packera tomentosa* (Woolly Ragwort) and *Tradescantia hirsuticaulis* (Hairy Spiderwort) are naturally occurring on granite outcrops throughout the Piedmont and are currently underrepresented in the nursery industry and vegetated roof plantings. Data on plant survivability and vegetated cover was collected across different conditions and sites. Two variables, substrate composition and substrate depth, were observed. These variables were chosen in order to find the optimal, typical extensive roof conditions for granite outcrop plant success. Findings may be used to promote their adoption into standard vegetated roof designs, where scientifically-backed evidence on the performance of regionally specific native plant species is missing.

This project asks what differences in mean vegetative cover may result from the interactions of granite outcrop plant species planted within two substrate depths and two substrate compositions. This question was explored in order to build upon previous research that supports the use of native plants in vegetated roof design and emphasizes the importance of substrate depth and composition in regard to plant health (MacIvor and Lundholm 2011; Durham, Rowe and Rugh 2007; Emilsson 2008). Through the exploration of this research question, we hope to assist in the development of a palette of diverse native plants for future vegetated roof designs that may contribute to further research on the possibility of vegetated roof microrefugia and increase ecosystem services offered by regionally appropriate vegetated roofs.

Objectives and Justification

Soil, vegetation and natural ecosystems naturally form a harmonious and delicate balance. Rapid human development has introduced a disturbance to this balance, and some symptoms of the resultant dysfunction are flooding, plant and animal species decline and the urban heat island effect (UHIE) (Dwivedi and Buddhiraju 2018). UHIE is a particularly salient issue in developed areas, and estimates suggest that human deaths associated with the urban heat island effect will increase some 253% by the year 2050 (Kinney et al. 2004). UHIE occurs when paved surfaces like streets, roads and building rooftops reflect the solar energy usually absorbed by soil and vegetation, which can sometimes dramatically raise the ambient temperature of cities compared to their surrounding rural landscapes. A common strategy has been to paint roof surfaces white to reflect solar energy away from the building and streetscape (Santamouris 2013). However, as a result of pollution from traffic and industrial processes, reflectivity likely declines as surfaces become covered in particulate matter. Alternatively, vegetation has been shown to decrease ambient temperature, and a vegetated roof has the added insurance of the ability to absorb and filter out pollutants, remaining immune to the decline in cooling capabilities endured by painted surfaces (Salman et al. 2018). Spatial analysis research using thermal imaging clearly illustrates the dramatic differential between vegetated areas and pavement or building rooftops, revealing the impact even small greenspaces that otherwise are surrounded by concrete can have on ambient temperature. (Dwivedi, 2018). In fact, combining equal parts concrete and greenspace in urban areas can reduce ambient heat by 25%.

A more complete understanding of the plants that will survive and thrive under harsh rooftop conditions in Southeastern North America is required in order to encourage a more widespread adoption of vegetated roofs in the Georgia Piedmont. Vegetated roof plant recommendations are heavily reliant on sedums native to Europe and Asia (MacIvor and Lundholm, 2011). With more extreme temperature, humidity and moisture-level fluctuations than Europe, these sedums often battle insect issues, fungus and disease when planted on North American vegetated roofs (Dvorak and Volder, 2010). Furthermore, monocultures present their own issues, as they are more vulnerable to collapse and infestation than a diverse planting, which offer more ecosystem services, resilience and aesthetic appeal. More research on regionally-appropriate native plant alternatives may inspire the confidence of individuals to expand the use of vegetative roofs, thereby increasing habitat for the threatened granite outcrop plant community.

Limitations

The limitations of a research study are any outside influences which can cannot be controlled by the researcher. Any research study of this nature will have to contend with inherent limitations. While these limitations do not necessarily invalidate the results of the experiment, they should be considered when weighing the significance of findings. It was a goal to keep these limitations to a minimum, which is reflected in the design of experiment. For example, two locations were chosen, or blocked (The Mimsie Lanier Center and UGArden), in order to measure the variation in mean vegetative cover between these groups against one another. Should the variation between these groups roughly equal the variation within these groups, it is possible to state that location was not a significant impact on results, ruling out many limitations that may have presented themselves should all of the modules have been located in one area.

Furthermore, it is important to consider that the development of urban ecosystem biodiversity is no easy task. With an increasing lack of free space, urban real estate is often at a premium. This is one reason why rooftops present a convenient alternative to building ecological complexity on the ground, and why it is so important to consider the possibility of building retrofits in this research study.

This study focuses on extensive vegetated roofs only. Extensive vegetated roof modules were acquired from a local vegetated roof nursery, James Greenroofs, and as standard practice in the vegetated roof nursery industry, this trial was conducted on the ground. It is believed that black landscaping fabric, and full solar exposure, adequately mimics rooftop conditions for the purposes of a plant trial. However, there were inevitably occurrences, such as rodents digging up plants and ant infestations, that may have been avoided on a building rooftop. Ultimately, it was deemed preferable to follow the industry standard of ground-level plant trials, with the bonus of easier access for regular research monitoring, than to place modules on a building rooftop. Therefore, the nature of the ground trial did present some limitations to the experiment. Fortunately, the experiment was designed with eight repetitions of each substrate combination (substrate depth x media composition). Thus, when evidence of rodent tampering presented in August, we were able to exclude all data from those trays for the duration of the experiment without impacting the statistical significance of the findings.

Delimitations

Delimitations are restrictions or boundaries placed on the experiment by the researcher. One delimitation of this project was the window of time during which data was collected. Monitoring took place over the course of one growing season only: May through November of 2018. Furthermore, the sampling size was a delimitation of this study, as well as the number of plant species. Sixty-four total plants of each species were observed, with thirty-two plants installed in *shallow* substrate and thirty-two in *deep* substrate. Deep and shallow trays were both filled with a mixture of expanded aggregate, coarse sand and worm castings. Further research is required to study the long-term adaptability of these plant species, and other granite outcrop plant species to extensive roof conditions. The diversity of the granite outcrop plant community is vast, and further research will be useful to test each species' suitability to vegetated roofs, and further expand the diversity of species available for use in vegetated roof designs.

Research shows that there is a variability among plant species on mature vegetated roofs that correlates to roof age, suggesting that succession is at play (Gabrych, 2016). For this reason, it is recommended that this plant trial be extended to continue to quantify the success of these species as vegetated roof plant recommendations.

The purpose of this study was to test species suitability to placement on these surfaces by simulating an extensive vegetated roof environment and to assess the interactions between plant species, their planting depth and their growing medium composition. As cities are characterized by habitat patches that are small, fragmented and isolated, it is especially important to consider the wider context, or matrix of connectivity, when planning for biodiversity enhancement. Therefore, it is further recommended that the lessons of this research study inform the planning of a network of granite outcrop vegetated roof designs that can more thoroughly support plant and animal habitat and build resiliency in the event of roof failure or unforeseen circumstances.

CHAPTER 2

LITERATURE REVIEW

This research project aims to enhance ecological resiliency in the Piedmont region of Georgia through biodiversity conservation. Biodiversity faces challenges in the form of climate change, decreased habitat through roads and infrastructure, deforestation and development, and invasive species (Salman et al., 2018). It is important to find ways to mitigate these challenges because biodiversity is a vital component of ecosystem function. Vegetated roofs provide an opportunity to address these challenges. According to research in the United Kingdom, green infrastructure planning can prioritize nature-based solutions that combat loss, degradation and fragmentation of habitat, while also benefiting the health and wellbeing of society (Bellamy, 2017). Findings demonstrate that increasing visibility of green infrastructure, e.g., green roofs, can spur more interest in environmental stewardship, and create a more attractive city in which to live, work and invest. The confluence of social and ecological benefits that stem from green roof proliferation suggest strong human investment in their maintenance, support and success, a critical factor to consider when analyzing potential long-term impacts.

In terms of substrate adaptation, research demonstrates that soil is often too shallow and thus too hot and dry for large herbaceous plants or trees to grow atop granite outcrops (Klein, 2015). This is attributed to bedrock right below the soil surface. This environment poses a number of challenges to plant success including shallow substrate, subjection to extreme temperature fluctuations, increased wind exposure and evapotranspiration are also the most salient environmental conditions affecting plant performance on vegetated green roofs (Klein and Coffman, 2015). This implies that granite outcrop plant communities may be naturally suited to extensive vegetated roof growing conditions and could award the opportunity to extend native plant refugia into urban and suburban areas through their incorporation into vegetated roof planting design.

Research describes that many granite outcrop plant communities are endemic to specific regions, or even singular outcrop systems (Ware, Crow and Waitman, 2011). This leads to the assumption that plant communities which exist in limited, highly-specialized environments might exhibit exacting standards when it comes to the surfaces on which they grow and adapt. However, it has been shown, through studies on United States rock outcrop plants, that only one plant population that typically exploits limestone and sandstone demonstrates strong substrate specialization (Ware, Crow and Waitman 2011). Georgia's native outcrop species grow atop granite flat rocks or domes and have been shown to be much more adaptable to substrate material. These factors lead to the hypothesis that vegetated roofs present a viable opportunity for refugia for granite outcrop plant communities threatened by increasing development.

Literature focusing on vegetated roof plants have emphasized the importance of two variables: the effect of substrate depth on plant survivability and diversity, and the importance of considering implicit trade-offs between system weight requirements, substrate water-holding capacity, oxygen diffusion to plant roots and long-term substrate stability, stability which becomes more sensitive to decomposition and erosion with increased proportions of organic matter (Emilsson, 2008).

Vegetated Roof Substrate Composition

Ground-level gardens have the advantage of rich, organic soils to nourish plants and provide ample space for root growth. Conversely, vegetated roof substrate must achieve a delicate balance between lightweight and porous growing medium that is able to hold enough water and nutrients and provide some stability for plant root structure. If substrate retains too much water, plants may experience root rot and die. Likewise, if a substrate contains high levels of organic materials, stormwater runoff will carry these nutrients from the roof and negatively impact water sources. Also, nutrient runoff shortens the lifespan of the growing medium and leads to substrate shrinkage, effecting long-term structural integrity. Ultimately, while high proportions of organic materials in the substrate composition of vegetated roofs may offer benefits to some plant species, there are evidently trade-offs worth considering. System weight requirements, substrate water-holding capacity, oxygen diffusion to plant roots and long-term substrate stability, stability which becomes more sensitive to decomposition and erosion in proportion to increases in organic matter, may influence a trend toward lighter substrates and the plant species which prefer these conditions. (Emilsson, 2008). These lighter substrates would theoretically include fewer organic materials in proportion to expanded aggregates and sand, which would in turn hold less water, and therefore be less susceptible to the erosive effects of time and weather. The geographically isolated communities of Piedmont granite outcrop plant species exhibit a natural preference for substrates low in organics. Most outcrop substrates have been found to be composed of greater than 85% sands through the third, annual-perennial, successional stage (Shure, 1997). This adaptation may indicate a unique suitability of granite outcrop plant species to extensive vegetated roof substrates low in organic matter.

Ideal extensive roof substrate consists of very little organic material, often as little as 10%, although, typical extensive substrate mixes in the Southeastern U.S. generally contain 20% organic matter. This organic material must take the form of organic compost, not soil, which would compact over time. In Southeastern North America, the remainder of vegetated roof substrate generally consists of expanded slate and coarse sand. The expanded slate may be substituted with expanded shale or expanded clay, depending on regional availability. The precise ratios of organic material, sand and expanded slate is determined by the plant species composition, the site's environmental conditions, drainage needs, and load weight.

Considering the preference of granite outcrop plant species for rocky, shallow substrate, we chose to observe the effects of a typical Southeastern extensive substrate composition and a composition with much lower rates of organic material in order to determine the lightest, most stable substrate structure suitable to support these threatened plant species. In theory, a lightweight and sturdy substrate will offer the most inexpensive and therefore most applicable substrate for widespread usage, vegetated roof, that will also require minimal intervention, therefore increasing the roof's plant safeguarding potential. For these reasons, we chose to examine the effects of both substrate depth and substrate composition in this research project.

Vegetated Roof Substrate Depth

Roof load bearing capacity is one of the most critical considerations in vegetated roof design. Extensive roofs are typically lighter than intensive roofs; however, dead load requirements of an extensive vegetated roof are still higher than those of a traditional roof. *Dead load* is the weight of the roof itself along with any permanent components that make up the roof structure. In contrast, *live load* weight includes more transient factors like additional weight from rain and snowfall, the weight of human foot traffic or temporary furniture. While structural engineers ultimately evaluate the roof load, vegetated roof designers must appraise both dead and live load during the development phase, taking into consideration the 15 to 25 pounds per square foot an extensive vegetated roof can add when fully saturated, or the 59 to 199 pounds added by fully saturated intensive roofs (Snodgrass et al., 2006). In light of the structural considerations mandated when planning for vegetated roofs, it is almost always most cost-effective to plan for these considerations early in the architectural design process. However, in dense urban areas there is little room for new construction but a pressing need for the benefits offered by vegetated roofs. In this situation, *extensive* vegetated roofs, in contrast to *intensive,* offer compromise between additional costs of a building retrofit with the cost-saving measures offered by vegetated roofs in general. Extensive vegetated roofs relieve some of the burden a heavy load of deep planting medium and large plants may impose on a building with their relatively thin substrate and smaller, lighter plant material. Extensive vegetated roofs are often the most economically feasible choice for building retrofits as well as new construction, and are certainly the most widely used. Germany leads the world in vegetated roof installations, and close to 80% off all their vegetated roofs are extensive (Harzmann 2002).

Substrate depth is also an important consideration when it comes to the lifespan of vegetated roof plantings. Influencing factors such as length of time for plant establishment, groundcover density, and tolerance of extreme environmental conditions, research illustrates the crucial role substrate depth plays in the success of vegetated roofs (Durhman, Rowe and Rugh, 2007). However, research examining how substrate depth interacts with Southeastern native plant communities is comparatively lacking. For this reason, as well as the adaptation to shallow substrates exhibited by granite outcrop plant species in the wild, we chose to observe the effects of two extensive roof substrate depths common in the vegetated roof industry on plant performance. The goal of this comparison between granite outcrop plant species performance and substrate depth is to determine the optimal balance of adequate growing conditions with weight minimization. Lighter vegetated roofs will provide more opportunities for building retrofits and the potential for wider application, therefore increasing opportunities for safeguarding plants and other ecological benefits.

In order to prove successful on extensive vegetated roofs, plant species must establish themselves quickly, tolerate extreme environmental conditions and provide high groundcover density (Durham, 2007). One hypothesis of this study presumes that substrate depth will variably effect individual plant species. For instance, we hypothesized plant species in the *Opuntia* family would likely flourish in the comparatively dry media offered by the thinner substrate; whereas more herbaceous species such as *Helianthus porteri* would respond positively to a deeper, more organic substrate. Therefore, this study asks how substrate depth impacts vegetative cover and survivability of eight individual plant species under all distinct variables in the hopes of determining the optimal plant species mixture for the widest application of future extensive vegetated roof projects throughout the Georgia Piedmont.

Native Plants and Vegetated Roofs

Traditionally, vegetated roofs were planted with drought tolerant sedum species. Lately, there has been interest in increasing plant diversity of vegetated roof landscapes using native plants (Butler, Butler and Orians, 2012). Native-plant vegetated roof designs tend to focus on the ecosystem services that native plant communities can provide over non native species, which are often chosen solely for their drought-tolerance. However, the environmental conditions of green roofs differ greatly from ground conditions, and thus extra deliberation is required to determine the most suitable native plant species. This research project hypothesizes that granite outcrop plant communities support a long-term, sustainable solution to how best to incorporate native plants into green roof infrastructure projects due to the microenvironmental parallels between vegetated roof conditions and granite outcrop habitat.

Microrefugia

Refugia is an ecological concept that has gained interest across scientific and planning fields, as it promises the opportunity to facilitate the survival of organisms under unstable climate patterns (Keppel et al., 2019). Simply put, a refugia is a safe-haven for plant or animal species. It provides the environment necessary for species survival until the environmental issues either resolve, the population stabilizes, or the population evolves. Microrefugia, is an interesting concept in that it involves a much smaller spatial scale. Microrefugia is a small area of habitat patch, within the typical species' range, where conditions for survival are relatively stable, and from where they can potentially expand once environmental conditions improve. Research in Poland emphasizes the need to think of microrefugia not only in terms of a smaller spatial scale, but also in terms of a shorter time scale (Kiedrzynski, 2017). They argue that utilizing shorter time-scale microrefugia does not undermine the ultimate goal of establishing a species safe haven and may in fact be an important tool or stepping stone to establishing longer-term microrefugia that operates on a longer, evolutionary time scale.

Furthermore, it is worth noting that the physically small size of microrefugia does not necessarily lead to unhealthy populations, as genetic diversity can remain high even under these restrictive conditions (Bai and Zhang, 2015). Research on two granite outcrop plant species, both assessed as a part of this research project reinforce the idea that small, isolated populations can sustain high genetic diversity and healthy populations. Thirty-three populations of *Tradescantia hirsuticaulis* were found to have exceptionally high levels of genetic diversity among populations studied in the wild, despite their relatively rare and scattered occurrence (Godt and Hamrick, 1993). Likewise, *Helianthus porteri*, a granite outcrop endemic, typically possesses slightly lower rates of genetic diversity, which have possibly been homogenized over its long evolutionary history, but remains healthy due to incredibly large populations at each outcrop where it makes its home, ensuring healthy genetic function (Bowsher, Gevaert and Donovan, 2016).

Plant Monitoring Technique

Point intercept is a technique used by researchers to monitor and measure plant canopy cover in the field and atop vegetated roofs (Elziner, 1998; McIvor, 2011). Canopy coverage is measured by comparing the total number of "touches," or interceptions between a target plant species and point, out of the total number of points measured. Points are represented by pins suspended within a frame. The frame is necessary to prevent sampling bias. The frame also supports the angle of the pin's drop, as cover measures need to be calculated perpendicular to the ground.

Point intercept is considered the most objective and least biased technique for measuring plant cover (Bonham, 1989). However, it does have its limitations. As each pin is lowered perpendicular to the ground while suspended from the pin frame, some plants with more narrow, upright leaves have a lower chance of being encountered than more prostrate-formed species. It follows that species with low cover values, relative to other species, would not be sampled as efficiently using the point-intercept method. While these limitations may influence the cover value of certain plant species, the main concern of this study examined the change in mean cover over time; therefore, cover value alone was of less concern than the observable changes in that value over time as it interacted with the various treatment combinations. While these limitations in sampling technique should not go unacknowledged, the overall trends this technique provide outweigh the potential limits.

Data Collection and Statistical Analysis

ANOVA, or analysis of variance, is a method of testing the statistical significance of a difference in means in order to test a hypothesis. ANOVA is fairly straightforward in concept. One-way ANOVA, the statistical test used during this research project, simply compares three or more factors within a random sampling. Should the amount of variance between the different groups of factors, the independent variables, be considerably higher than the amount of variance within the groups of factors, then it is scientifically acceptable to conclude that the factors had a statistically significant impact on the dependent variable (Holt, 2018). If there is a statistically significant difference between groups of factors, then it is possible to confirm the substantive hypothesis of the study. Should the variation between groups not rise significantly higher than the variation observed within these groups, then it is impossible to reject the null hypothesis, that there would be no variance between groups, as the possibility that any observed variations may have been due to sampling error alone. During this research project, ANOVA was used to compare all combinations of the two substrate depths and two substrate compositions in order to determine which, if any, of these groups of factors would demonstrate a statistically significant impact on mean vegetative cover of the roof modules.

CHAPTER 3

METHODS

This study will help determine which plants are able to withstand the harsh environmental conditions characteristic of extensive vegetated roofs in the Piedmont region of Georgia, a humid subtropical climactic zone. The objective was to gather data on plant performance and survivability during one growing season while investigating the effects of two substrate depths and planting media compositions on eight granite outcrop plant species. This project will help designers, nurseries, and developers select appropriate plants for extensive vegetated roofs under similar environmental conditions and encourage the adoption of native and threatened plant species in vegetated roof planting designs through evidence-backed plant recommendations.

Plant Species

As granite outcrop ecology so closely resembles vegetated roof environmental conditions, suggesting a wide suitability among endemic plant species, eight granite outcrop plant species were selected for observation based on their availability and propagation success at regional horticultural conservation nursery facilities. Species are presented below.

Table 1. Plant Species Tested in the Vegetated Roof Modules

Botanical Name	Common Name	Flowering Season
Coreopsis grandiflora	Large-flowered Coreopsis	Late Spring-Summer
Helianthus porteri	Confederate Daisy	Late Summer-Fall
Oenothera fruticosa	Narrow-leaved Sundrops	Spring-Summer
Opuntia mesacantha	Eastern Prickly-pear	Spring-Summer
Packera tomentosa	Woolly Ragwort	Early-Late Spring
Phemeranthus teretifolius	Appalachian Rock-portulaca	Spring-Fall
Sedum glaucophyllum	Cliff Stonecrop	Later Spring-Summer
Tradescantia hirsuticaulis	Hairy Spiderwort	Spring-Summer

Design of Experiment

A full factorial design of experiment tested the levels a.) substrate depth (2 and 4 inches) and b.) substrate composition (a mixture of 70% stalite, 20% coarse sand and 10% organic matter or a mixture of 70% stalite, 10% coarse sand and 20% organic matter) installed in modules resting on black weed barrier fabric.

There were eight replicates of each combination for a total of sixty-four modules, each planted with the same eight granite outcrop plant species in identical configurations.

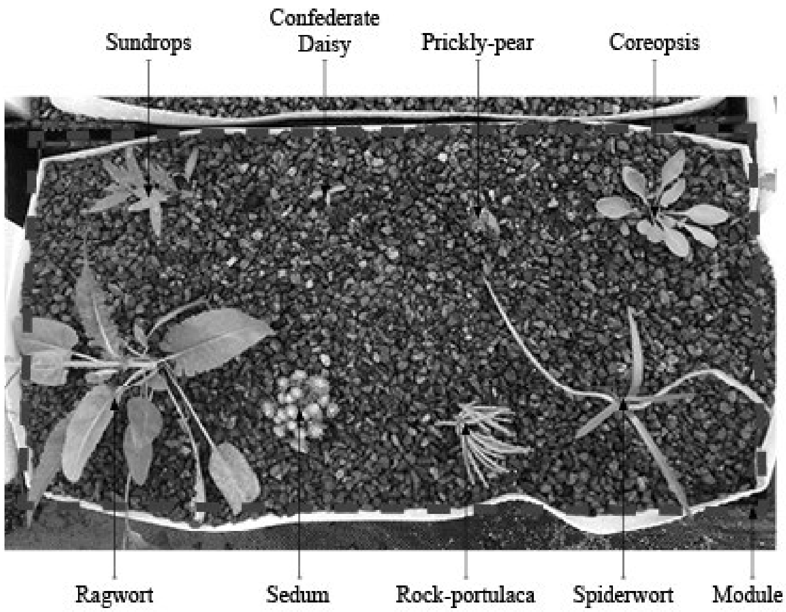

Figure 1. One Vegetated Roof Module (Module #33) During Establishment Phase

Sixty-four vegetated roof modules were randomly assigned to one of four treatment combinations, and randomly assigned within two blocks, the Mimsie Lanier Center for Native Plant Studies and approximately one mile away at the UGArden, the University of Georgia's farm. These two sites were chosen for their ease of access to campus for regular monitoring visits and reflected hilltop and valley floor conditions.

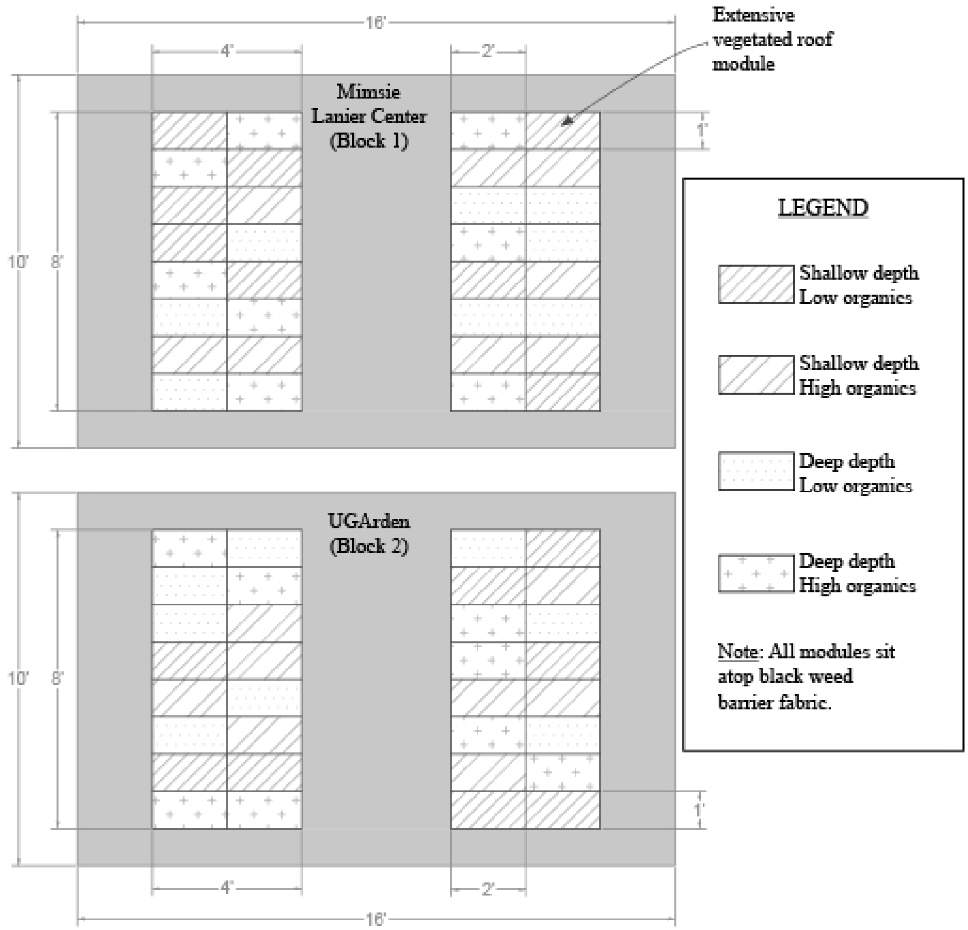

Figure 2. A Diagram of the Design of Experiment

The trays were planted one month before the initial monitoring, and during this time, modules were irrigated twice-weekly for the establishment of the plants. During the experimental period (May through November), plants were irrigated only when registering as “1” (very dry) on an electronic moisture meter that randomly tested one experimental unit per replication. Tap water at each site was used to irrigate modules using a handheld hose and sprayer that was uniformly applied. Plant measurements were conducted monthly for seven months (May through November), during the fourth week of each month. Any germinating plants not planted in the module were removed by hand.

A "routine" and "textural" soil analysis was performed on the two manufactured substrate compositions during the plant establishment phase (May 2018). The sample was taken using recommended soil sampling procedures as listed on the provided sample collection bags. Soil sampling procedures aim to assist in obtaining the most representative sample of a given soil. Soil tests are a method of chemically measuring relative nutrient levels in soil samples, indicating soil fertility. Soils vary tremendously across the state and are highly heterogeneous in nature, demonstrating the importance of a baseline soil sample to which future results can be compared (Kissel and Sonon, 2011). This analysis was conducted by the University of Georgia's Agriculture and Environmental Science's Soil, Plant and Water Laboratory.

Plant Monitoring

Measurements were taken using the point-intercept method. Mean vegetative cover was calculated using data from ten evenly spaced points dropped lengthwise via pin-frame. The pin frame was situated on top of each module, with the transect crossing the midpoint of the shortest side of each module. Every time a plant came into contact with a pin, the touch was attributed to an individual plant species, the height of the highest touch cataloged, and the total number of touches tallied, with the same operations performed for each species that touched each of the ten pins as it was dropped in every module at both blocks. The amount of touches indicates vegetative cover for each module, an indicator of the vigor of plant material within the module conditions. Coverage is an important consideration for vegetated roofs because higher coverage produces more ecosystem services, suppresses weeds and increases vegetated roof functionality (Elzinga, Salzer and Willoughby, 1998; Getter and Rowe, 2006).

In our case, the sampling unit is a linear point frame of ten pins.

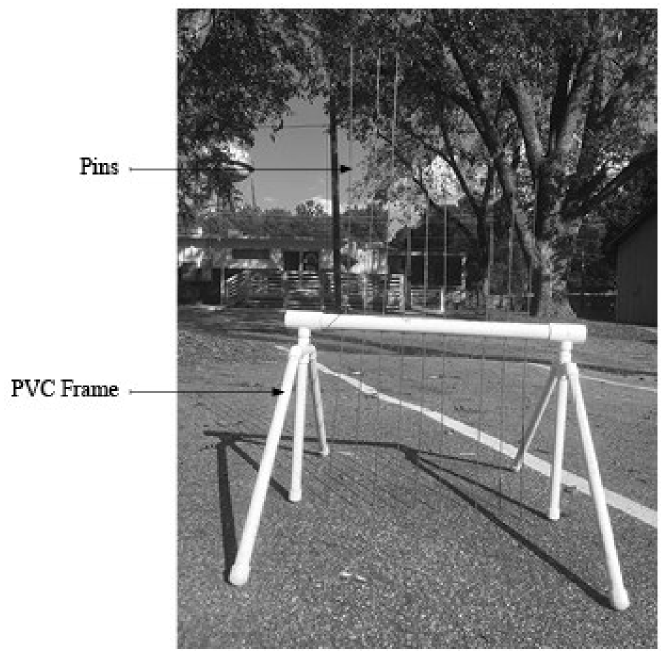

Figure 3. Pin Frame Used During Plant Sampling

The frame was constructed from PVC pipe and 1/8" diameter welded steel rods in 4-foot lengths. The PVC formed the frame, while the steel rods served as pins. Ten pins were suspended through the two-foot frame transect at even intervals, and slowly lowered until contacting vegetation. Each plant species touch was measured at the highest interception with each pin, with subsequent touches to the same pin totaled for each species (Poissonet et al., 1973). Ten points were chosen for each sampling unit to control for the resolution value of plant coverage and create a detailed portrait of plant performance within the modules. With ten points, a clear indication of plant coverage for each module can be calculated (ex. 0%, 10%, 20% coverage, etc.). Only living and green stems, leaves and flowers touching the pins were recorded.

Plant survival was assessed visually and compiled on a monthly basis. As several plants appeared to die back only to reemerge later, likely a result of granite outcrop species adaptations to survive the stress of particular seasons or events, this data may prove useful in future research, although final survival rates reflect only those findings from November's monitoring event. Plant survival data is not absolute, as data was collected through visual inspection of above-ground plant appearance only. However, these findings may be useful to consider during future planting design phases. Furthermore, it is worth considering this plant characteristic when designing vegetated roofs with aesthetics in mind, and survival data collected as a part of this study may help designers make informed decisions to insure all-season interest even during periods of plant dormancy.

Data Collection and Statistical Analysis

Plant monitoring took place in the field, monthly. Notes were compiled by hand. These measurements were then entered into spreadsheet to complete the analysis and aid in graphical representation of the findings. ANOVA, or analysis of variance, compared the two substrate depths (2 and 4 inches) with the two substrate compositions (10% and

20% organics) on the total number of touches on each vegetated roof module, across all different combinations. The total number of touches was used as an indicator of vegetative cover, a significant determinant of vegetated roof success. For instance, the mean vegetative cover of the combination of four-inch media and 10% organic matter was compared against the mean vegetative cover of the two-inch media and 10% organic matter, and so on in all combinations of substrate composition and depth.

CHAPTER 4

RESULTS AND DISCUSSION

Results of this research project should be used to build confidence in the incorporation of granite outcrop plant species into vegetated roof designs in the Piedmont region of Georgia. Not only will this assist in building more successful vegetated roofs, which struggle when planted with non-native sedums that face pest, fungus and disease, but will also assist in extending granite outcrop plant species habitat, a sensitive and threatened ecology unique to Southeastern North America.

Interaction Between Substrate Depth and Composition

Research was conducted between May 2018 and November 2018 on extensive vegetated roof modules in Athens, Georgia. Results indicate that the interaction between deep substrate (4 inches) and low organics (10%) produced the most vegetative cover in each module $F(3,396) = 2.89$, $p = .035$.

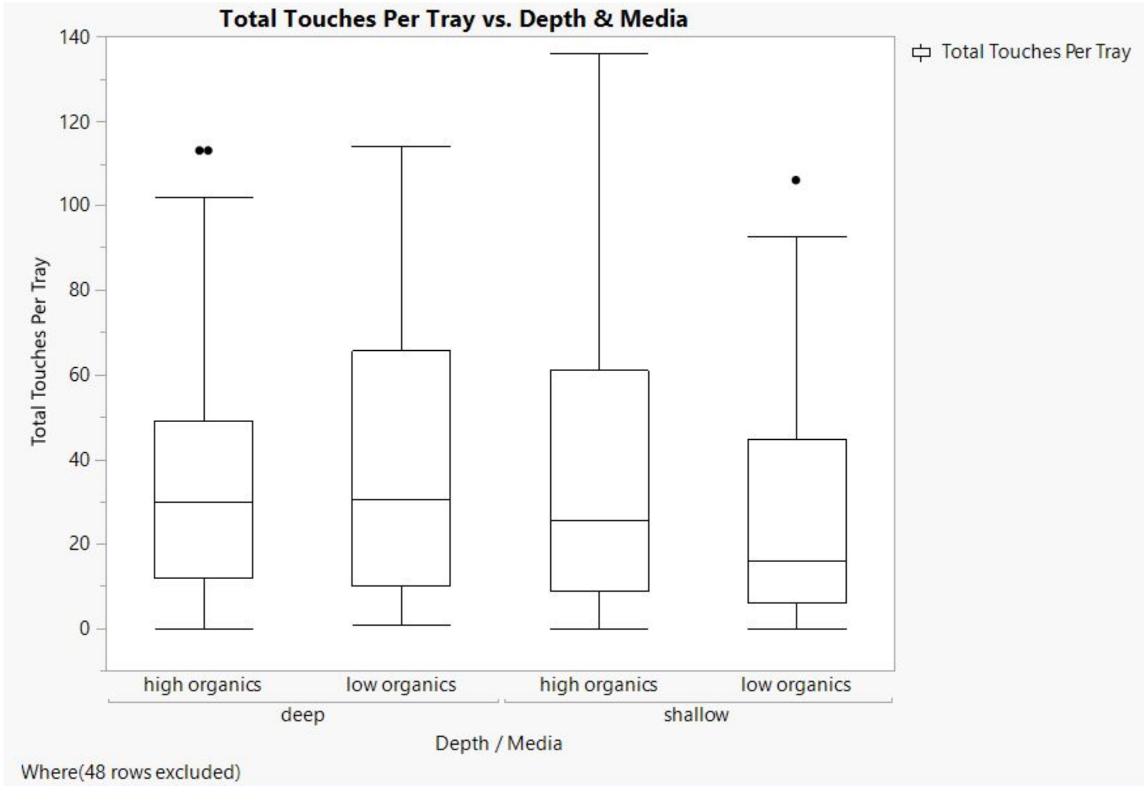

Figure 4. Box and Whisker Plot of Vegetative Cover vs. Depth and Media Composition

The null hypothesis, that there would be no difference in mean vegetative cover resulting from interactions between substrate depth and composition was rejected. Furthermore, findings support the substantive hypothesis that substrate composition and depth interact to influence vegetative cover within extensive vegetated roof modules.

A Tukey analysis comparing the means of every treatment combination to the means of every other treatment combination revealed the details of the statistically significant variation in means between the combination of deep substrate with low organics and the combination of shallow substrate with low organics.

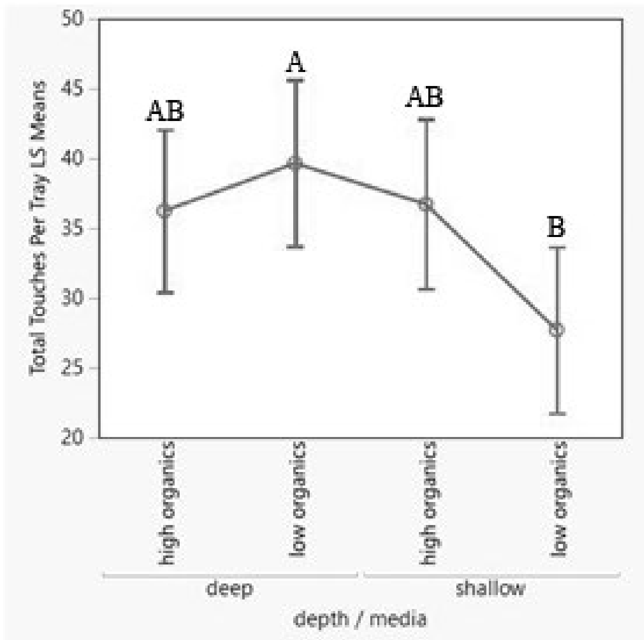

Figure 5. Plot of Least Squares Means Between All Treatment Combinations

Notice that those levels not connected by a similar letter, deep substrate with low organics and shallow substrate with low organics, are significantly different. This analysis further supports the conclusion that substrate depth was the most salient influencing factor on vegetative cover. However, intuitively, the finding that the interaction of shallow substrate with low organics produced the lowest mean vegetative cover would suggest that the interaction of deep media with low organics would also produce low mean vegetative cover. As this is not the case, we suggest further research examining the interaction of organic matter and substrate depth on vegetative cover, perhaps in lower concentrations.

Interaction Between Time and Mean Vegetative Cover

Each month also demonstrated statistically significant effects on vegetative cover, $F(15,384) = 3.29$, $p < .0001$, which is to be expected, as the plants were installed as young plugs and continued to grow throughout the observation period.

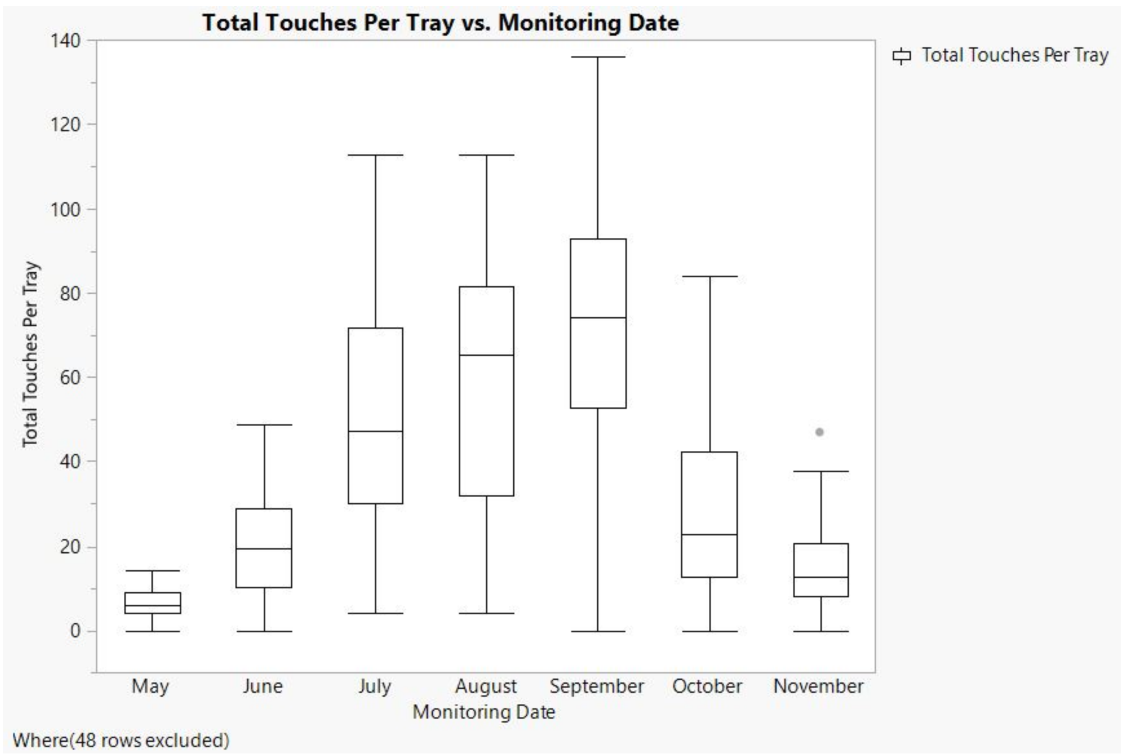

Figure 6. Box and Whisker Plot of Vegetative Cover vs. Month

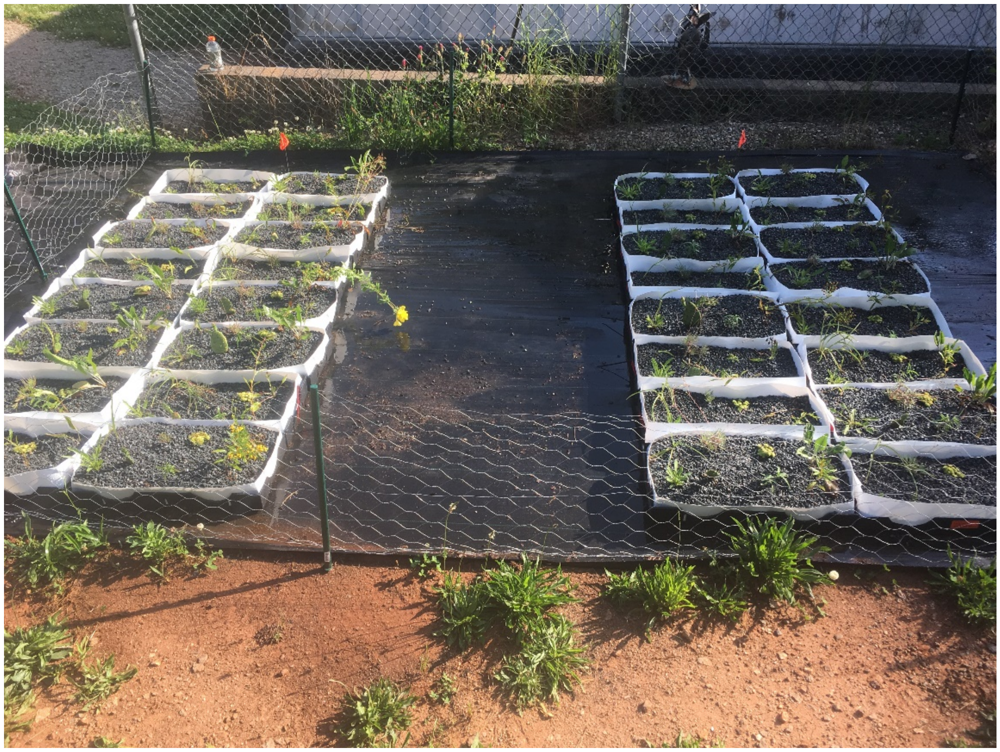

Figure 7. Photo of Block 1 (Mimsie Lanier Center) During Early May

Figure 8. Photo of Block 1 (Mimsie Lanier Center) During Early August

Interaction Between Mean Vegetative Cover and Substrate Depth

Substrate depth was not statistically significant $F(1,398) = 3.64$, $p = .057$, although these findings fall just outside the accepted threshold for statistical significance and may require further testing. Deep substrate did produce the most vegetative cover in total. Although, the variation in means between the two depths was close enough to the variation in means within the two depths to indicate a possible sampling error. While this analysis does not definitively rule out the possibility that the higher touch counts in the 4-inch depth were due to sampling error alone, it also does not reject the possibility that depth did influence the amount of total touch counts. This appears to support the hypothesis that depth is an important determining factor in vegetative cover of extensive vegetated roof modules, although, the level of statistical significance cannot conclusively conclude in support of the substantive hypothesis. On this point, we have failed to reject the null hypothesis.

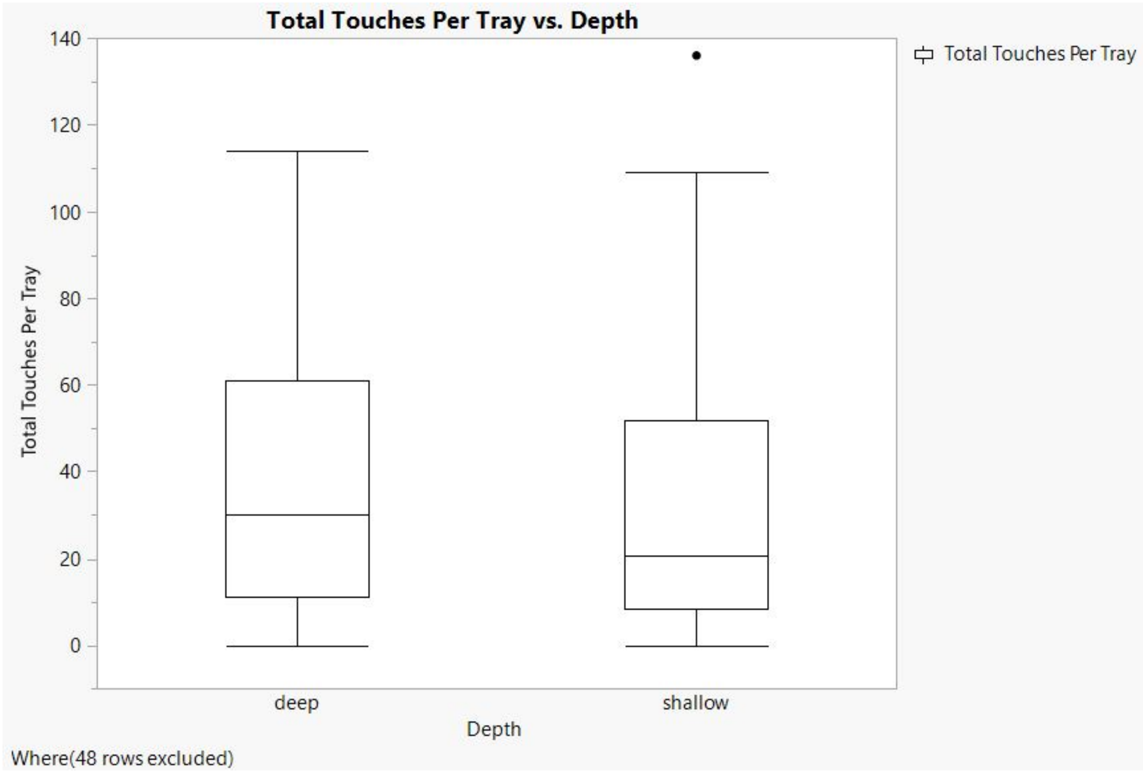

Figure 9. Box and Whisker Plot of Vegetated Cover vs. Depth

Interaction Between Mean Vegetative Cover and Substrate Composition

No statistically significant difference in means was observed between the two substrate compositions, $F(1,398) = .84$, $p = .359$. This finding suggests that it may be possible to trial plant species in even less organics in the future. As fewer organics makes for a more stable, lighter and less polluting substrate, and these plant species displayed little differences in mean vegetative cover between the two compositions, it may be desirable to see how low organics can go before mean vegetative cover is conclusively impacted.

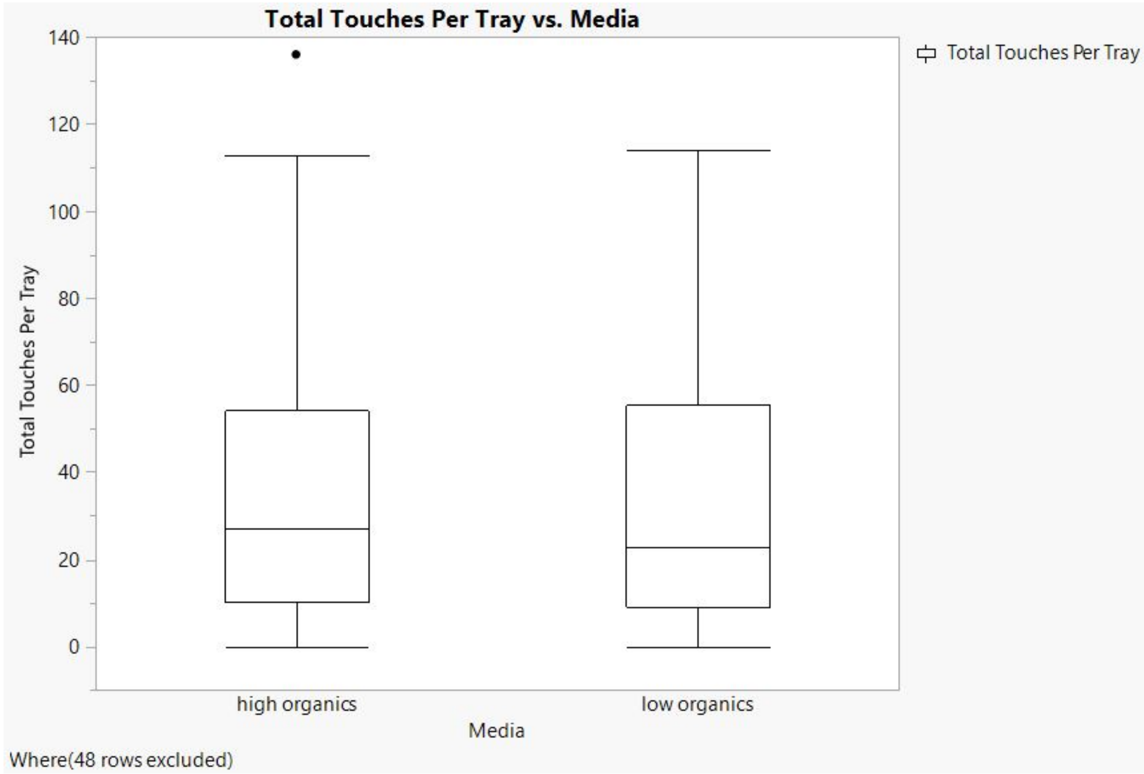

Figure 10. Box and Whisker Plot of Vegetated Cover vs. Media Composition

Interaction Between Mean Vegetative Cover and Location

There is no statistically significant difference in mean vegetative cover between location blocks, $F(1,398) = 2.57$, $p = .109$. This supports the conclusion that the interaction of deep planting media (4 inches) and low organics (10%), alone contributed to the increased vegetative cover and was not a result of location or siting.

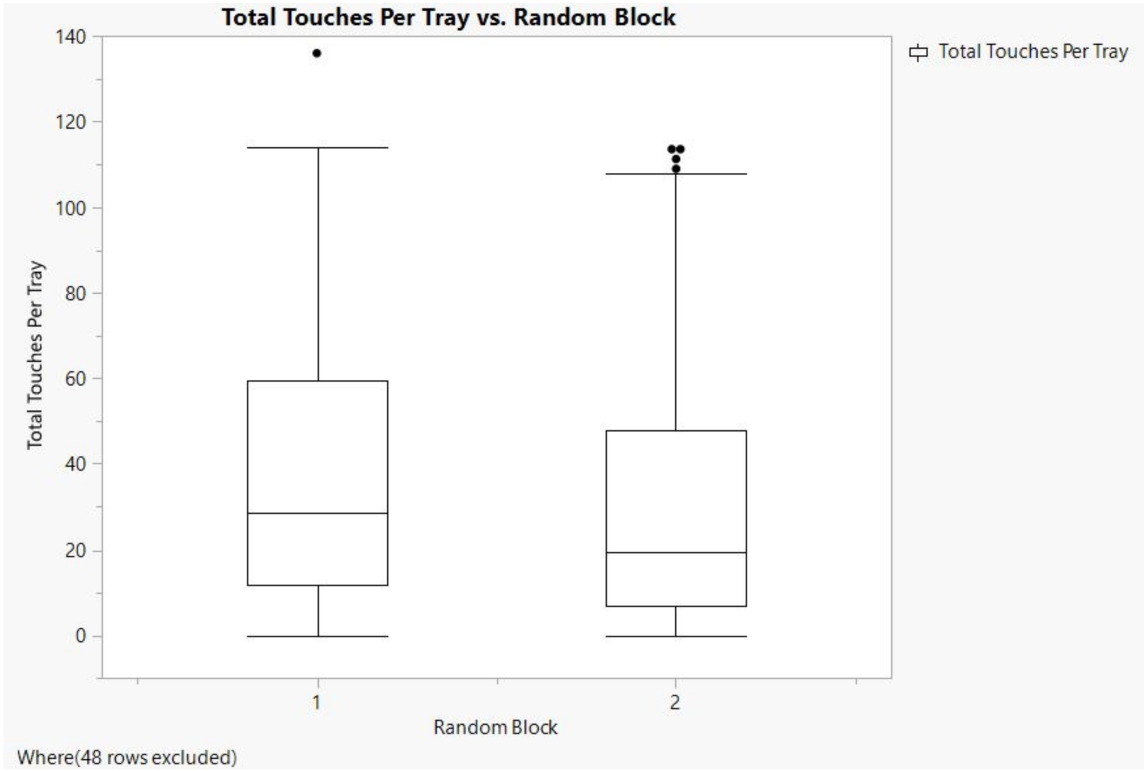

Figure 11. Box and Whisker Plot of Vegetated Cover vs. Location Block

Plant Survival

Packera tomentosa, $F(3,48) = 2.95$, $p = .042$, and *Oenothera fruticosa,* $F(3,48) = 3.67$, $p = .019$, both showed statistical significance favoring deep planting media (4 inches) when an analysis of means compared the interaction of planting depth and media on plant survival totals taken during November sampling. The other six species exhibited no statistically significant preference between the two depths.

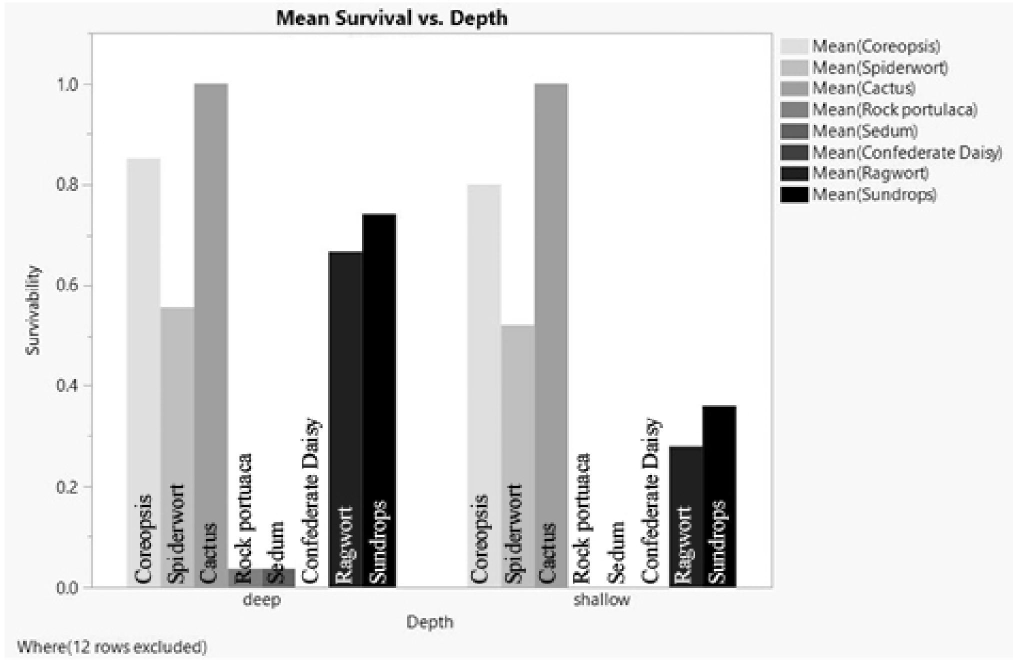

Figure 12. Bar Chart of Plant Species Survival vs. Substrate Depth

Furthermore, Substrate composition did not demonstrate any statistically significant difference in means between the two compositions and their impact on any of the eight species' plant survival rates.

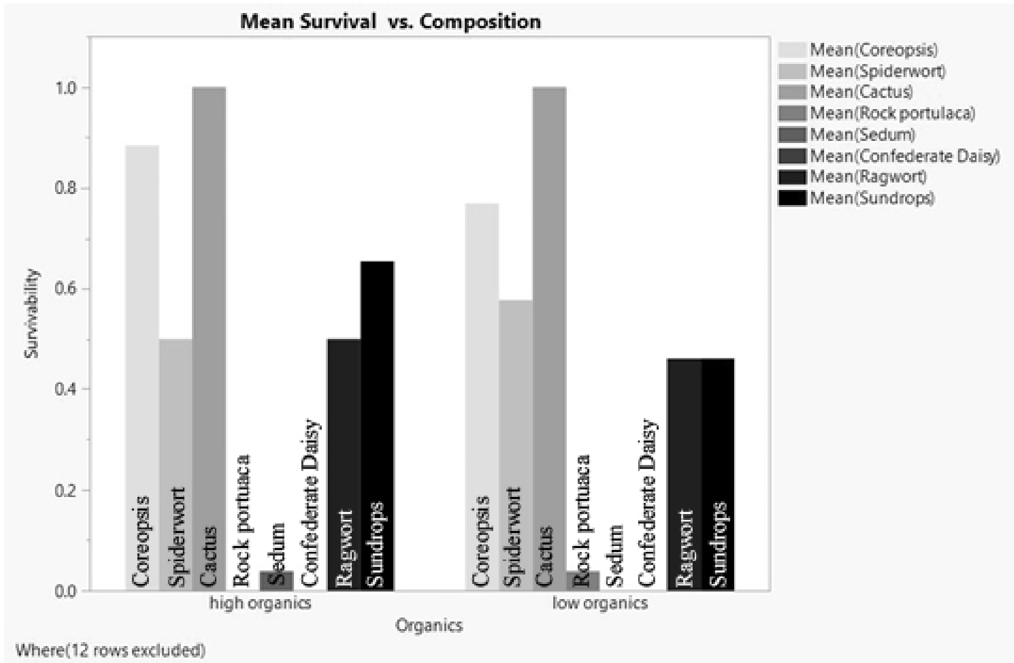

Figure 13. Bar Chart of Plant Species Survival vs. Substrate Composition

Discussion

By observing the effects of eight combinations of extensive vegetated roof conditions on eight species of granite outcrop plants, we identified optimal species and substrate combinations for a variety of vegetated roof goals and scenarios. Furthermore, while some individual species may have outperformed others, it is recommended that vegetated roofs be designed with the intentions of both performance and resilience in mind. A high diversity of plant species will insure the most resilient vegetated roof (Niemala 2014). Likewise, the more diverse the vegetated roof, the more opportunity for plant conservation and development of habitat microrefugia.

Aesthetic appeal and plant form are also important considerations in vegetated roof planting design, as research on the psychological benefits of the scenic quality of vegetated roofs demonstrates (Nurmi et al. 2016). Thus, the results of this study on plant performance should be considered with all factors in mind during the vegetated roof design process.

While November's plant survival data indicates that substrate composition has no statistically significant impact on plant survival, and substrate depth exhibited no statistically significant impact on survival in all but two cases, *Packera tomentosa* and *Oenothera fruticosa*, we recommend caution when drawing any conclusions on ultimate plant survival viability in any of these circumstances. The varying life cycles of granite outcrop plant species studied in this trial means that certain species enter periods of dormancy following spring and summer bloom periods. The data collection, which ended in November, was limited by the length of this study. Although some species, such as *Phemeranthus teretifolius* and *Helianthus porteri*, may have appeared dead during November's monitoring window, it is likely that they were either dormant, in the case of *Phemeranthus*, or will re-emerge from seed in the case of an annual like *Helianthus*. In fact, one of the many aesthetic benefits offered by granite outcrop plant species to vegetated roofs, especially when planted diversely, are the successive bloom periods and all-season interest (Edwards et al., 2013). Davidson-Arabia Mountain Nature Preserve, a granite outcrop in DeKalb county, Georgia, is prized for the striking seasonal interest offered by its granite outcrop plant species from spring, when outcrops are contrasted between swaths of bright, red elf-orpine and yellow woolly ragwort, to summer's yellow blooms of coreopsis and sundrops, fall's blazing star and confederate daisies and winter's vibrant mosses and lichens (2013). As one species fade, another is just coming into bloom.

While all *Opuntia mesacantha* survived the plant trial, this species was underrepresented in touch counts. This is due to a limitation in the chosen plant sampling method, as it favored wider-spreading species. Bushier species have an increased likelihood of encountering a pin drop during plant sampling events due to the nature of their form, especially when compared to the more compact form of *Opuntia*. It may be worth considering planting fewer herbaceous species in granite outcrop vegetated roof plantings as there is anecdotal evidence that their bushier form may cast shade over smaller, more prostrate species, slowing their growth. For example, *Coreopsis grandiflora* and *Helianthus porteri* were so successful, and exhibited such comparatively high survival rates, that we feel their numbers can be successfully cut back without impacting vegetation density.

2018 was an exceptionally wet year. According to the National Oceanic and Atmospheric Association, Athens, Georgia experienced a total of 69.26 inches of rain over the course of the year. The thirty-year average for Athens is only 46.33 inches (1981-2010). With a difference of almost twenty-three inches, plant growth and survival may have been impacted, especially considering the lower-water use typical of granite outcrop plant species in the wild.

In summary, granite outcrop extensive vegetated roofs exhibit potential for survival in the Piedmont region of Georgia. This potential is exciting for two reasons, the possibility vegetated roofs offer to the expansion of granite outcrop plant habitat, as well as the ecosystem service increases these native plants would provide over conventional, sedum-planted vegetated roofs.

Recommended Vegetated Roof Design

The following section discusses a recommended extensive vegetated roof design for a site in Athens, Georgia. 1021 North Chase Street is currently Maepole restaurant, a healthy, fast-casual dining option in the Historic Boulevard neighborhood. This site was chosen because the restaurant is currently in need of a new roof, and an extensive vegetated roof retrofit may be a feasible option. Furthermore, owners are concerned with increasing sustainability in the small-business community of Athens, having already taken steps to use only compostable food and beverage containers, and are taking additional steps to organize for a city-wide composting service and a sustainable business-owners’ committee.

Figure 14. Proposed Granite Outcrop Vegetated Roof Site

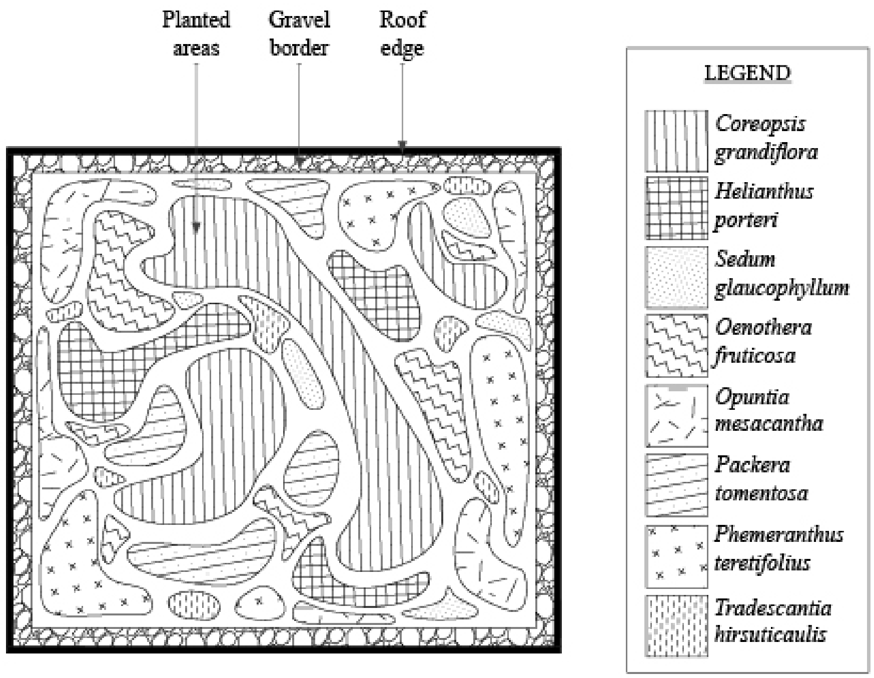

Figure 15. Granite Outcrop Vegetated Roof Planting Plan

The proposed planting plan features all eight of the granite outcrop plant species trialed over the course of this experiment. Observations made during the duration of the trial informed the size of planting groups and their placement on the roof with respect to their visibility from the ground, their relationship to one another and their preferences for a protected interior vs. the higher exposure of an edge environment. In general, the taller species are clustered more toward the roof interior, where they would cast less shade on other species, although, as some species seemed to benefit from the protection of bushier species during the hottest part of the summer, this was not a rule. Furthermore, as plants occur in clusters on natural rock outcrops, likely a result of the specialization of certain plant species to pockets of varying soil depths, this clustering organization was mirrored in the planting plan. Plant habit observed during the experiment seemed to confirm this tendency as most species naturally formed clumps within the modules. Therefore, the planting plan emphasizes this plant characteristic by specifying species masses rather than individual plants.

Opuntia mesacantha is specified primarily near the roof edge. In this location, the prostrate, slow-growing species is less at risk of being shaded-out by more herbaceous species like *Coreopsis* and *Helianthus*. Also, as this is an evergreen, the edge placement will supply visual interest during all seasons when viewed from the ground, especially in spring when *Opuntia* is topped by enormous yellow blooms.

Tradescantia hirsuticaulis was observed to be an incredibly fast colonizer during the experiment. One or two grass-like blades were planted in each module at the beginning of trial, and subsequently grew into approximately five-inch clumps over the growing season. This species is specified in small clusters throughout the roof. It remains evergreen through the winter, taking on shades of bronze and olive in its leaves, and is topped by small purple flowers each spring. *Tradescantia* did not seem to mind the shade offered by shrubbier species during the plant trial, and so is clumped somewhat uniformly across the rooftop, although many clumps are placed near the edge where they will be visible from the ground, as this species is somewhat shorter than others.

Phemeranthus teretifolius is planted in large swaths. When in bloom, this plant is incredibly beautiful, with small, magenta flowers suspended in a dense cloud high above the succulent-like leaves on fine, airy stems. The texture, color and movement this plant creates is stunning, and blooms last from early spring through summer. *Phemeranthus* was massed in large clusters for dramatic visual impact. *Phemeranthus* appeared to prefer sunnier areas when tested in the vegetated roof modules, so it is specified adjacent to species of similar height and near rooftop edges.

Packera tomentosa is planted in medium-sized clumps toward the interior of the vegetated roof. This species exhibited a preference for deeper planting substrate, and did not seem to mind the summer shade offered by taller, shrubbier species. Leaves remain evergreen and spread to form clumps of erect leaves with a somewhat silver, fuzzy appearance. In spring, thick stalks bloom with bright yellow flowers.

Oenothera fruticosa is grouped toward the roof interior as it also appears to prefer deeper substrate. Masses are somewhat smaller than Packera as the texture of *Oenothera* leaves is much finer. The smaller clumps balance well with the delicacy of the leaves and flowers, and the cluster size allows them to be spread throughout the entirety of the roof, adding dynamism to the somewhat uniformly low habit of the other spring-blooming species. Flower stalks support buttery yellow, cup-shaped blooms.

Sedum glaucophyllum is grouped in small pockets. As we did not have much success with this species during the plant trial, we did not rely too heavily on *Sedum* in the planting design. Anecdotal evidence suggests that this species may have been shocked by the sudden exposure of a full-sun environment when planted on roof modules, as it was first propagated in a friendlier, greenhouse environment. Leaf yellowing early in the growing season was the first sign that this species was not adjusting. Furthermore, the extremely wet year may have also played a role in the lack of plant success, as sedum usually prefer drier conditions. It was ultimately decided to give this species another chance, while offering it some protection tucked in pockets of other plant species, as the unusual yearly rainfall may have skewed survival during the trial.

Helianthus porteri is massed in three groups near the roof interior. This species was incredibly successful in the vegetated roof modules, possibly to the detriment of other species that were heavily shaded under its dense foliage. For this reason, it is predominantly grouped near *Coreopsis*, another tall, dense species. Furthermore, these plants seemed to complement one another in their growth cycles, with *Coreopsis* offering shade to the young vulnerable *Helianthus*. As *Helianthus* caught up to *Coreopsis* in size, *Coreopsis* was just finishing its bloom cycle, and the *Helianthus* blooms seemed to begin right as *Coreopsis* was fading. Interestingly, as *Helianthus* faded in the fall, *Coreopsis* experienced a second flush of flowers. The proximity of these species to one another on the rooftop will serve to protect the other, lower growing species from their dense shade, and offer the longest bloom period and most dramatic visual interest.

Coreopsis grandiflora is massed in swaths through the center of the vegetated roof plan. These flowers were the tallest, and some of the longest-lasting. In fact, basal leaves remained evergreen, and even appeared to grow denser, in the fall and winter. Flowers will still be easily visible from the ground when planted in the roof interior, as they occur atop tall, airy stems. Dense yellow blooms put on a dramatic show for much of the growing season.

This vegetated roof plan is designed to provide seasonal interest to customers and for the enjoyment of the restaurant staff and neighborhood. As there is a new mixed-use development slated for construction less than a mile away on Miles Street, along with an expanded Creature Comforts brewery, this area will be gaining significant visibility from the addition of apartments, retail and office space. Additionally, the aesthetic appeal of the planting design may inspire educational potential, and raise awareness about granite outcrop plant species, native plants in general, and help encourage more businesses to take an interest in sustainable practices.

Future Research

Future research should continue to monitor plant survivability on extensive roof modules as long-term studies are lacking, and plant growth may be limited by diminishing availability of micronutrients over the roof's lifespan (Sutton 2008).

Assessments on the potential spread and pollination support provided by arthropod populations is needed in order to make recommendations for long term population success. The role of arthropods in seed dispersal and consumption, and their impact on plant survival in various sized conditions will assist in developing long term plant microrefugia (Shure, 1999). Future studies should incorporate observations on arthropod visitation and interactions with granite outcrop plants species planted in extensive vegetated roof modules to fill the gap in this knowledge.

Plant survival data-collection, in particular, should be continued. As was discussed previously, the nature of granite outcrop plant species' life cycles means that some species may appear lifeless when they are in fact only dormant. Data collected on survival over the course of this trial can be used for comparison to future data collection on species survival rates. When compared monthly over several years, a clearer picture of the distinction between those plants that are dead and those that just appear so may begin to emerge.

Future granite outcrop plant species trials might also consider incorporating local mycorrhizal fungi inoculation of the growing medium. A study on prairie plant community establishment on extensive vegetated roofs showed promising results when combining inoculation with various extensive vegetated roof substrate mixes, when past studies on the same plant species had been either inconclusive or unsuccessful (Sutton 2008). Local microbial communities may assist plant species in nutrient cycling, and water uptake, positively contributing to growth, establishment and long-term vegetated roof success.

Weaknesses in the point-intercept plant monitoring technique, namely the underrepresentation of slow growing and prostrate species in vegetative cover data, should lead future researchers to consider alternative sampling techniques. Researchers have recently embraced multi spectral drone technology for field data collection, and as this technology further develops and becomes less expensive and more user-friendly, this technique may show potential for similar vegetated roof plant trials.

As there are many plant populations at risk due to human development and climate change, we see an opportunity for further research on the potential of vegetated roofs to serve as temporary microrefugia for these threatened populations. While it is unlikely all threatened plant communities will have as many microenvironmental parallels between their natural ecology and the rooftop environment, it is worth considering the site-specific environments offered by different rooftops in different locations, elevations and cultures across the world, and the support they may offer to species in need of refuge.

CHAPTER 5

CONCLUSION

The information gleaned from this research project will help shape future vegetated roof infrastructure projects in our region. Currently, a lack of studies surrounding Southeastern native plants in vegetated roof design exist, and non-native sedums have long-dominated the green roof landscape. The widespread use of sedums in vegetated roof designs is likely a carry-over from Europe, where research has focused on plant species suited to their own unique environmental and climactic conditions (Dvorak 2010). In Georgia, where summers are hot and humid and winters are brief and wet compared to those in Northern Europe, vegetated roofs require plant species adapted to Southeastern North America's climate. Based on one year of research, albeit an exceptionally wet year, granite outcrop plant species have proven they have the potential to flourish in place of sedums in vegetated roof plantings in our region.

Four-inch substrate low in organic matter (10%) was shown to elicit the highest mean vegetative cover, suggesting its use as the optimal substrate combination for roof success. Research surrounding the use of other granite outcrop plant species in vegetated roof designs should continue and expand, as higher plant diversity will contribute to more resilient vegetated roof designs, which will in turn provide more ecosystem services. Furthermore, potential plant safeguarding offered by vegetated roofs is especially exciting. This research will hopefully encourage further exploration of opportunities to extend refugia into urban landscapes, which may not already be considered.

Continued research and support are fundamental to building a clearer picture of the potential of extensive vegetated roofs populated with granite outcrop plant species, and their true potential and applicability in the unique North American climate and urban landscape over the long-term. This data, once completed, will spur more informed vegetated roof designs, more confidence in their long-term sustainability and, hopefully, the extension of granite outcrop plant habitat. Ultimately, the success of vegetated roofs is dependent on the survival of the plant species growing atop it.

REFERENCES

2018. "68% of the World Population Projected to Live in Urban Areas by 2050, Says UN DESA Department of Economic and Social Affairs." United Nations. Accessed March 17, 2019. https://www.un.org/development/desa/en/news/population/2018-revision-of-world-urbanization-prospects.html.

Bai, Wei-Ning, and Da-Yong Zhang. 2015. “Small Effective Population Size in Microrefugia?” *Journal of Systematics and Evolution*, no. 2: 163. doi:10.1111/jse.12128.

Bennett, Joseph R. and Arcese, Peter. 2013. “Human Influence and Classical Biogeographic Predictors of Rare Species Occurrence.” *Conservation Biology* 27 (2): 417. doi:10.1111/cobi.12015.

Bonham, C. D. 1989. *Measurements for Terrestrial Vegetation*. New York, NY: John Wiley and Sons.

Bowsher, Alan W., Scott D. Gevaert, and Lisa A. Donovan. 2016. “Field Performance and Common-Garden Differentiation in Response to Resource Availability in

Helianthus Porteri (A. Gray) Pruski, a Granite-Outcrop Endemic.” *Southeastern Naturalist* 15 (3): 467. doi:10.1656/058.015.0308.

Buehler, Ralph, Arne Jungjohann, Melissa Keeley, and Michael Mehling. 2011. “How Germany Became Europe’s Green Leader: A Look at Four Decades of Sustainable Policymaking.” *Solutions Journal* 2 (5): 51–63. http://proxy-remote.galib.uga.edu/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=eih&AN=67474977&site=eds-live.

Burbanck, Madeline P. and Robert B. Platt. 1964. “Granite Outcrop Communities of the Piedmont Plateau in Georgia.” Ecology 45 (2): 292. doi:10.2307/1933842.

Butler, Colleen, Erin Butler, and Colin 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.

Claire Farrell, Christopher Szota, Nicholas S. G. Williams, and Stefan K. Arndt. 2013. “High Water Users Can Be Drought Tolerant: Using Physiological Traits for Green Roof Plant Selection.” *Plant and Soil* 372 (1/2): 177. doi:10.1007/s11104-013-1725-x.

Connelly, M., and M. Hodgson. 2015. “Experimental Investigation of the Sound Absorption Characteristics of Vegetated Roofs.” *Building and Environment* 92 (October): 335–46. doi:10.1016/j.buildenv.2015.04.023.

DeNardo, J. C., A. R. Jarrett, H. B. Manbeck, D. J. Beattie, and R. D. Berghage. 2005. “Stormwater Mitigation and Surface Temperature Reduction by Green Roofs.” *Transactions- American Society of Agricultural Engineers*. http://proxy-remote.galib.uga.edu/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=edsbl&AN=RN174961424&site=eds-live.

Donald J. Shure, and Harvey L. Ragsdale. 1977. “Patterns of Primary Succession on Granite Outcrop Surfaces.” *Ecology* 58 (5): 993. doi:10.2307/1936920.

Dunnett, Nigel, and Noël Kingsbury. 2008. *Planting Green Roofs and Living Walls*. Portland, OR: Timber Press, 2008.

Durhman, A. K., D. B. Rowe, and C. L. Rugh. 2007. “Effect of Substrate Depth on Initial Growth, Coverage, and Survival of 25 Succulent Green Roof Plant Taxa.” *Hortscience*.

Dvorak, Bruce, and Astrid Volder. 2010. “Green Roof Vegetation for North American Ecoregions: A Literature Review.” *Landscape & Urban Planning* 96 (4): 197–213. doi:10.1016/j.landurbplan.2010.04.009.

Dwivedi, Aparna, and Buddhiraju Krishna Mohan. 2018. "Impact of Green Roof on Micro Climate to Reduce Urban Heat Island." *Remote Sensing Applications: Society and Environment* 10 (April): 56–69. doi:10.1016/j.rsase.2018.01.003.

Edwards, Leslie, Jonathan Ambrose, L. Katherine Kirkman, Hugh O. Nourse, and Carol Nourse. 2013. *The Natural Communities of Georgia*. Athens : University of Georgia Press, ℗♭2013.

Elzinga, Caryl L., Daniel W. Salzer, and John W. Willoughby. 1998. *Measuring & Monitoring Plant Populations* [Electronic Resource] / Authors, Caryl L. Elzinga, Daniel W. Salzer, and John W. Willoughby. Technical Reference (United States. Bureau of Land Management): 1730-1. [Denver, Colo. : U.S. Dept. of the Interior, Bureau of Land Management, National Applied Resource Sciences Center, 1998. http://proxyremote.galib.uga.edu/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=edsgpr&AN=edsgpr.000638216&site=eds-live.

Emilsson, Tobias. 2008. "Vegetation Development on Extensive Vegetated Green Roofs: Influence of Substrate Composition, Establishment Method and Species Mix." *Ecological Engineering* 33 (January): 265–77. doi:10.1016/j.ecoleng.2008.05.005.

Eriksson, Charlotta, Theo Bodin, and Jenny Selander. 2017. “Burden of Disease from Road Traffic and Railway Noise – A Quantification of Healthy Life Years Lost in Sweden.” *Scandinavian Journal of Work, Environment & Health* 43 (6): 519–25.

Gabrych, Małgorzata, D. Johan Kotze, and Susanna Lehvävirta. 2016. “Substrate Depth and Roof Age Strongly Affect Plant Abundances on Sedum-Moss and Meadow Green Roofs in Helsinki, Finland.” *Ecological Engineering* 86 (January): 95–104. doi:10.1016/j.ecoleng.2015.10.022.

Getter, K. L., and D. B. Rowe. 2006. “The Role of Extensive Green Roofs in Sustainable Development.” *HORTSCIENCE* 41 (5):1276-1285.

Godfrey, Michael A. 2012. *Field Guide to the Piedmont*. [Electronic Resource] : The Natural Habitats of America’s Most Lived-in Region, from New York City to Montgomery, Alabama. Chapel Hill : The University of North Carolina Press, 2012. http://proxy-remote.galib.uga.edu/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=cat06564a&AN=uga.9913727606102931&site=eds-live.

Godt, Mary Jo W. , and J. L. Hamrick. 1993. “Genetic Diversity and Population Structure in Tradescantia Hirsuticaulis (Commelinaceae).” *American Journal of Botany* 80 (8): 959. http://proxy-remote.galib.uga.edu/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=edsjsr&AN=edsjsr.2445517&site=eds-live.

Hanley, Thomas. 2006. “Piedmont Geologic Province.” *New Georgia Encyclopedia*. Last modified August 10, 2018. https://www.georgiaencyclopedia.org/articles/science-medicine/piedmont-geologic-province.

Harzmann, Uwe. 2002. German green roofs. In Proceedings of the 1st Annual Green Roof Construction Conference, Chicago, Illinois. Roofscapes, Inc.

Holt, Martin P., 2018. “Analysis of Variance (ANOVA).” *Salem Press Encyclopedia of Science*.

Kahn, Peter H., Jr. 1997. “Developmental Psychology and the Biophilia Hypothesis: Children’s Affiliation with Nature.” *Developmental Review* 17 (1): 1–61. http://proxy-remote.galib.uga.edu/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=eric&AN=EJ541623&site=eds-live.

Kaplan, Rachel, and Stephen Kaplan. 1995. *The Experience of Nature : A Psychological Perspective*. Ann Arbor, MI : Ulrich’s Bookstore, 1995.

Keppel, Gunnar, Karel Mokany, Grant W. Wardell-Johnson, Ben L. Phillips, Justin A. Welbergen, and April E. Reside. 2019. “The Capacity of Refugia for Conservation Planning under Climate Change.” *Frontiers In Ecology And The Environment* 13 (2): 106–12. Accessed March 23. doi:10.1890/140055.

Kiedrzyaski, Marcin, Katarzyna M. Zieliaska, Edyta Kiedrzyaska, and Agnieszka Rewicz. 2017. “Refugial Debate: On Small Sites According to Their Function and Capacity.” *Evolutionary Ecology*, no. 6: 815. doi:10.1007/s10682-017-9913-4.

Kinney, Patrick, Joyce Rosenthal, Kim Knowlton, Cynthia Rosenzweig, Richard Goldberg, Barry Lynn, Christian Hogrefe, et al. 2004. “Assessing Potential Public Health and Air Quality Impacts of Changing Climate and Land Use in Metropolitan New York: A Study by the New York Climate & Health Project.” *Columbia Earth Institute Report*. http://nrs.harvard.edu/urn-3:HUL.InstRepos:12775262

Kissel, David E. and Sonon, Leticia. 2008. “Soil Test Handbook for Georgia.” Athens, GA: Georgia Cooperative Extension.

Klein, Petra M., and Reid Coffman. 2015. “Establishment and Performance of an Experimental Green Roof under Extreme Climatic Conditions.” *Science of the Total Environment* 512–513 (April): 82–93. doi:10.1016/j.scitotenv.2015.01.020.

Kohler M., and M. Keeley. 2005. “Berlin: Green roof technology and development.” In *Earth Pledge*, 108-112. Atglen, Pa: Schiffer Books

Ksiazek, Kelly, Jeremie Fant, and Krissa Skogen. 2012. “An Assessment of Pollen Limitation on Chicago Green Roofs.” *Landscape and Urban Planning* 107 (September): 401–8. doi:10.1016/j.landurbplan.2012.07.008.

MacIvor, J. Scott, and Jeremy Lundholm. 2011. “Performance Evaluation of Native Plants Suited to Extensive Green Roof Conditions in a Maritime Climate.” *Ecological Engineering* 37 (January): 407–17. doi:10.1016/j.ecoleng.2010.10.004.

Marcus, Clare Cooper, and Marni Barnes. 1999. *Healing Gardens: Therapeutic Benefits and Design Recommendations*. Wiley Series in Healthcare and Senior Living Design. New York: Wiley.

Murdy, William H., and M. Eloise Brown Carter. 2000. *Guide to the Plants of Granite Outcrops*. Athens : University of Georgia Press.

Nawaz, R., McDonald, A., Postoyko, S., 2015. “Hydrological Performance of a Full Scale Extensive Green Roof Located in a Temperate Climate.” *Ecological Engineering* 82, 66–80.

Niemelä, Jari. 2014. “Research Paper: Ecology of Urban Green Spaces: The Way Forward in Answering Major Research Questions.” *Landscape and Urban Planning* 125 (May): 298–303. doi:10.1016/j.landurbplan.2013.07.014.

Novotney, Amy. 2011. “Silence, Please.” *Monitor on Psychology* 42 (7): 46

Nurmi, Vaino, Athanasios Votsis, Adriaan Perrels, and Susanna Lehvavirta. 2016. “Green Roof Cost-Benefit Analysis: Special Emphasis on Scenic Benefits.” *Journal of Benefit-Cost Analysis* 7 (3): 488–522. doi:https://www-cambridge-org.proxy-remote.galib.uga.edu/core/journals/journal-of-benefit-cost-analysis/all-issues.

Osmundson, Theodore. 1999. *Roof Gardens: History, Design and Construction*. New York, NY: W. W. Norton and Company, Inc.

Poissonet, P. S., Poissonet, J. A. and Bodron, M. P. 1973. “A Comparison of Sampling Methods in Dense Herbaceous Pasture.” *Journal of Range Management* 26: 65-67.

Reade, Julian. "Alexander the Great and the Hanging Gardens of Babylon." *Iraq* 62 (2000): 195-217. doi:10.2307/4200490.

Rogers, McVaugh. 1943. "The Vegetation of the Granitic Flat-Rocks of the Southeastern United States." *Ecological Monographs* 13 (2): 119. doi:10.2307/1943526.

Rohde, C. L. E.; Kendle, A. D. 1994. *Human Well-Being, Natural Landscapes and Wildlife in Urban Areas: A Review*. England, UK: English Nature.

Salman, I. N. A., B. Schindler, H. Agra, O. Bawab, A. Friedman-Heiman, G. J. Kadas, M. Seifan, and L. Blaustein. 2018. "Green Roof Research towards Enhancing Urban Biodiversity, Storm-Water Retention and Air Pollution Abatement." *CAB Reviews* 13 (39): 1–14.

Santamouris, M. 2014. "Cooling the Cities – A Review of Reflective and Green Roof Mitigation Technologies to Fight Heat Island and Improve Comfort in Urban Environments." *Solar Energy* 103 (May): 682–703. doi:10.1016/j.solener.2012.07.003.

Scholz-Barth, Katrin. 2001. "Green Roofs: Stormwater Management From the Top Down." *Environmental Design & Construction*. http://proxy-remote.galib.uga.edu/login?url=http://search.ebscohost.com/login.aspx?direct=true&db=edsggo&AN=edsgcl.70976353&site=eds-live.

Sebba, Rachel. 1991. “The Landscapes of Childhood: The Reflection of Childhood’s Environment in Adult Memories and in Children’s Attitudes.” *Environment and Behavior* 23 (4): 395–422. doi:10.1177/0013916591234001.

Shure, Donald J. 1999. *Granite Outcrops of the Southeastern United States*. United States: Cambridge University Press: Cambridge, MA, United States.

Snodgrass, Edmund C., and Lucie L. Snodgrass. 2006. *Green Roof Plants : A Resource and Planting Guide*. Portland, Or: Timber Press, 2006.

Sutton, Richard K. 2008. "Media Modifications for Native Plant Assemblages on Extensive Green Roofs." Landscape Architecture Program: Faculty Scholarly and Creative Activity. 16. http://digitalcommons.unl.edu/arch_land_facultyschol/16

Tallamy, Douglas W. 2007. *Bringing Nature Home*. Portland, OR: Timberpress

Velazquez, Linda. 2011. “Current Green Roof Trends in Germany.” Greenroofs.com. https://www.greenroofs.com/2011/12/17/current-green-roof-trends-d/ (Accessed February 22, 2019).

Ware, Stewart, Susan E. Crow, and Benjamin A. Waitman. 2011. “Mode of Substrate Adaptation in Rock Outcrop Plants: Cyperus Aristatus Rottb. and Cyperus Granitophilus McVaugh.” *Castanea* 76 (4): 377–85. doi:10.2179/10-051.1.

Wilson, Edward O. 1984. *Biophilia*. Cambridge, Mass.: Harvard University Press.

Wolf, Derek, and Jeremy T. Lundholm. 2019. “Water Uptake in Green Roof Microcosms: Effects of Plant Species and Water Availability.” *Ecological Engineering* 33 (2): 179–86. Accessed March 23. doi:10.1016/j.ecoleng.2008.02.008.