Ecosystem Services on Green roofs in the Southeastern United States: Effects of Management, Age, and Other Variables

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Abstract

Widespread urbanization is causing land cover changes that have dramatic impacts on the structure and functions of natural ecosystems. To mitigate these impacts, green infrastructure (vegetated urban habitat) is implemented to improve environmental quality and protect crucial ecosystem services. As roofs can represent up to 32% of horizontal surfaces in a typical urban setting, they are ideal candidates for green infrastructure. However, despite their potential and growing implementation in cities across the world, green roofs remain very poorly researched, particularly regarding ecosystem services and management practices, compared to other kinds of green infrastructure. This study examines ecosystem services provided by green roofs in 13 urban locations across three states in the Southeastern United States: Asheville, NC; Atlanta, GA; Chattanooga, TN; Knoxville, TN; and Nashville, TN. The ecosystem services studied are assessed through proxies including invertebrate abundance and diversity, decomposition rate and stabilization factor, plant diversity and frequency, and substrate composition. Samples of each proxy, except substrate, were collected over the course of 6 months from March to August 2024. Management intensity (high and low) shows a statistical significance on several variables. High management has a negative on effect on plant and invertebrate biodiversity and a positive effect on soil decomposition rates. Also, soil moisture of the green roofs showed a significant negative effect plant diversity and positive effect on plant frequency. With inverse results for soil temperature on plant diversity. Individual maintenance practices such as irrigation, weeding, and chemical treatments only showed significance for a few proxies: decomposition rate, plant diversity and frequency, and OM levels. In general, roofs with lower levels of management exhibit higher biodiversity as compared to their high-management counterparts. This aligns with many other urban habitats, such as residential and commercial landscapes, where intensive management often aims to reduce biodiversity. Interestingly, decomposition rates show a significant increase with higher management. As green roofs in the United States are sparsely researched, this study helps examine the complexity of a green roof ecosystem and provide insight onto the best management practices to promote ecosystem services.

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Chapter 1. Introduction

1.1 Ecosystem Services in the Urban Environment

An ecosystem service (ES) can be defined simply as nature's benefits to humans (Boyd & Banzhaf, 2007), or what "humans gain from functioning ecosystems" (Ruppert & Duncan, 2017). These services have become more important in policy discussions as they articulate how "ecosystems are socially valuable in ways that may not be immediately intuited" (Boyd & Banzhaf, 2007). An ES directly or indirectly benefits human life and can be tangible or intangible (Ruppert & Duncan, 2017). In general, ES can be divided into four groups: provisioning, regulating, supporting and cultural services (Roeland et al., 2019; Tan et al., 2020). These services include, but are not limited to, nutrient cycling, decomposition, soil turnover, pest control, air and water regulation, and pollination (Gardiner et al., 2013; MacIvor & Ksiazek, 2015; Roeland et al., 2019).

ES are important to preserve and promote within urban environments as urban areas are projected to increase by 2050 to inhabit over two thirds of the world's population (Elmqvist et al., 2013; Roeland et al., 2019). Within the last 30 years, urban land has increased twice as fast as the urban population (Elmqvist et al., 2013; Zhang et al., 2017). Thus, important ES provided by natural habitats are being threatened by anthropogenic activities. As urbanization increases, land cover also changes, affecting the structure, processes, and functions of a natural habitat (Ouyang et al., 2021). Urban ecosystems are incredibly complex and dynamic systems that require an ecological perspective to promote ES (Lovell & Taylor, 2013).

To mitigate negative environmental impacts of urbanization, green infrastructure is often implemented to improve environmental quality, protect the remaining ES, and promote new ES (Beichler et al., 2017; Roeland et al., 2019). Green spaces play a critical role in "conserving biodiversity, protecting water resources, improving microclimate, sequestering carbon, and even supplying [fresh food to the urban community]" (Lovell & Taylor, 2013). Urban environments often only consist of mosaic green spaces limited to small, fragmented patches and corridors, such as parks, yards, and vacant lots (Lovell & Taylor, 2013). With roofs representing up to 32% of the horizontal surface of urban or built areas (Orberndorfer et al., 2007), this is a prime location for green infrastructure. While ES are dependent on the design choices of a green roof, they have the potential to fill a gap where ES are lacking within an urban area (Langemeyer et al., 2020).

1.2 What is a Green Roof?

1.2.1 The History Behind Green roofs in the United States

The modern idea of a green roof first appeared in 1867 at the World Expo in Paris (Abass et al., 2020). This model illustrated waterproofing and a drainage system, this was to be considered the first extensive green roof design (Abass et al., 2020). As improvements were made, including new materials and designs of drainage systems, many countries adopted the idea, starting with Germany, followed by Northern Europe and North America (Abass et al., 2020). As green roofs migrated from Europe to the United States research started in the 1960s to help generate a market for them in America by the 1970s (Snodgrass & Mcintyre, 2010).

In the United States the implementation of green roofs has been stunted by numerous policies and lack of incentives (Snodgrass & Mcintyre, 2010). The US EPA first started releasing green roof related documents in 2009, and only in the last decade have green roofs become a popular building feature in the United States (Shafique et al., 2018). This growing popularity has been facilitated by policies incentivizing building owners to incorporate a green roof in the construction of their building (Meyer & Trandafir, 2023). For example, New York state has proposed a bill called the Public-School Green Rooftop Program to fund the installation of green roofs on public school buildings (Meyer & Trandafir, 2023). Other policies in the United States are also being passed to catalyze the growth of the green roof infrastructure (Meyer & Trandafir, 2023). Green roofs have become increasingly more popular in the United States in recent years; however, much research is still lacking, especially in the Southeastern United States (Shafique et al., 2018).

1.2.2 Components and Maintenance of a Green roof

Green roofs are specially designed roofs planted with several different vegetation types on top of a substrate, or growth medium (Shafique et al., 2018). The goal is to generally improve a roof's appearance and ES performance (Snodgrass & Mcintyre, 2010). There are three main green roof typologies: 'extensive' = shallow growth medium and low-maintenance ground cover, 'intensive' = deep growth medium with full garden, comparable to ground-level parks, and 'semi-intensive'= medium depth growth medium with a mixture of extensive and intensive plants (MacIvor & Lundholm, 2010; Snodgrass & Mcintyre, 2010; Shafique et al., 2018;

Cascone, 2019; Langemeyer et al., 2020). Green roofs are comprised of six layers: a waterproofing layer, storage layer, drainage layer, filter layer, substrate, and vegetation layer (UChicago, n.d.; Shafique et al., 2018; Cascone, 2019; Nguyen et al., 2021). These layers are illustrated below in ***Figure 1*** (UChicago, n.d.). A waterproofing layer protects the building underneath from leakage issues and drainage and a storage layer is utilized to divert and store water. The root-permeable filter layer allows for the roots to reach the water storage while also preventing the substrates from sliding during rain events. Finally, the growing media and vegetation layer choices are made based on the climatic conditions of the region the roof will be built in (Leite & Antunes, 2023).

The growing medium of a green roof bears little resemblance to the soil found in a typical garden. For example, it is manufactured to have larger particle sizes making it coarser in texture, lightweight, structurally stable, and it is superior to most soils for long-term maintenance and permeability (Snodgrass & Mcintyre, 2010). It allows for consistent drainage and aeration, with a structure that holds water, makes necessary nutrients available for plants, and is resistant to decomposition and compression (Snodgrass & Mcintyre, 2010; Cascone, 2019; Kader et al., 2022). Sufficient plant nutrients must be present to support the plant community, while excess nutrients should be avoided to reduce over polluted runoff (Berghage et al., 2008). To date, green roof "substrate composition has yet to be fully optimized" (Goldschmidt & Buffam, 2023), with very little research done in a natural field setting, showing green roof substrate composition to be a novel aspect in the field of green roofs (Kader et al., 2022).

Plants suitable for green roofs are characterized by a shallow root system, low nutrient and maintenance requirements, and resistance to disease (Snodgrass & Mcintyre, 2010). The most popular genera for green roofs include *Sedum*, *Talinum*, *Delosperma*, and some cacti (Snodgrass & Mcintyre, 2010; Cascone, 2019; Leite & Antunes, 2023). These are ideal for a green roof ecosystem as they can conserve and store water in times of drought, which is frequent on a green roof (Snodgrass & Mcintyre, 2010). Different plant types are often considered for the different green roof types. Plants with shallow roots systems work best for extensive roofs and plants with deeper root systems are better suited for an intensive roof design (Leite & Antunes, 2023). The success of a green roof can be dependent on the design choices of construction, substrate, and plants.

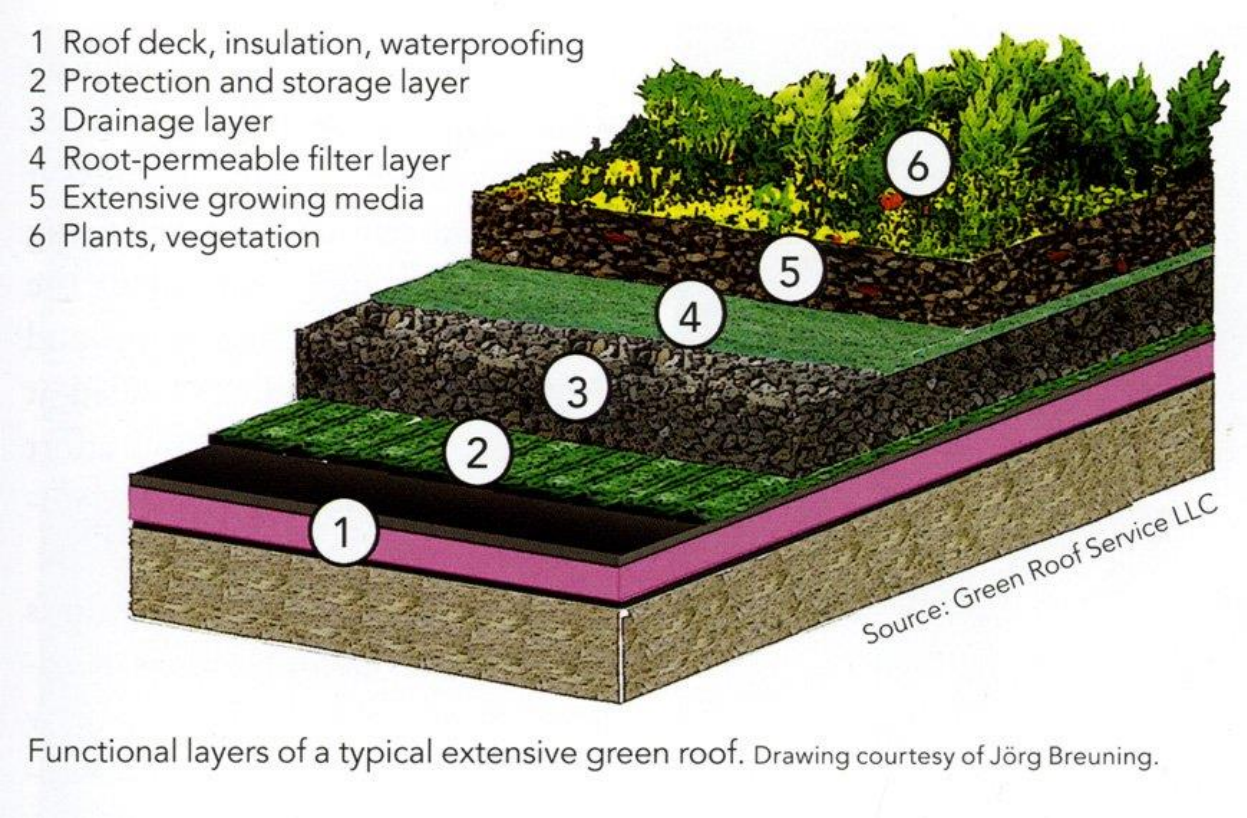

Figure 1 Image from Green Roof Service LLC illustrating the six layers of an extensive green roof. The layers start with the roof deck then build up to the vegetation layer.

1.2.3 Benefits and Challenges Associated with Green Roofs

Green roofs offer a wide range of benefits compared to a conventional roof, including environmental, social, and economic benefits (Nguyen et al., 2021). Primary ES that green roofs help promote are reduction in heat, reduction in runoff and peak flow during storm events, and provisioning habitat for urban wildlife (Snodgrass & Mcintyre, 2010; Shafique et al., 2018; Nguyen et al., 2021). In terms of ES, green roofs provide habitats for pollinators, thermal regulation of cities, and can provide a sense of social cohesion within a community (Langemeyer et al., 2020). Given that green roofs are not all created equal, it is important to study different ES proxies to get a diverse representation of ES on green roof. There are numerous benefits to green roofs, but it is also important to consider the challenges of a green roof especially in the knowledge of care and construction of green roofs (Joshi & Teller, 2021).

In ***Figure 2***, the Venn diagram, from a review of 739 papers of green roof benefits and challenges by Joshi & Teller (2021), outlines the challenges experienced in adopting green roofs. Joshi and Teller's (2021) review suggests a lack of understanding and awareness in many green initiatives as well as a lack of understand on how to maintain. It also suggests that, although there is potential for social acceptance of green roofs for their aesthetic designs, they are often unaffordable with potential for damage and additional costs in the future (Joshi & Teller, 2021). Another review of green roof papers outlining the benefits and challenges of green roofs found that many challenges in green roof implementation can be traced to research gaps involving costs, insufficient knowledge about construction mechanics, maintenance, and a lack of coordination between different disciplines (Shafique et al., 2018). Green roofs are a relatively understudied topic of the urban ecosystem especially in terms of ES (Langemeyer et al., 2020), with much of the research being done from small test plots in controlled environments and not on large established green roofs (Snodgrass & Mcintyre, 2010).

1.3 Proxies for Ecosystem Services

To study ES in a rigorous and quantifiable way, ES indicators, or proxies, are needed (Roeland et al., 2019). A review of 77 studies showed that many papers researching ES focused on taxonomic diversity, species richness and diversity as indicators for various kinds of ES (Schwarz et al., 2017). Other common ES indicators include physical and chemical conditions,

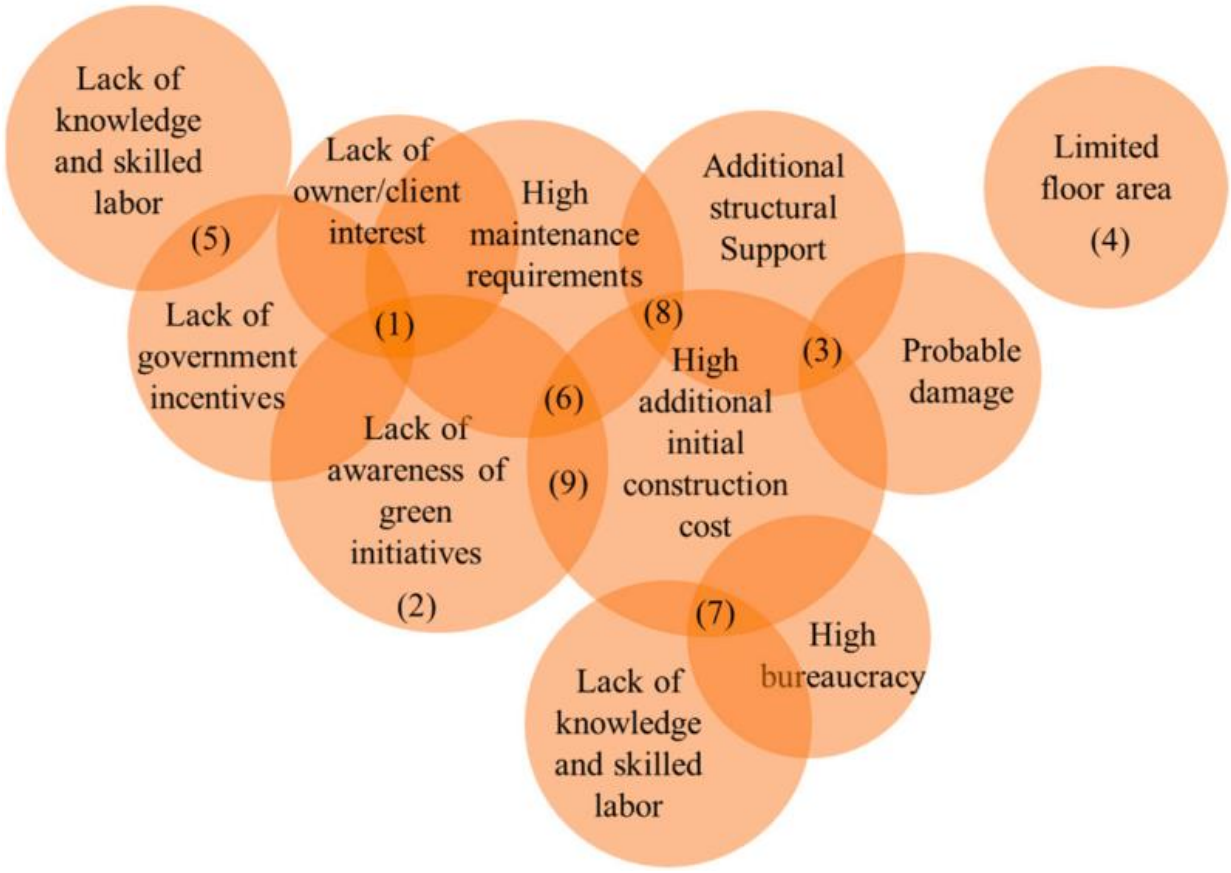

Figure 2 A Venn diagram produced by Joshi & Teller 2021 outlining the challenges observed in the adoptions of green roofs

plant cover, sequestered carbon, and abundance (Grima et al., 2023). As discussed below, ES of urban areas can be measured using diversity and abundance of invertebrates and plants. They can also be measured with soil composition and the rate at which litter decomposes. These proxies were chosen based on their simplicity to collect and wide range of previous research in the literature. They were also chosen based on their relevance to one type of service, supporting services.

1.3.1 Arthropod, Mollusk, and Annelid Diversity

Various invertebrates can be used as an ES proxy because they provide a key ecological role in terrestrial ecosystems such as economic and non-economic benefits in crop production (Noriega et al., 2018). It is widely accepted that ES provided by arthropods, such as pollination and pest control, provide many financial, food and health benefits to humans (MacIvor & Ksiazek, 2015; Noriega et al., 2018). Arthropods can also provide ES such as soil turnover, decomposition and nutrient cycling and they play an important role in local food webs (Gill et al., 2016). Recent studies document hundreds of arthropod species on green roof indicating how green infrastructure can contribute to regional biodiversity by providing resources to a variety of species (MacIvor & Ksiazek, 2015). Invertebrates such as mollusks and annelids also have key ecological roles as they fill many niches and are the globally abundant and diverse (Prather et al., 2012), and their acute responsiveness to climate changes helps us monitor and evaluate the rate of climate change (Prather et al., 2012). Terrestrial mollusks and annelids provide such ES as seed dispersal, pollination, decomposition, nutrient cycling, among many others (Prather et al., 2012). Quantifying diversity and abundance of these groups can thus serve as proxies for ES.

1.3.2 The Teabag Index

Decomposition rate can be used as a proxy for ES because decomposition provides carbon sequestration, reduction in soil erosion (Faucon et al., 2017), biogeochemical cycling, soil formation, greenhouse gas emissions (Guo et al., 2021), and can give insight into microbial activities within the soil community (Buchholz et al., 2017). Specifically, litter decomposition in urban environments can be a proxy for ES. However only a few studies have focused on plant litter globally and using a standardized method can help examine ES in urban areas as well as many other biomes, ecosystems, and soil types (Keuskamp et al., 2013). One standardized

method of calculating the decomposition rate and stabilization factor is known as the *teabag index* or the tea composition initiative. This index can show decomposition rate, how fast organic matter is broken down, and the stabilization factor, how much of that broken down matter is stored as carbon in the soil, of a specific location and soil. The *teabag index* utilizes the weight loss of green and rooibos tea over an incubation time to find this. This index is outlined by Keuskamp and others (2013) and has been implemented in a handful of studies to explore decomposition in natural environments (Buchholz et al., 2017; Guo et al., 2021). However, very little research has been conducted using this method to determine decomposition in urban environments or green roofs specifically.

1.3.3 Plant Diversity

Plant diversity is utilized as an ES proxy as the flora of an area can indicate many different ES (Robinson & Lundholm, 2012; Buchanan et al., 2020; Walston et al., 2021). These include a regulatory effect on urban climates (Lehmann et al., 2014), food production, raw materials, medicines, and decoration (Robinson & Lundholm, 2012). A study on how plant diversity can enhance ecosystem services shows that as plant diversity increases the amount of aboveground biomass increases which in turn provides more ES (Quijas et al., 2010). Plant diversity can also provide erosion control, resistance to plant invasions, regulation of plant pathogens, pollinator supply (Quijas et al., 2010; Walston et al., 2021), and nutrient cycling (Buchanan et al., 2020). Plant diversity is an excellent ES proxy as it encompasses all service types. Thus, it is important to promote a diverse plant community when designing green spaces. By looking at plant diversity over time in these urban areas, conclusions can be drawn about the changing health of the ecosystem and how green roofs can provide comparable services to that of a natural ecosystem.

1.3.4 Substrate Survey

Green roofs are an artificial environment that require the right substrate formula to ensure proper plant growth and survival (Krawczyk et al., 2021; Kader et al., 2022). Soils and substrates are a key component in water and nutrient cycling, providing pollution remediation and pollinator habitats (Vannucchi et al., 2021). Because of the increase in urbanization, soil disturbances such as compaction and pollution are common and inevitable (Vannucchi et al.,

2021). Green roofs are a way to bring the ES of soil back to the traditional non-green roof ecosystem. Studies have shown that green roof substrate composition is a direct determinant of plant species richness and diversity in the long-term (Harada & Whitlow 2020; Vannucchi et al., 2022; Kader et al., 2022; Van der Kolk et al., 2023). It is important for a green roof substrate to have proper nutrient loads to support plant growth, but to not have an overload which will increase the pollutants in runoff (Berghage et al., 2008). On green roofs specifically, it is not clear what a deficient, sufficient, or excessive nutrient content is, or what tests should be used to evaluate nutrient content (Berghage et al., 2008). A paper published by The Pennsylvania State University Department of Horticulture suggests a range of nutrient content levels to be shown as deficient, sufficient, or excessive (Berghage et al., 2008). Specifically, the organic matter content should be between 1-6% and pH between 6.5-7.8 (Berghage et al., 2008). Other nutrients are outlined in ***Table 1***, defining their low, desirable, and high ranges, as well as impacts from high levels. Substrate composition has value as an ES proxy as it can positively or negatively impact the roof, from plant growth and microbial activity to the performance of ES.

1.4 Research Question and Approaches

We aimed to answer two basic questions outlined below. In all cases, ES refers to the proxies measured in this study: invertebrate diversity and abundance, decomposition rate and stabilization factor, plant diversity and frequency, and substrate composition.

1. How do ES compare between management types (high or low) of green roofs in Asheville, Atlanta, Chattanooga, Knoxville, and Nashville?

H0. 1: There is no difference in ES between management types of the studied green roofs.

Ha. 1: Low management yields more ecosystem services on the studied green roofs.

2. How does green roof age and physical variables (e.g., soil temperature and moisture) affect the availability of ES over time in Asheville, Atlanta, Chattanooga, Knoxville, and Nashville?

H0. 2: There is no difference in ES at different ages and with different physical variables on the studied green roofs.

Ha. 2: There are more ecosystem services with age and different physical variables on the studied green roofs.

We have four parts and approaches based on collected data from green roofs in each of the five cities. They are outlined below in ***Table 2***.

Table 1 Adapted from Berghage et al., 2008, list of green roof nutrients outlining low, desirable, and high concentration ranges, with a comment on the effect of a high-level nutrient.

Nutrient	Low or deficient (mg/L)	Desirable range (mg/L)	High or toxic (mg/L)	Comments
Phosphorus	< 2.15	2.15 - 5.0+	> 5.0	High levels are not toxic but may contribute to nutrient runoff
Potassium	< 8.0	8.0 - 20.0	Unknown	High levels are not toxic but may contribute to nutrient runoff
Calcium	< 40.0	40.0 - 180.0	> 180+	High levels increase pH and inhibit uptake of Mg and other cations
Magnesium	< 11.0	11.0 - 53.0+	Unknown	High levels may not be toxic but may contribute to nutrient runoff
Boron	< 0.04	0.04 - 0.2+	> 0.2	High B is toxic to most plants
Copper	< 0.4	0.5 - 3.0	> 4.0	High levels may not be toxic but may contribute to nutrient runoff
Manganese	< 1.0	1.0 - 4.0+	> 17.0	Levels between 4 and 17 may not be toxic but may contribute to nutrient runoff
Sodium	None	0.0 - 20.0	> 20.0	High Na may promote moss and clover
Zinc	< 1.2	1.2 - 10.0	> 12.0	

Table 2 Outline of the approaches taken to analyze ecosystem services on the studied green roofs.

Part	Approach
1	Pitfall traps are set at all locations. Within each city, diversity and abundance is found. Data collected from the traps will answer questions about ecosystem services based on time, age, management, and other factors on green roofs in the Southeast U.S.
2	Teabags are buried at each of the locations. Decomposition rate and stabilization factor is then found. Data collected from the teabag index will answer questions about ecosystem services based on time, age, management, and other factors on green roofs in the Southeast U.S.
3	Plant sampling quadrat locations are set at all locations. Plant identification is done, then used to find precent frequency and diversity. Data collected from the plant survey will answer questions about ecosystem services based on time, age, management, and other factors on green roofs in the Southeast U.S.
4	Substrate samples are taken from each location. These samples will determine the soil composition. Data collected from the substrate samples will answer questions about ecosystem services based on time, age, management, and other factors on green roofs in the Southeast U.S.

Chapter 2. Methods

2.1 Pre-sampling

2.1.3 Management Review

In January 2024 thirty-five roofs were selected in five Southeastern US cities: Asheville, Atlanta, Chattanooga, Knoxville, and Nashville. These cities were chosen due to the drivable proximity of 2-3 hours from the University of Tennessee, Knoxville. Being larger cities allows for all the green roofs to be in a central location, making sampling more feasible. Access for research was secured through cold calls to each building, resulting in 13 of 35 contacted roofs accepting the research proposal to participate in this study.

Each green roof was surveyed regarding structural attributes, past, current, and future management practices. The survey questions (Appendix 1) were designed to classify each roof into one of two management classifications: high or low. High management is defined as regular irrigation of more than once a month and weeded every 3-12 weeks and low management occurred when the roof had little to no irrigation or weeding throughout the year.

The responses were compiled summarizing the management practices of each of the thirteen roofs are shown below in ***Table 3***, organized from highest to lowest management. This detailed categorization provided a foundation for analyzing the impact of different management practices on the ecosystem services provided by green roofs.

2.1.2 Study Area and Sample Size

The thirteen chosen locations are illustrated in ***Figure 4***, with red dots indicating their locations across the five cities. The specific green roof location details including acronyms and coordinates are outlined in Appendix 2.

Table 3 Summary of location information including age, size, elevation, substrate depth, and the different management practices. Each yes for management is scored as a 1 and no as a 0. Providing us with a score, where >2.5 indicates 'high' management and <2.5 indicates 'low' management.

Location	Age (years)	Size (ft2)	Elevation (stories)	Substrate depth (in)	Irrigation	Replant	Weed	Chemical treatment	Substrate addition	Mgmt. score	Mgmt. classification
MCC	14	191,000	9	2.5	yes	yes	yes	yes	yes	5	high
FW	15	5,000	3	5	yes	yes	yes	yes	no	4	high
RMH	9	2,200	1	4.25	yes	yes	yes	no	no	3	high
HCH	13	4,200	2	6	yes	yes	yes	no	no	3	high
GS	1	200	1	4	yes	yes	no	no	yes	3	high
ZEC	3	4,000	5	10	yes	no	yes	no	no	2	low
ABG	16	200	1	24	no	yes	yes	no	no	2	low
SF	15	1,200	2	6	no	no	yes	no	yes	2	low
SB	15	2,500	2	6	no	no	yes	no	no	1	low
BLR	19	9,000	1	6	no	no	no	yes	no	1	low
CCB	6	1,200	4	6	yes	no	no	no	no	1	low
LSH	16	200	1	4	no	no	no	no	no	0	low
GR	2	100	1	12	no	no	no	no	no	0	low

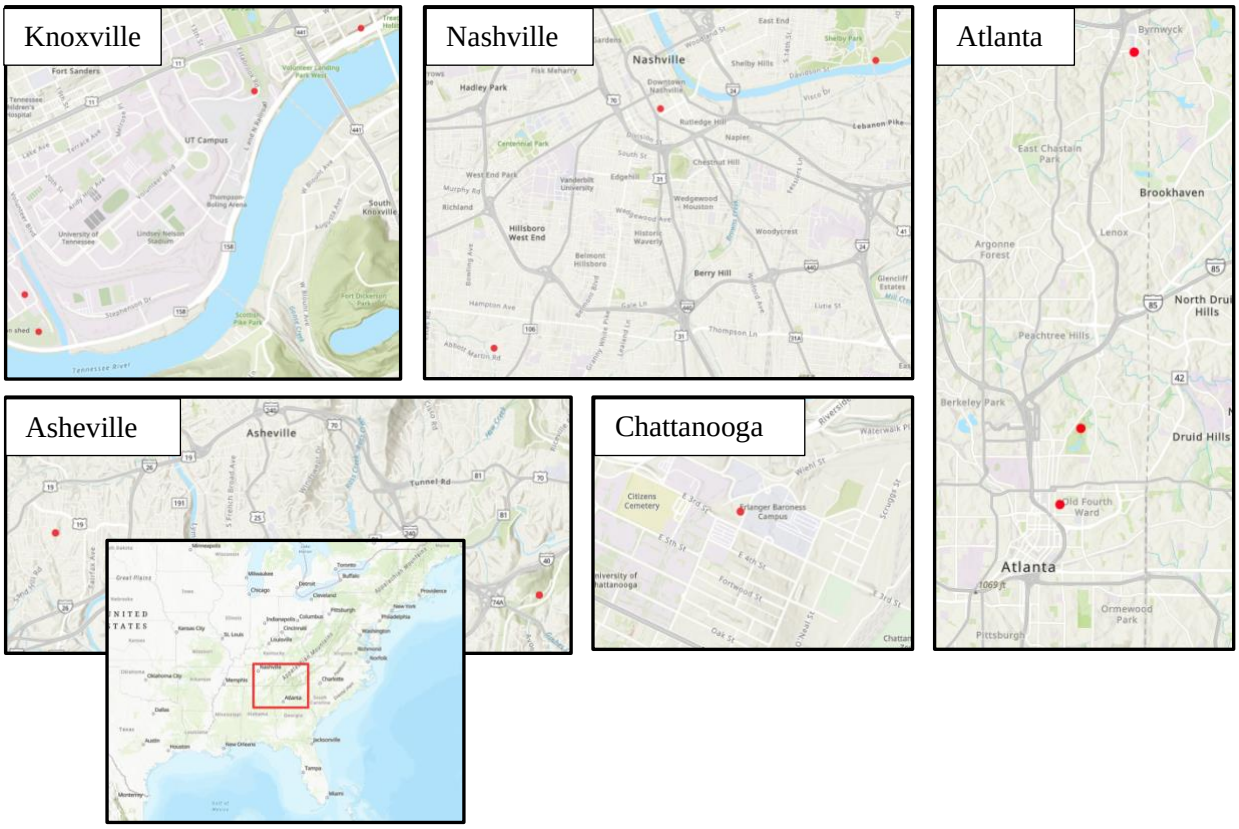

Figure 3 Locations of 13 studied green roofs, denoted by a red dot in each of five cities, Asheville, Atlanta, Chattanooga, Knoxville, and Nashville. Locations adapted from McKinney et al., 2019 and found through internet searches (ie. www.greenroofs.com).

Each of the 13 roofs vary in size, ranging from 191,000 ft^2 to around 200 ft^2. To ensure proportional sampling across the different roofs, a systematic approach was adopted. Pitfall traps were set at intervals of one every 200 ft^2. Every 400 ft^2 twenty total teabags buried, with one plant survey, and one soil sample collected. Given the variability in roof sizes, samples were collected proportionally up to a maximum area of 4,800 ft^2 per roof. This was done to ensure a feasible workload. Specifically, sampling was done with a minimum of two traps, two plant surveys, two soil collections and twelve teabags per roof. With a maximum of twenty-four traps, twelve plant surveys, twelve soil collections, and one hundred-twenty teabags for the large roofs. For roofs exceeding 4,800 ft^2, only 4,800 ft^2 total was sampled to ensure manageable data collection. Roofs exceeding 4,800 ft^2 were randomly sampled from across the entirety of the roof. ***Table 4*** summarizes the total samples per roof for the duration of the study.

1.4 Invertebrate Abundance and Diversity Collection

1.4.1 Field Methods and Identification

To study diversity and abundance, pitfall traps were used. These were chosen for this study because they are very commonly used. They were used in almost 90% of field studies on ground beetles from 2008 to 2010 (Knapp & Ruzicka, 2012; Knapp et al., 2016). They are also used in over 200 studies just in 2014 alone (Knapp & Ruzicka, 2012; Knapp et al., 2016), remaining one of the most popular sampling techniques (Knapp & Ruzicka, 2012; Knapp et al., 2016). Typically, on each of the roofs, traps were set randomly, keeping each trap a minimum of about 4 meters apart (MacIvor & Lundholm, 2010; Fabián et al., 2021). Trap design is variable

Table 4 An outline of the sample size of each proxy, how often they were collected, and how many total samples were taken.

Collection dates: March 1, 2024 to August 13, 2024				
	Pitfall traps	Teabags	Plant survey	Substrate sample
Total at each location	1 trap per 200 ft^2	20 total tea per 400 ft^2	1 per 400 ft^2	1 per 400 ft^2
Collection times	25 days	25 days until 100 days	50 days	March
Total collections	6	4	4	1

between studies and has been shown to highly affect catch size (Knapp et al., 2016). Traps with no lid obtained higher catches than lidded traps and traps made with a smoother material showed higher catch efficiencies as well (Knapp et al., 2016). Samples have also been shown to be affected by trap size (Knapp et al., 2016), trap color (Buchholz et al., 2010), and preservative fluid (Knapp & Ruzicka, 2012).

We utilized pitfall traps made from 9 oz smooth clear plastic beverage cups, where one cup is placed in a hole in the ground, lip flush to the surface, and the second is placed inside with a white top above it (MacIvor & Lundholm, 2010; Jacobs et al., 2023). We used the lidded design due to the longer collection intervals to keep the traps free of debris and rainfall. The cup is then filled with about 2 oz of propylene glycol (Jacobs et al., 2023). When choosing the preservation fluid, it is important to consider the efficiency as well as the environmental impact and risk (Knapp et al., 2016). Compared to other options propylene glycol is low in toxicity and has a slower evaporation rate maintaining its capture efficiency and preservation (Martin & Murphy, 2000). Knapp and others (2012, 2016) showed propylene glycol to have a higher trapping efficiency than the compared preservatives. Pitfall traps are typically collected every ten days to three weeks for five months (MacIvor & Lundholm, 2010; Jacobs et al., 2023). Due to scheduling restraints and distance from the University of Tennessee, Knoxville campus, traps were collected every 25-30 days. The propylene glycol and captured invertebrates were drained through a coffee filter in efforts to reuse the propylene glycol. After the invertebrates from each pitfall trap were collected in the coffee filter, they were washed, air dried, sorted, and stored in 99.9% ethanol to be later be counted and identified (MacIvor & Lundholm, 2010; Fabián et al., 2021; Jacobs et al., 2023). The invertebrates were identified using dichotomous keys or online databases such as bugguide.net to the family level and genus where applicable (MacIvor & Lundholm, 2010; Fabián et al., 2021). ***Figure 5*** illustrates the process of identifying the found species. During the collection times, weather and temperatures were tracked, as well as any invertebrate or human activity.



Figure 4 Photo example of the identified family Carabidae, or the common ground beetle. This family is easily identified through the presence of the notch at the top of its bottom leg.

2.2.1 Calculating Diversity

The invertebrate's richness and abundance metrics were used to determine diversity in the sampled area by using the Shannon index outlined in *Equation 1* below (MacIvor & Lundholm, 2010; Wang et al., 2015).

$$H'_e = -\sum_{i-1}^{S} P_i \ \ln \ P_i$$

Equation 1 The Shannon Index (Wang et al., 2015)

Where p_i is the number of individuals of the ith species and S is the total number of species (Lönnqvist et al., 2021). The Shannon index, H', ranges from 0-3.5 with lower number indicating less diversity. This index can be calculated between green roofs to compare diversity.

1.5 Soil Decomposition Rate and Stabilization Factor

1.5.1 Field Methods

The Teabag Index (TBI) is a novel approach proposed by Keuskamp and others (2013) to assess organic matter decomposition by using commercial green and rooibos tea leaves. Green tea and rooibos tea have contrasting decomposition rates with rooibos having a much lower rate. Thus, there is remaining labile material in rooibos tea when all the labile material in green tea is

already consumed (Fujii et al., 2016). In other words, green tea decomposes early on, whereas rooibos tea is more recalcitrant and decomposes at a much slower rate. The TBI uses this difference to estimate the decomposition rate *k*, and calculate the stabilization factor S, at a single point in time (Fujii et al., 2016). S indicates long-term carbon stability in that area, and *k* indicates the rate at which the litter is broken down (Fujii et al., 2016; Fanin et al., 2019). This index is indicative of microbial activity in the soil community and can give an insight into the soil health of the sampled area (Buchholz et al., 2017).

To make the teabags, we measured 2 grams each of rooibos and green tea (Keuskamp et al., 2013; Mori, 2022). We placed the teas into individual 0.25 mm acrylic mesh tea bag and double sealed the bags (Keuskamp et al., 2013; Mori, 2022). We then buried them ~8 cm deep in individual holes 15 cm apart from each other for a select incubation period (Keuskamp et al., 2013; Pino et al., 2021; Daebeler et al., 2022). Time of incubation can vary depending on climatic conditions and locations ranging from 45 days to over 90 days (Keuskamp et al., 2013). We chose to retrieve the teabags on 25-to-30-day intervals for a total of 100 days. After incubation, we retrieved the teabags and dried them in an oven for 48 hours, not exceeding 70 ºC (Keuskamp et al., 2013; Pino et al., 2021). After the bags were completely dry, we removed excess soil and reweighed each bag four times to get the average weight. The mass remaining of the tea only is subtracted from the original mass of the tea only to show how much of the material was decomposed in the incubation period of 25, 50, 75, and 100 days. This mass change in green tea was then used to determine S. This change as well as the weight change in rooibos tea were used to determine *k* using the equations below as outlined in Keuskamp and others (2013).

2.3.2 Calculating S and *k*

Keuskamp et al., 2013 outlines how to find S and *k* as factors of weight loss and constants. *k* is estimated by the equation below.

$$W(t)=ae^{-kt}+(1-a)$$

Equation 2 Finds decomposition rate (k) from Keuskamp et al., 2013

Where $W(t)$ is the weight of the tea after incubation time t, a is the labile fraction and $1-a$ is the recalcitrant fraction (Keuskamp et al., 2013; Mori, 2022). Since rooibos tea has a low

decomposition rate as compared to green tea, decomposition of labile material still occurs in rooibos tea after the labile material is gone in green tea. Thus, the difference between these two teas allows us to estimate the decomposable fraction (a_g) of green tea and the decomposition rate *k* from rooibos tea (Keuskamp et al., 2013). To solve the equation, the decomposable fraction (a_r) of rooibos tea is needed. This is solved by using the decomposable fraction *a*, and the hydrolysable fraction H found in Keuskamp et al., 2013. The stabilization factor can be found using the equation below.

$$S=1-a_g/H_g$$

Equation 3 Outlines the equation needed to find the stabilization factor (S) from Keuskamp et al., 2013

Where a_g is the decomposable fraction of green tea and H_g is the hydrolysable fraction of green tea. The decomposable fraction (a_r) is calculated using the hydrolysable fraction (H_r), also found in Keuskamp et al., 2013, of rooibos tea and the previously found stabilization factor *S*.

$$a_r = H_r(1-S)$$

Equation 4 Outlines the equation needed to find the decomposable fraction of rooibos tea from Keuskamp et al., 2013

After these two equations are solved the first equation is used to find *k*. These are used to compare weight loss, decomposition, and stabilization of the different sampled green roof ecosystems.

1.6 Plant Diversity Collection

1.6.1 Field Methods and Identification

We completed random sampling vegetation surveys during the growing season at each location every 50 days from March until August. This was done using 0.75m x 0.75m plastic quadrat frame on the roof, with the same sampled location being surveyed each time (Bagella et al., 2020). These quadrats were placed at random locations across the roof, marking the location to ensure the same spot was sampled each time. Quadrat size and shape can vary with vegetation; with herbaceous vegetation, quadrats are recommended to be 1-2m^2 (Higgins et al., 1996). For this study the quadrat size was smaller due to the size restraints of many green roofs. Vegetation frequency was estimated visually through 15cm x 15cm grids in each quadrat (Lönnqvist et al., 2021). Occurrence of each plant species was used to estimate percent frequency. For example, where if there were 12 squares and one species occurs in 6 of them, the frequency would be 6/12

x 100, or 50% (Higgins et al., 1996). Plant identification followed a key or online databases such as wildflowersearch.org. All the plants identified within the quadrat were recorded to genus or species and number of occurrences of each species within the grid (Zhao et al., 2010; Wang et al., 2015; Lönnqvist et al., 2021).

2.4.2 Calculating Diversity

We calculated diversity using the Shannon Index, *Equation 1*, to evaluate the diversity, using richness, of the sampled areas (Wang et al., 2015). This diversity index can be examined between roofs to compare diversity and determine the ES being performed. ***Figure 6*** below illustrates the survey method to find estimated percent cover and plant diversity for the duration of the study.

2.5 Substrate Survey

2.5.1 Field Methods

To find the substrate composition, we gathered samples from the research sites. These were collected by combining six random samples from the same plot at each roof from the topsoil to bottom depth of the substrate (Singh et al., 2020). The substrate samples from the same roof were homogenized, air dried, and packaged into bags consisting of one to two cups of substrate (Singh et al., 2020; Bagella et al., 2020; Clemson University n.d.). We then sent the soil samples to the Clemson Soil Extension Lab to test for pH, P, K, Ca, Mg, Zn, Mn, Cu, Na, and organic matter %. Nutrient levels were found through the Mehlich 1 procedure, pH through a soil to water ratio, and organic matter though loss on ignition (LOI) (Clemson University n.d.).

2.6 Statistical Analyses

To complete the statistical analysis of the influences on each proxy I ran a Principal Component Analysis (PCA) using the statistical software package IBM SPSS Statistics Version 29.0.2.0 (20) (Phoomirat et al., 2020). This was done to identify covarying components and create groupings of the independent variables that explain much of the variance in the data set. I then produced linear mixed models for each ES proxy variable against each of those groupings.

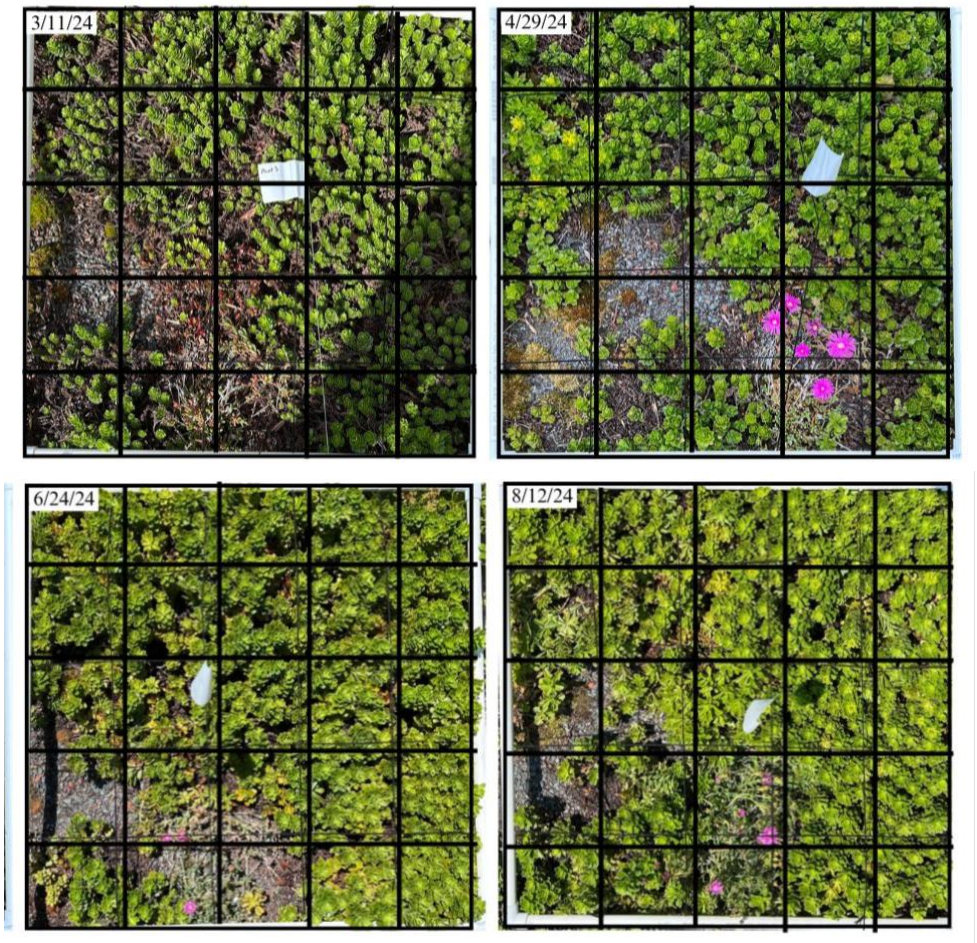

Figure 5 Showing the sampling method for the plant survey. Utilizing a sectioned quadrat plant species and coverage in the same spot can be monitored over the course of the study.

The substrate survey utilized a correlations matrix and a nonparametric test. The independent variables are: soil temperature, soil moisture, age (years), elevation (stories), substrate depth (inches), irrigation, replanting, weeding, substrate addition, chemical treatments, and management classification. Soil temperature and moisture levels were taken each month using a handheld probe. Within the analyses each data set was checked for normality. For non-normal distributions, a logarithmic transformation was used to produce normality. If the transformation did not work, nonparametric tests were used utilizing the Spearman correlation. The normal values were compared via the Pearson correlation.

Linear mixed models were utilized over a univariate ANOVA or other test as it considers the location and sample dates of each data point. Using a univariate ANOVA does not account for location differences and uses an inflated sample size, leading to misleading results. Showing the linear mixed model to provide more meaningful results. The linear mixed models were completed using a manual stepwise regression to determine which of the independent variables showed the highest significance. To do this each time the model was run, the least significant variable was removed, until the final variables showed statistical significance. Since the independent variables in the groupings found during the PCA were compared to the proxy's using covariance, this led us to a better story of what is truly influencing each proxy while holding all other variables constant. This was done to find the statistical significance and effect of the environmental, management, and site characteristic on the proxy variables. Finally, to check the assumptions of statistically significant influences of each component a linear mixed model was run using the component scores found from the PCA.

Chapter 3. Results

3.1 Independent Variable Analysis

A PCA analysis was run on each of the independent variables. ***Table 5*** illustrates the extraction numbers representing the proportion of each variable's variance that can be explained by the principal components.

PCA values range from 0 to 1, where values closer to 1 represent higher communality. Meaning the variable is well represented by the components and that a significant portion of its variance is captured. Based on the values in ***Table 5***, variables with high communalities and are well represented by the extracted components include soil moisture, soil temperature, age, size, elevation, irrigation, replanting, chemical treatment, and substrate addition. With management classification showing to be very well explained with an extraction of 0.966. Variables that show moderate communalities are substrate depth and weeding. This indicates that the PCA shows the variables to be well represented by the selected components with communalities above 0.70 for all variables, suggesting that the principal components capture most of the variance in each variable.

Table 5 Extraction results from the completed PCA. Where values closer to 0 represent higher communality.

Independent Variable	Extraction
Soil Moisture	0.831
Soil Temperature	0.731
Age (years)	0.885
Size (ft2)	0.89
Elevation (stories)	0.899
Substrate Depth (in)	0.774
Irrigation	0.896
Replanting	0.878
Weeding	0.756
Chemical Treatments	0.807
Substrate Addition	0.884
Management Classification	0.966

Table 6 illustrates the total variance explained, providing details about how much variance each principal component captures in my data set. The initial eigenvalues show the amount of variance in the data each component explains indicating the percentage of the total variance that individual component accounts for. This shows that only the first five components are showing significance with eigenvalues over 1. These five components explain 84.983% of the total variance. A Varimax rotation was applied to this PCA to further explain the variables by redistributing the variance more evenly across the components. Rotation sums of squared loadings show the total variance explained by each component after rotation, leading to a more balanced solution. Based on these findings, component 1 explains about 23% of the variance, component 2 explains about 18% of the variance, component 3 explains 17% of the variance, component 4 explains 14% of the variance and component 5 explains 11% of the variance. Together explaining almost 85% of the total variance in the data, indicating a strong representation.

Table 6 The results of the PCA, outlining the explained variance from each component. Noting that components 1-5 are the only that have a total eigenvalue of over 1, indicating more significance.

	Initial Eigenvalues			Extraction of Squared Loadings			Rotation Sums of Squared Loadings		
Component	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	3.79	31.587	31.587	3.79	31.587	31.587	2.766	23.053	23.053
2	2.186	18.219	49.806	2.186	18.219	49.806	2.175	18.122	41.175
3	1.812	15.099	64.905	1.812	15.099	64.905	2.112	17.598	58.774
4	1.382	11.519	76.423	1.382	11.519	76.423	1.763	14.694	73.468
5	1.027	8.56	84.983	1.027	8.56	84.983	1.382	11.515	84.983
6	0.658	5.483	90.466						
7	0.476	3.967	94.433						
8	0.295	2.46	96.894						
9	0.229	1.905	98.798						
10	0.131	1.092	99.891						
11	0.009	0.076	99.967						
12	0.004	0.033	100						

The varimax rotation yielded the component matrix in ***Table 7***. Where high loadings are indicated by values over 0.50, indicating that variable is strongly associated with a component. High loadings on component 1 are irrigation, replanting and management classification. Interpreted as management practices component or grouping. Component 2 shows high loading on soil moisture and temperature, interpreted as a substrate condition grouping. Component 3 has high loadings on size, elevation, and substrate additions, interpreted as a roof features component. Component 4 has high loadings on age and chemical treatment, or an age and chemical management grouping. Finally, component 5 shows high loading on weeding and substrate depth, suggesting a focus on a substrate and vegetation management grouping.

Based on the findings of the varimax rotated PCA I can plausibly use these components as groupings for linear mixed models using the variables in each component as covariates. This analysis has reduced the complexity of my data by identifying five key components, each representing a unique aspect of the independent variables. This will in turn tell me the influence of the most correlated variables on each proxy. It also provides information on how the management, the substrate condition, roof features, age and chemical management, and substrate and vegetation management influence each of my proxies.

Table 7 Rotated component matrix results from the PCA. Highlighted values indicate the most significant variables (>0.50). These variables are then grouped together for the corresponding component by their communalities.

Rotated Component Matrix

	1	2	3	4	5
Soil Moisture	0.141	0.889	-0.099	-0.078	0.680
Soil Temperature	0.197	-0.792	-0.156	0.068	0.189
Age (years)	-0.177	-0.283	-0.058	0.851	0.214
Size (ft2)	0.200	0.251	0.795	0.39	0.063
Elevation (stories)	0.182	0.555	0.698	0.233	0.127
Substrate Depth (in)	-0.319	-0.154	-0.232	-0.221	0.739
Irrigation	0.825	0.396	0.143	-0.164	-0.108
Replanting	0.855	-0.205	0.117	0.080	0.291
Weeding	0.350	0.061	0.149	0.220	0.747
Chemical Treatments	0.200	0.097	0.251	0.813	-0.185
Substrate Addition	0.138	-0.259	0.866	-0.141	-0.167
Management Classification	0.953	-0.055	0.179	0.102	-0.110

The trends in the soil moisture and temperature are outlined in ***Figure 7***. This is indicative of an inverse trend in temperature and moisture. Where the quadratic line is indicative of the mean with a confidence interval of 0.05. And blue indicates soil moisture and red indicates soil temperature. As each roof collectively increases in temperature throughout the season, the moisture tends to decline. Where each roof was more moist than hot in the initial collection in late February early March. Then in late March early April each roofs moisture and temperature are equal, as represented as the crossing of the lines in ***Figure 7***. Where moisture and temperature peak at their lowest and highest in late June early July and the trend starts to verge back towards equilibrium. This is indicative of the seasonality changes from March until August, early Spring to late Summer. ***Figure 7*** illustrates how the summer season effected the substrate conditions over time, informing us of the impacts of the seasonality across this research.

3.2 Invertebrate Community

There was a total of six sample collection points, where the pitfall trap collection was used to find the abundance and diversity of Arthropods, Mollusks, and Annelids on each roof. Of the 160 total pitfall traps set out in March, on average only 135 traps were collected at each sample time. This was due to uncontrollable outside forces such as invertebrate and human activity, weather patterns, and plant overgrowth. At the end of the six collections a total of 807 traps were collected, capturing a total of more than 136,500 individuals from three respective phyla and 193 different genera. Captured were: 13,296 Mollusca, 123,194 Arthropoda, and 22 Annelida. Within these phyla are multiple ground dwelling orders, the most notable of which are: 5,273 Coleoptera, 2,778 Araneae, 38,666 Entomobryomorpha, 5,107 Polydesmida, 4,887 Orthoptera, and 180 larva and caterpillars. Notable flying orders within these phyla were 24,665 Hymenoptera and 4,727 Diptera. Appendix 3 outlines all discovered genera.

Figure 8 illustrates the trends of the invertebrate community throughout the duration of this study. Where red represents the invertebrate log abundance and blue represents invertebrate diversity. The quadratic line represents the mean of all the points with a confidence interval of 0.05. Over the course of this research invertebrate abundance on these green roofs shows a declining trend. Diversity however trends in an increasing pattern until about June then declines for the remainder of the study. This is indicative of the seasonality from March to August.

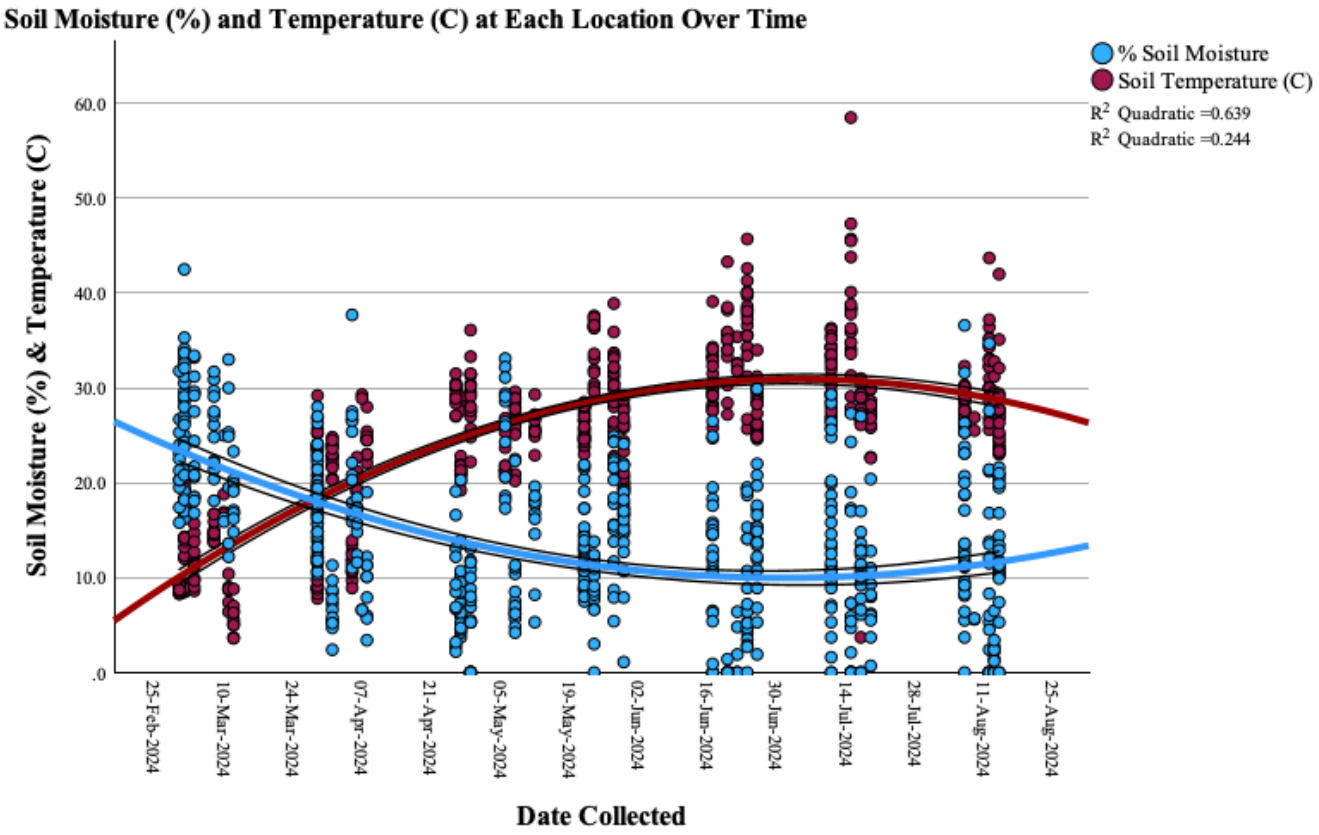

Figure 6 Visualization of collected soil moisture and temperature from March until August 2024.

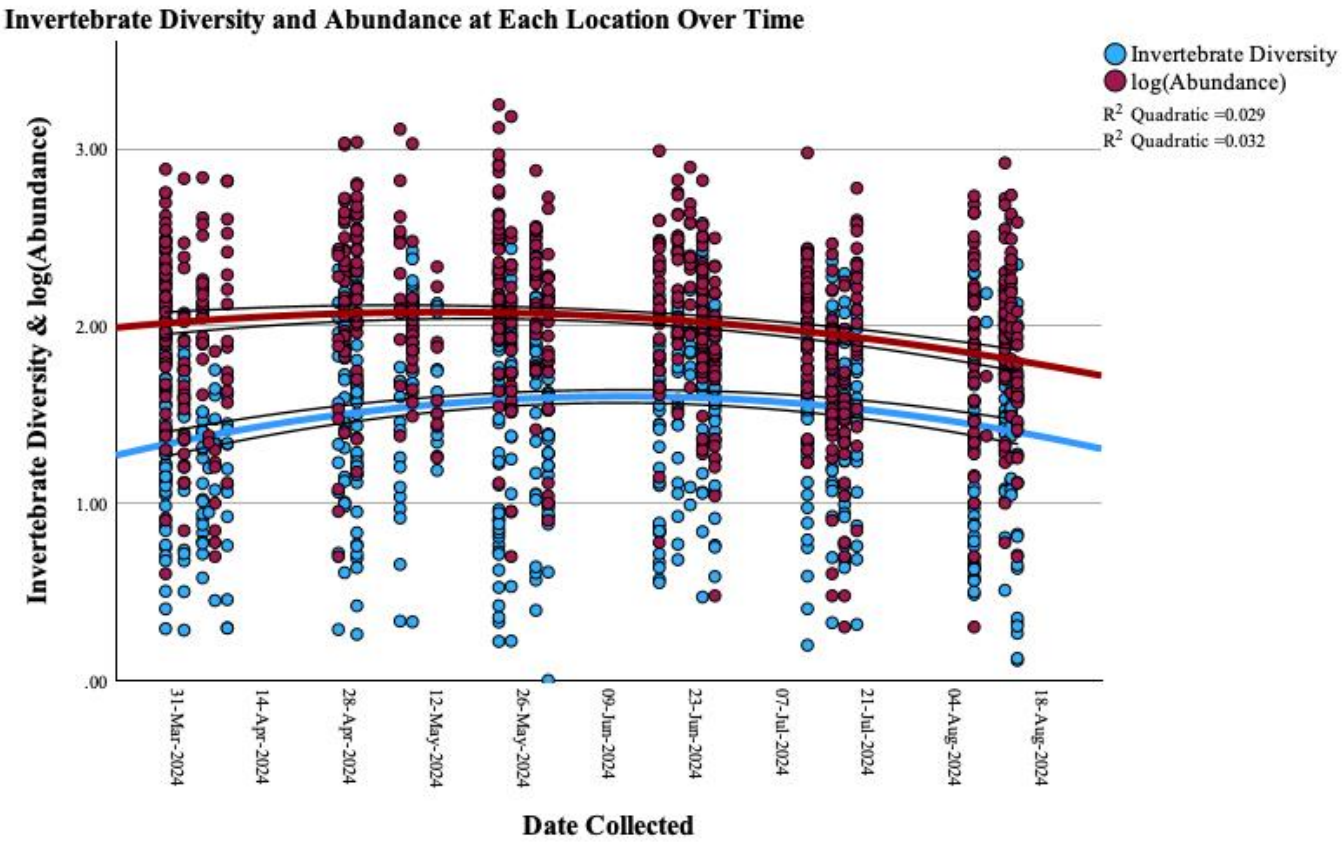

Figure 7 Visualization of invertebrate diversity and abundance from March until August 2024.

Table 8 outlines the significance of each of the highly correlated management practices found in the completed PCA. The darker shaded cells indicate statistical significance to the 0.05 level and the striped cells indicate statistical significance to the 0.10 level. The 0.10 level is included in this study as green roofs are highly complex ecosystems and therefore the 0.10 level also indicates high significance. The p-value is shown at the first value in the table with the effect in parenthesis next to it. Invertebrate diversity shows to be significantly influenced negatively by irrigation, only when replanting efforts are used as a covariate. All management practices together as covariates show no statistical significance on the invertebrate diversity, when tested against diversity without covariates they also show no significance. Irrigation is only shown to be significant to the 0.05 level when replanting is held constant. Replanting and management are not shown to have any significance with or without the covariates of management practices in component 1 on invertebrate diversity.

Like the trends of invertebrate diversity, there is no statistical significance of any of the variables when used as covariates or tested singularly compared to invertebrate abundance. It is however found that both replanting and management are significant to the 0.10 level when run as covariates of each other, removing irrigation as an influence. Replanting shows a negative influence and management shows an opposite positive influence on abundance.

Table 8 Results of the linear mixed model comparing the component variables outlined by the PCA. With grayed squares representing significance to the 0.05 level and dashed squares indicate significance to the 0.10 level. Where the number in parenthesis indicate the effect.

Invertebrate Diversity Component 1: Management Practices								
Irrigation	0.160 (-0.305)		0.037 (-0.365)		0.112 (-0.234)			
Replant	0.219 (0.345)		0.150 (0.241)			0.788 (0.041)		
Management	0.631 (-0.165)							0.56 (-0.090)
Invertebrate Abundance Component 1: Management Practices								
Replant	0.125 (-0.482)		0.090 (-0.501)			0.631 (-0.076)		
Management	0.247 (0.447)		0.090 (0.513)		0.661 (0.071)			
Irrigation	0.777 (0.064)							0.449 (0.119)

Overall, component 1 indicates statistical significance when comparing irrigation on invertebrate diversity using replanting as a covariate and replanting and management together on invertebrate abundance. There is no significance when comparing all three components or the components alone on either invertebrate diversity or abundance.

Table 9 outlines the significance of the highly correlated variables from component 2, substrate conditions, compared to invertebrate diversity and abundance. Soil temperature is only found to be statistically significant for invertebrate diversity. Where moisture is held constant temperature is positively significant to the 0.10 level, when moisture is removed from the equation temperature is found to be positively significant to the 0.05 level for invertebrate diversity. Soil moisture is not found to be statistically significant to any level for either invertebrate diversity or abundance, under conditions of temperature as a covariate compared without covariates.

However, there is an increase in significance when soil moisture is compared to diversity and abundance without covariance. Similarly with soil temperature, significance increases when moisture is taken out of the equation. Overall, component 2 shows minimal significance for invertebrate diversity and abundance, as only soil temperature is significant to any level when compared to diversity but not abundance.

There is moderate significance of soil temperature to the 0.10 level when soil moisture is held constant when compared to diversity but not when compared to abundance.

Table 10 outlines the significance of the highly correlated variables from component 3, roof features, as compared to the invertebrate community. We found that no combination of covariance is shown to be significant when comparing roof features to invertebrate diversity and

Table 9 Results of the linear mixed model comparing the component variables outlined by the PCA. With grayed squares representing significance to the 0.05 level and dashed squares indicate significance to the 0.10 level. Where the number in parenthesis indicate the effect.

Invertebrate Diversity Component 2: Substrate Conditions			
Soil Temperature	0.080 (0.016)	0.025 (0.017)	
Soil Moisture	0.700 (-0.003)		0.123 (-0.010)
Invertebrate Abundance Component 2: Substrate Conditions			
Soil Temperature	0.543 (-0.005)	0.389 (-0.006)	
Soil Moisture	0.781 (0.002)		0.504 (0.004)

abundance. When all three variables are compared to diversity, elevation is found to be the most significant with a p-value of 0.138 and becomes more significant with a p-value of 0.110 when substrate additions are removed from the equation. However, elevation is insignificant when no covariates are used in the comparison. Like elevation size also shows to become a more significant influence on diversity when substrate addition is removed but is found to be highly insignificant when compared without any covariates, however the effect flips when size is not compared with covariates from a positive to a negative influence on invertebrate diversity. Substrate is a highly insignificant influence on invertebrate diversity with or without the other roof feature covariates.

Similarly, roof features have no statistical significance on invertebrate abundance either. Elevation is the most significant when comparing to abundance without covariance and shows to be less significant when only using size as a covariate than when having size and substrate addition as covariates. Similar trends are shown for green roof size, as it shows the most significance when using the other roof features as covariates, then loses significance when substrate addition is removed and gains more significance when all covariates are removed. Like the trends of green roof size and diversity, the influence of size and abundance flips from a negative influence with covariates to a positive influence without covariance. Substrate addition is found to become slightly more significant when the roof feature covariates are fully removed. Overall, component 3 shows no significance on the invertebrate community with or without the use of the other roof feature covariates.

Table 10 Results of the linear mixed model comparing the component variables outlined by the PCA. With grayed squares representing significance to the 0.05 level and dashed squares indicate significance to the 0.10 level. Where the number in parenthesis indicate the effect.

Invertebrate Diversity Component 3: Roof Features				
Elevation	0.138 (-0.096)	0.110 (-0.100)	0.386 (-0.030)	
Size	0.306 (3E-6)	0.177 (3E-6)	0.989 (-2E-8)	
Substrate Add	0.644 (0.097)			0.533 (0.107)
Invertebrate Abundance Component 3: Roof Features				
Elevation	0.305 (0.070)	0.327 (0.064)	0.281 (0.038)	
Size	0.505 (-2E-6)	0.623 (-1E-6)	0.532 (9E-7)	
Substrate Add	0.580 (0.126)			0.495 (0.127)

Table 11 outlines the significance of the highly correlated variables from component 4, age and chemical management, as compared to the invertebrate community. We found that age has a positive significance to the 0.05 level on invertebrate diversity when chemical treatments are used as a covariate. However, when chemical treatments are removed, the significance of age on diversity is lost. Chemical treatments show a similar trend where, when age is removed as a covariant, all significance is lost when compared to invertebrate diversity.

When component 4 is compared to invertebrate abundance there is no significance found when covariance is used or removed, showing minimal effect on the significance levels when covariance is removed. Overall, component 4 only shows significance of age when covariance is used against invertebrate diversity, but no other significance of these variables on invertebrate diversity or abundance.

Table 12 outlines the significance of the highly correlated variables from component 5, substrate and vegetation management, as compared to the invertebrate community. There is no significant effect of substrate depth and weeding with or without covariance on invertebrate diversity. There is a slight increase in significance for substrate depth when weeding is not considered as a covariant and a large decrease in significance for weeding when substrate depth is not considered as a covariant, when compared to invertebrate diversity.

Contrasting the results from diversity, substrate depth is found to be highly significant to the 0.05 level with a p-value of 0.003, when weeding is used as a covariant when compared to abundance. Weeding is also found to be moderately significant with a p-value significant to the 0.10 level, having substrate depth as a covariant when compared to invertebrate abundance. Substrate depth is still highly significant when weeding is removed as a covariate, showing a

Table 11 Results of the linear mixed model comparing the component variables outlined by the PCA. With grayed squares representing significance to the 0.05 level and dashed squares indicate significance to the 0.10 level. Where the number in parenthesis indicate the effect.

Invertebrate Diversity Component 4: Age and Chemical Management			
Age	0.050 (0.028)	0.128 (0.019)	
Chemical Treatments	0.170 (-0.259)		0.654 (-0.081)
Invertebrate Abundance Component 4: Age and Chemical Management			
Age	0.216 (0.019)	0.197 (0.017)	
Chemical Treatments	0.772 (-0.060)		0.743 (0.061)

negative effect on abundance, indicating that as substrate depth increases abundance decreases. When weeding is tested against abundance without substrate depth as a covariate, we found that all significance is lost and the effect is reversed, where when substrate depth is used as a covariant for weeding, weeding shows to negatively affect abundance, but when substrate depth is removed, weeding is found to positively affect abundance. Overall, component 5 is only found to significantly effect invertebrate abundance and not diversity. We found that substrate depth is highly significant in predicting invertebrate abundance and weeding is moderately significant in predicting invertebrate abundance, when compared as covariates.

Table 13 outlines the statistical significance of the component scores against the invertebrate community, using the other component scores as covariates. When all other variables are held constant, we found that the only significant component is component 2, substrate conditions, when compared to invertebrate diversity only. Indicating an overall negative influence on diversity. This tells us that substrate conditions are highly significant and explains most of the variance found in invertebrate diversity. Although the other components do not show significance it is found management practices have a negative influence, and roof features, age and chemical management, and substrate and vegetation management all have a positive influence on invertebrate diversity. For invertebrate abundance it shows that: management practices, substrate conditions, roof features, and age and chemical management have a positive influence and substrate and vegetation management have a negative influence as a whole component, rather than the individual features as shown in the above models.

Table 12 Results of the linear mixed model comparing the component variables outlined by the PCA. With grayed squares representing significance to the 0.05 level and dashed squares indicate significance to the 0.10 level. Where the number in parenthesis indicate the effect.

Invertebrate Diversity Component 5: Substrate and Vegetation Management			
Substrate Depth	0.375 (0.013)	0.360 (0.013)	
Weeding	0.857 (-0.29)		0.957 (-0.008)
Invertebrate Abundance Component 5: Substrate and Vegetation Management			
Substrate Depth	0.003 (-.037)	0.009 (-0.34)	
Weeding	0.055 (-0.060)		0.217 (0.199)

3.3 Stabilization Factor and Decomposition Rate

A total of 1,620 teabags were buried across the thirteen roofs, with half being rooibos tea and the other half being green tea. At each interval we collected ¼ of the teabags, for a total of around 405 total teabags. At the end of the 100-day sample set, only 1,552 total teabags were collected. The 68-bag difference can be attributed to outside forces such as invertebrate and human activity, vegetation overgrowth and weather patterns. After each bag was dried, they were individually weighed four separate times. We found the stabilization factor and decomposition rate for each pair of teabags. Over the 100-day period, green tea had a minimum weight loss of 0.31 and a maximum of 1.68, and rooibos tea had a minimum of 0.03 and a maximum of 0.33. These produced a minimum stabilization factor of 0.008 and a maximum of 1.80 and a minimum decomposition rate of 0.005 and a maximum of 0.17.

Figure 9 illustrates the decomposition rate (*k*) and stabilization factor (S) over the course of the research. Where the red indicates stabilization factor and blue indicating decomposition rate. The line shows the mean of each with confidence intervals of 0.05. Visual trends indicate that across each roof *k* and S decrease steadily until the end of collections in June and July where the data levels off. This is in line with trends found in Keuskamp et al., 2013, therefore indicating that the equations outlined in the novel paper are validated and appropriate to use in this research. To complete the statistical analysis only one collection time should be used, this collection time should be the last time when all *k* and S values are able to be computed. This is highlighted on the figure by the dotted line, at an incubation time of 50 days. For the upcoming analyses the *k*, S, and soil moisture and temperature values used are from only the collection at 50 days, late April, and early May.

Table 13 Results of the linear mixed model comparing the component scores found by the PCA. With grayed squares representing significance to the 0.05 level and dashed squares indicate significance to the 0.10 level. Where the number in parenthesis indicate the effect.

	Component 1	Component 2	Component 3	Component 4	Component 5
Invertebrate Diversity	0.453 (-0.057)	0.015 (-0.126)	0.781 (0.018)	0.648 (0.030)	0.314 (0.066)
Invertebrate Abundance	0.767 (0.024)	0.315 (0.049)	0.532 (0.050)	0.299 (0.050)	0.578 (-0.045)

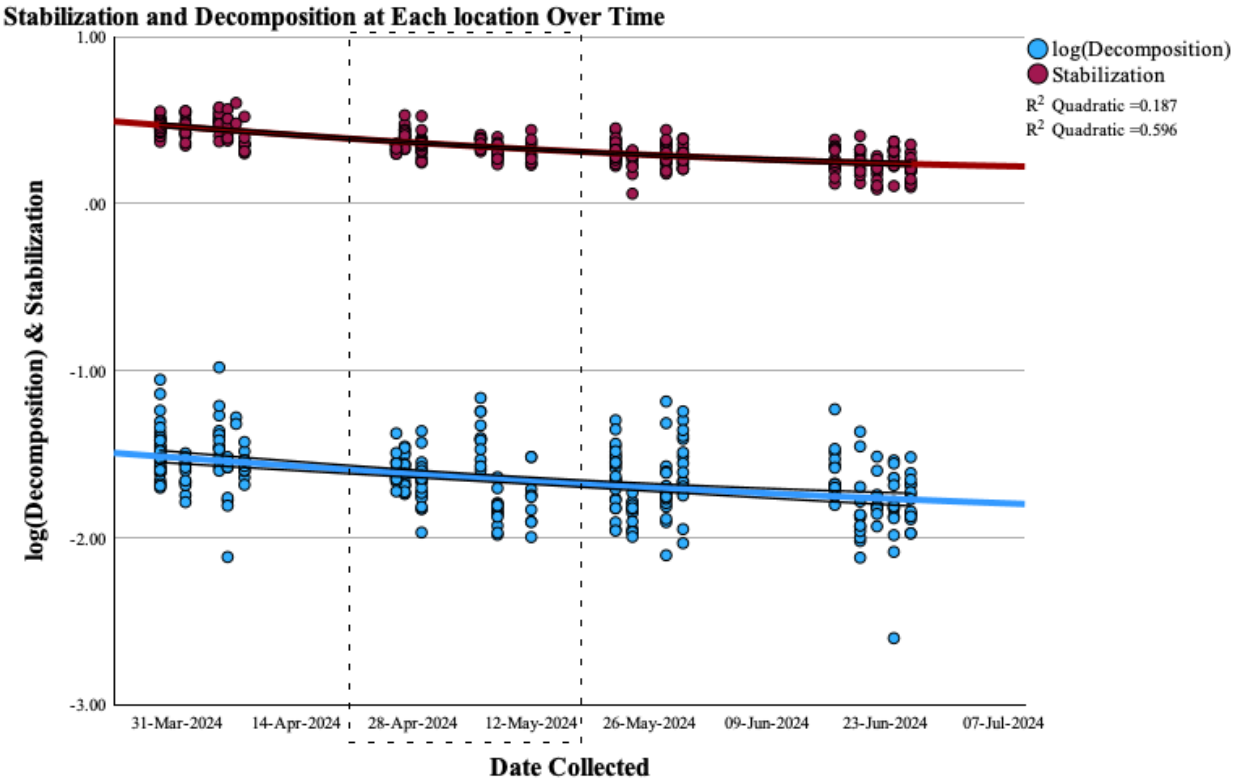

Figure 8 Visualization of the decomposition rate and stabilization factor found from March until June 2024. With the dotted square indicating the results used for analysis.

Table 14 outlines the significance from component 1, management practices, on stabilization and decomposition. When all three variables from component 1 are compared to stabilization as covariates there is minimal significance, however when irrigation is removed, as it is far insignificant, it is found that replanting and management classification show to become significant. Replanting to the 0.10 level and management to the 0.05 level. When management is removed as a covariate and replanting is compared straight to stabilization it loses all significance, indicating that replanting is only significant when management classification is held constant. When replanting is removed as a covariate and management is compared directly to stabilization, we find that some significance is lost, and it is now significant only at the 0.10 level. Irrigation is insignificant when replanting and management are used as covariates but shows to be very significant when compared without covariates to stabilization. This indicates that high management and irrigation show a significant positive effect on stabilization and replanting shows a significant negative impact on stabilization.

When comparing the variables of component 1 to decomposition, we found that irrigation and management classification is highly significant when replanting is used as a covariate as well as when replanting is removed as a covariate. With irrigation being highly significant even when no covariates are used. Inversely, management is highly insignificant when compared to decomposition without covariates. Replanting is highly insignificant across all levels of covariations when compared to decomposition.

Table 14 Results of the linear mixed model comparing the component variables outlined by the PCA. With grayed squares representing significance to the 0.05 level and dashed squares indicate significance to the 0.10 level. Where the number in parenthesis indicate the effect.

Stabilization Factor Component 1: Management Practices					
Replant	0.114 (-0.080)	0.071 (-0.090)		0.515 (0.020)	
Management	0.125 (0.098)	0.016 (0.132)	0.072 (0.054)		
Irrigation	0.345 (0.035)				0.031 (0.061)
Decomposition Rate Component 1: Management Practices					
Irrigation	0.001 (0.332)	0.001 (0.326)	0.007 (0.182)		
Management	0.045 (-0.234)	0.006 (-0.203)		0.602 (0.042)	
Replant	0.703 (0.032)				0.821 (0.018)

We found that irrigation has a positive effect on decomposition and high management has a negative influence on decomposition. Overall, replanting and management classifications show to have the highest statistical influence on both stabilization and decomposition, with or without the use of covariates.

Table 15 outlines the effects of component 2, substrate conditions, on stabilization and decomposition. Soil temperature is the only statistically significant variable when compared to the stabilization factor. We found that soil temperature is significant to the 0.10 level when soil moisture is used as a covariate. It is also significant at the 0.10 level when soil moisture is removed as a covariate. However, the significance decreases when soil moisture is removed. Indicating that soil moisture is an important covariate on soil temperature when predicting stabilization. Soil moisture shows a similar trend where when soil temperature is removed as a covariate it becomes far less significant in predicting stabilization. Our findings suggest that soil temperature has a negative effect on stabilization.

When the variables of component 2, substrate conditions, are compared to decomposition rate, we find that there is no significance regardless of covariance. However, when covariance is disregarded both soil moisture and soil temperature become far more significant in predicting decomposition than before. Although, not significant at the 0.10 or 0.05 levels. Our findings suggest that soil moisture has a positive effect and soil temperature has a negative effect on decomposition, however insignificant. Overall, only soil temperature is found to have significance at the 0.10 level when covariance is included and when covariance is removed, and soil moisture does not show significance on stabilization. Substrate conditions show to not statistically influence decomposition.

Table 15 Results of the linear mixed model comparing the component variables outlined by the PCA. With grayed squares representing significance to the 0.05 level and dashed squares indicate significance to the 0.10 level. Where the number in parenthesis indicate the effect.

Stabilization Factor Component 2: Substrate Conditions			
Soil Temperature	0.068 (-0.012)	0.092 (-0.008)	
Soil Moisture	0.312 (-.003)		0.585 (0.001)
Decomposition Rate Component 2: Substrate Conditions			
Soil Moisture	0.404 (0.006)	0.163 (0.007)	
Soil Temperature	0.896 (-0.002)		0.275 (-0.013)

Table 16 outlines the significance levels for the variables in component 3, roof features, against stabilization and decomposition. Size is found to be highly insignificant with no p-value produced when compared to both stabilization and decomposition. We found that when size is removed from the covariance elevation becomes more significant and substrate addition becomes very slightly less significant. The only variable we found to be significant in component 3's comparison to stabilization is elevation with all covariance removed. Indicating significance at the 0.10 level when predicting stabilization.

When compared to decomposition, we found that elevation is highly significant at the 0.05 level with and without covariation. With elevation showing to be most significant when substrate addition and size are used as covariates and steadily losing significance as covariates are removed, however still maintaining significance at the 0.05 level with no covariation. Substrate addition becomes slightly more significant when size is removed but quickly becomes highly insignificant when no covariance is included in the model. We found that elevation shows a positive effect on both stabilization and decomposition. Overall, elevation is the only variable of component 3 that predicts stabilization and decomposition with and without covariance. We found size and substrate additions to be insignificant and when predicting both stabilization and decomposition.

Table 16 Results of the linear mixed model comparing the component variables outlined by the PCA. With grayed squares representing significance to the 0.05 level and dashed squares indicate significance to the 0.10 level. Where the number in parenthesis indicate the effect.

Stabilization Factor Component 3: Roof Features				
Elevation	0.327 (0.012)	0.160 (0.010)	0.078 (0.011)	
Substrate Add	0.488 (0.029)	.490 (0.025)		0.229 (0.043)
Size	X			
Decomposition Rate Component 3: Roof Features				
Elevation	0.001 (0.090)	0.013 (0.042)	0.021 (0.036)	
Substrate Add	0.909 (-0.007)	0.261 (-0.089)		0.922 (-.009)
Size	X			

Table 17 outlines the significance levels of component 4 variables, age, and chemical management, on stabilization and decomposition. We found that for both stabilization and decomposition, none of the variables show to be statistically significant to the 0.10 or 0.05 level. Where for both stabilization and decomposition when covariance is removed both age and chemical treatments decline in significance. Although insignificant, we find that age has a negative effect on both stabilization and age. And chemical treatments have a positive effect on stabilization and decomposition except when compared with no covariance to decomposition, which illustrates a negative effect. Overall, none of the variables that make up component 4 show significance in predicting stabilization and decomposition.

Table 18 outlines the statistical significance of each of the variables that makes up component 5, substrate and vegetation management, on stabilization and decomposition. We found that substrate depth is highly significant when weeding is used as a covariate and even when it is removed as a covariate. With substrate depth being significant at the 0.05 level, showing a negative effect on stabilization. Weeding is insignificant when substrate depth is used as a covariate, but when depth is removed, weeding becomes highly insignificant. Indicating that weeding shows no individual significance on stabilization but may become more significant when other covariates are involved.

Neither weeding nor substrate depth indicate a statistical significance at the 0.10 or 0.05 level when compared to decomposition. Both variables decline in significance when covariation is removed. Overall, we only found substrate depth to have a slightly negative significant effect on stabilization factor.

Table 17 Results of the linear mixed model comparing the component variables outlined by the PCA. With grayed squares representing significance to the 0.05 level and dashed squares indicate significance to the 0.10 level. Where the number in parenthesis indicate the effect.

Stabilization Factor Component 4: Age and Chemical Management		
Age	0.319 (-0.003)	0.388 (-0.002)
Chemical Treatments	0.564 (0.024)	0.900 (0.005)
Decomposition Rate Component 4: Age and Chemical Management		
Age	0.141 (-0.011)	0.152 (-0.009)
Chemical Treatments	0.567 (0.057)	0.885 (-0.014)

Where covariance is removed in both models for stabilization and decomposition, significance is lost, indicating the need for covariance when analyzing component 5, substrate and vegetation management.

Table 19 outlines the statistical significance of the component scores against the stabilization and decomposition on each roof. Utilizing the other component scores as covariates. When all other variables are held the same, we found that component 2 is significant to the 0.05 level and component 1 is significant to the 0.10 level for decomposition only. Indicating an overall positive effect from management and substrate conditions on the decomposition rate. This indicates that the substrate conditions and management practices are highly significant and explain most of the variance found in the decomposition rate data. Although the other components do not show significance, management practices, substrate conditions, and roof features all have a positive influence on both stabilization and decomposition. Whereas age and chemical management show a negative influence on stabilization and substrate and vegetation management show a negative effect for stabilization and a positive effect on decomposition.

Table 18 Results of the linear mixed model comparing the component variables outlined by the PCA. With grayed squares representing significance to the 0.05 level and dashed squares indicate significance to the 0.10 level. Where the number in parenthesis indicate the effect.

Stabilization Factor Component 5: Substrate and Vegetation Management			
Substrate Depth	0.009 (-0.007)	0.010 (-0.006)	
Weeding	0.345 (0.023)		0.700 (0.012)
Decomposition Rate Component 5: Substrate and Vegetation Management			
Weeding	0.155 (0.116)	0.158 (0.110)	
Substrate Depth	0.570 (-0.004)		0.731 (-0.003)

3.4 Vascular Plant Community

Across the thirteen roofs there were 87 total plant surveys. At the end of the four collections a total of 348 surveys were collected. Identifying only the vascular plants in the Tracheophyta phylum, a total of 102 different species and variations were identified. The most common families across the roofs are: *Crassulaceae, Poaceae, Fabaceae,* and *Asteraceae*. Appendix 4 outlines all identified vascular plant genera.

Figure 10 illustrates the plant frequency and diversity found at each roof throughout the entirety of our study. Blue illustrates the plant frequency found at each roof and red illustrates the diversity of the vascular plant community found atop each roof. The quadratic lines represent the mean with a confidence interval of 0.05. The trend in frequency and diversity are similar in that they increase until about June and then start to decline. This is in line with the seasonality from March until August.

Table 19 Results of the linear mixed model comparing the component scores found by the PCA. With grayed squares representing significance to the 0.05 level and dashed squares indicate significance to the 0.10 level. Where the number in parenthesis indicate the effect.

	Component 1	Component 2	Component 3	Component 4	Component 5
Stabilization Factor	0.104 (0.025)	0.196 (0.019)	0.138 (0.021)	0.806 (-0.003)	0.303 (-0.014)
Decomposition Rate	0.065 (0.061)	0.014 (0.091)	0.406 (0.023)	0.509 (-0.019)	0.142 (0.046)

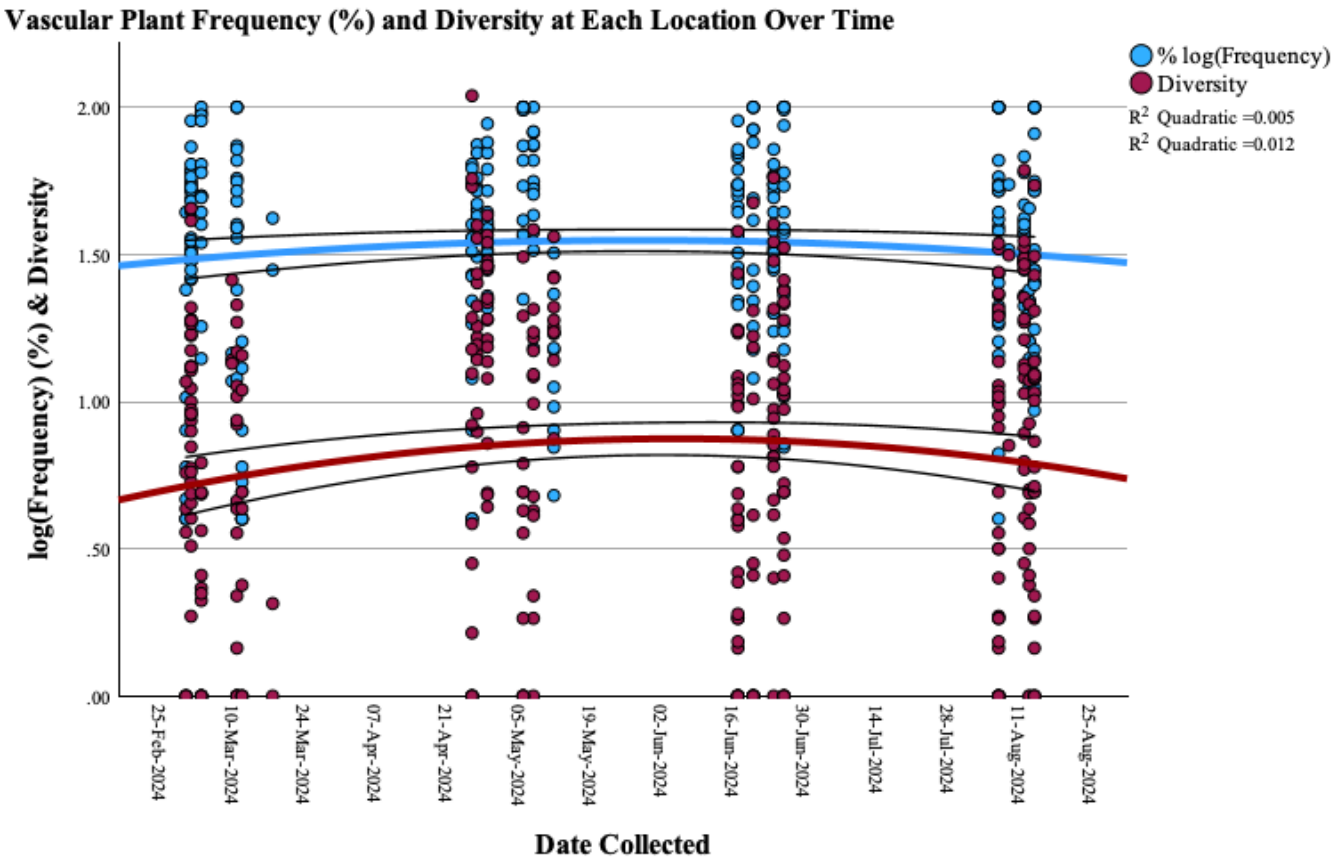

Figure 9 Visualization of plant diversity and frequency on each roof from March until August 2024.

Table 20 outlines the significance values of component 1, management practice, on plant diversity and frequency. We found that irrigation is the only significant variable on plant diversity. Where it is significant to the 0.10 level when all component 1 is used as covariates. After removing the least significant variable, management, both irrigation and replanting becomes more significant. Where irrigation becomes significant to the 0.05 level. All variables when compared to plant diversity without covariates show to become highly insignificant, and management showing an inverse effect on diversity when covariates are removed. We find that irrigation shows to have a negative effect on the diversity of the plant community on each roof, especially when replanting and/or management are used as covariates. Replanting shows to have an overall positive effect on plant diversity.

We found no variables to show significance for plant frequency. Where no variable is moderately significant. When the least significant variable was removed, irrigation and management gained slight significance but not to a statistically relevant level. When each variable from component 1 are compared to frequency with no covariance, they become even less significant. Although no variable is significant when predicting plant frequency, we found that irrigation overall shows a positive effect on frequency and management shows an overall negative effect on frequency. Replanting shows to have an inverse effect when covariates are involved and not involved, starting as a positive effect when all variables are accounted for and then becoming a slightly negative effect when covariance is removed. Overall, only irrigation is found to have any significance on plant diversity only. It is found to be significant at two levels when covariance is utilized.

Table 20 Results of the linear mixed model comparing the component variables outlined by the PCA. With grayed squares representing significance to the 0.05 level and dashed squares indicate significance to the 0.10 level. Where the number in parenthesis indicate the effect.

Plant Diversity Component 1: Management Practices					
Irrigation	0.070 (-0.413)	0.048 (-0.358)	0.167 (-0.209)		
Replant	0.539 (0.176)	0.124 (0.270)		0.615 (0.080)	
Management	0.676 (0.150)				0.992 (-0.002)
Plant Frequency Component 1: Management Practices					
Irrigation	0.253 (16.3)	0.243 (15.4)	0.447 (6.7)		
Management	0.449 (-17.4)	0.363 (-12.2)		0.954 (-0.526)	
Replant	0.764 (5.4)				0.979 (-0.240)

Table 21 outlines the significance levels of each variable from component 2, substrate conditions, on plant diversity and frequency. When soil moisture and temperature are analyzed as covariates, we find that there is no significance. But when all covariance is removed both soil moisture and temperature become statistically significant to the 0.05 level. This illustrates that, when predicting plant diversity each soil moisture and temperature need to be analyzed as their own entities rather than as covariates. We find that soil moisture shows a negative effect on diversity and soil temperature shows a positive effect on diversity.

When component 2 is compared to plant frequency, we find that soil temperature and moisture are only significant when covariance of each variable is involved. Soil temperature shows to be significant at the 0.05 level and soil moisture at the 0.10 level. When covariance is removed the variables become highly insignificant. Both temperature and moisture influence plant frequency in a positive way. Overall, when comparing component 2 to the plant community, soil moisture and temperature need to be looked at as individual variables to predict plant diversity, but as covariates to predict plant frequency.

Table 21 Results of the linear mixed model comparing the component variables outlined by the PCA. With grayed squares representing significance to the 0.05 level and dashed squares indicate significance to the 0.10 level. Where the number in parenthesis indicate the effect.

Plant Diversity Component 2: Substrate Conditions			
Soil Moisture	0.196 (-0.010)	0.016 (-0.014)	
Soil Temperature	0.514 (0.005)		0.032 (0.012)
Plant Frequency Component 2: Substrate Conditions			
Soil Temperature	0.036 (0.617)	0.254 (0.241)	
Soil Moisture	0.063 (0.617)		0.589 (0.119)

Table 22 outlines the significance levels of component 3, roof features, on the plant community. We find that elevation is significant at the 0.10 level when all of component 3 variables are utilized as covariates. When the least significant variable, substrate additions, is removed elevation and size gain significance. With elevation becoming significant at the 0.05 level and size becoming significant at the 0.10 level. When all covariance is removed elevation and size both become highly insignificant. However, when covariance is removed from substrate additions, they become slightly more significant, however not statistically. Elevation has an overall negative effect on plant diversity, whereas roof size and elevation show a positive effect on plant diversity.

There is minimal significance when component 3 is compared to plant frequency. None of the roof feature variables show significance when all covariance is applied. When the least significant variable, size, is removed from covariance we find that elevation becomes significant to the 0.10 level, but substrate additions are still found to be insignificant. When all covariance is removed both elevation and substrate additions decline in significance, whereas size increases in significance, but not in a statistically significant way. We find that substrate additions show a negative effect on plant frequency while elevation and roof size show positive effects. Overall, elevation and size show significance when compared to plant diversity without substrate additions as a covariate, and elevation only shows significance for plant frequency when roof size is removed from covariance.

Table 22 Results of the linear mixed model comparing the component variables outlined by the PCA. With grayed squares representing significance to the 0.05 level and dashed squares indicate significance to the 0.10 level. Where the number in parenthesis indicate the effect.

Plant Diversity Component 3: Roof Features					
Elevation	0.062 (-0.117)	0.042 (-0.124)	0.294 (-0.036)		
Size	0.195 (3E-6)	0.079 (4E-6)		0.975 (4E-8)	
Substrate Add	0.463 (0.146)				0.374 (0.158)
Plant Frequency Component 3: Roof Features					
Substrate Add	0.304 (-12.3)	0.253 (-11.9)	0.649 (-4.8)		
Elevation	0.310 (3.6)	0.065 (3.8)		0.112 (3.0)	
Size	0.938 (1E-5)				0.281 (9E-5)

Table 23 outlines the significance levels of component 4, age and chemical management, on the plant community. Age and chemical management show high significance when compared to plant diversity. Utilizing covariance, chemical treatments are significant at the 0.05 level and age is significant at the 0.10 level. When covariance is removed, both variables lose significance, however, chemical treatments still show to be highly significant at the 0.05 level, whereas age loses all significance. Age is found to positively influence plant diversity while the application of chemical treatments, like herbicides, are found to negatively influence the plant diversity.

No variables from component 4 show significance when compared to the plant frequency with covariance. When covariance is removed from both variables, their significance increases but not to a statistically significant level. Although insignificant, age and chemical treatment applications both show a positive effect on the plant frequency. Overall, component 4 only statistically effects plant diversity and not frequency, with chemical applications showing a negative effect and age showing a positive effect on diversity.

Table 24 outlines the significance levels of component 5, substrate and vegetation management, on plant diversity and frequency. Neither weeding nor substrate depth have a significant effect on plant diversity or frequency, with or without covariance. When covariates are removed in analyzing plant diversity, significance slightly increases but not in a significant way. When covariates are removed in analyzing plant frequency, significance is gained for weeding but lost for substrate depth. Although insignificant, weeding is found to have a positive effect on both diversity and frequency, whereas substrate depth is found to have a positive effect on diversity but a negative effect on frequency. Overall, component 5 shows no significance in predicting plant diversity or frequency.

Table 23 Results of the linear mixed model comparing the component variables outlined by the PCA. With grayed squares representing significance to the 0.05 level and dashed squares indicate significance to the 0.10 level. Where the number in parenthesis indicate the effect.

Plant Diversity Component 4: Age and Chemical Management			
Chemical Tretaments	0.005 (-0.515)	0.032 (-0.364)	
Age	0.059 (0.023)		0.620 (0.007)
Plant Frequency Component 4: Age and Chemical Management			
Age	0.658 (0.390)	0.538 (0.463)	
Chemical Tretaments	0.856 (2.2)		0.656 (4.7)

Table 25 outlines the statistical significance of the component scores produced by the PCA against the plant diversity and frequency of each roof. Utilizing the other scores as covariates. When all other variables are held the same, we found that only component 2 shows significance to the 0.10 level for plant diversity. Indicating the substrate conditions to have an overall negative effect on plant diversity. This tells us that substrate conditions are moderately significant and can explain much of the variance found in the plant diversity data. Although the other components do not show significance, roof features and substrate and vegetation management show a positive effect on diversity and frequency. Whereas high management and age and chemical management shows a negative effect on plant diversity but a positive effect on frequency.

3.5 Substrate Survey

We completed one substrate survey at the beginning of this study, for a total of 87 surveys taken across the thirteen roofs. Across the roofs fourteen independent studies of pH, phosphorus, potassium, calcium, magnesium, zinc, manganese, copper, boron, sodium, and organic matter were done at the Clemson Soil Extension. ***Table 26*** outlines the composition of the substrate in mg/L for each element at each location.

Table 24 Results of the linear mixed model comparing the component variables outlined by the PCA. With grayed squares representing significance to the 0.05 level and dashed squares indicate significance to the 0.10 level. Where the number in parenthesis indicate the effect.

Plant Diversity Component 5: Substrate and Vegetation Mangement		
Weeding	0.612 (0.086)	0.561 (0.095)
Substrate Depth	0.650 (0.007)	0.583 (0.008)
Plant Frequency Component 5: Substrate and Vegetation Mangement		
Weeding	0.132 (13.9)	0.125 (13.4)
Substrate Depth	0.743 (-0.259)	0.922 (-0.081)

Figure 11 illustrates the mean levels of boron, sodium, zinc, and manganese at each roof. The horizontal line indicates the maximum healthy level of the respective nutrient, as outlined in Berghage et al., 2008. We found that each locations levels of boron and manganese are well above the healthy limit. Whereas only RMH, ZEC, and SF are above healthy limits for sodium and MCC, FW, and CCB are above their healthy limits of zinc. ***Figure 11*** is organized from high to low management. There is no clear trend in these nutrient levels and management.

Figure 12 illustrates the mean nutrient levels of phosphorus, potassium, and magnesium, with the horizontal line referring to the maximum healthy limit as outlined in Berghage et al., 2008. All levels of nutrients are well above the maximum healthy limit with phosphorus and magnesium in extreme excess. These are also organized from high to low management, with no clear trend based on nutrient levels of phosphorus, potassium and magnesium and management.

Figure 13 illustrates the mean pH across all locations. With the healthy rage illustrated by the black horizontal lines. Again, outlined by Berghage et al., 2008. All locations are within this healthy range except RMH and BLR, which are just below the threshold, not low enough to be the cause of concern.

Figure 14 illustrates the mean organic matter levels across all locations with the maximum OM in SF at a striking 32.14% and the lowest OM at ABG with 5.43%. Every location is above the healthy threshold except for ABG. With many locations like CCB, HCH, FW, LSH, and BLR being only slightly above healthy levels. However, GS, GR, ZEC, MCC, SF, and SB all show to be well above the healthy range. This figure is organized from youngest to oldest roof. There is no clear trend between OM levels and age of the roof.

Table 25 Results of the linear mixed model comparing the component scores outlined by the PCA. With grayed squares representing significance to the 0.05 level and dashed squares indicate significance to the 0.10 level. Where the number in parenthesis indicate the effect.

	Component 1	Component 2	Component 3	Component 4	Component 5
Plant Diversity	0.720 (-0.026)	0.060 (-0.110)	0.507 (0.041)	0.358 (-0.067)	0.294 (0.077)
Plant Frequency	0.539 (3.0)	0.815 (0.620)	0.917 (0.496)	0.420 (4.1)	0.220 (6.2)

Table 26 Summary of levels (mg/L) of each chemical found in the substrate of each roof as well as the pH and percent organic matter. Ordered from highest to lowest management styles.

	pH	Buffer pH	Phosphorus (mg/L)	Potassium (mg/L)	Calcium (mg/L)	Magnesium (mg/L)	Zinc (mg/L)	Manganese (mg/L)	Copper (mg/L)	Boron (mg/L)	Sodium (mg/L)	OM (%)
MCC	6.9	7.57	102.23	112.89	3472.32	221.56	10.83	19.31	0.20	1.73	12.69	24.26
RMH	6.4	7.57	66.56	182.21	2318.37	276.17	8.77	21.33	4.49	1.51	32.54	11.91
ZEC	6.8	7.53	234.06	75.57	3891.91	329.12	5.15	14.16	0.15	1.56	22.06	20.58
FW	6.9	7.68	107.38	59.76	3126.10	194.90	25.94	32.54	0.53	1.67	15.08	8.44
ABG	7	7.78	48.17	36.77	1875.81	89.73	6.18	16.55	0.55	0.88	6.25	5.43
HCH	6.7	7.73	40.82	49.64	1269.97	90.09	6.89	7.35	0.53	0.99	6.62	8.18
SF	6.8	7.53	481.36	72.08	4000.57	282.79	8.31	9.56	0.11	1.34	20.96	32.14
CCB	7.15	7.75	74.47	31.63	2058.57	162.91	11.75	19.12	0.53	0.97	13.97	6.19
SB	7	7.65	45.05	108.67	3296.55	169.53	9.58	15.08	0.26	1.69	11.95	15.56
GS	7.1	7.73	186.26	73.55	3052.92	245.83	6.56	30.52	0.37	1.49	12.87	16.06
BLR	6.2	7.63	19.31	24.45	1057.78	60.31	8.27	9.38	0.99	0.75	4.96	6.88
LSH	6.8	7.73	33.83	68.77	1475.53	93.04	10.19	16.36	1.29	0.97	9.93	6.19
GR	6.9	7.7	33.10	40.08	1372.01	282.42	4.34	14.71	0.31	0.90	8.27	26.13

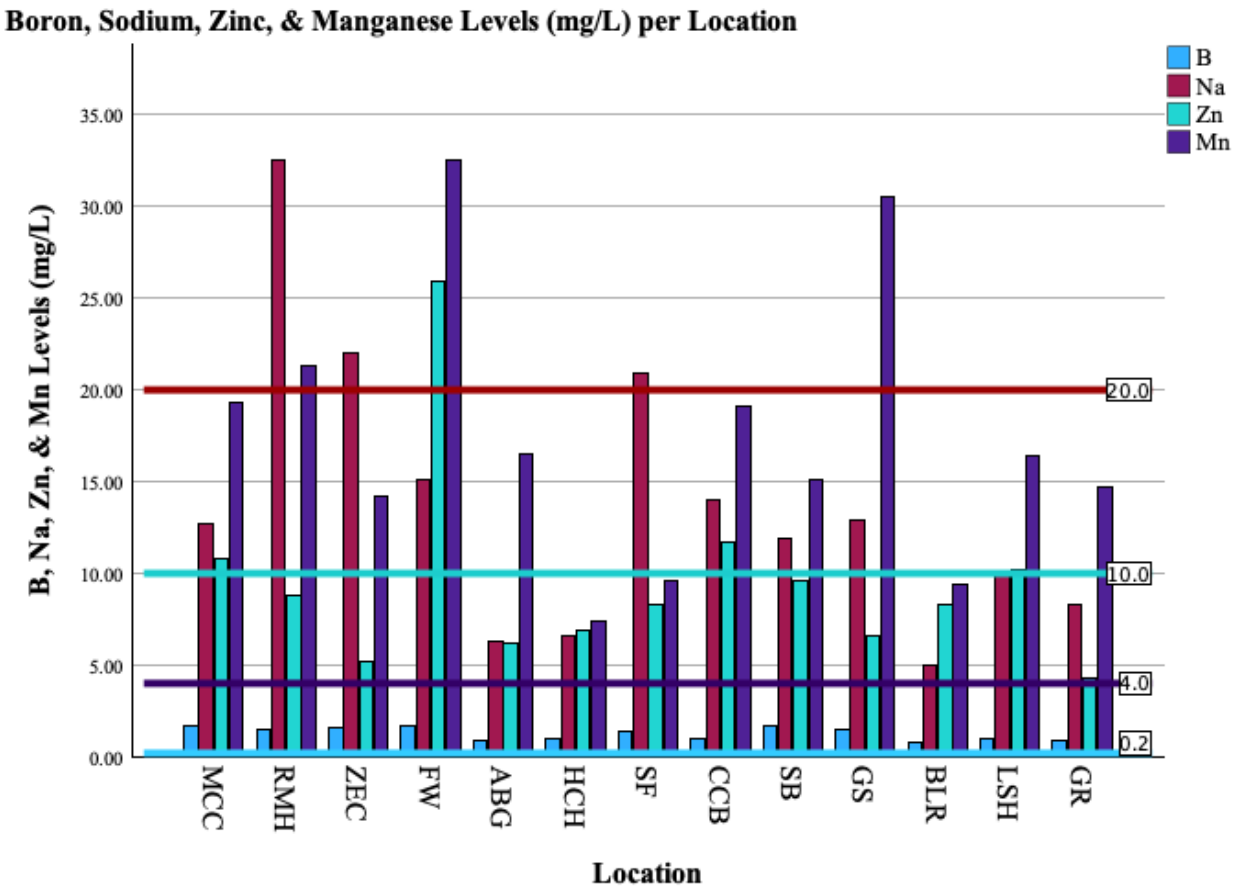

Figure 10 Levels of boron, sodium, zinc, and manganese on each roof. Organized from high to low maintenance. With the horizontal lines indicating the maximum healthy level of that nutrient.

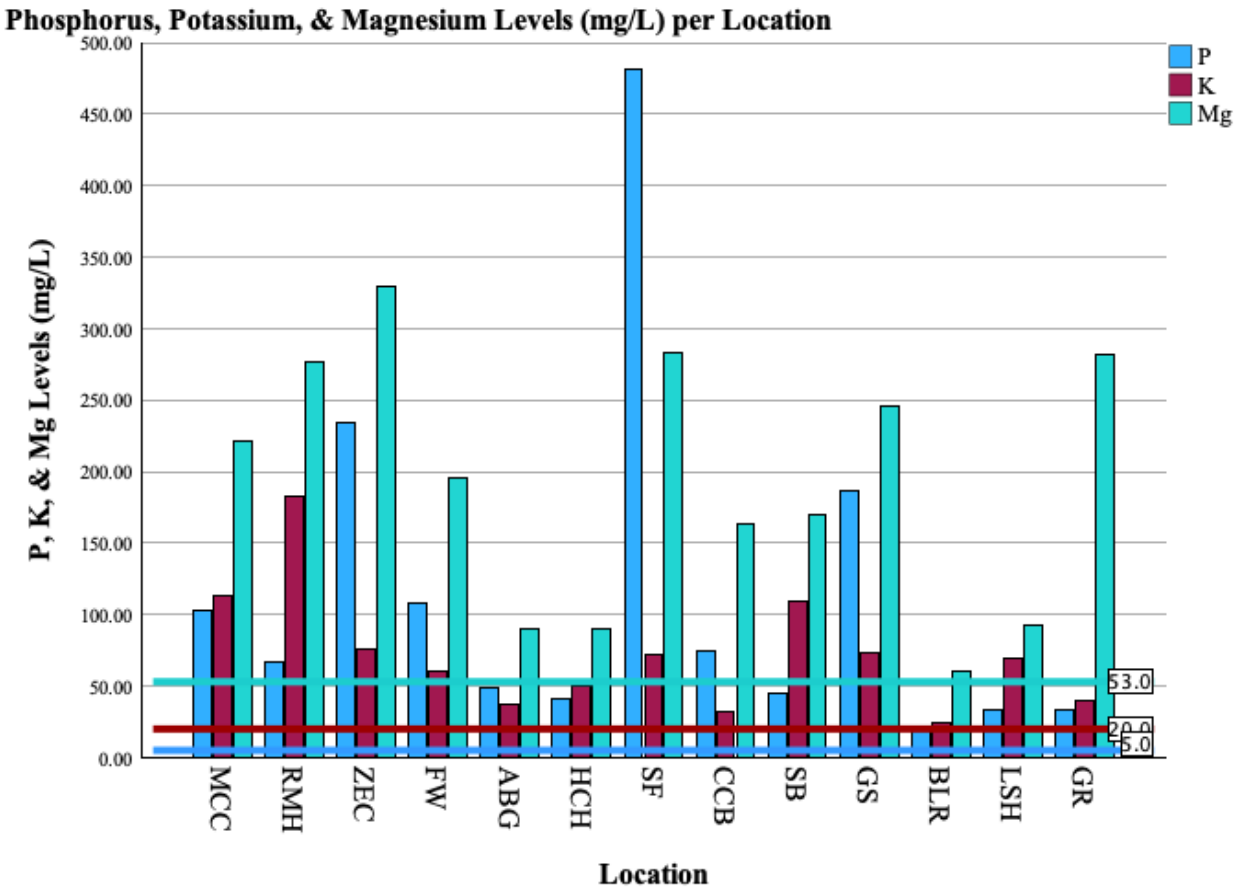

Figure 11 Levels of phosphorus, potassium, and magnesium on each roof. Organized from high to low maintenance. With the horizontal lines indicating the maximum healthy level of that nutrient.

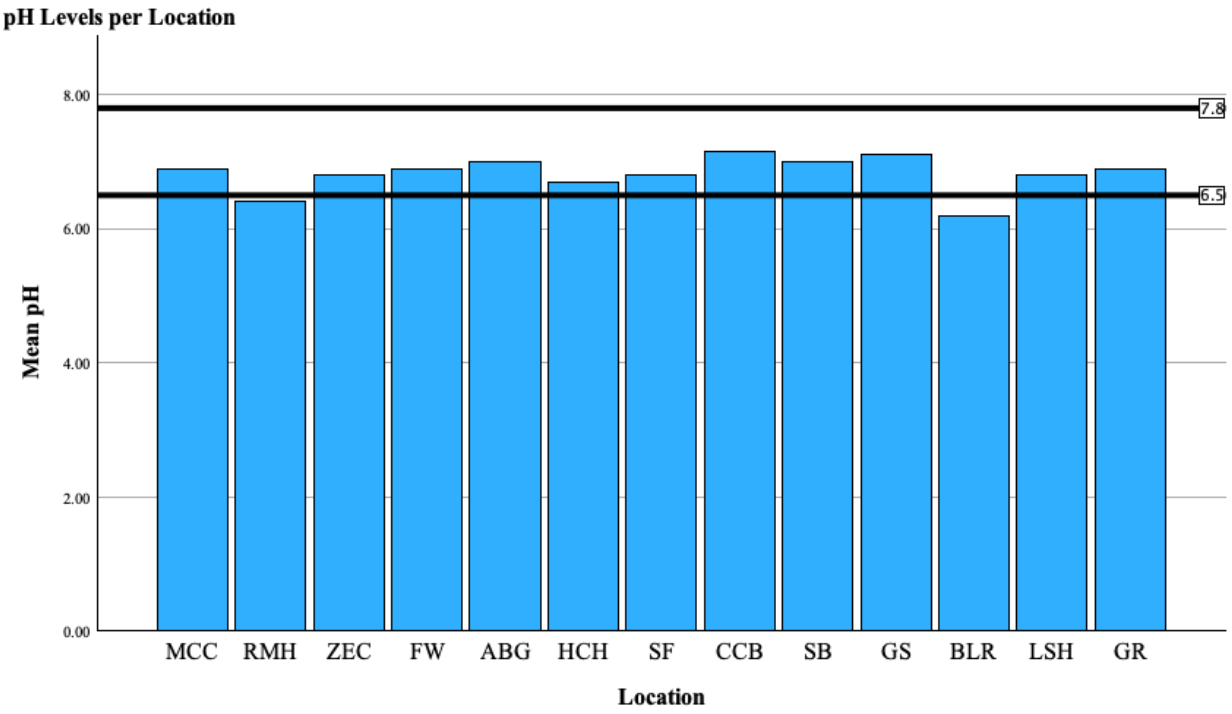

Figure 12 Levels of pH on each roof. Organized from high to low maintenance. With the horizontal lines indicating the healthy range of pH.

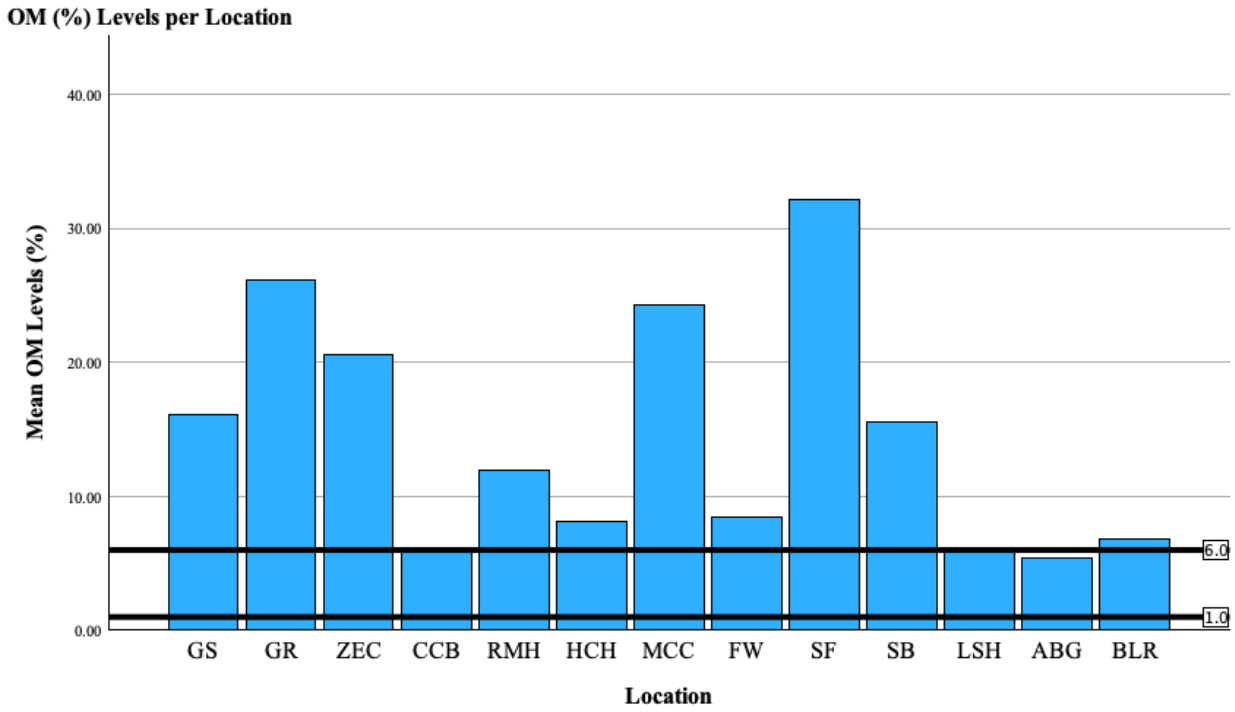

Figure 13 Levels of OM on each roof. Organized from youngest to oldest. With the horizontal lines indicating the healthy range of OM.

Table 27 illustrates the significance levels of each independent variable against each nutrient and pH and OM levels. Independent variables show the most significance across all nutrients, significance for 2 or more nutrients, are roof age, roof elevation, irrigation, weeding habits and substrate additions. Roof age shows significance at the 0.05 level for magnesium and at the 0.10 level for OM. Where elevation shows significance at the 0.05 level for copper and boron, and at the 0.10 level for phosphorus and calcium. Irrigation only shows significance at the 0.10 level for boron and sodium. Weeding habits have significance to the 0.05 level for boron and to the 0.10 level for potassium and calcium. Finally, substrate additions show to be significant at the 0.05 level for potassium and OM and to the 0.10 level for copper. Overall, we found that excess nutrients are more common on these roofs than not enough nutrients, and that the main influences of these nutrient levels come from roof age and elevation, irrigation and weeding habits, and substrate additions.

Table 27 Results of the linear mixed model comparing the individual independent variables to the found nutrient levels. With grayed squares representing significance to the 0.05 level and dashed squares indicate significance to the 0.10 level. Where the effect is noted in parenthesis.

	Soil Moisture	Age	Elevation	Substrate Depth	Irrigation	Replant	Weed	Substrate Addition	Mgmt.
pH	(-) 0.738	(-) 0.303	(+) 0.528	(+) 0.892	0.836	0.836	0.622	0.573	0.833
Phosphorus	(+) 0.505	(-) 0.239	(+) 0.056	(-) 0.475	0.101	0.534	0.171	0.049	0.435
Potassium	(+) 0.384	(-) 0.36	(+) 0.416	(-) 0.105	0.295	0.445	0.093	0.217	0.171
Calcium	(+) 0.606	(-) 0.622	(+) 0.079	(-) 0.466	0.445	1	0.065	0.077	0.833
Magnesium	(+) 0.142	(-) 0.013	(+) 0.378	(-) 0.605	0.445	0.731	0.524	0.217	0.833
Zinc	(+) 0.344	(+) 0.281	(+) 0.154	(-) 0.028	0.445	0.836	0.833	1	0.435
Manganese	(+) 0.722	(-) 0.318	(+) 0.782	(-) 0.404	0.138	0.073	1	0.573	0.093
Copper	(-) 0.782	(+) 0.231	(-) 0.037	(-) 0.737	0.945	0.445	0.354	0.077	0.724
Boron	(+) 0.187	(-) 0.409	(+) 0.022	(-) 0.177	0.073	0.366	0.045	0.287	0.093
Sodium	(+) 0.046	(-) 0.127	(+) 0.151	(-) 0.281	0.073	1	0.284	0.469	0.435
OM%	(+) 0.654	(-) 0.096	(+) 0.379	(-) 0.776	0.836	0.731	0.524	0.049	0.724

3.6 Results Summary

Component 1 (Management Practices):

- Irrigation is negatively significant for invertebrate diversity when replanting is a solo covariate.
- Irrigation is negatively significant when compared to stabilization with no covariance.
- Irrigation is highly positively significant with or without covariance when compared to decomposition rate.
- Irrigation is most negatively significant when replanting is a covariate for plant diversity.
- Replanting is negatively and management is positively significant when used as covariates for invertebrate abundance.
- Replanting is negatively and management is positively significant when used as covariates for stabilization factor.
- Management classification is only negatively significant with covariance for decomposition rate.
- Component 1 is only slightly significant when each variable is individually compared to nutrient levels.

Component 2 (Substrate Conditions):

- Soil temperature is positively significant with no covariance for invertebrate diversity.
- Soil temperature is negatively significant when soil moisture is a covariance for stabilization factor.
- Soil temperature is positively, and soil moisture is negatively significant for plant diversity when covariance is removed.
- Soil temperature and moisture are positively significant with covariance for plant frequency.

Component 3 (Roof Features):

- Elevation is positively significant with all or no covariance for decomposition.
- Elevation is positively significant when only substrate addition is used as a covariate for plant frequency.

- Elevation is negatively and size is positively significant when used as covariates for plant diversity.
- Roof features are significant when predicting nutrient levels.

Component 4 (Age and Chemical Management):

- Age is positively significant only when chemical treatment is used as covariance for invertebrate diversity.
- Age is positively and chemical treatments are negatively significant when used as covariates for plant diversity.

Component 5 (Substrate and Vegetation Management):

- Substrate depth is most negatively significant when weeding is used as a covariate for stabilization factor.
- Substrate depth and weeding are negatively significant when used as covariates for invertebrate abundance.

Overall, substrate conditions are the most significant when predicting invertebrate and plant diversity, with an overall negative effect. Management practices and substrate conditions are most significant when predicting decomposition rate, with an overall positive effect. Although insignificant, management practices show a negative effect on invertebrate and plant diversity and a positive effect on invertebrate abundance, plant frequency and stabilization factor. With components 3, 4, and 5 showing minimal to no significance on each proxy.

Chapter 4. Discussion

Our findings suggest that less managed green roofs promote higher biodiversity, likely because more natural conditions allow for and promote more plant growth, acting as habitat for invertebrates such as arthropods and mollusks. These findings also suggest that higher management and substrate conditions promotes invertebrate abundance, plant frequency, and decomposition, possibly due to more favorable conditions for growth. Analyses of each variable within the component groups indicates that specific management practices like irrigation, replanting, weeding, and chemical treatment application show majority negative effects on biodiversity, plant frequency, decomposition, and substrate composition. Most likely due to the removal of habitats and applications of herbicides and pesticides that harm the biodiversity. These analyses also imply that substrate conditions, soil moisture and temperature, play a majority positive role in predicting biodiversity and plant frequency. Possibly due to favorable conditions, moist and warm for invertebrate and plant growth. Finally, roof features, like age, elevation, size, and substrate depth, indicate a mostly positive effect on biodiversity and plant frequency. Possibly attributed to the idea that older, larger, and deeper green roofs may have higher successional growth. Therefore, we conclude that typical intensive management practices, as it compares to the lower management counterparts, negatively effects the supporting services provided by the studied green roofs. However, the low managed roofs may also negatively affect the supporting services provided by the studied green roofs. In all aspects of low management as well as high management should be considered to properly maintain and promote these supporting services on the studied green roofs.

4.1 Influences on Arthropod, Mollusk, and Annelid

The general trend of invertebrate diversity over time across the roofs shows that diversity increases until June, and then starts to decline until August 2024. This can be attributed to the rise in temperature as the spring and summer seasons progress. Invertebrates tend to become more diverse as temperatures increase, with them falling off as temperatures decrease (Ghiglieno et al., 2020). However, invertebrate abundance decreases from the first to last collections, spanning from March to August 2024. This can also be attributed to the increase in temperatures as spring and summer progresses (Ghiglieno et al., 2020; Prather et al., 2020). The rise in temperature allows for more niches increasing the diversity. However, temperature rise can

increase the diversity (Figueroa et al., 2021, Prather et al., 2020). We found that green roof substrate depth has a negative effect on abundance when weeding is used as a covariate. This may be due to the lack of available resources and habitability at lower depths (Madre et al., 2013). Other studies show the opposite of this where plant-pollinator interactions increase with deeper substrates (Dusza et al., 2020). Higher levels of management shows a decline in invertebrate diversity. Intensive management practices have been shown to lower invertebrate diversity as it can destroy niches and reduce habitat structures (Proske et al., 2022; Harada & Whitlow 2020). Like low managed ground environments, diversity increases in more natural settings.

4.2 Influence on Stabilization Factor and Decomposition Rate

The general trend of the stabilization factor and decomposition rate is that they start high and decrease quickly until they slow down and level out around May and June 2024. Our results agree with previous studies showing that decomposition and stabilization tend to follow these trends (Keuskamp et al., 2013). The stabilization factor is directly linked to the decomposition rate so that, as decomposition increases, stabilization will tend to increase as well. Soil temperature and moisture should have similar effects on stabilization and decomposition (Keuskamp et al., 2013). Thus, as soil temperature increases, stabilization, and decomposition decrease. Many findings related to the teabag index indicate that climatic conditions such as temperature and moisture have varying effects on *k* and S (Gmach et al., 2024; Artefeh & Reinhardt, 2020). Soil moisture is found to increase decomposition rate, as moisture allows for more microbial productivity, thus increasing the decomposition rate (Keuskamp et al., 2013).

We also found that irrigation also affects the decomposition process. On roofs that have, and use, and irrigation system, both stabilization and decomposition tend to increase. Soil moisture has also been found in other studies to increase decomposition (Keuskamp et al., 2013; Técher et al., 2024). Higher levels of management also tend to increase decomposition. Highly managed green roofs typically irrigate more often and add organics to their substrates, among other practices, which, as seen above, causes decomposition rate to increase with more intensive practices (Gmach et al., 2024; Técher et al., 2024; Yang & Davidson, 2021). However, some studies such as Djukic et al., 2018 and Saint-Laurent and Arsenal-Boucher 2020, do not find any significant effect of management practices on decomposition or stabilization. The reason for this

is unclear but may be related to the way they measured management practices. Elevation also shows a positive effect on decomposition, in contrast to previous studies (Ma et al., 2024; Reddy et al., 2024).

4.3 Influence on Plants

The general trend of the plant community is that frequency and diversity increase until May or June then decreases until August 2024. This can be attributed to the changes in temperature seasonally from March to August. Soil moisture has a positive effect on frequency and a negative effect on diversity when temperature is used as a covariate. This may be due to the plant selection found on typical green roofs. Selections are usually chosen based on their ability to be drought tolerant having lower watering needs, so as soil moisture increases, plants are not able to perform as well, decreasing the diversity, however, possibly increasing the frequency due to the takeover of possible invasive or other monocultures (Price et al., 2011). As soil temperatures increase so does frequency and diversity. Again, the plants on a typical green roof are special selected for their ability to withstand and thrive in high temperatures (Snodgrass & McIntyre 2010). So, as soil temperatures increase the plants on the roof tend to thrive better. This however contrasts to other studies that show lower soil temperatures and higher soil moisture levels allow for higher plant diversity (Atefeh & Reinhardt, 2020; Van der Kolk et al., 2020; Bollman et al., 2021; Wang et al., 2022).

Perhaps not surprisingly, roofs that do not employ chemical treatments, i.e., herbicides and pesticides, tend to have more plant diversity. As chemical treatments are used, they can often kill more than the targeted plant thus decreasing diversity. Higher levels of management also tend to decrease plant diversity (Harada & Whitlow 2020; Smith et al., 2020; Proske et al., 2022).

4.4 Influence on Substrate Composition

For most locations we found that all nutrient levels show to be in above the maximum healthy level except for some locations of sodium and zinc, with all locations being in major excess of phosphorus, manganese, and magnesium. There also shows no clear trend in nutrient levels based on management styles. Sodium tends to increase with soil moisture. This may be attributed to possible poor drainage causing sodium accumulation or high sodium content water

from irrigation (Aitkenhead-Peterson et al., 2010). Higher elevation is found to decrease levels of copper and increase levels of boron. Lower levels of copper at high elevations may be attributed to organic matter levels in the soil or substrate, as organic matter lessens with elevation (Massaccesi et al., 2020), studies show that copper can decrease as well (Jeon et al., 2024). Boron levels increases as elevation increases, in contrast to other studies finding no significance in boron levels and elevation (Zhang et al., 2020).

Deeper substrates typically showed lower zinc levels. This may be explained by the plant chosen to be on a typical green roof. Green roofs typically have shallow rooted plants growing, meaning shallower roots taking up more zinc at the topsoil, depleting zinc from lower layers of the substrate (Recena et al., 2021). Irrigation levels show to influence boron and sodium. Irrigation can affect boron levels negatively or positively based on the chemical composition of the water used to irrigate, as well as the soil type and drainage (Aitkenhead-Peterson et al., 2010). Weeding also showed to affect boron levels. This can be attributed to the idea that weeding can reduce competition for boron. Substrate addition can positively or negatively influence the levels of phosphorus and organic matter. The added substrate may have a higher level of phosphorus and organics allowing the levels to increase in the substrate of the green roof. Higher management levels can also show an effect on numerous chemical levels in the substrate composition. The intensive management styles are to be able to impact multiple nutrients positively or negatively in the substrate composition.

Chapter 5. Conclusions, Limitations, and Future Work

It is important to note the limitations to our study to provide a more stable story. Our results show important conclusions for the future work of green roofs in the Southeastern United States, however, our findings here are found with a relatively small sample size so this can be considered tentative, requiring further study and a larger sample size. As well as most of the studied roofs are mature, or well established, with an average age of 11 years. Due to these limitations the results may be partially misleading, requiring the use of future research to validate these results.

- A Principal Component Analysis was run to find the highest communalities between the independent variables.
    - Creating 5 component groups: management practices, substrate conditions, roof features, age and chemical management, and substrate and vegetation management.
- Significant findings based on linear mixed model analyses utilizing covariance suggest:
    - Invertebrate diversity is influenced by irrigation (-), soil temperature (+), and green roof age (+).
    - Invertebrate abundance in influenced by replanting (-), management classification (+), substrate depth (-), and weeding (+).
    - Plant diversity is influenced by irrigation (-), soil moisture (-), soil temperature (+), green roof age (+), and chemical treatments (-).
    - Plant frequency is influenced by soil moisture (+), soil temperature (+), and elevation (+).
    - Stabilization factor is influenced by irrigation (+), replanting (-), management classification (+), soil temperature (-), elevation (+), and substrate depth (-).
    - Decomposition rate is influenced by irrigation (+), management classification (-), and elevation (+),
- Significant findings based on component scores suggest:
    - Substrate conditions negatively influenced invertebrate abundance.
    - Substrate conditions negatively influenced plant diversity.

- Management practices and substrate conditions positively influence decomposition rates.

Over the course of this research, we found more than 136,500 individual invertebrates comprising of three phyla, 1,552 teabags were analyzed for stabilization factor and decomposition rate, 102 plant genera were identified, and a chemical soil composition was found for each of thirteen roofs. These variables were used as proxies for understanding supporting services created by green roofs in the southeast. We aimed to investigate the effect of management, age and other environmental and roof features on the promotion or demotion of these proxies. Our results suggest that higher management levels on the studied green roofs do not promote as many ES whereas the lower managed roofs do support more ES in all cases except decomposition. Further multi-year studies are needed to investigate management's roles in the promotion of ecosystem services in urban habitats. Additional research is also needed to fully explore these proxies and green roofs to a deeper level.

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Appendix

General questions:

1. What is the substrate type and depth?
2. What is the original plant list? (If possible)
3. What is the current plant list? (If possible)
4. Have there been any leakage issues?
5. Was there any major die off? If so, how was this problem fixed?
6. What year was the green roof installed? By what company (name, city, and contact info)?
7. How many stories high is the green roof?

Present maintenance:

1. How often is the roof watered?
2. How often does the roof get plants added/replaced since the roof's installation?
3. How often do you remove weeds?
4. Have you ever used pesticides/herbicides since it was installed? When?
5. Have you ever added substrate/soil since the roof was installed? When?
6. Would you classify your current management strategy as: A) high maintenance (the roof is regularly watered/weeded every few weeks) B) medium (roof is watered/weeded every 3-6 months), or C) low (little or no watering/weeding occurs throughout the year).

Past maintenance:

1. Have your current management practices above generally been the same every year since the roof was installed?
2. If not, how did past management differ in previous years?

Future maintenance:

1. Are your current management practices subject to change in the future?
2. Is there any new management happening soon? If so, what kinds?

Appendix 1 Survey questionnaire distributed to each of the study roofs.

City	Roof name	Acronym	Location
Asheville	Blueridge Parkway Visitor Center	BLR	(35.5657, -82.4863)
	Lucy S. Herring Elementary School	LSH	(35.5775, -82.6012)
Atlanta	Atlanta Botanical Gardens	ABG	(33.7899, -84.3725)
	Ronald McDonald House Charities	RMH	(33.9026, -84.3535)
	Southface Energy Institute	SF	(33.7673, -84.3805)
Chattanooga	Hamilton County Health Department	HCH	(35.0487, -85.2923)
Knoxville	City County Building	CCB	(35.9603, -83.9167)
	Garden Shed	GS	(35.9450, -83.9376)
	Green Roof Experimental Lab	GR	(35.9435, -83.9361)
	Zeanah Engineering Complex	ZEC	(35.9557, -83.9237)
Nashville	Freeman Webb Company Corporate Office	FW	(36.1087, -86.8198)
	Music City Center	MCC	(36.1570, -86.7782)
	Shelby Bottoms Nature Center	SB	(36.1661, -86.7249)

Appendix 2 Location acronyms and coordinates.

Common Name	**Phylum**	**Class**	**Order**	**Family**	**Genus**	**TOTAL**
Acorn Fly	Arthropoda	Insecta	Diptera	*Drosophilidae*	*Chymomyza*	13
American Cockroach	Arthropoda	Insecta	Blattodea	*Blattidae*	*Periplaneta*	6
Aphid	Arthropoda	Insecta	Hemiptera	*Aphididae*	*Aphidoidae spp.*	1321
Argentine Ant	Arthropoda	Insecta	Hymenoptera	*Formicidae*	*Linepethema*	3898
Asian Wall Jumper	Arthropoda	Arachnida	Araneae	*Salticidae*	*Attulus*	3
Assassin Bug	Arthropoda	Insecta	Hemiptera	*Reduviidae*	*Zelus*	70
Beautiful Wireworm	Arthropoda	Insecta	Coleoptera	*Elateridae*	*Monocrepidius*	129
Beet Flea Beetle	Arthropoda	Insecta	Coleoptera	*Chrysomelidae*	*Chaetocnema*	3
Big-Eyed Bug	Arthropoda	Insecta	Hemiptera	*Geocoridae*	*Geocoris*	113
Big-Headed Simple Riverbank Ground Beetle	Arthropoda	Insecta	Coleoptera	*Carabidae*	Scarites	2
Black Carpenter Ant	Arthropoda	Insecta	Hymenoptera	*Formicidae*	*Camponotus*	6
Black Firefly	Arthropoda	Insecta	Coleoptera	*Lamyridae*	*Lucidota*	2
Black Garden Ant	Arthropoda	Insecta	Hymenoptera	*Formicidae*	*Lasius*	24
Boreal Yellow-Headed Soil Centipede	Arthropoda	Chilopoa	Geophilomorpha	*Geophilidae*	*Geophilus*	1
Bristly Millipede	Arthropoda	Diplopoda	Polyxenida	*Polyxenidae*	*Polxenus*	17
Broad-Faced Sac Spider	Arthropoda	Arachnida	Araneae	*Trachedlidae*		3
Brown Centipede	Arthropoda	Chilopoda	Lithobiomorpha	*Lithobiidae*	*Lithobius*	25
Brown Chafer	Arthropoda	Insecta	Coleoptera	*Melolonthidae*	*Serica*	12
Brown Lacewing	Arthropoda	Insecta	Neuroptera	*Hemerobiidae*		11
Bull-Headed Dung Beetle	Arthropoda	Insecta	Coleoptera	*Scarabaeidae*	*Onthophagus*	3
Bumblebee	Arthropoda	Insecta	Hymenoptera	*Apidae*	*Bombus*	2
Buzzer Midge	Arthropoda	Insecta	Diptera	*Chironomidae*	*Chironomus*	68
Caddisfly Larva	Arthropoda	Insecta	Trichoptera	*Oeconesidae*	*Oeconesidae (larva)*	4
Carolina Grasshopper	Arthropoda	Insecta	Orthoptera	*Acrididae*	*Dissosteira*	15
Carolina Ground Cricket	Arthropoda	Insecta	Orthoptera	*Trigonidiidae*	*Eunemobius*	3633
Chestnut-Footed Click Beetle	Arthropoda	Insecta	Coleoptera	*Elateridae*	*Melanotus*	42

Chrysanthemum Lace Bug	Arthropoda	Insecta	Hemiptera	*Tingidae*	*Corythuca*	6
Cicada	Arthropoda	Insecta	Hemiptera	*Cicadidae*	*Cicada*	2
Clover Weevil	Arthropoda	Insecta	Coleoptera	*Curculionidae*	*Sitona*	38
Common Capsid	Arthropoda	Insecta	Hemiptera	*Miridae*		20
Common House Spider	Arthropoda	Arachnida	Araneae	*Theridiidae*	*Parasteatoda*	29
Common Milkweed Bug	Arthropoda	Insecta	Hemiptera	*Lygaeidae*	*Lyaegus*	1
Common Pill Woodlouse	Arthropoda	Malacostraca	Isopoda	*Armadillidiidae*	*Armadillidium*	20859
Common Pill-Beetle	Arthropoda	Insecta	Coleoptera	*Byrrhidae*		7
Common Spiny Digger Wasp	Arthropoda	Insecta	Hymenoptera	*Crabronidae*	*Oxybelus*	1
Common Thrips	Arthropoda	Insecta	Thysanoptera	*Thripidae*	*Frankiniella*	593
Coppery Leafhopper	Arthropoda	Insecta	Hemiptera	*Cicadellidae*	*Jikradia*	449
Crab Spider	Arthropoda	Arachnida	Araneae	*Thomisidae*	*Xysticus*	294
Cupboard Spider	Arthropoda	Arachnida	Araneae	*Theridiidae*	*Steatoda*	16
Dark Flower Scarab	Arthropoda	Insecta	Coleoptera	*Cetoniidae*	*Euphoria*	61
Dark-Tipped Wingwaver	Arthropoda	Insecta	Diptera	*Ulidiidae*	*Seioptera*	2
Dirt-Colored Seed Bug	Arthropoda	Insecta	Hemiptera	*Rhyparochromidae*	*Ozophora*	694
Draparnaud'S Glass Snail	Mollusca	Gastropoda	Stylommatophora	*Oxychilidae*	*Oxychilus*	4407
Early Mining Bee	Arthropoda	Insecta	Hymenoptera	*Adrenidae*	*Adrena*	1
Eastern Boxelder Bug	Arthropoda	Insecta	Hemiptera	*Rhopalidae*	*Boisea*	1
Eastern Honeybee	Arthropoda	Insecta	Hymenoptera	*Apidae*	*Apis*	3
Eastern Parson Spider	Arthropoda	Arachnida	Araneae	*Gnaphosidae*	*Herpyllus*	4
Eastern Subterranean Termite	Arthropoda	Insecta	Blattodea	*Heterotermitidae*	*Reticulitermes*	10
Eastern Tent Caterpillar	Arthropoda	Insecta	Lepidoptera	*Lasiocampidae*	*Malacosoma (larva)*	10
Elf Shoe Stink Bug	Arthropoda	Insecta	Hemiptera	*Pentatomidae*	*Menecles*	1
Elm Leaf Beetle Larva	Arthropoda	Insecta	Coleoptera	*Chrysomelidae*	Xanthogaleruca (larva)	49

European Ambersnail	Mollusca	Gastropoda	Stylommatophora	*Succineidae*	*Succinea*	182
European Earwig	Arthropoda	Insecta	Dermaptera	*Forficulidae*	*Forficulidae*	198
European Harvestman	Arthropoda	Arachnida	Araneae	*Phalangiidae*		6
European Paper Wasp	Arthropoda	Insecta	Hymenoptera	*Vespidae*	*Polistes*	6
Fairy Wasp	Arthropoda	Insecta	Hymenoptera	*Mymaridae*	*Mymaridae spp.*	264
Fall Armyworm Moth	Arthropoda	Insecta	Lepidoptera	*Noctuidae*	*Noctuidae (larva)*	19
Fall Field Cricket	Arthropoda	Insecta	Orthoptera	*Gryllidae*	*Gryllus*	888
Fire Ant	Arthropoda	Insecta	Hymenoptera	*Formicidae*	*Solenopsis*	12308
Flat Wireworm	Arthropoda	Insecta	Coleoptera	*Elateridae*	*Aeolus*	49
Four-Lined Jumping Spider	Arthropoda	Arachnida	Araneae	*Salticidae*	*Marpissa*	19
Four-Spurred Assassin Bug	Arthropoda	Insecta	Hemiptera	*Reduviidae*	*Zelus*	1
Fruit Fly	Arthropoda	Insecta	Diptera	*Drosophilidae*		678
Gall Midge	Arthropoda	Insecta	Diptera	*Ceceidomyiidae*		56
Garden Arion	Mollusca	Gastropoda	Stylommatophora	*Arionidae*	*Arion*	536
Garden Ghost Spider	Arthropoda	Arachnida	Araneae	*Anyphaenidae*		156
Garden Wolf Spider	Arthropoda	Arachnida	Araneae	*Lycosidae*		1106
Glossy Pillar	Mollusca	Gastropoda	Stylommatophora	*Cochlicopidae*	*Cochlicopa*	589
Golden Sweat Bee	Arthropoda	Insecta	Hymenoptera	*Halticidae*		6
Grass Snail	Mollusca	Gastropoda	Stylommatophora	*Valloniidae*		46
Great Grey Slug	Mollusca	Gastropoda	Stylommatophora	*Limacidae*	*Limax*	5
Green Junebug	Arthropoda	Insecta	Coleoptera	*Scarabaeidae*	*Cotinis*	1
Greenhouse Millipede	Arthropoda	Diplopoda	Polydesmida	*Paradoxosomatidae*	*Oxidus*	5107
Grooved Minute Rove Beetle	Arthropoda	Insecta	Coleoptera	*Staphylinidae*	*Drusilla*	140
Hairy Fungus Beetle	Arthropoda	Insecta	Coleoptera	*Anamorphidae*	Clemmus	2
Highland Midge	Arthropoda	Insecta	Diptera	*Ceratopogonidae*	*Cullicoides*	11
Homopteran Bug	Arthropoda	Insecta	Hemiptera	*Cicadellidae*	*Idiocerus*	2
Hop-Garden Earwig	Arthropoda	Insecta	Dermaptera	*Forficulidae*	*Apterygida*	75
Horned Leafhopper	Arthropoda	Insecta	Hemiptera	*Cicadellidae*		63
Hornworm Parasitic Wasp	Arthropoda	Insecta	Hymenoptera	*Braconidae*	*Cotesia*	37

House Centipede	Arthropoda	Chilopoa	Scutigeromorpha	*Scutigeridae*	*Scutigera*	33
House Fly	Arthropoda	Insecta	Diptera	*Muscidae*	*Musca*	249
Japanese Leafhopper	Arthropoda	Insecta	Hemiptera	*Cicadellidae*	*Orientus*	2
Jumping Spider	Arthropoda	Arachnida	Araneae	*Salticidae*		260
Keelback Slug	Mollusca	Gastropoda	Stylommatophora	*Limacidae*		99
Lacewing Larva	Arthropoda	Insecta	Neuroptera	*Hemerobiidae*	*Hemerobiidae (larva)*	66
Ladybeetle Larva	Arthropoda	Insecta	Coleoptera	*Coccinellidae*	*Coccinellidae (larva)*	43
Larder Beetle	Arthropoda	Insecta	Coleoptera	*Dermestidae*	*Demestes (larva)*	1
Large Conehead Katydid	Arthropoda	Insecta	Orthoptera	*Tettigoniidae*		1
Large Yellow Underwing	Arthropoda	Insecta	Lepidoptera	*Noctuidae*	*Noctuidae (larva)*	3
Leaf Beetle	Arthropoda	Insecta	Coleoptera	*Chrysomelidae*	*Demotina*	10
Leafcutter Bee	Arthropoda	Insecta	Hymenoptera	*Megachilidae*	*Megachilini*	3
Lesser Yellow Underwing	Arthropoda	Insecta	Lepidoptera	*Noctuidae*	*Noctuidae (larva)*	20
Lewis'S Silken Fungus Beetle	Arthropoda	Insecta	Coleoptera	*Cryptophagidae*	Atomaria	251
Long-Necked Seed Bug	Arthropoda	Insecta	Hemiptera	*Rhyparochromidae*	*Mydocha*	162
March Fly	Arthropoda	Insecta	Diptera	*Bibionidae*	*Bibio*	37
Meadow Spittlebug	Arthropoda	Insecta	Hemiptera	*Aphrophoridae*		80
Mealworm	Arthropoda	Insecta	Coleoptera	*Tenebrionidae*		1
Mealybug Destroyer	Arthropoda	Insecta	Coleoptera	*Coccinellidae*	*Cryptolaemus*	6
Mealybugs	Arthropoda	Insecta	Hemiptera	*Pseudococcidae*	*Pseudococcus*	64
Metallic Blue Lady Beetle	Arthropoda	Insecta	Coleoptera	*Coccinellidae*	*Curinus*	448
Metallic Dung Beetle	Arthropoda	Insecta	Coleoptera	*Scarabaeidae*	*Onthophagus*	1
Millipede	Arthropoda	Diplopoda	Julida	*Julidae*	*Ophyiulus*	388
Mosquito Larva	Arthropoda	Insecta	Diptera	*Culicidae*	*Culicidae (larva)*	1
Mouse Spider	Arthropoda	Arachnida	Araneae	*Gnaphosidae*	*Scotophaeus*	92
Multicolored Asian Ladybeetle	Arthropoda	Insecta	Coleoptera	*Coccinellidae*	*Harmonia*	1
Narrow-Necked Grain Beetle	Arthropoda	Insecta	Coleoptera	*Anthicidae*	*Omonadus*	23

Nettle Pollen Beetle	Arthropoda	Insecta	Coleoptera	*Kateretidae*	Brachypterus	10
Norman'S Quaker	Arthropoda	Insecta	Lepidoptera	*Noctuidae*	*Noctuidae (larva)*	14
Northern Paper Wasp	Arthropoda	Insecta	Hymenoptera	*Eumenidae*	*Polistes*	6
Oak Apple	Arthropoda	Insecta	Hymenoptera	*Cynipidae*	*Biorhiza*	194
Oak Carl	Arthropoda	Insecta	Lepidoptera	*Tischeriidae*	*Tischeria*	1
Oriental Beetle	Arthropoda	Insecta	Coleoptera	*Scarabaeidae*	*Exomala*	11
Outer Barklice	Arthropoda	Insecta	Psocodea	*Actopsocidae*	*Ectopsocus*	22
Pale Bordered Field Cockroach	Arthropoda	Insecta	Blattodea	*Blattellidae*	*Pseudomops*	8
Pavement Ant	Arthropoda	Insecta	Hymenoptera	*Formicidae*	*Tetramorium*	3840
Peanut Burrower Bug	Arthropoda	Insecta	Coleoptera	*Cydnidae*	*Pangaeus*	63
Phantom Midge	Arthropoda	Insecta	Diptera	*Chaoboridae*	*Chaoborus*	57
Pigweed Flea Beetle	Arthropoda	Insecta	Coleoptera	*Chrysomelidae*	*Disonycha*	2
Pirate Otter Spider	Arthropoda	Arachnida	Araneae	*Lycosidae*		12
Pirate Wolf Spider	Arthropoda	Arachnida	Araneae	*Lycosidae*	*Pirata*	2
Plant Bug	Arthropoda	Insecta	Hemiptera	*Miridae*		1
Plum Fruit Moth	Arthropoda	Insecta	Lepidoptera	*Tortricidae*	*Torticidae (larva)*	1
Post Dwarf Weaver	Arthropoda	Arachnida	Araneae	*Linyphiidae*	*Erigone*	656
Potato Leafhopper	Arthropoda	Insecta	Hemiptera	*Cicadellidae*	*Empoasca*	5
Privet Leaf Hopper	Arthropoda	Insecta	Hemiptera	*Cicadellidae*		8
Razorjaw Ant	Arthropoda	Insecta	Hymenoptera	*Formicidae*	*Leptogenys*	2427
Red House Spider	Arthropoda	Arachnida	Araneae	*Theridiidae*	*Nesticodes*	34
Red Log Beetle	Arthropoda	Insecta	Coleoptera	*Prostomidae*	*Prostomis*	2
Red Mason Bee	Arthropoda	Insecta	Hymenoptera	*Megachilidae*		2
Red-Flanked Scymnus	Arthropoda	Insecta	Coleoptera	*Coccinellidae*	Scymnus	11
Red-Headed Ant	Arthropoda	Insecta	Hymenoptera	*Formicidae*	*Creamtogaster*	1083
Red-Headed Ash Borer	Arthropoda	Insecta	Coleoptera	*Cerambycidae*	*Neoclytus*	44
Red-Shouldered Bostrichid	Arthropoda	Insecta	Coleoptera	*Bostrichidae*	*Xylobiops*	3
Redworm	Annelida	Clitellata	Crassiclitellata	*Lumbricidae*	*Eisenia*	22
Ring-Legged Earwig	Arthropoda	Insecta	Dermaptera	*Anisolabididae*	*Euborellia*	10
Rove Beetle	Arthropoda	Insecta	Coleoptera	*Staphylinidae*		5

Salt And Pepper Microcaddisfly	Arthropoda	Insecta	Trichoptera	*Hydroptilidae*	*Agraylea*	1
Seed Bug	Arthropoda	Insecta	Hemiptera	*Rhyparochromidae*		200
Seven-Spotted Ladybeetle	Arthropoda	Insecta	Coleoptera	*Coccinellidae*	*Coccinella*	3
Simple Riverbank Ground Beetle	Arthropoda	Insecta	Coleoptera	*Carabidae*	*Bembidion*	3069
Simple Riverbank Ground Beetle Larva	Arthropoda	Insecta	Coleoptera	*Carabidae*	*Carabidae (larva)*	119
Slender Springtails	Arthropoda	Entoghnatha	Entomobryomorpha	*Entomobryidae*	*Entomobrya spp.*	38666
Small Dingy Tubic	Arthropoda	Insecta	Lepidoptera	*Oecophoridae*		11
Small Grass Fly	Arthropoda	Insecta	Diptera	*Lonchopteridae*	*Lonchoptera*	1875
Small Striped Flea Beetle	Arthropoda	Insecta	Coleoptera	*Chrysomelidae*	*Phyllotreta*	25
Soft Winged Flower Beetle	Arthropoda	Insecta	Coleoptera	*Melyridae*		1
Southern Flatcoil	Mollusca	Gastropoda	Stylommatophora	*Polygyridae*	Polygyra	7432
Southern Paper Wasp	Arthropoda	Insecta	Hymenoptera	*Vespidae*	*Polistes*	2
Spider Mite	Arthropoda	Arachnida	Trombidiformes	*Tetranychidae*	*Tetranychus spp.*	2329
Spotted Lacehopper	Arthropoda	Insecta	Hemiptera	*Cixiidae*	*Tachycixius*	3
Spotted Wolf Spider	Arthropoda	Arachnida	Araneae	*Lycosidae*		31
Spotted Wolf Spider	Arthropoda	Arachnida	Araneae	*lycosidae*	*Paradosa*	31
Spotted-Wing Drosophila	Arthropoda	Insecta	Diptera	*Drosophilidae*	*Drosophila*	1
Spring Harvestman	Arthropoda	Arachnida	Araneae	*Phalangiidae*		11
Stilt Bug	Arthropoda	Insecta	Hemiptera	*Berytidae*	*Neoneides*	23
Striped Ground Cricket	Arthropoda	Insecta	Orthoptera	*Trigonidiidae*	*Allonemobius*	160
Striped Lynx Spider	Arthropoda	Arachnida	Araneae	*Oxyopidae*	*Oxyopes*	31
Summer Sap Beetle	Arthropoda	Insecta	Coleoptera	*Nitidulidae*		61
Thickjawed Orb Spider	Arthropoda	Arachnida	Araneae	*Tetragnathidae*	*Pachygnatha*	2
Tropical House Cricket	Arthropoda	Insecta	Orthoptera	*Gryllidae*	*Gryllodes*	190
Two-Lined Soldier Beetle	Arthropoda	Insecta	Coleoptera	*Cantharidae*	Polemius	1

Two-Lined Spittlebug	Arthropoda	Insecta	Hemiptera	*Cercopidae*	*Prosapia*	7
Two-Marked Harp Ground Beetle	Arthropoda	Insecta	Coleoptera	*Carabidae*	*Harpalus*	459
Varied Carpet Beetle	Arthropoda	Insecta	Coleoptera	*Dermestidae*	*Anthrenus*	3
Variegated Golden Tortrix	Arthropoda	Insecta	Lepidoptera	*Tortricidae*	*Archips*	17
Varroa Mite	Arthropoda	Arachnida	Mesostigmata	*Varriodae*	*Varroa*	7025
Velvet Ant	Arthropoda	Insecta	Hymenoptera	*Multillidae*		1
Wall Spider	Arthropoda	Arachnida	Araneae	*Oecobiidae*	*Oecobius*	11
Water Lily Leaf Beetle	Arthropoda	Insecta	Coleoptera	*Chrysomelidae*		40
Water Measurer	Arthropoda	Insecta	Hemiptera	*Hydrometridae*	*Hydrometra*	4
Water Penny Beetle	Arthropoda	Insecta	Coleoptera	*Psephenidae*		1
Weevil Larva	Arthropoda	Insecta	Coleoptera	*Curculionidae*	*Curculionidae (larva)*	15
Western Big-Eyed Bug	Arthropoda	Insecta	Hemiptera	*Geocoridae*	*Geocoris*	248
Western Flower Thrips	Arthropoda	Insecta	Thysanoptera	*Thripidae*	*Frankiniella*	788
Western Honeybee	Arthropoda	Insecta	Hymenoptera	*Apidae*	*Apis*	1
Western Wood Cockroach	Arthropoda	Insecta	Blattodea	*Blattellidae*	*Parcoblatta*	869
White Margined Burrower Bug	Arthropoda	Insecta	Hemiptera	*Cynidae*	*Sehirinae*	4
White Spotted Stink Bug	Arthropoda	Insecta	Hemiptera	*Pentatomidae*	*Eysarcoris*	18
Winter Gnat	Arthropoda	Insecta	Diptera	*Trichoceridae*	*Trichocera*	10
Yellow Striped Armyworm	Arthropoda	Insecta	Lepidoptera	*Noctuidae*	*Noctuidae (larva)*	83
Yellow Swarming Fly	Arthropoda	Insecta	Diptera	*Chloripidae*	*Thaumatomyia*	416

Appendix 3 List of all captured invertebrate over the duration of this study, indicating the abundance of each genus.

Common Name	Phylum	Class	Order	Family	Genus	Species	Variety
Alfredo Stonecrop	Tracheophyta	Magnoliosida	Saxifragales	*Crassulaceae*	*Sedum*	*formosanum*	
Angelina Stonecrop	Tracheophyta	Magnoliopsida	Saxifragales	*Crassulaceae*	*Sedum*	*reflexum*	‘Angelina'
Annual Bluegrass	Tracheophyta	Liliopsida	Poales	*Poaceae*	*Poa*	*annua*	
Black Medick	Tracheophyta	Magnoliopsida	Fabales	*Fabaceae*	*Medicago*	*lupulina*	
Blackeyed Susan	Tracheophyta	Magnoliopsida	Asterales	*Asteraceae*	*Rudbeckia*	*hirta*	
Blue Spruce Sedum	Tracheophyta	Magnoliopsida	Saxifragales	*Crassulaceae*	*Sedum*	*reflexum*	‘Blue spruce'
Bristle Bent	Tracheophyta	Liliopsida	Poales	*Poaceae*	*Agrostis*	*curtisii*	
Broadleaf Weed	Tracheophyta	Magnoliopsida					
Buttonweed	Tracheophyta	Magnoliosida	Gentianales	*Rubiaceae*	*Diodia*	*virginiana*	
Californian Poppy	Tracheophyta	Magnoliopsida	Ranunculales	*Papaveraceae*	*Escholizia*		
Carolina Crane'S-Bill	Tracheophyta	Magnoliopsida	Geraniales	*Geraniaceae*	*Geranium*	*carolinianum*	
Carpetweed	Tracheophyta	Magnoliosida	Caryophyllales	*Molluginaceae*	*Mollugo*		
Catmint	Tracheophyta	Magnoliopsida	Lamiales	*Lamiaceae*	*Nepeta X*	*faassennii*	
Chamberbitter	Tracheophyta	Magnoliopsida	Malpighiales	*Phyllanthaceae*	*Phyllanthus*		
Clasping Venus'S Looking Glass	Tracheophyta	Magnoliopsida	Asterales	*Campanulaceae*	*Triodanis*	*perfoliata*	
Clover	Tracheophyta	Magnoliopsida	Fabales	*Fabaceae*	*Trifolium*		
Common Purselane	Tracheophyta	Magnoliosida	Caryophyllales	*Portulacaceae*	*Portulaca*	*oleracea*	
Common Ragweed	Tracheophyta	Magnoliopsida	Asterales	*Asteraceae*	*Ambrosia*	*artemisiifolia*	
Common Vetch	Tracheophyta	Magnoliopsida	Fabales	*Fabaceae*	*Vicia*	*sativa*	
Common Yarrow	Tracheophyta	Magnoliopsida	Asterales	*Asteraceae*	*Achillea*	*millefolium*	
Compact Prairie Clover	Tracheophyta	Magnoliopsida	Fabales	*Fabaceae*	*Dalea*		
Crab Grass	Tracheophyta	Liliopsida	Poales	*Poaceae*	*Digitaria*	*sanguinalis*	
Crimson Clover	Tracheophyta	Magnoliopsida	Fabales	*Fabaceae*	*Trifolium*	*incarnatum*	
Daisy Fleabane	Tracheophyta	Magnoliopsida	Asterales	*Asteraceae*	*Erigon*	*strigosus*	
Dandelion	Tracheophyta	Magnoliopsida	Asterales	*Asteraceae*	*Taraxacum*		

False Motherwort	Tracheophyta	Magnoliopsida	Lamiales	*Lamiaceae*	*Chaiturus*	*marrubiastrum*	
False Pennyroyal	Tracheophyta	Magnoliopsida	Lamiales	*Lamiaceae*	*Trichostema*	*brachiatum*	
Fameflower	Tracheophyta	Magnoliopsida	Caryophyllales	*Montiaceae*	*Phemeranthus*		
Geranium	Tracheophyta	Magnoliopsida	Geraniales	*Geraniaceae*	*Geranium*		
Goldenrod	Tracheophyta	Magnoliopsida	Asterales	*Asteraceae*	*Solidago*		
Grass	Tracheophyta	Liliopsida	Poales	*Poaceae*			
Green And White Sedge	Tracheophyta	Liliopsida	Poales	*Cyperaceae*	*Carex*		
Hairy Crabweed	Tracheophyta	Magnoliosida	Rosales	*Moraceae*	*Fatoua*	*villosa*	
Hardy Iceplant	Tracheophyta	Magnoliopsida	Caryophyllales	*Azioaceae*	*Delosperma*	*cooperi*	
Hare'S-Foot Clover	Tracheophyta	Magnoliopsida	Fabales	*Fabaceae*	*Trifolium*	*arvense*	
Hemp Dogbane	Tracheophyta	Magnoliopsida	Gentianales	*Apocynaceae*	*Apocynum*	*cannabium*	
Honey Locust	Tracheophyta	Magnoliopsida	Fabales	*Fabaceae*	*Gledistia*	*tricanthos*	
Horseweed	Tracheophyta	Magnoliopsida	Asterales	*Asteraceae*	*Erigeron*	*canadensis*	
Lance-Leaved Coreopsis	Tracheophyta	Magnoliopsida	Asterales	*Asteraceae*	*Coreopsis*	*lanceolata*	
Lanceleaf Figwort	Tracheophyta	Magnoliopsida	Lamiales	*Scrophulariaceae*	*Scrophularia*		
Lavender Cotton	Tracheophyta	Magnoliopsida	Asterales	*Asteraceae*	*Santolina*		
Lemon Grass	Tracheophyta	Liliopsida	Poales	*Poaceae*	*Cymbopogon*		
Lemongrass	Tracheophyta	Liliopsida	Poales	*Poaceae*	*Cymbopogon*	*citratus*	
Live-Forever	Tracheophyta	Magnoliopsida	Saxifragales	*Crassulaceae*	*Hyltelephium*		
Maple	Tracheophyta	Magnoliopsida	Sapindales	*Sapindaceae*	*Acer*		
Marsh Parsley	Tracheophyta	Magnoliopsida	Apiales	*Apiaceae*	*Cyclospermum*	*leptophyllum*	
Mexican Feathergrass	Tracheophyta	Liliopsida	Poales	*Poaceae*	*Nassella*	*tenussima*	
Mock Strawberry	Tracheophyta	Magnoliopsida	Rosales	*Rosaceae*	*Potentilla*	*indica*	
Monkey Grass	Tracheophyta	Liliopsida	Asparagales	*Asparagaceae*	*Liriope*	*muscari*	
Mouse-Eared Hawkweed	Tracheophyta	Magnoliopsida	Asterales	*Asteraceae*	*Pilosella*		
Murale Stonecrop	Tracheophyta	Magnoliopsida	Saxifragales	*Crassulaceae*	*Sedum*	*album*	‘Murale'
No Veg							
Oat Grass	Tracheophyta	Lilipsida	Poales	*Poaceae*	*Helictotrichon*		

Orange Stonecrop	Tracheophyta	Magnoliopsida	Saxifragales	*Crassulaceae*	*Sedum*	*kamtschaticum*	
Oxalus	Tracheophyta	Magnoliosida	Oxalidales	*Oxalidaceae*	*Oxalis*		
Pale Smartweed	Tracheophyta	Magnoliosida	Caryophyllales	*Polygonaceae*	*Persicaria*	*lapathifolia*	
Panicle Hydrangea	Tracheophyta	Magnoliopsida	Cornales	*Hydrangeaceae*	*Hydrangea*	*paniculata*	
Perennial Ryegrass	Tracheophyta	Liliopsida	Poales	*Poaceae*	*Lolium*	*perenne*	
Pine	Tracheophyta	Pinopsida	Pinales				
Poison Oak	Tracheophyta	Magnoliopsida	Sapindales	*Anacaridaceae*	*Toxicodendron*		
Potato Dwarfdandelion	Tracheophyta	Magnoliopsida	Asterales	*Asteraceae*	*Krigia*		
Prickly Lettuce Weed	Tracheophyta	Magnoliosida	Asterales	*Asteraceae*	*Lactuca*	*serriola*	
Prickly Pear Cactus	Tracheophyta	Magnoliopsida	Caryophyllales	*Cactaceae*	*Opuntia*		
Prostrate Knotweed	Tracheophyta	Magnoliopsida	Caryophyllales	*Caryophyllales*	*Polygonum*	*aviculare*	
Purple Coneflower	Tracheophyta	Magnoliopsida	Asterales	*Asteraceae*	*Echinacea*	*purpurea*	
Purple Lovegrass	Tracheophyta	Liliopsida	Poales	*Poaceae*	*Eragrostis*		
Quack Grass	Tracheophyta	Liliopsida	Poales	*Poaceae*	*Elymus*		
Red Clover	Tracheophyta	Magnoliopsida	Fabales	*Fabaceae*	*Trifolium*	*pratense*	
Red Columbine	Tracheophyta	Magnoliopsida	Ranunculales	*Ranunculaceae*	*Aquilegia*	*canadensis*	
Red Velvet Yarrow	Tracheophyta	Magnoliopsida	Asterales	*Asteraceae*	*Achillea*	*millefolium*	Red velvet'
Ribwort Plantain	Tracheophyta	Magnoliopsida	Lamiales	*Plantaginaceae*	*Plantago*	*lanceolata*	
Rice Flat Sedge	Tracheophyta	Liliopsida	Poales	*Cyperaceae*	*Cyperus*	*iria*	
Roundseed Panicgrass	Tracheophyta	Liliopsida	Poales	*Poaceae*	*Dichantheliu m*		
Rust Weed	Tracheophyta	Magnoliopsida	Lamiales	*Tetrachondrace ae*	*Polypremum*	*procumbens*	
Sedum 'Coral Reef'	Tracheophyta	Magnoliosida	Saxifragales	*Crassulaceae*	*Sedum*	*tetractinum*	Coral Reef'
Shwienitz's Ragwort	Tracheophyta	Magnoliopsida	Asterales	*Asteraceae*	*Packera*	*schweinitzia na*	
Silvermound	Tracheophyta	Magnoliopsida	Asterales	*Asteraceae*	*Artemisia*		
Spotted Spurge	Tracheophyta	Magnoliopsida	Malpighiales	*Euphorbiaceae*	*Euphorbia*	*maculata*	

Stonecrop X	Tracheophyta	Magnoliopsida	Saxifragales	*Crassulaceae*			
Switchgrass	Tracheophyta	Liliopsida	Poales	*Poaceae*	*Panicum*	*virgatum*	
Tasteless Stonecrop	Tracheophyta	Magnoliopsida	Saxifragales	*Crassulaceae*	*Sedum*	*sexangulare*	
Thyme-Leaved Sandwort	Tracheophyta	Magnoliopsida	Caryophyllales	*Caryophyllaceae*	*Arenaria*	*serpyllifolia*	
Tree Of Heaven	Tracheophyta	Magnoliosida	Sapindales	*Simaroubaceae*	*Ailanthus*	*altissima*	
Tropical Finger-Grass	Tracheophyta	Liliopsida	Poales	*Poaceae*	*Digitaria*		
Veronica Speedwell	Tracheophyta	Magnoliosida	Lamiales	*Plantaginaceae*	*Veronica*	*spicata*	
Violet	Tracheophyta	Magnoliopsida	Malpighiales	*Violaceae*	*Viola*		
Virginia Creeper	Tracheophyta	Magnoliopsida	Vitales	*Vitaceae*	*Parthenocissus*		
White Clover	Tracheophyta	Magnoliosida	Fabales	*Fabaceae*	*Trifolium*	*repens*	
White Gaura	Tracheophyta	Magnoliopsida	Myrtales	*Onagraceae*	*Oenothera*	*linheimeri*	
White Mazus	Tracheophyta	Magnoliopsida	Lamiales	*Mazaceae*	*Mazus*	*miquelii*	
White Stonecrop	Tracheophyta	Magnoliopsida	Saxifragales	*Crassulaceae*	*Sedum*	*album*	
Whitewort	Tracheophyta	Magnoliopsida	Lamiales	*Lamiaceae*	*Leucas*		
Wild Chive	Tracheophyta	Liliopsida	Asparagales	*Amaryllidaceae*	*Allium*		

Appendix 4 Summary of every plant species found throughout each plant survey

Vita

Reilly Swanson was born and raised in Knoxville, Tennessee. She completed the International Baccalaureate Program at her high school, Knoxville West. During that time, she served as president of FBLA, maintained and recorded data from the school's rain garden, and completed multiple environmental field research projects for the program. Being raised by environmental engineers, Reilly has always been passionate about the environment and researching the impacts of urbanization. After high school she attended the University of Tennessee, Knoxville where she majored in Geology and Environmental Studies with a concentration in Soil Sciences and a minor is Sustainability. During her time as an undergraduate, Reilly was active in environmental restoration efforts and volunteer work with the Office of Sustainability. Upon her completion of her bachelors, Reilly stayed in Knoxville to continue her studies as a master's student in Geology. While there she was an active member of the Society of Ecological Restoration and Tennessee Academy of Science. Through these organizations, Reilly travelled to Vancouver, B.C. and Harrogate, TN to present her work. Additionally, Reilly was a part of a research team at the Ijam's Nature Center and acted as head TA.