

Article

Effects of Green Roof Features, Management Practices, and Age on Decomposition Rates, Carbon Storage, and Substrate Composition

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Abstract: (1) Green infrastructure, such as green roofs, is emerging as an important way to improve environmental quality and protect crucial ecosystem services in urban areas across the globe. However, limited data exist on the specific ecosystem services provided by green roofs, particularly regarding how these services evolve over time and under varying management regimes. (2) This study examines how management, age and other variables influence some key substrate features, such as decomposition and carbon storage, that drive ecosystem services provided by green roofs in 13 urban locations across three states in the Southeastern United States. Data were collected over 4 months from March to June 2024, using the teabag index and substrate nutrient sampling. (3) We identified several significant effects of green roof management, age and other variables on key drivers of ecosystem services, including decomposition rate, carbon storage, and nutrient composition. (4) Specifically, intensive management practices were associated with lower substrate decomposition rates, while irrigation, substrate additions and elevation had significant positive impacts on decomposition rates, the stabilization factor (carbon storage), organic matter and other nutrient levels. Overall, intensive management, which often involves higher costs, did not consistently enhance ecosystem service delivery and was associated with slight reductions in service provisions. Although further work is needed, this study is among few that have examined green roofs substrates in a statistically rigorous way.

Keywords: green roofs; urbanization; management; substrate; teabag index; ecosystem services



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1. Introduction

An ecosystem service (ES) can be defined as nature's benefits to humans [1], or what 'humans gain from functioning ecosystems' [2]. 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' [1]. An ES directly or indirectly benefits human life and can be tangible or intangible [2]. These services include, but are not limited to, nutrient cycling, decomposition, soil turnover, pest control, air and water regulation, and pollination [3–5].

Ecosystem services are becoming increasingly critical urban areas, which are projected to accommodate more than two-thirds of the global population by 2050 [5,6]. Even within the last 30 years, urban land has increased twice as fast as the urban population [6,7]. Consequently, key ESs provided by natural habitats are being degraded by anthropogenic pressures, particularly urbanization, which alters the structural and functional integrity of ecosystems [8].

To mitigate these negative environmental impacts of urbanization, green infrastructure is often constructed to improve environmental quality, protect the remaining ESs, and promote new ones [5,9]. Such green spaces play a critical role in ‘conserving biodiversity, protecting water resources, improving the microclimate, sequestering carbon, and even supplying [fresh food to the urban community]’ [10]. However, urban environments often only consist of mosaic green spaces limited to small, fragmented patches and corridors, such as parks, yards, and vacant lots [10]. As roofs can represent between 19 and 25% of the horizontal surface of urban or built areas [11], green roofs have great potential for expanding green infrastructure in cities.

While ESs are dependent on the design choices of a green roof, they all have the potential to fill gaps in many locations where ESs are lacking within an urban area [12]. Specifically, green roofs offer a wide range of benefits compared to the conventional roof, including environmental, social, and economic benefits [13]. For example, major ESs that green roofs provide are as follows: a reduction in runoff and peak flow during storm events, provisioning habitats for urban wildlife, thermal regulation, and social cohesion within a community [12–15].

The growing medium of a green roof usually 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, and structurally stable, and it is superior to most substrates for long-term maintenance and permeability [14]. It allows for consistent drainage and aeration, with a structure that holds water, makes necessary nutrients available for plants, and is resistant to detrimental decomposition and compression [14,16,17]. Sufficient plant nutrients must be present to support the plant community, while excess nutrients should be avoided to reduce over-polluted runoff [18]. To date, green roof substrate composition remains suboptimal [19], with limited research conducted under field conditions. Thus, studies of green roof substrate composition, as a factor effecting ESs like nutrient cycling, remain a relatively novel approach [17].

Indeed, green roofs in general are a relatively understudied aspect of the urban ecosystem especially in terms of measuring ESs [12]. Much of the research thus far is from small test plots in controlled environments and not on large established green roofs [14], or from countries such as China or the United Kingdom, with much of the research within the United States being from northern or western universities like Michigan State, Penn State, Princeton, and Arizona State [20]. These locations are all situated outside the Southeastern United States (the focus of this study), highlighting a notable gap in regional green roof research. A review of 739 papers of green roof benefits and challenges by Joshi and Teller [21] outlines the challenges experienced in maintaining green roofs. Their review also suggests that, although there is potential for the social acceptance of green roofs for their aesthetic designs, they are often unaffordable, with potential for damage and additional costs in the future [21]. 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 [15].

To study ESs in a rigorous and quantifiable way, indicators or proxies are needed [5]. Common ES indicators include physical and chemical processes and sequestered carbon [22]. For example, as discussed below, ESs can be measured with the rate at which litter decomposes, how much carbon is stored and which nutrients (e.g., organic matter and nitrogen compounds) are found in the substrate. 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 common ES: supporting services.

1.1. Teabag Index

The teabag index (sometimes referred to as the tea composition initiative) can be utilized as a proxy for ESs because it measures the decomposition rate and stabilization factor (carbon storage) which can provide information about: the ability to reduce substrate erosion [23], inform biogeochemical cycling, soil formation, greenhouse gas emissions [24], and can give insight into microbial activities within the substrate's community [25]. Specifically, litter decomposition and stabilization factor (carbon storage) in urban environments can be a proxy for ESs. Despite their potential utility, these proxies have been the focus of relatively few empirical studies. Here, a standardized method is utilized to examine these proxies and compare ESs across a wide range of ecosystems, biomes, and substrate types [26]. The teabag index measures the weight loss of green and rooibos tea over a specific incubation time to find the 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 substrate) in a specific location. It was proposed and outlined by Keuskamp and others [26] and has been implemented in a handful of studies to explore decomposition in natural environments [24,25]. However, very little research has been conducted using this method to determine decomposition in urban environments or on green roofs specifically.

1.2. Substrate Survey

Green roofs require the proper substrate formula to ensure proper plant growth and survival [17,27]. Substrates are a key component in water and nutrient cycling, providing pollution remediation and pollinator habitats [28]. In urban environments, substrate disturbances such as compaction and pollution are common [28], so green roofs can help recover the ESs of urban substrates. For example, studies have shown that green roof substrate composition is a direct determinant of plant species richness and diversity [17,29–31]. An optimal nutrient load in green roof substrates is essential to sustain plant growth while avoiding nutrient excess, which could lead to elevated pollutant concentrations in runoff [18]. A paper published by The Pennsylvania State University Department of Horticulture suggests a range of nutrient content levels on green roofs as deficient, sufficient, or excessive [18]. Throughout this study, 'substrate composition' is used as an umbrella term representing the aspects of ESs it influences, particularly nutrient cycling and substrate fertility.

1.3. Research Questions and Approaches

This paper aimed to answer the two basic questions outlined below. In all cases, ESs refer to decomposition rate, stabilization factor and substrate composition.

1. How do ESs compare between management types (high or low) of green roofs in Asheville (North Carolina), Atlanta (Georgia), Chattanooga (Tennessee), Knoxville (Tennessee), and Nashville (Tennessee)?
2. How does green roof age and physical variables affect the availability of ESs over time in the elected cities?

This study serves as a preliminary investigation into ecosystem services provided by green roofs in the Southeastern United States. The primary focus of this study is to establish baseline patterns and identify possible influencing variables.

2. Materials and Methods

2.1. Study Area

In January 2024, 35 intensive/semi-intensive green roofs were selected in five southeastern US cities: Asheville, Atlanta, Chattanooga, Knoxville, and Nashville. These cities

were selected based on their 2–3 h proximity to The University of Tennessee, Knoxville, and their relatively uniform humid subtropic climates during the study period. The urban scale of these cities enabled the selected green roofs to be located within centralized areas, thereby facilitating efficient sampling logistics. Research access was obtained through contacting building managers directly, with 13 of the 35 approached buildings consenting to participate in the study. To enhance the generalizability of the findings across the Southeastern US, a diverse range of green roofs were deliberately included. The 13 roofs were intentionally selected to reflect variation in design, structure, and functional purpose. This allows us to capture a wide range of green roofs typical to the region, enhancing the generalizability of the results to similar urban environments within the Southeastern United States.

The thirteen chosen locations are illustrated in Figure 1, with red dots indicating their locations across the five cities. The specific green roof location details, including acronyms and coordinates, are outlined in Table A1.



Figure 1. Locations of 13 studied green roofs, denoted by red dots in each of five cities, Asheville, Atlanta, Chattanooga, Knoxville, and Nashville. The study area in the southeastern region of the US is denoted by a red rectangle. Locations adapted from [32] and found through internet searches (i.e., www.greenroofs.com Accessed on 20 January 2024).

2.2. Sample Determination and Collection

Each green roof was surveyed regarding structural attributes and past, current, and future management practices. The survey questions (Table A2) were designed to classify each roof into one of two management classifications: high or low. High management is defined as the regular irrigation of more than once a month and weeding every 3–12 weeks, and low management occurred when the roof had minimal (less than once per month) or no irrigation and no weeding throughout the year.

The responses were compiled by summarizing the management practices of each of the thirteen roofs, as in Table 1. This detailed categorization provided a foundation for

analyzing the impact of different management practices on the ecosystem services provided by green roofs.

Table 1. 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 (mgmt.) and <2.5 indicates ‘low’ management.

Location	Age (years)	Size (ft ²)	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	5000	3	5	Yes	Yes	Yes	Yes	No	4	High
RMH	9	2200	1	4.25	Yes	Yes	Yes	No	No	3	High
HCH	13	4200	2	6	Yes	Yes	Yes	No	No	3	High
GS	1	200	1	4	Yes	Yes	No	No	Yes	3	High
ZEC	3	4000	5	10	Yes	No	Yes	No	No	2	Low
ABG	16	200	1	24	No	Yes	Yes	No	No	2	Low
SF	15	1200	2	6	No	No	Yes	No	Yes	2	Low
SB	15	2500	2	6	No	No	Yes	No	No	1	Low
BLR	19	9000	1	6	No	No	No	Yes	No	1	Low
CCB	6	1200	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

Each of the 13 roofs varies in size, ranging from 100 ft² to 191,000 ft². To ensure proportional sampling across the different roofs, a systematic approach was adopted. For every 400 ft² of roof area, twenty total teabags were buried and one substrate sample was collected. Given the variability in roof sizes, samples were collected proportionally up to a maximum area of 4800 ft² per roof. This was to ensure a feasible workload. Specifically, sampling included a minimum of two substrate collections and twelve teabags per roof, with up to twelve substrate collections and 120 teabags for the largest roofs. For roofs exceeding 4800 ft², only 4800 ft² total was sampled to ensure manageable data collection. Roofs exceeding 4800 ft² were randomly sampled from across the entirety of the roof. Table 2 summarizes the total samples per roof for the duration of the study. Throughout the study, substrate moisture (%) and temperature (°C) measurements were also taken at each collection date using a handheld probe. These were taken at, or around, the location where the teabags were buried at the same time of day at each collection. Early to mid-morning samples were collected from MCC, ZEC, BLR, CCB, and SF each month. Midday samples were collected at LSH, GR, GS, ABG, and SB each month. Mid-afternoon samples were collected from RMH, HCH, and FW each month.

Table 2. An outline of the sample size of each proxy, how often they were collected, and how many total samples were taken.

Collection Dates: 31 March 2024 to 23 June 2024		
	Teabags	Substrate Survey
Total at each location	20 total per 400 ft ²	1 per 400 ft ²
Collection times	25 days until 100 days	March
Total Collections	4	1

2.3. Teabag Index Methods

The (TBI) is a novel approach proposed by Keuskamp and others [26] 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 [33]. 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 [33]. S indicates long-term carbon stability in that area and k indicates the rate at which the litter is broken down [33,34]. This index is indicative of microbial activity in the substrate community and can provide an insight into the substrate health of the sampled area [25].

To make the teabags, 2 g each of rooibos and green tea was measured and placed into individual 0.25 mm acrylic mesh tea bag, and we double-sealed the bags [26,35]. They were then buried ~8 cm deep in individual holes 15 cm apart from each other for a select incubation period [26,36,37]. The time of incubation can vary depending on climatic conditions and locations, ranging from 45 days to over 90 days [26]. We chose to retrieve the teabags at 25-to-30-day intervals for a total of 100 days. After incubation, the teabags were retrieved and dried in an oven not exceeding 70 °C for 48 h [26,36]. After the bags were completely dry, we removed excess substrate and reweighed each bag four times to obtain the average weight. The final mass of the dried tea was subtracted from the initial mass to calculate the amount of material decomposed during each incubation period of 25, 50, 75, and 100 days. This mass change in green tea was then used to determine S . These weight changes, including the weight loss in rooibos tea, were used to calculate the decomposition rate (k) using the equations below, as outlined in Keuskamp and others [26].

Equation (1) outlines the equation needed to estimate k .

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

In the equation, $W(t)$ represents the weight of the tea after incubation time t , a is the labile fraction and $1 - a$ is the recalcitrant fraction [26,35]. Since rooibos tea has a low decomposition rate as compared to green tea, the 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 [26]. 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 below, found in Keuskamp and others [26].

Equation (2) outlines the equation needed to find the stabilization factor (S).

$$S = 1 - a_g/H_g \quad (2)$$

In the equation, 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) [26] of rooibos tea and the previously found stabilization factor S .

Equation (3) outlines the equation needed to find the decomposable fraction of rooibos.

$$a_r = H_r(1 - S) \quad (3)$$

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

A total of 1620 teabags were buried across the 13 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 1552 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 drying, each teabag was weighed four times to obtain an average mass. The stabilization factor and decomposition rate were found for each pair of teabags.

2.4. Substrate Survey Methods

To find the substrate composition and understand the ES of nutrient cycling, we gathered samples from the research sites. These were collected by combining six random samples from the same plot at each roof from the top to bottom depth of the substrate [38]. The substrate samples from the same roof were homogenized, air dried, and packaged into bags consisting of one to two cups of substrate [38–40]. Each collected sample underwent two independent substrate analyses, for a total of 87 surveys taken across the 13 roofs. The substrate samples were then sent to the Clemson Soil Extension Lab to test for pH, phosphorus, potassium, calcium, magnesium, zinc, manganese, copper, boron, sodium, and organic matter %. Nutrient levels were found through the Mehlich 1 procedure, pH through a substrate to water ratio, and organic matter through loss on ignition (LOI) [40].

2.5. Statistical Analyses

For the statistical analysis of the influences of management and other independent variables on each proxy variable, we performed a Principal Component Analysis (PCA) using the statistical software package IBM SPSS Statistics Version 29.0.2.0 (20) [41]. This was carried out to identify covarying components and create groupings of the independent variables that explain much of the variance in the data set. The independent variables input into the PCA analysis were substrate temperature (°C), substrate moisture (%), age (years), elevation (stories), substrate depth (inches), irrigation (yes/no), replanting (yes/no), weeding (yes/no), substrate addition (yes/no), chemical treatments (yes/no), and management classification (mgmt. score 0–5). We then produced fixed-effects linear mixed models for each ES proxy against each of those groupings. Interaction terms for the components were not tested as we aimed to look at each component as an individual separate event; thus, future research should implement interaction testing. The substrate survey utilized a correlations matrix and a nonparametric test. 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. Univariate ANOVA does not account for spatial variability and may overestimate the sample size, potentially leading to biased results. Showing the linear mixed model provided 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. For each iteration of the model, 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 helped identify the most influential independent variables (environmental, management, and site characteristics) on each proxy while holding all other variables constant. Finally, to check the assumptions of statistically significant influences of each component, a linear mixed model was implemented using the component scores found from the PCA.

3. Results

3.1. Temporal Trends in Substrate Temperature and Moisture

Figure 2 presents temporal trends in substrate moisture and temperature throughout the study period. The data reveal an inverse relationship between substrate temperature and moisture content. The fitted quadratic curves represent the average trend, with 95% confidence intervals indicated. Substrate moisture is represented by the blue trendline, while substrate temperature is depicted in red. Overall, substrate temperature increases

over the course of the season, while moisture levels exhibited a decreasing trend. Thus, Figure 2 illustrates the influence of seasonal summer changes on substrate temperature and moisture dynamics.

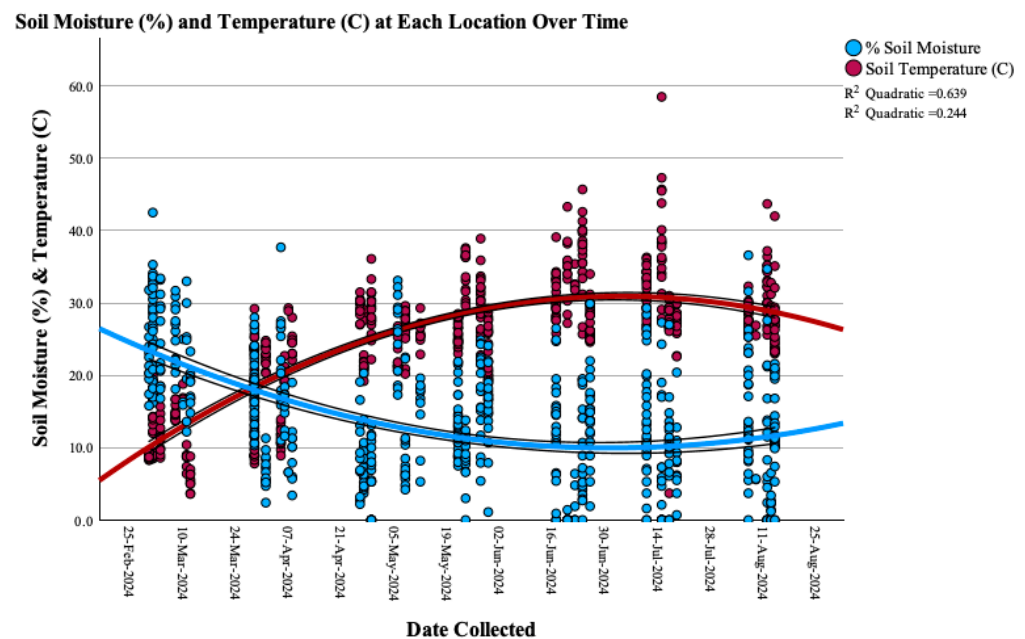


Figure 2. Substrate moisture and temperature from March to August 2024.

3.2. PCA Analysis

Table 3 summarizes the extraction results from the PCA analysis of each of the independent variables, indicating the proportion of each independent variable's variance accounted for by the principal components. PCA values range from 0 to 1, where values closer to 1 represent higher communality. Higher communality indicates the variable is well represented by the components and that a significant portion of its variance is captured. Based on the values in Table 3, variables with high communalities include substrate moisture, substrate temperature, age, size, elevation, irrigation, replanting, chemical treatment, and substrate addition. Management classification exhibited the highest communality, at 0.966. Variables that show moderate communalities are substrate depth and weeding. In general, the PCA shows the variables to be well represented, with communalities above 0.70 for all variables. This suggests that the principal components capture most of the variance in each variable.

Table 4 illustrates the total variance explained, providing details about how much variance each principal component captures in the data set. The initial eigenvalues show the amount of variance in the data each component explains, indicating the percentage of the total variance that an individual component accounts for. The first five components demonstrated statistical significance, each with eigenvalues over 1, in accordance with the Kaiser criterion. 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, these account for almost 85% of the total variance in the data, indicating a strong representation.

Table 3. Extraction results from the completed PCA, where values closer to 1 represent higher communality.

Independent Variable	Extraction
Substrate Moisture (%)	0.831
Substrate Temperature (°C)	0.731
Age (yrs)	0.885
Size (ft ²)	0.890
Elevation (stories)	0.899
Substrate Depth (in)	0.774
Irrigation (Y/N)	0.896
Replanting (Y/N)	0.878
Weeding (Y/N)	0.756
Chemical Treatments (Y/N)	0.807
Substrate Addition (Y/N)	0.884
Management Classification (high/low)	0.966

Table 4. The results of the PCA, outlining the explained variance from each component. Note that components 1–5 are the only ones that have a total eigenvalue of over 1, indicating more significance.

Component	Total	Initial Eigenvalues		Extraction of Squared Loadings			Rotation Sums of Squared Loadings		
		% of Variance	Cumulative %	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	3.790	31.587	31.587	3.790	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	8.560	84.983	1.027	8.560	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	2.460	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 5, where high loadings are indicated by values over 0.50, indicating that a variable is strongly associated with a component. High loadings on component 1 are irrigation, replanting and management classification. Component 1 is thus designated here as a *management practices* component. Component 2 shows high loading on substrate moisture and temperature, designated here as a *substrate conditions* component. Component 3 has high loadings on size, elevation, and substrate additions, designated here as a *roof features* component. Component 4 has high loadings on age and chemical treatment, designated here as an *age and chemical management* component. Finally, component 5, characterized by strong loadings on weeding and substrate depth, is interpreted as representing *substrate and vegetation management*.

Based on the findings of the varimax rotated PCA, we can identify these components as groupings for linear mixed models using the variables in each component as covariates. Thus, this analysis has reduced the complexity of the data by identifying five key components, each representing a unique aspect of the independent variables. These components provide a basis for assessing the influence of the most strongly correlated variables on each ES proxy. They also provide information on how the management practices, the substrate condition, roof features, age and chemical management, and substrate and vegetation management influence each of the proxies.

Table 5. Rotated component matrix results from the PCA. Highlighted values (gray squares) indicate the most significant variables (>0.50). These variables are then grouped together for the corresponding component by their communalities.

Variable	Rotated Component Matrix				
	1	2	3	4	5
Substrate Moisture (%)	0.141	0.889	−0.099	−0.078	0.68
Substrate Temperature (°C)	0.197	−0.792	−0.156	0.068	0.189
Age (yrs)	−0.177	−0.283	−0.058	0.851	0.214
Size (ft ²)	0.200	0.251	0.795	0.390	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 (Y/N)	0.825	0.396	0.143	−0.164	−0.108
Replanting (Y/N)	0.855	−0.205	0.117	0.080	0.291
Weeding (Y/N)	0.35	0.061	0.149	0.220	0.747
Chemical Treatments (Y/N)	0.200	0.097	0.251	0.813	−0.185
Substrate Addition (Y/N)	0.138	−0.259	0.866	−0.141	−0.167
Management Classification (high/low)	0.953	−0.055	0.179	0.102	−0.11

3.3. Temporal Trends in Decomposition Rate and Stabilization Factor

Over the 100-day period, green tea had a minimum weight loss of 0.31 g and a maximum of 1.68 g, and rooibos tea had a minimum of 0.03 g and a maximum of 0.33 g. The observed values of the stabilization factor (S) ranged from 0.008 g to 1.80 g, and decomposition rate (k) ranged from 0.005 g to 0.17 g. Figure 3 illustrates the decomposition rate (k) and stabilization factor (S) over the course of the research, where the red indicates the stabilization factor and blue indicates the 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 trend levels off. The validity of using the teabag index in this study on green roofs is thus supported, where the 100-day incubation revealed decomposition and stabilization trends consistent with those in Keuskamp et al. [26]. This provides confidence in applying Equations (1)–(3) to the dataset. Despite chemical and structural differences between green roof substrates and natural soils, the findings suggest these do not substantially impact the reliability or applicability of the teabag index. The consistency of results over the full 100-day incubation period shows that the teabag index behaves similarly in green roof media as well as in traditional soil environments, thereby supporting its use as a valid proxy for decomposition and carbon stabilization in this context.

To complete the statistical analysis, only one collection time should be used, and this collection time should be the last time when all k and S values are able to be computed. K and S are unable to be computed when green tea has transitioned to phase 2 of decomposition, meaning the recalcitrant material in the tea is starting to be decomposed. The highlighted region in Figure 3 denotes the subset of results used for subsequent analyses. For the upcoming analyses, the k , S, and substrate moisture and temperature values used are from only the collection at 50 days—in late April and in early May.

Decomposition rates and stabilization factors (carbon storage) were compared to each of the components from the PCA to examine the interactions of each individual component to the efficiency of decomposition and stabilization. This comparison provides an indication of how each component affects the provision of ESs on these green roofs. In all cases, the results reference to Table 6.

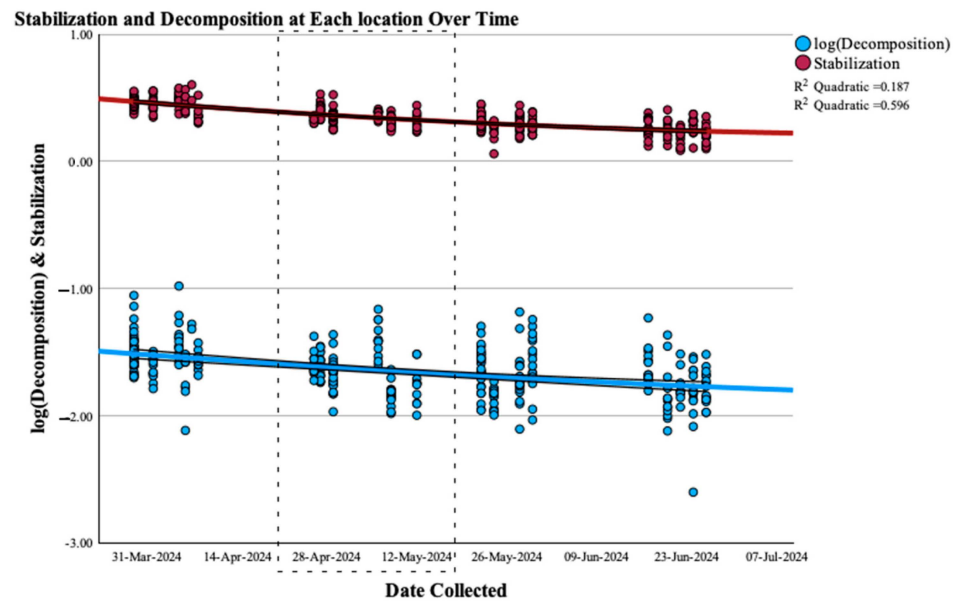


Figure 3. Decomposition rate and stabilization factor found from March to June 2024. The dotted square indicates the results used for analysis.

In the case of decomposition rate, irrigation has a positive effect on decomposition, and increasing management intensity has a negative influence on decomposition rate. The most significant relationship (to the 0.05 level) to decomposition is irrigation with a net positive effect. The second most significant relationship (to the 0.05 level) is the management level with a net negative effect. There is no relation with decomposition on replanting. In the case of stabilization, management classification (intensity) and irrigation have the most significant relationship. Management level and irrigation (to the 0.05 level) show a net positive effect. Whether the green roof management included routine replanting shows a minimal significant relationship (to the 0.10 level) with stabilization.

The only significant relationship (0.10 level) shown when comparing component 2 to decomposition and stabilization is that substrate temperature has a negative effect on stabilization.

Regarding component 3, for decomposition rates, elevation is highly positively significant at the 0.05 level, indicating increasing decomposition with elevation. The only variable found to be a significant factor affecting stabilization is also elevation, at the 0.10 level. It has a positive influence, indicating that taller green roofs tend to have increased stabilization factors. Interestingly, roof size and substrate additions do not significantly impact either stabilization or decomposition.

Regarding component 5, it is found that substrate depth is highly significant, showing a negative effect on stabilization, i.e., stabilization (carbon storage) is less in deeper substrates. In contrast, substrate depth has no effect on decomposition rates.

Table 7 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 (substrate conditions) is significant to the 0.05 level and component 1 (management practices) is significant to the 0.10 level for decomposition only. These indicate an overall positive effect of management and substrate conditions on the decomposition rate. Importantly, this implies that the substrate conditions and management practices are highly significant and explain most of the variance found in the decomposition rate data.

Table 6. Results of the linear mixed model comparing the component variables outlined by the PCA. Grayed squares represent significance to the 0.05 level and dashed squares indicate significance to the 0.10 level. The number in parenthesis indicates the effect.

Decomposition Rate Component 1: Management Practices					
Replant	0.703 (0.032)				0.821 (0.018)
Management	0.045 (−0.234)	0.006 (−0.203)		0.602 (0.042)	
Irrigation	0.001 (0.332)	0.001 (0.326)	0.007 (0.182)		
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 2: Substrate Conditions					
Substrate Temperature	0.896 (−0.002)		0.275 (−0.013)		
Substrate Moisture	0.404 (0.006)	0.163 (0.007)			
Stabilization Factor Component 2: Substrate Conditions					
Substrate Temperature	0.068 (−0.012)	0.092 (−0.008)			
Substrate Moisture	0.312 (−0.003)		0.585 (0.001)		
Decomposition Rate Component 3: Roof Features					
Elevation	0.001 (0.090)	0.013 (0.042)	0.021 (0.036)		
Substrate Addition	0.909 (−0.007)	0.261 (−0.089)		0.922 (−0.009)	
Size	X				
Stabilization Factor Component 3: Roof Features					
Elevation	0.327 (0.012)	0.160 (0.010)	0.078 (0.011)		
Substrate Addition	0.488 (0.029)	0.490 (0.025)		0.229 (0.043)	
Size	X				
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)		
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 5: Substrate and Vegetation Management					
Substrate Depth	0.570 (−0.004)	0.731 (−0.003)			
Weeding	0.155 (0.116)		0.158 (0.110)		
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)		

Table 7. Results of the linear mixed model comparing the component scores found by the PCA. Grayed squares represent significance to the 0.05 level and dashed squares indicate significance to the 0.10 level. The number in parenthesis indicates the effect.

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

3.4. Substrate Composition Results

Results from the substrate survey are found in Table A3, listing the composition of the substrate of each roof in mg/L. Figure 4 illustrates the mean levels of boron, sodium, zinc, and manganese at each roof. It is found that all locations had levels of boron and

manganese well above the healthy limit. In contrast, only RMH, ZEC, and SF are above healthy limits for sodium, and MCC, FW, and CCB are above their healthy limits of zinc. This shows no clear trend based on nutrient levels of boron, sodium, zinc, and manganese and management.

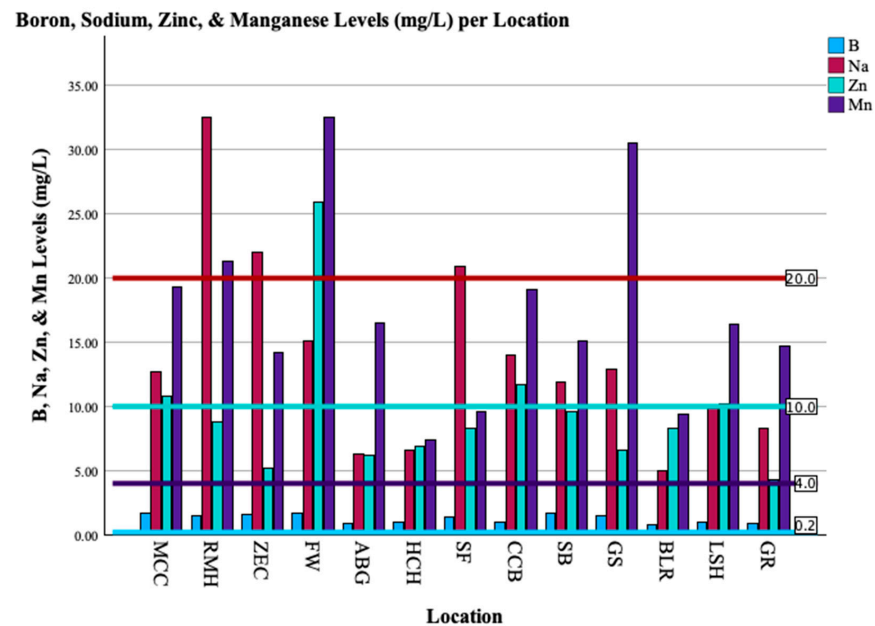


Figure 4. Levels of boron, sodium, zinc, and manganese on each roof, organized from high to low management. The horizontal line indicates the maximum healthy level of the respective nutrient, as outlined in Berghage [18].

Figure 5 illustrates the mean nutrient levels of phosphorus, potassium, and magnesium, showing that all levels of nutrients are well above the maximum healthy limit, with phosphorus and magnesium in extreme excess. This shows no clear trend based on nutrient levels of phosphorus, potassium and magnesium and management.

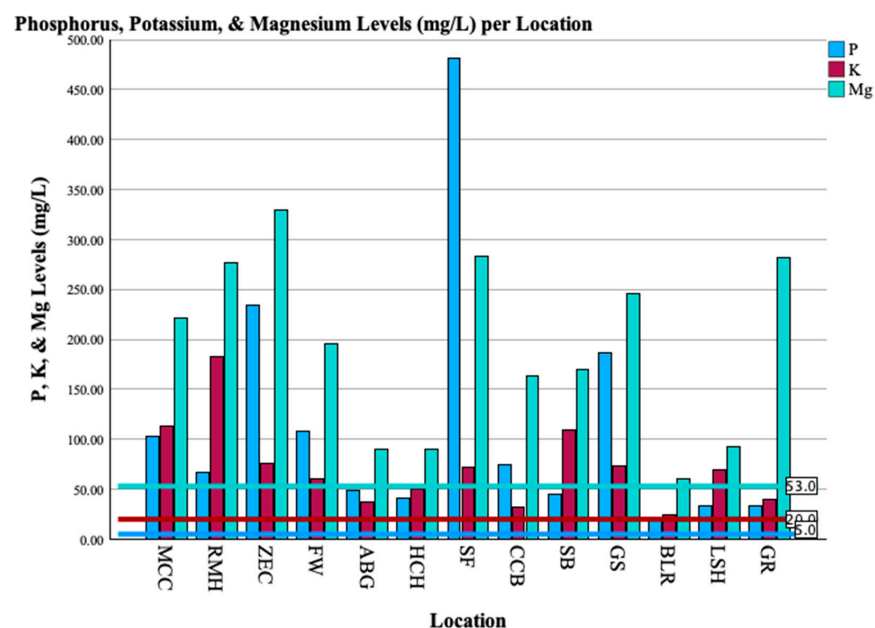


Figure 5. Levels of phosphorus, potassium, and magnesium on each roof. Organized from high to low management. The horizontal line indicates the maximum healthy level of the respective nutrient, as outlined in Berghage [18].

Figure 6 illustrates the mean pH across all locations, illustrating that all locations are within this healthy range, except RMH and BLR, which are just below the threshold. Again, this shows no clear trend in pH and management.

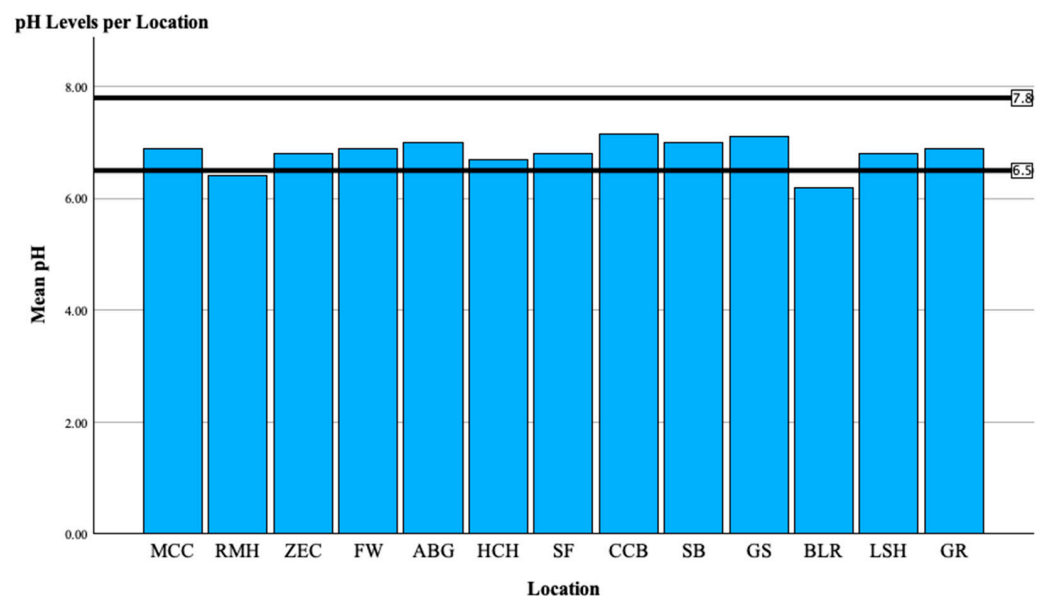


Figure 6. Levels of pH on each roof. Organized from high to low management. The horizontal line indicates the healthy pH range, as outlined in Berghage [18].

Figure 7 illustrates the mean organic matter levels across all locations, with the maximum OM in SF at a very high 32.14% and the lowest OM in ABG with 5.43%. Every location is above the healthy threshold except for ABG. Many locations, like CCB, HCH, FW, LSH, and BLR, are only slightly above healthy levels. However, GS, GR, ZEC, MCC, SF, and SB are all well above the healthy range. This shows there is no clear trend between OM levels and age of the roof.

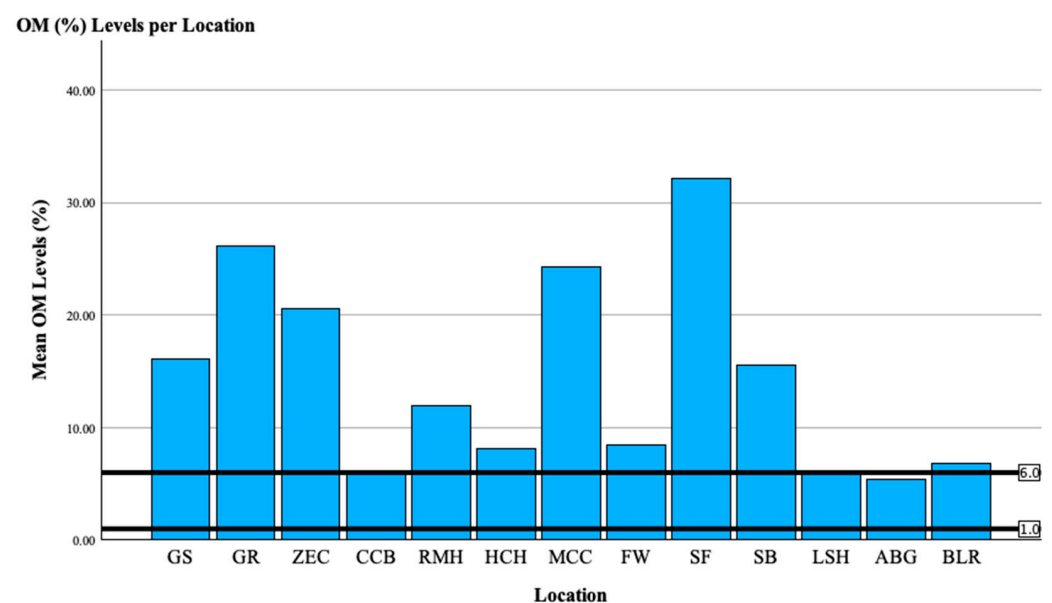


Figure 7. Levels of OM on each roof. Organized from youngest to oldest. The horizontal line indicates the healthy range of OM, as outlined in Berghage [18].

The substrate nutrient loads were compared to each of the components from the PCA to examine the interactions in the composition of the substrate of each green roof. This

provides insight into how each component affects the availability of ESs provided by the makeup of the substrate.

Table 8 illustrates the significance levels of each independent variable against each nutrient and pH and OM levels. Independent variables with significance for two or more analytes 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. 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 effort has significance to the 0.05 level for boron and to the 0.10 level for potassium and calcium. Finally, substrate additions are significant at the 0.05 level for phosphorus and OM and at the 0.10 level for copper.

Table 8. Results of the linear mixed model comparing the individual independent variables to the found nutrient levels. Grayed squares represent significance to the 0.05 level and dashed squares indicate significance to the 0.10 level. 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	(−) 0.360	(+) 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

3.5. Summary of Results

- Stabilization factor (carbon storage) increases with management and irrigation and decreases with substrate depth;
- Decomposition rates increase with irrigation and elevation and decreases with management;
- No significant influence of substrate conditions on the stabilization factor (carbon storage) and decomposition rates is indicated;
- No significant influence of roof features on the stabilization factor (carbon storage) is indicated;
- No influence of roof age and chemical management on the stabilization factor (carbon storage) and decomposition is indicated;
- No significant influence of substrate conditions individually, i.e., temperature and moisture separately, and vegetation management on decomposition rates is indicated;
- Overall, substrate conditions (component 2), i.e., temperature and moisture interacting, are highly significant (to the 0.05 level) and explain most of the variance found in the decomposition rate data. Thus, roofs that are warmer and wetter at the same time have faster decomposition;
- All sampled locations exhibited nutrient concentrations of boron, manganese, phosphorus, potassium, and magnesium exceeding recommended thresholds;
- All locations show health levels of pH, except two roofs: RMH and BLR;
- All locations have an excess of organic matter, except roof ABG;

- Substrate moisture and elevation show positive effects on sodium and boron, respectively;
- Roof age, elevation, and substrate depth were negatively associated with magnesium, copper, and zinc, respectively;
- Substrate addition shows a significant positive effect on phosphorus and organic matter levels.

4. Discussion

4.1. Green Roof Features Affecting Decomposition Rate and Stabilization Factor

Substrate stabilization (carbon storage) and decomposition rates exhibited high initial values that declined rapidly, stabilizing by May–June 2024. Our results thus agree with previous studies showing that decomposition and stabilization tend to a generally exponentially declining trend [26]. The stabilization factor and decomposition rate are positively correlated; as decomposition increases, stabilization typically rises. Substrate temperature and moisture are generally expected to exert parallel influences on both stabilization and decomposition dynamics [26]. However, these findings suggest that substrate conditions do not show a major significant effect on both decomposition and stabilization. Many findings related to the teabag index indicate that climatic conditions such as temperature and moisture have varying effects on k and S [42,43]. For example, green roof temperatures in Oslo, Norway, varied within an optimum temperature range, and vegetation was highly negatively correlated with temperature [43]. This relationship is particularly relevant to k and S , given that vegetation root systems (and temperature) play key roles in shaping the soil microbiome and its metabolic activity.

We also found that irrigation affects the decomposition and stabilization processes with a positive relationship. Roofs equipped with active irrigation systems generally exhibited elevated levels of both stabilization and decomposition. The increase in irrigation also increases substrate moisture, which has been found in numerous studies to increase decomposition [26,44]. Contrary to expectations, greater management intensity was associated with reduced decomposition rates. Highly managed green roofs typically irrigate more often and add organics to their substrates, among other practices, which would be indicative of decomposition rate increasing with more intensive practices [42,44,45]. In this study, we emphasize that while high management practices like irrigation alone may be supportive, the simultaneous application of frequent chemical treatments, replanting, and substrate additions may alter substrate conditions in a way that reduces overall ecosystem services. However, some studies do not find any significant effect of management practices on decomposition or stabilization [46,47]. This discrepancy may stem from methodological differences in the classification and quantification of management practices. In addition, these studies suggest that litter quality and the nature of organic compounds (substrate) are the predominant factors for early-stage decomposition [46,47]. Differences in decomposition rates tend to be more pronounced across contrasting climatic regimes, such as xeric vs. mesic environments [46]. Finally, we note the role of climatic factors may be important when comparing substrate properties among green roofs that are widely separated by distance (and thus climate). However, the green roofs in our study are all less than 300 miles apart. Furthermore, they are all located at approximately the same latitude (35 degrees north $\pm$ 2 degrees) and are all in the same plant hardiness zone. Therefore, given the geographic proximity and climatic similarities among sampled sites, climatic variables are likely secondary to other factors influencing substrate properties.

Elevation also shows a positive effect on decomposition, in contrast to previous studies [48,49]. This pattern remains unexplained, though it may result from the limited sample size, which increases susceptibility to random variation. Another explanation could be that the previous studies [48,49] focused on natural environments (e.g., forests), which clearly differ in important ways compared to the urban environments of our green roofs.

4.2. Green Roof Features Affecting Substrate Composition

For most locations, we found that all nutrient levels are above the maximum healthy level. The exception is some locations of sodium and zinc, with all locations being in clear excess of phosphorus, manganese, and magnesium and minor excess of boron and potassium. Also, we find no clear trend in nutrient levels based on management styles across all roofs, although sodium tends to increase with substrate moisture. This may be attributed to roofs with poor drainage causing sodium accumulation or high sodium content water from irrigation. For example, it has been found that irrigation water can have significantly higher sodium content than precipitation and conventional roof stormwater runoff [50]. Higher elevation is found to decrease levels of copper and increase levels of boron. Although these patterns are not easily explained, one plausible interpretation is that lower levels of copper at higher elevations could be related to lower organic matter levels in the substrate, as organic matter lessens with roof elevation [45]. This may be attributed to the known tendency of organic matter to bind with copper, thereby reducing its bioavailability and mitigating toxicity to soil organisms [51]. Boron concentrations were found to increase with elevation, in contrast to previous studies that reported no significance in boron levels and elevation [52].

Deeper substrates typically showed lower zinc levels. This could be explained by the plants chosen to be on a typical green roof. Due to the prevalence of shallow-rooted vegetation on green roofs, zinc uptake is concentrated near the substrate surface, potentially depleting deeper layers of the substrate [53]. We also found that irrigation levels influence boron and sodium. It has been previously shown that irrigation can influence sodium levels [50] so perhaps a similar process is occurring with boron, i.e., it correlates with boron content of the water used for irrigation. Weeding was also found to affect boron levels. This could potentially occur because weeding can reduce competition for boron. In general, substrate additions can elevate organic content and nutrient levels, which may explain their positive association with management intensity.

5. Conclusions

This research analyzed 1552 teabags to assess stabilization factors (carbon storage), decomposition rates, and substrate composition as proxies for ecosystem services, across 13 green roofs in Asheville, NC, Atlanta, GA, Chattanooga, TN, Knoxville, TN, and Nashville, TN. Our findings align with existing research and reveal distinct differences in ecosystem provision relative to management intensity. The results suggest that higher management intensity is associated with reduced decomposition rates and increased stabilization, indicating greater carbon storage. However, these same roofs provided fewer overall ESs compared to those under low management practices. *Although intensive management may enhance specific functions like carbon sequestration, it can compromise other ecosystem services, indicating that lower intensity strategies may achieve a more balanced service profile.* These findings imply that reduced management intensity could decrease maintenance costs while supporting a wider array of ecosystem services.

In addition to management intensity, we examined the role of green roof age and physical variables such as substrate temperature and moisture on these ecosystem service proxies. Initial observations indicate that green roof age, along with substrate moisture and temperature, may influence the long-term stability and availability of ecosystem services over time.

Although the roofs studied had an average age of 11 years, indicating mature and well-established systems, our study is among the few to analyze roofs of varying ages and management practices using this methodology. These findings present preliminary but potentially actionable patterns that may inform management strategies aimed at sustaining healthy and resilient green roof ecosystems. Despite their preliminary nature, the results

offer meaningful insights and establish a baseline for future research. Ultimately, understanding how green roof age and physical conditions interact with management practices is essential for developing strategies that maximize ESs across urban environments in the Southeastern United States.

This study represents an introductory investigation into ecosystem services on green roofs in the southeastern region of the US, an area that remains largely understudied. The primary focus of this study is to establish baseline patterns and identify possible influencing variables. While more advanced methodologies could enhance the analysis, they were beyond the scope of this initial exploratory study. This research should be viewed as a foundational step, warranting further development through expanded datasets and more robust analytical methods in future investigations.

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Abbreviations

The following abbreviations are used in this manuscript:

ES Ecosystem Service

Appendix A

Table A1. Location acronyms and coordinates.

City	Roof Name	Acronym	Location
Asheville	Blueridge Parkway Visitor	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)

Table A1. *Cont.*

City	Roof Name	Acronym	Location
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)

Table A2. Survey questionnaire distributed to each of the study roofs.

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?

Table A3. Summary of levels (mg/L) of each chemical found in the substrate of each roof as well as the pH and percent organic matter (OM). Ordered from highest to lowest management styles.

	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 (%)
ABG	7.00	48.17	36.77	1875.81	89.73	6.18	16.55	0.55	0.88	6.25	5.43
BLR	6.20	19.31	24.45	1057.78	60.31	8.27	9.38	0.99	0.75	4.96	6.88
CCB	7.15	74.47	31.63	2058.57	162.91	11.75	19.12	0.53	0.97	13.97	6.19
FW	6.90	107.38	59.76	3126.10	194.90	25.94	32.54	0.53	1.67	15.08	8.44
GR	6.90	33.10	40.08	1372.01	282.42	4.34	14.71	0.31	0.90	8.27	26.13
GS	7.10	186.26	73.55	3052.92	245.83	6.56	30.52	0.37	1.49	12.87	16.06
HCH	6.70	40.82	49.64	1269.97	90.09	6.89	7.35	0.53	0.99	6.62	8.18
LSH	6.80	33.83	68.77	1475.53	93.04	10.19	16.36	1.29	0.97	9.93	6.19
MCC	6.90	102.23	112.89	3472.32	221.56	10.83	19.31	0.20	1.73	12.69	24.26
RMH	6.40	66.56	182.21	2318.37	276.17	8.77	21.33	4.49	1.51	32.54	11.91
SB	7.00	45.05	108.67	3296.55	169.53	9.58	15.08	0.26	1.69	11.95	15.56
SF	6.80	481.36	72.08	4000.57	282.79	8.31	9.56	0.11	1.34	20.96	32.14
ZEC	6.80	234.06	75.57	3891.91	329.12	5.15	14.16	0.15	1.56	22.06	20.58

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