Spring 6-16-2024

How Different Modes of Photosynthesis Impact Stormwater Runoff and Weed Growth on Ecoroof Trays During Early Establishment?

Michelle Hesek
Portland State University

How Different Modes of Photosynthesis Impact Stormwater Runoff and Weed Growth on Ecoroof Trays During Early Establishment?

by

Michelle Hesek

An undergraduate honors thesis submitted in partial fulfillment of the

requirements for the degree of

Bachelor of Science

in

University Honors

and

Environmental Science

Thesis Adviser

Olyssa Starry

Portland State University

2024

Keywords: ecoroof, stormwater runoff, leaf area index, plant selection, establishment, weeds

Abstract

Ecoroofs remove of stormwater runoff from the combined sewer system in Portland, Oregon. Reducing runoff is essential in cities considering how impervious surfaces promote flooding. A limited number of studies focus on comparing stormwater retention of ecoroof plants during their establishment period within Portlands climate. Different photosynthetic pathways in plants may impact stormwater runoff based on their water use efficiency. This study undertook a one-year study to determine the effect of plant establishment on water retention for a C4 and CAM species in six ecoroof trays. Weeds were investigated as a factor in water retention, and whether plant type within the tray impacts weed growth. Retention varied based on the season, with both species reaching about 25% at the end of the study. Plant coverage reached 63% for buffalograss and 69% for white stonecrop in by the end of the study. Across all seasons, buffalograss trays had a lower LAI than white stonecrop, but runoff did not differ between the two species. No difference was found in the weed count and species within the two types of trays. Water retention in this study had comparable observations to local ecoroof research, with winter having the lowest retention. Neither plant type outperformed the other in retention, which could be investigated further in longer studies comparing the full establishment period including many species in each pathway. Clients and ecoroof professionals may use these data to strengthen their understanding of two commonly used species and their probable interactions with weeds during establishment.

Introduction

Impervious surfaces, including roofs, roads, and sidewalks, prevent stormwater runoff from being absorbed into the ground. Excess runoff drains into nearby water bodies and soil, impacting the local environment with pollutants residing on these impervious surfaces (Bergahge et al., 2007). The rapid expansion of urban areas increases the installation of impermeable surfaces by approximately 326,000 ha/year globally, with North America having higher impervious cover, from 33.1% in 2012 to 33.8% in 2017 (Nowak & Greenfield, 2020). Runoff collects into nearby water bodies until they flood, impacting vulnerable low-income communities living in the area (Micheletty, 2023; Pallathadka et al., 2022). Portland, Oregon, is especially more prone to flooding from heavy rainfall and close proximity to the Willamette and Columbia River. 13% of Portland's buildings are at around 34% risk of flooding for 1.5 feet over the period of 30 years (Climate Check, n.d). To mitigate precipitation overflow, Portland upgraded its combined sewer system in 2011. The Big Pipe Project can store up to 119 million gallons of rainfall runoff and domestic/industrial effluence which is directed to a treatment plant rather than being outflowed into the Willamette river (City of Portland, 2023a). Compared to Portland's previous sewage system, sewage overflows to the Willamette River have been reduced by 94% (City of Portland, 2023b). Although the improvement is significant, excess flow adds untreated water with potentially harmful bacteria, metals, and greases or oils, polluting the natural system. Impervious surfaces continue to grow alongside urban expansion, amplifying this effect.

One way that Portland manages its excess stormwater runoff is by using green infrastructure, which utilizes environmental features to absorb rainfall while providing additional benefits of removing harmful pollutants and metals ("ecoroof" City of Portland, 2023a; City of Portland, 2024). Green infrastructure has become commonplace on Portland's streets, with 2665 features as of 2024 managing 51% of the city-controlled impervious surfaces, mostly streets (City of Portland, 2024). Out of all impervious surfaces in Portland, streets make up 25% and rooftops 40%, a significantly larger source of impermeable surfaces (Natural Resources Defense Council, 2024, n.d.). The flat surface of a roof absorbs runoff, while weathering causes the leaching of roofing materials, particularly in metal roofs, which are a common roofing type in Portland (De Buyck et al., 2021; McIntyre et al., 2019). Similarly to streets, green infrastructure can be implemented on rooftops to manage precipitation. These structures, known as ecoroofs, are built as part of the roof system, protecting the roof from weathering and doubling its longevity (Ecoroofs- City of Portland, 2024). The Portland Ecoroof Incentive began funding ecoroofs in 2008, resulting in the removal of 9 million gallons of rainwater per year (Bureau of Environmental Services [BES], 2013). As of recent, there are 134 ecoroofs in Portland based on the ecoroof map maintained by the Bureau of Environmental Services (Starry, n.d.). With increasing interest from its successful program, Portland developed its own ecoroof guidelines for owners and contractors in creating and maintaining a healthy system. Since 2015, ecoroofs have become required on large-scale roofs, with the Portland City Council adopting a new zoning code with adjusted ecoroof requirements (City of Portland, 2021). Ecoroof requirements are fluctuating, especially in plant selection as researchers learn about what plants can be utilized the best in Portland's climate.

Much of the information that exists on plant selection for ecoroofs comes from the German FLL guidelines and local plant lists. Although, limited information is published on the utilization of plant adaptations to provide the best stormwater performance. Each plant species is unique in its water use efficiency based on the type of photosynthetic pathway it has, making the right plant selection a complicated task. These adaptations determine how plants relieve water vapor through their shoot system, known as transpiration, which helps alleviate runoff from a precipitation event. Plants differentiate by function in one of three photosynthetic pathways: C3 carbon fixation plants, C4 carbon fixation plants, and Crassulacean Acid Metabolism (CAM) plants. About 90% of plants are C3, making it the most common type of plant adaptation. C4 and CAM are less common photosynthetic pathways, making up ~9% and ~1% of plants, respectively (Raghavendra, 2003). Most CAM plants are sedum species. C3 plants function by opening their stomata during the day to take in carbon dioxide and release water vapor, leading to energy loss (Urry et al., 2016, pg 204). C4 plants have specialized mesophyll cells in their leaves to prevent energy loss needed for the production of biomass. Their functionality is similar to C3 plants, with the main difference being greater water use efficiency in C4 plants (Urry et al., 2016 pg 205). CAM plants differentiate the most in function as they undergo carbon fixation during the day and engage in gas exchange at night (BD Editors, 2019; Urry et al., 2016 pg 206). This cycle allows CAM plants to preserve water effectively to stay alive in dry conditions, making them a preferred choice for ecoroofs based on their drought-tolerance and survivability during long periods of nonattendance (Cao et al., 2019; Bergahge et al., 2007). There is a limited variety of CAM species that can tolerate intense roof conditions. Depending on the species, some C4 and C3 plants can outperform CAM plants in an ecoroof setting by having greater water storage capacity, effective cooling functions, and providing ecosystem services (Cao et al., 2019; Schroll et al., 2011a). All three types of plants are utilized on ecoroofs to reduce stormwater runoff, although C4 and CAM have the added benefit of drought tolerance which makes them easiest to maintain over the summer.

The establishment period is crucial for successful ecoroof performance in the long term. Plants are subjected to extreme wind and solar exposure at an unusual elevation, requiring additional monitoring and maintenance (Zhang et al., 2021). Young plants are the most vulnerable to these conditions until they achieve maturity which takes approximately three years for full coverage (BES, 2020). The required amount of irrigation during the establishment period is ½ inch per week per 4 inches of growing media, according to the 2020 BES Stormwater Management Manual. It is essential to reach 90% coverage within two years of the establishment period to provide the greatest retention (City of Portland & BES, 2020). Therefore, plants with fast growth, the ability to self-sustain and self-seed are preferred (City of Portland & BES, 2020). The use of fertilizers or pesticides is not supported on ecoroofs to prevent nutrient and chemical runoff (City of Portland & BES, 2020). Frequent maintenance is important to ensure plants are healthy and at low risk of being displaced by weeds.

Proper maturity of ecoroof plants include the frequent removal of weeds, which can hinder plant growth and eventually replace intentionally planted species (Zaid et al., 2022). Open gaps in vegetation serve as potential places for weeds to establish through seed or segments introduced by wind, birds, rodents, contaminated growing media, and humans (Nagase et al., 2013). Weeds cover a broader range of plant types, including native, naturalized, and noxious species (BLM, 2024). Allowing their spread can cause destruction to the roof membrane, deteriorate roof aesthetics, become fire fuel, and pose a risk to human health through pollen exposure (Vanstockem et al., 2019). Weeds with high biomass, especially tree saplings and grass species, have been observed to impact stormwater retention by displacing species and influencing dieback (GRPGM module 3-maintenance; Vanstockem et al., 2019). Weeding is advised during the spring to prevent establishment as per the Portland Ecoroof Guidelines. Proper establishment of intended species will result in increased biomass, reducing the ability of weeds to seed. Taller grasses are effective as they reduce room for weed introduction, whereas low-cover plants allow space for weeds to grow over them (The City of Portland, 2005). The generalization of weeds and variability in removal schedules underestimates their potential impact on the system and becomes a major expense for ecoroof owers if left unmanaged (Sherk et al., 2020). It is important to identify and evaluate weeds as a probable factor in stormwater runoff absorption considering their plant displacement. Identifying the weeds that grow on ecoroofs in the Portland area will allow for better knowledge on their removal methods and timing.

Most plant species on ecoroofs are challenging to utilize during the wet season because, regardless of the species selected, water retention is at its lowest (Schroll et al., 2011a, Spolek, 2008). In some cases, the plant substrate, also known as growing media, is more effective at retaining precipitation than the plants. An Oregon State University study by Schroll et al., 2011a found no significant difference between vegetated and growing media only ecoroof trays during the wet season during the first year of implementation. On the other hand, vegetated roofs retained around 13% more rainwater during the dry months, with higher retention occurring in rain events greater than 3.81 mm (Schroll et al., 2011b). Another study in Portland analyzed stormwater retention after the establishment period with similar observations to Schroll's study. Retention decreased from over 90% to approximately 45% retention a month after the wet season began (The City of Portland, 2005). At least 80% retention was observed from May- October for both years (The City of Portland, 2005). These local studies suggest that retention capacity may depend mostly on the frequency of rain events, with a lesser factor being the plant species used. Space restrictions also make it difficult for taller, more absorbent species to thrive and perform better retention. Low runoff rates from an ecoroof are challenging to attain due to seasonal variations, especially considering Portland's climate of wet winters and dry summers. Multiple studies observe weaker water absorption during the winter season regardless of the study's location (Spolek, 2008; Schroll et al., 2011b; Bergahge et al., 2007). One sure way to increase water retention is through the maturity of ecoroof plants. Maturity increases retention capabilities, improving the gap between runoff and retention when it most matters (The City of Portland, 2005; Shultz et al., 2018).

Multiple researchers have questioned the effectiveness of sedum species on stormwater management, noting how C4 plants remove greater amounts of water from the growing media (Starry et al., 2014; Nagase & Dunnett, 2012; Matsuoka et al., 2019). Unlike grasses, sedum species transpire less, leading to an eventual buildup and release of its retained water as runoff (Galliot, 2012). In addition, grasses have higher rainfall interception and a higher water demand than sedum species (Sherk et al., 2020). Another study done in the UK observed sedum species to be the least effective when compared to dense grasses, with *Sedum album* having the least effective runoff retention during heavy rain events (Dunnet, 2008). Transpiration is mainly influenced by the Leaf Area Index (LAI), which is the ratio of leaf area to total surface area, and may impact water retention in plants (Tesemma et al., 2015). An in-depth study using a hydrological model in various catchments observes lower runoff when LAI is higher (Tesemma et al., 2015). Variations in LAI depend on many factors, including the plant species, growth stage, and air humidity. Plants with variable LAI work best on ecoroofs in temperate regions based on their flexibility to remove energy from the roof during the hot summers and maintain energy during the cold winters (Zhou et al., 2018). Evaporation induced by higher LAI led to significantly greater roof cooling than a bare roof (Zhou et al., 2018). While this study focused on simulating seasonal LAI on performance on energy potential in ecoroofs, it does not specify the difference in functionality between C4 and CAM species. The climate of Shanghai was used in the simulation, specifying the use of grasses and sedum. While the study focused on energy potential, there is a lack in research regarding how varying LAI can effect stormwater runoff using a C4 and CAM species. Evaluating the impact of plant characteristics on stormwater runoff will be helpful towards understanding ecoroof performance throughout the establishment period.

This research will study stormwater retention during the first year of establishment using plant coverage and LAI within six simulation trays, including a control tray for retention comparison. Based on the functionality difference by C4 and CAM species, how do plants with different photosynthetic pathways impact stormwater runoff? This research will compare buffalograss (Bouteloua dactyloides), a C4 drought-tolerant turfgrass, and white stonecrop (Sedum album), a CAM succulent plant with tolerance for hot and cold temperatures. Trays planted with buffalograss are predicted to retain more stormwater runoff throughout any season compared to white stonecrop based on its capability to regulate water usage alongside its extensive sponge-like root system. The growth of each species is measured using LAI. Subsequently, this research will study seasonally variable LAI measurements and compare it to the water retention of the ecoroof trays. As part of establishment, this research will identify weeds growing within the trays and whether weed establishment is affected by the plant type within the trays. Considering the difference in root structure, white stonecrop is predicted to have greater weed establishment of deep-rooted weeds as a result of its primarily lateral roots, which would allow weed establishment in deeper soil depth. Our results aim to understand plant absorption of runoff in different photosynthetic pathways.

Methods

Study area

Portland is in a region of the Pacific Northwest located within the Willamette Valley that averages around 37 inches of rain annually (Spolek, 2008). The city has a Mediterranean climate, with dry summers peaking at about 30℃ and wet winters as low as 2℃ (Dvorak et al., 2021). Stormwater retention is highest during the summer, when there are fewer rain events (Spolek, 2008). Furthermore, Portland experiences droughts on a frequent basis in the summer, which favors drought-tolerant plants (NOAA and NIDIS, 2024). These climatic conditions of Portland make it an ideal location for testing plant selection. Based on USDA's Hardiness Zone Map, Portland State University (PSU) is a 9a (20 to 25 °F/ -6.7 to -3.9 ℃), referring to the lowest temperatures that occur (Breen, 2023). Growing media met FLL compliance (FLL, 2004). The FLL guidelines are professional standards used in the ecoroof industry and serve as a guide for building successful ecoroofs, from the waterproofing materials to the plant selection. The guidelines are used to assist ecoroof building in North America, although the information is based on German research and regulations (Philippi, n.d.).

Tray design

Seven 16 ft2 low-level extensive trays are assembled near the Walk of the Heroines on PSU campus (45°30'44.0" N, 122°41'12.0" W). The trays are designed and built by the Civil & Environmental Engineering Department 2022 senior environmental capstone team. Each tray is built with a waterproofing membrane and a filter fabric on top (Figure 1). The trays are titled to a 2% slope to aim runoff toward a drainage hole placed in one corner, leading to a tipping bucket (Figure 2). Extensive runoff is measured using a Unidata Model 6506G Tipping Bucket Flow Gauge, where 1 tip is measured at 75 mL. A drainage pipe is secured to the hole, with the pipe protected from root penetration with chicken wire secured around the pipe with zip ties. Weed control film is wrapped to cover the mesh and stapled to the chicken wire. Once secured to the tray, it is filled with gravel of approximately 1- inch size to the top. The trays are filled with a depth of 10cm growing media bought from Columbia Green Technologies, Phillips' Soil Products, composed of a regional blend containing volcanic cinder rock, pumice, perlite, and clay aggregate with high water content (CGT, 2016). Seedlings were grown on the PSU campus and planted on April 28, 2023. Three trays are planted with white stonecrop, three with buffalograss, and one left with bare growing media as the control. Each tray was planted with 47 plants and watered with approximately two gallons each. More plant plugs were added on June 14, 2023 to enhance establishment during the summer. The study began shortly after the trays were planted and ended on May 12, 2024.

Watering schedule

The trays were watered uniformly for 27 seconds per tray, equivalent to two gallons per event starting daily from July 17, 2023 until September 4, 2023. The watering times were between 8:00 AM and 12:00 PM, with two days being in the afternoon. Subsequently, the trays were watered 6 times every 2-5 days until October, decreasing to three watering events and stopping on October 20, 2023. Irrigation records were kept in a spreadsheet. Irrigation data was considered as part of runoff data and included in runoff analysis.

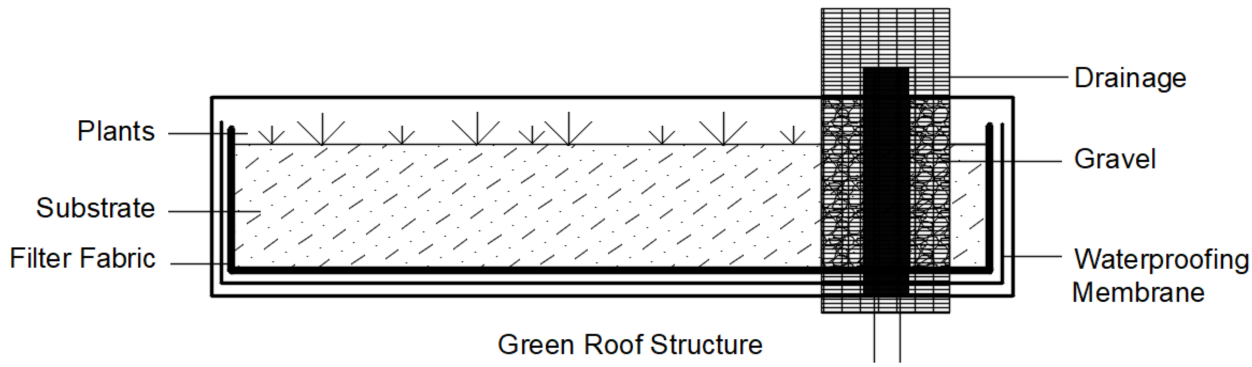


Figure 1. Components of the extensive roof tray made in AutoCAD.

Figure 2. Photo of one out of seven trays and a closeup of the tipping bucket used to measure stormwater runoff (mL), located underneath each tray.

Plant Selection

Buffalograss (*Bouteloua dactyloides*): C4 low-growing grass that grows up to approximately 0.5 ft tall (USDA, 2023). It prefers full sun or partial shade based on naturally residing in plains in Central North America (Snodgrass E. & Snodgrass L., 2006; Brown, 1979; iNaturalist, 2023a). Buffalograss is one of the only drought-tolerant turfgrass species that establish fast, providing 80% coverage within its first growing season (Sutton, 2017; LBJWF, 2023). Compared to other grasses in the same study, Bouteloua hirsuta and Bouteloua gracilis grew to ~55% and ~25% coverage within the same season, respectively (Sutton, 2017). Buffalograss has been used as a substitute for non-native grasses for having lower evapotranspiration rates, slower growth rates, and greater survivability (USDA, 2013). Naturally, they are found on clay soils in low- to medium-rainfall regions (USDA, 2013). Buffalograss was grown from seed in the research greenhouses on PSU campus, while white stonecrop arrived as plugs from a plant nursery (Figure 3).

White stonecrop (*Sedum album*): CAM evergreen sedum that is capable of switching to C3 photosynthetic pathway based on the water availability in its environment (Portland Nursery, n.d.; iNaturalist, 2023b). It is a relatively small, low-maintenance sedum for ground cover that grows up to 1 ft wide (MBG, 2023). Their preferred condition includes full sun. It is able to withstand drought conditions and very cold temperatures up to -34 °C (Perennial Obsessions, 2020). White stonecrop is native to Europe and Asia and has been used commonly in American vegetated roofs (Snodgrass E. & Snodgrass L., 2006). They thrive in shallow soil depths of 4 inches, with their roots having a spread of 1-1.5 ft (Snodgrass E. & Snodgrass L., 2006; MBG, 2023). It was grown in the PSU Science Research and Teaching Center (SRTC) greenhouse for three months in shallow trays.

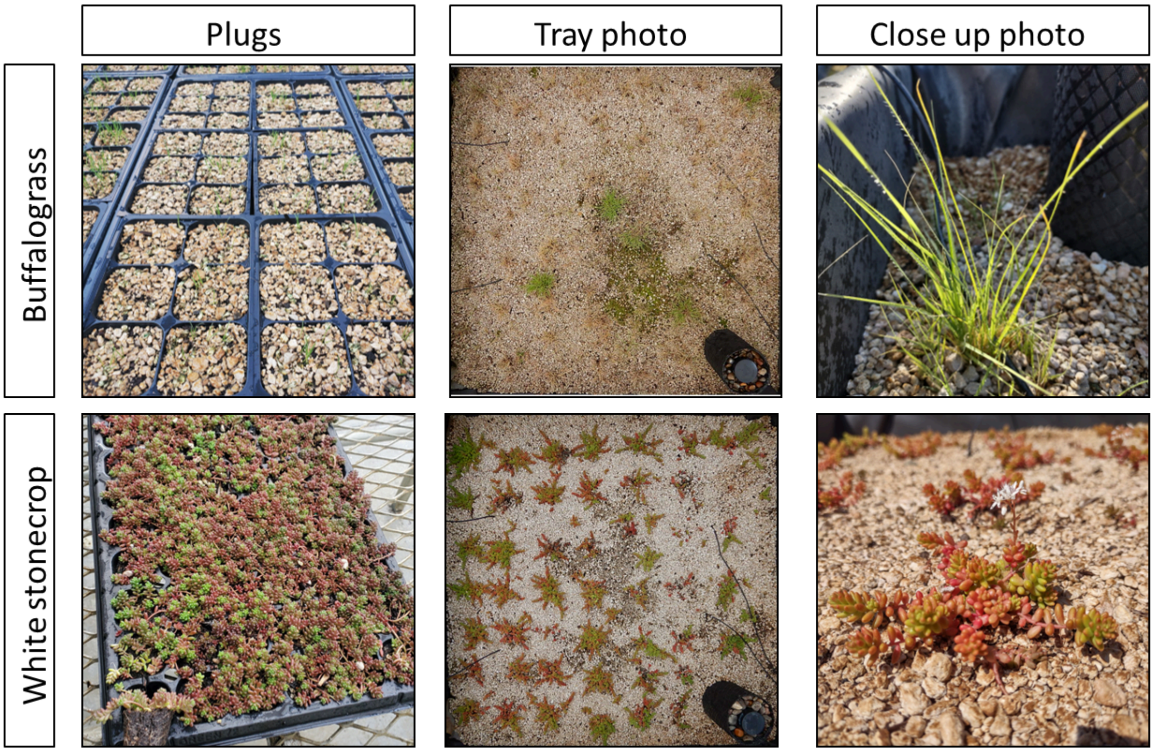


Figure 3. Photos of related plant species used for the project: plants before planting (left), top view of plants in ecoroof trays (middle), and a closeup shot of each plant (right).

Plant coverage

Plant growth is measured using horizontal plant coverage by using a 4ft^2 quadrat made of PVC pipes with a 5x5 grid. Plant coverage is measured by placing the quadrat rim to the side of the tray, starting at the drainage area and moving clockwise to the end (Figure 4). Coverage is visually rounded off to the nearest 5.

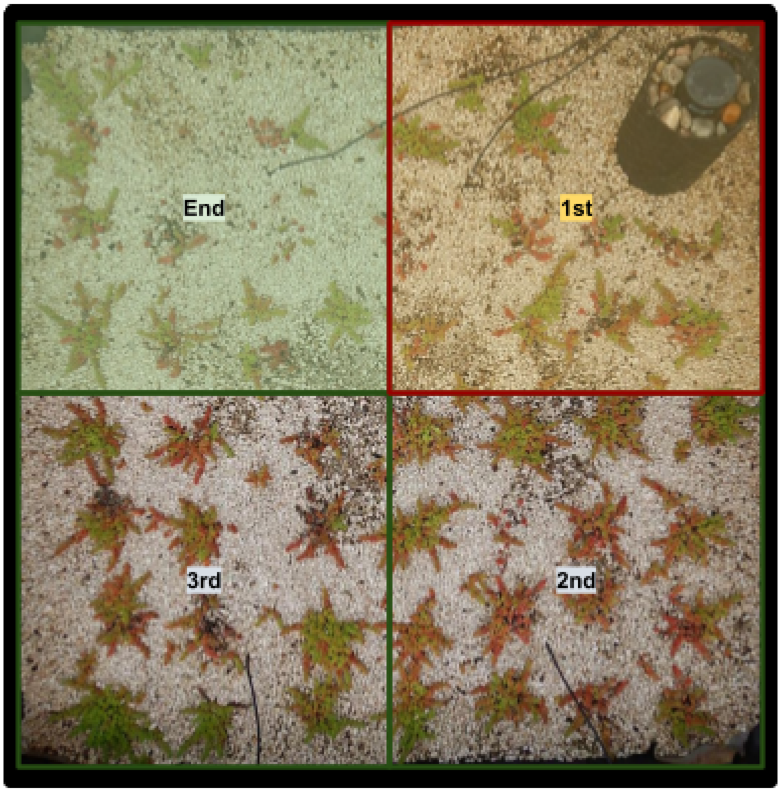


Figure 4. Diagram of quadrat placement within each tray. Sampling begins where the drainage is located and continues clockwise around the tray, ending at the area to the left of the drainage.

Leaf Area Index (LAI)- Non-destructive analyses

LAI is calculated to determine the ratio of foliage density to the ground area. In this study, we use both destructive and non-destructive methods to attain LAI measurements. Destructive measurements are taken by selecting a plant plug and counting/ measuring leaves. Photographs of the entire trays are taken using a Nikon CoolPix W300 attached to a camera stand with a height of ~43 inches on the top middle of the tray edge facing the sun to prevent shadow casts. Photos are taken once per season starting in September 2023. One photo from each planted tray is analyzed using the free scientific image-processing program ImageJ to achieve a raster image to estimate accurate coverage (Figure 4).

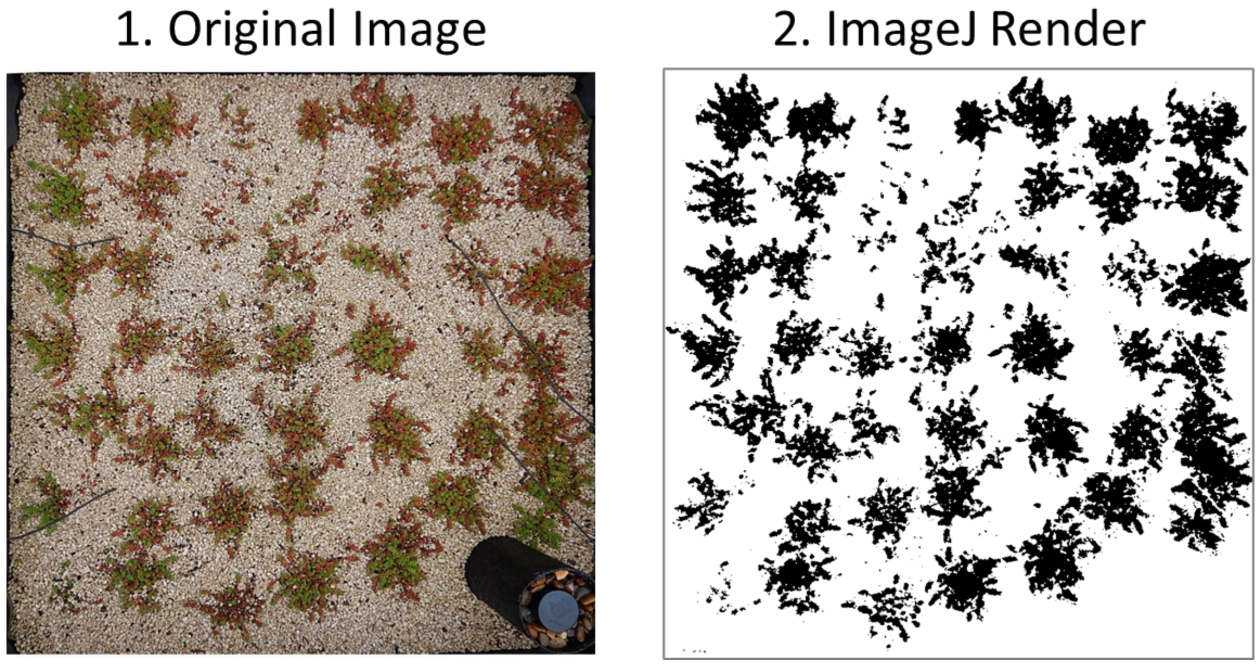


Figure 4. Example of a complete coverage analysis using ImageJ (2). The original image is of white stonecrop sampled on October 2, 2023.

<u>Leaf Area Index (LAI)- Destructive analyses</u>

Shoot and root biomass is sampled by taking one 6-inch soil core sample of a developed plant from each tray. Any plant material above the growing media is considered biomass in white stonecrop samples and split from the below-ground roots. Moss and weeds are removed and not counted towards the wet weight. White stonecrop samples have their wet weight (g) taken after the leaflets are taken apart to reduce excess growing media. The length (mm) of 20 buffalograss leaves and 20 white stonecrop leaves are taken. The volume (mL) of white stonecrop samples is measured by placing shoots into a syringe. Each leaflet is counted for white stonecrop. Lastly, the samples are dried in an incubator for approximately 24 hours at 105 ℃ and left to acclimate for about 30 minutes before measuring the dry weight (g) of both shoots and roots.

<u>Data Analysis- Leaf Area Index (LAI)</u>

The width (mm) was calculated for white stonecrop trays using the sample volume, the average length of 20 leaflet samples, and leaf count using a rearranged ellipsoid volume equation. Leaf dimensions are used to find the surface area of a prolate ellipsoid using the following equation:

$Surface\ area = 4\pi\,(a^p b^p a^p c^p b^p c^p/3)^{1/p}$, where a= length, b=c, and p=1.061

The result was multiplied by the leaf count to get the surface area of the entire core sample. LAI is calculated by taking the surface area of the entire sample and dividing it by the radius of the soil sampler (mm). The final result is multiplied by the coverage to adjust for non-vegetated segments for greater accuracy.

<u>Weed analysis</u>

Weed maintenance occurred every two weeks starting from the beginning of August 2023. The environmental engineering group was notified to refrain from weed removal on September 14, 2023 to prevent skewed results. Collection methods were changed to monthly sampling based on expert opinion. Each tray is thoroughly inspected for weeds, which are counted and removed. Cross-contamination of the trays is included in the count. Photos of weeds identified in each tray are taken of potentially identifiable weeds and identified using iNaturalist, Google Images, The University of California Statewide Integrated Pest Management Program (UC IPM), and *Weeds of the Northeast* by Richard H. Uva et al. Final results incorporate data from months without any external removals.

Evaluating stormwater performance

Stormwater runoff data is collected from each tray by a 6506 Tipping Bucket Flow Gauge tipping bucket connecting to a data logger. Four EC5 Soil Moisture Sensors are placed in each tray within a square formation a few inches from the edge of the tray. Precipitation data is taken from the PRISM Climate Group to compare to the data observed from the tipping buckets. The raw data is transferred into an Excel spreadsheet and analyzed using pivot tables.

Data Analysis- stormwater performance

Stormwater performance was compared between the plants and control tray using tipping bucket data and PRISM precipitation data using the nearest location. Runoff data was split into the total amount of runoff in millimeters (mL) per month. An average is taken among all trays to find the average of runoff per month per plant type. To account for all water inputs, the Irrigation total per month is added to the precipitation results. Irrigation data was calculated per month using a spreadsheet with irrigation records. PRISM precipitation data and irrigation volume were added before the result is subtracted from the average runoff data from each tray type. Percent retention from the trays is calculated using the following equation:

$$Percent\ retention = (retention\ (L)/\ irrigation\ +\ rain\ (L)\ *\ 100)$$

Results

Plant coverage

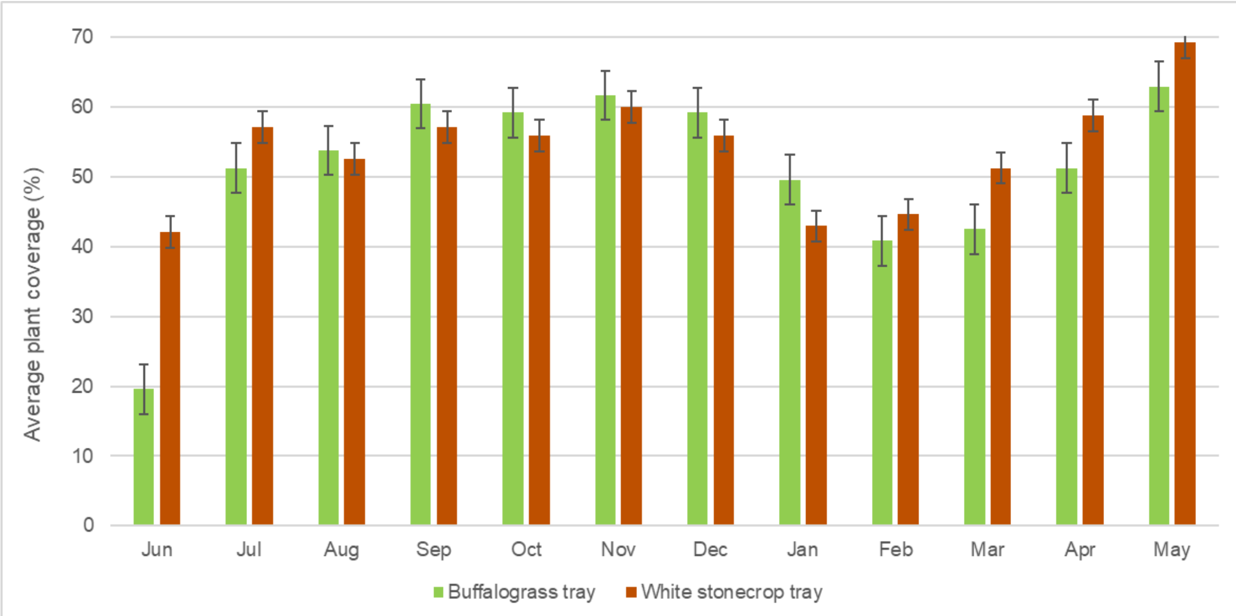


Figure 5. Average plant coverage (%) taken per buffalograss (green) and white stonecrop (brown) tray on a monthly basis. Averages are based on all six planted trays.

Both species increased in coverage during the year. Plant coverage started below 20% in June for buffalograss and 42% for white stonecrop trays (Figure 5). Buffalograss trays rose 30% in cover within a month from June to July and grew by 10% from July to October (Figure 5). White stonecrop trays increased in coverage by about 20% from June to July and stayed stagnant at around 55% in cover until October (Figure 5). Plant coverage steadily decreased in winter by about 20% for buffalograss and 15% for white stonecrop by February (Figure 5). Both species recovered from the harsh winter, with white stonecrop reaching peak coverage of 63% for buffalograss and 69% for white stonecrop in May (Figure 5). Most, if not all, initial plant plugs survived throughout the year. Overall, buffalograss increased coverage by 43% throughout the study period, whereas white stonecrop increased by 27% (Figure 5). The difference in plant coverage between the two species was not statistically significant.

<u>Stormwater performance</u>

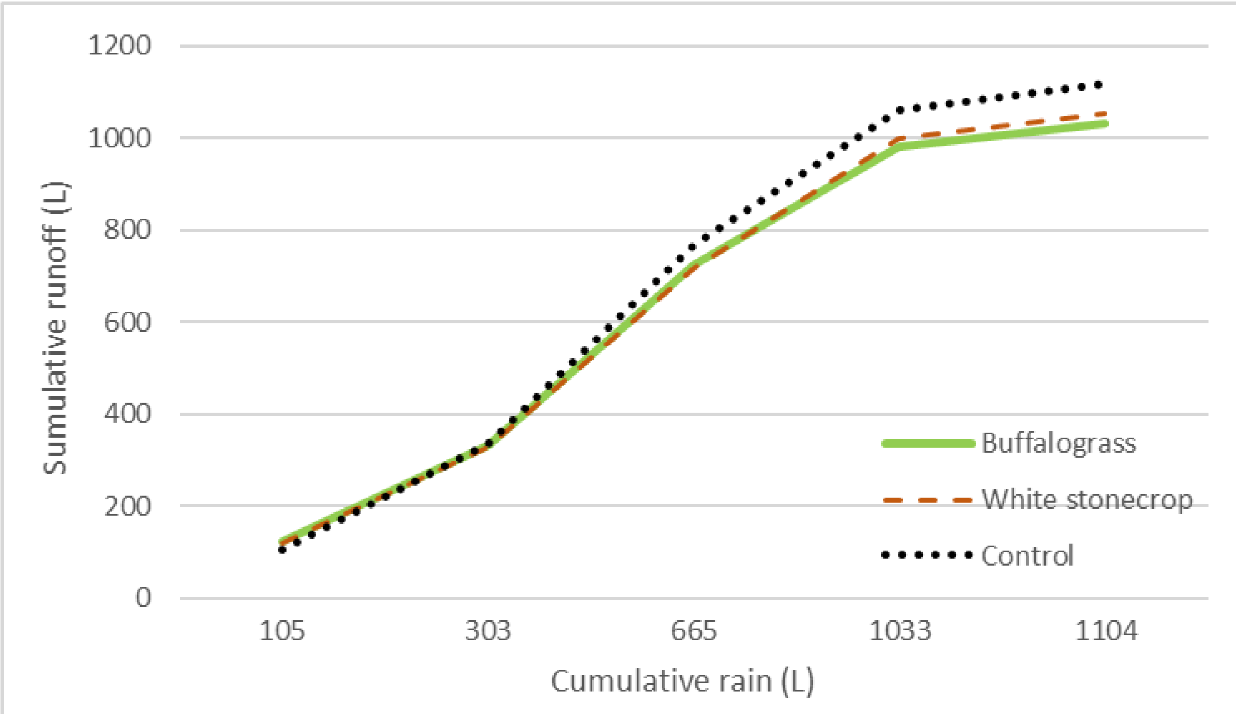


Figure 6. The influence of storm size on runoff between tray types by event size to cumulative runoff.

The control tray had the lowest runoff by about 20 gallons during smaller rain events of 105 L and 303 L (Figure 6). Larger rain events past 303 L experienced greater runoff differences between the control and planted trays. There is a 50 L difference in runoff between vegetated trays and the control when cumulative rain is 665 L (Figure 6). Buffalograss runoff was slightly higher than white stonecrop by 7 L at rain events of 665 L, but lower at rain events of 1033 L and 1104 L by nearly 20 L (Figure 6). Vegetated trays performed higher retention compared to the control by 76 L at the highest rain event (Figure 6).

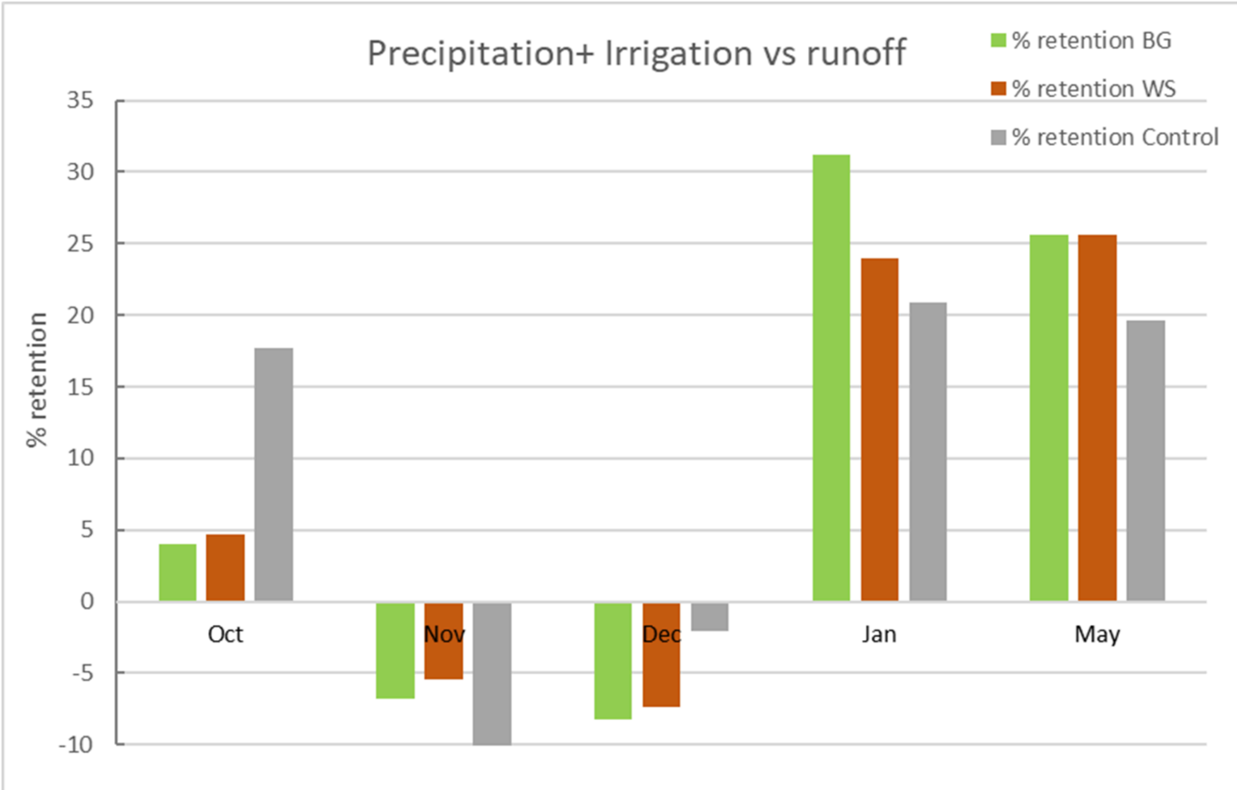


Figure 7. Graph showing the monthly retention rate between white stonecrop and buffalograss trays.

Runoff measurements were taken throughout the year in all seven trays starting July 23, 2023 and ending May 12, 2024. Breaks in data occurred from January to May, 2024 due to technical difficulties. Runoff varied throughout the seasons, with November and December receiving larger runoff than any other month- around -5% for vegetated trays (Figure 7). Negative retention resulted from sensor errors and spatial variability between the precipitation data's sampling and tray locations. Buffalograss had slightly higher runoff than white stonecrop from October- December by about 1% (Figure 7). The highest % retention was observed by buffalograss during January 2024 at over 30% (Figure 7). By May, retention had dropped to about 25% with white stonecrop (Figure 7).

__Leaf Area Index__

Table 1. LAI measurements per season, differentiated by white stonecrop (WS) and buffalograss (BG) samples. Buffalograss results for fall were unavailable.

	Summer	Fall	Winter	Spring
WS Average	2.68	4.85	2.67	34.11
BG Average	2.48	N/A	2.30	6.67

LAI was highest during the spring and lowest during the winter season for both species (Table 1). White stonecrop experienced a very small decrease in LAI from summer to winter, from 2.68 to 2.67, with a drastic increase to 34.11 in spring (Table 1). Similarly, buffalograss had the highest LAI for spring at 6.67 and the lowest during Winter at 2.30 (Table 1). LAI was larger for white stonecrop samples than buffalograss for any season where both were collected (Table 1). Given that just one dense sample was chosen for sampling per tray, these samples most likely overestimate overall tray coverage. Adjusting for coverage improves accuracy. However, not all grass clumps were as dense as the one we sampled.

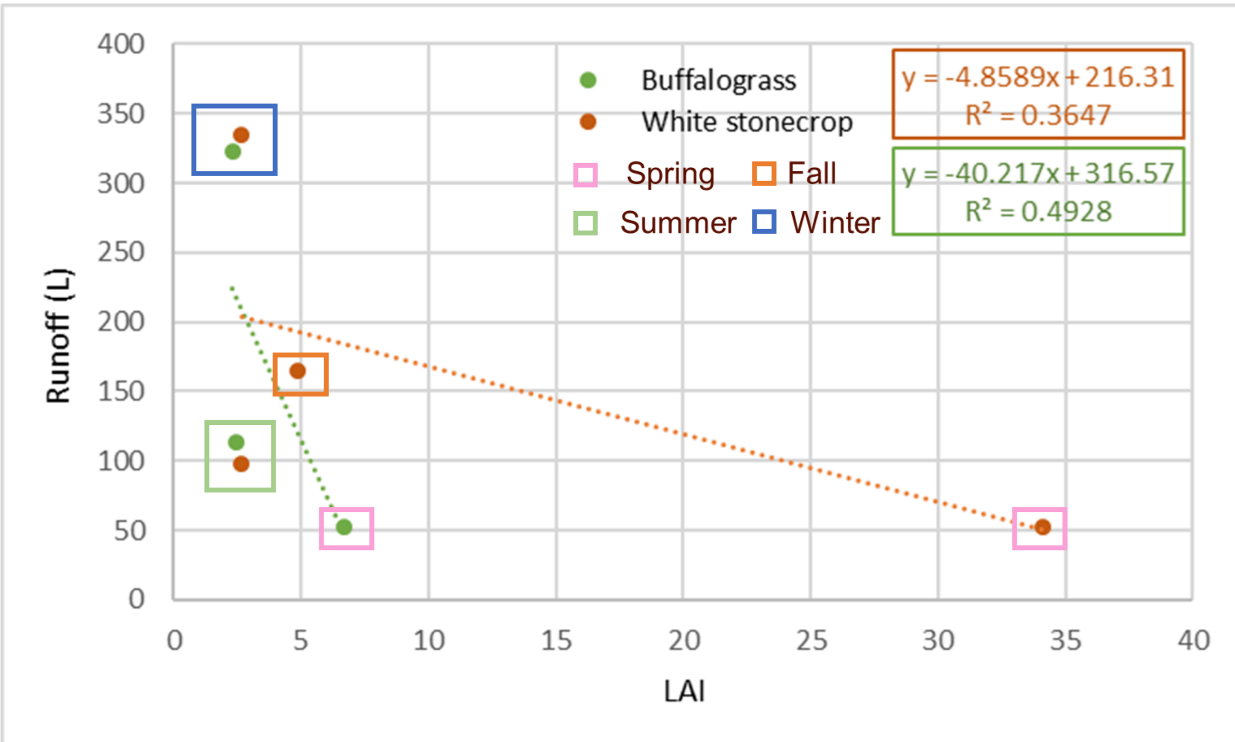


Figure 8. Relationship between leaf area index to runoff (L). Different points reflect different subsamples, with each color relating to the season the sample was taken: summer (green), fall (orange), winter (blue), spring (pink).

Regardless of the season, buffalograss LAI was consistently lower than white stonecrop (Figure 8). The regression equations indicate that LAI and runoff demonstrate a statistically stronger association in buffalograss than in white stonecrop. LAI was low for both species during the summer at the beginning of the experiment. Summer runoff was caused by irrigation. Fall LAI data was unavailable for buffalograss however white stonecrop experienced higher LAI and greater runoff (Figure 8). Runoff increased by over 200 L during the winter for both species, with LAI being at its lowest (Figure 8). Spring experienced the lowest runoff at around 50 L and the highest LAI for both species (Figure 8). Between the beginning and end of the study, LAI increased from 3 to 34 for white stonecrop and 2 to 7 for buffalograss. The difference in LAI between both species during the spring is 27, whereas the difference in runoff is 0 L.

Weed establishment

Table 2. Total count of weeds per tray type, buffalograss (BF) or white stonecrop (WS), distributed over three seasons.

Fall			Winter			Spring		
BG	WS	Control	BG	WS	Control	BG	WS	Control
118	100	100	11	13	7	35	33	24

The overall number of identified and unidentified weeds varies the most in buffalograss (Table 2). The control tray had the highest number of weeds during the fall season, followed by spring and winter (Table 2). The control tray had the same number of weeds during the fall season as the white stonecrop trays (Table 2). Running statistical analysis comparing the total monthly weed count in buffalograss and white stonecrop trays results in a statistically non-significant result of 0.763.

Table 3. The top five species with the highest total weed count separated per season based on the planted tray type buffalograss (BF) or white stonecrop (WS). Species are sorted by highest to lowest total count. *Prunella/ Epilobium coliatum* were combined for their similar characteristics and frequent observations.

Scientific Name	Fall		Winter		Spring		Total Count
	BG	WS	BG	WS	BG	WS	
Stellaria media	24	13	6	1	10	3	57
Prunella/ Epilobium ciliatum	19	18	1	3	3	1	45
Sonchus oleraceus	4	12	2	2	2	1	23
Geranium robertianum	21	10	0	1	0	0	32
Cardamine hirsuta	13	6	0	1	0	2	22

Fall had the highest weed count out of any season for any species (Table 3). Considering all species, spring had a lower weed count than fall by 118 (Table 3). Differences were observed in the tray type. Buffalograss trays had a total count of 105 weeds across all seasons compared to 74 weeds in white stonecrop trays (Table 3). Each season had a higher total count of weeds in buffalograss trays, with the fall season having the largest difference at 81 in buffalograss trays compared to 59 for white stonecrop (Table 3). *Stellaria media* has the highest weed count of all species (57 identifications) (Table 3). Each species had greater count in buffalograss trays during the fall except for *Sonus oleraceus*, a shallow-rooted plant with waxy leaves. Generally, a higher total count of weeds relates to a larger presence of said species across all trays.

Table 4. Plant specifics on the top five most observed weeds pertaining to functionality and runoff.

Scientific name	Life cycle type	Total count	Season with highest count	Root type	Photosynthetic pathway	Origin
Stellaria media	Annual	57	Fall	Fibrous	C3	Naturalized
Prunella/ Epilobium ciliatum	Perennial	45	Fall	Fibrous	C3	Native
Geranium robertianum	Annual	32	Fall	Fibrous	C3	Naturalized
Sonchus oleraceus	Annual	23	Fall	Taproot	C3	Naturalized
Cardamine hirsuta	Annual	22	Fall	Taproot	C3	Naturalized

The life cycle for most species was annual (one year), with *Prunella/ Epilobium coliatum* having a perennial (2 years or more) life cycle (Table 4). All species featured a C3 adaptation and had the highest observations during fall (Table 4). Root types varied between fibrous and taproot, although species with higher counts had fibrous roots (Table 4). *Prunella/ Epilobium coliatum* are the only native species in the Portland area.

Discussion

This study compared the water use efficiency of a C4 and CAM plant species throughout the first establishment year. Stormwater runoff between the species varied based on the seasonality and coverage of the plants (Figure 7). Larger rain events were absorbed slightly more by buffalograss than white stonecrop (Figure 6) Small rain events were retained the least by planted trays, although by a few liters (Figure 6). Greater retention during high rain storm events was similarly observed in a fully established ecroof system, with retention being the greatest during the second-largest rain event (Stovin et al., 2015). Both species retained more runoff during January and May, with the lowest performance occuring during December (Figure 7). Buffalograss and white stonecrop retained above 25% retention by the end of the study (Figure 7). Although buffalograss was predicted to outperform white stonecrop during any season, it only outperformed white stonecrop by a noticeable amount in January (Figure 7). Many months of runoff data were lost due to sensor issues and battery failure, resulting in uncertain results. Retention of vegetated trays was the lowest during the winter months, which is consistent with multiple ecoroof studies on runoff absorption (Schroll et al., 2011b; Stovin et al., 2015; Spolek, 2008). This consistency proves a problem when utilizing ecoroofs to reduce sizeable amounts of stormwater runoff from sewer systems.

Considering the study period of one year, coverage and seasonality likely impacted retention. Coverage reached less than 100%, limiting the amount of water each species could retain. Compared with the control tray, plant absorption accounted for a low percentage of stormwater retention (figure 7). These results are consistent with a Portland study that observed an average of 29% retention of all storm events throughout a 10-month establishment period (Bans, 2020). In developed systems, vegetated ecoroofs retain more than non-vegetated ecoroofs (Stovin et al., 2015; Schroll et al., 2009). One study estimated that growing media retains 35%-45% of moisture before it starts to become runoff (Bergahge et al., 2007). Plants retained an estimated 60% of rainfall (Bergahge et al., 2007). Lower retention in plants compared to the control tray could result from excess water release by dead plant material (Figure 7). Long-term rain events and colder weather can cause overwatering and root rot. The decomposition process releases water, which would add excess runoff from the trays within a closed system. White stonecrop was observed to have the lowest evapotranspiration and highest runoff during any simulated storm type (small, medium, and large) compared to two other sedum species, *Sedum kamtschaticum* and *Sedum sexangulare*, in one study (Starry, 2013). To generalize the retention of white stonecrop across all CAM species would create unreliable results.

Retention could be studied at a grander scale if the study continued for another year or more until plant coverage matured to 100%. Plant coverage increased steadily throughout the year, ending with 63% coverage for buffalograss and 69% coverage for white stonecrop (Figure 5). This trend of slow growth in coverage is observed in a similar study done in a Mediterranean climate using sedum mixtures (Miceli et al., 2022). The study found coverage to grow from ~40% for both mixes to ~50% by the end of the first year (Miceli et al., 2022). During the second year of growth, water retention was highest from May - October, nearing full retention capacity (Miceli et al., 2022). Winter months, January - March, had the lowest water retention in this study. The difference between the two mixes was not significant (Miceli et al., 2022). Growing media depth could impact plant growth in buffalograss, a deeper-rooted species. Rainfall retention between an ecoroof system with a 75mm depth and a 125mm depth had the largest differences during the summer (Shultz et al., 2018). Both systems were planted with sedum species, with the study specifying how different plant types could influence retention (Shultz et al., 2018). Multiple studies observed grass species outperforming sedum in precipitation retention given enough space (Nagase & Dunnett, 2012; Schrieke et al., 2023). Greater retention could be expected with plant maturity however, the difference between C4 and CAM influence remains. LAI differed significantly between C4 and CAM species, but stormwater runoff absorption did not (Figure 8). Seasonality affected the LAI in each plant, which was highest in spring and lowest in winter (Table 1). Plant coverage was difficult to estimate for buffalograss using ImageJ methods, especially considering its vertical growth and similar color to the substrate. As a result, an overestimation of LAI likely exists, especially for buffalograss. Although LAI did not differ significantly between buffalograss and white stonecrop, it could cause larger differences in long-term research.

Weeds were frequently removed throughout the experiment. Sampling was altered from biweekly to monthly beginning in late October, as Assistant Professor of Practice (Herbarium Curator) and Instructor Dr. James Mickley recommended for easier identification. The environmental engineering group was notified to stop removing weeds on September 14, 2023 to prevent accidental removal. Greater coverage of the intended plant species likely lowered the weed count. This trend is observed in Table 2, where spring experienced a lower count of weeds than fall, where coverage was around 60% (Figure 5). The gaps between vegetation increase as coverage increases throughout ecoroof maturity (Vanstockem et al., 2019). Most weeds were naturalized and commonly found in the area (Table 4). With their fast growth, it can be expected that weeds would impact water absorption, although the specifics are unclear from the results of this study. Most weed colonization can be mitigated by frequent maintenance throughout the year, especially before the parent plant can seed (Nagase et al., 2013). It is important to understand common weeds' seasonality, root structure, and seeding methods, as this information can be utilized for effective removal—for example, *Cardamine oligosperma* seed after just two weeks of establishment (OSU, 2018). Early removal is necessary not only to prevent deep root establishment but to prevent seeding. Some seeds can remain dormant in the soil for many years, as with Geranium robertianum (King County, 2018). Each system has its own maintenance needs based on the size, coverage, and establishment period. One study on weed maintenance found that weeding six times per year limited the amount of weed colonization within the system, reducing maintenance costs in the long run (Nagase et al., 2013).

Portland's climate also had a role in introducing moss into the trays. Moss began to grow starting in fall 2023, persisting throughout the rest of the study. Moss removal was difficult as it would proliferate between the plants. Not all trays developed moss, regardless of plant type, potentially absorbing more water in a greater area. The concentration of moisture allowed some weeds to grow within the moss. Portland's climate makes it ideal for moss in ecoroofs, although their weight absorption may pose a risk for the system. While moss was not a consideration for this research, local Pacific Northwest mosses can absorb about 10x their weight in water mass (Schroll et al., 2011b). An OSU study observed moss monocultures to outperform plant and medium-only ecoroofs during the winter, retaining 23% more water (Anderson et al., 2010). The main downside to moss ecoroofs is that they will go dormant if not watered often during dryer months.

Future Implications

This study collected samples for close to a full year. Unexpected errors in technology prevented a complete dataset for stormwater runoff, creating unfinished results. Results with continuous data include coverage and weed establishment, which could be built upon by future studies focusing on long-term monitoring of plant establishment. Considering how runoff retention may vary by species, trays with different C4 and CAM species could help find a more definitive answer as to whether photosynthetic pathways in plants impact stormwater runoff. It might be best to utilize plants active during the rainy season, including wetland plants, which are expected to provide greater water retention (Schroll et al., 2011b). Collecting data during the plant establishment period to its completion would be essential in understanding the growth and impact of different plant adaptations on stormwater runoff. One way for this study to have been improved is by including a C3 plant species to compare all plant adaptations to water retention. Biomass and plant coverage results will be utilized in hydrological modeling by Dr.Samantha Hartzell to understand how C4 and CAM species differ in stormwater runoff (Hartzell et al., 2018). The results from this study can help new ecoroof owners optimize their plant selection choices to benefit stormwater retention and gain insight on the establishment period on smaller simulated ecoroof trays. The Central City 2035 plan will require ecoroofs on newly built commercial buildings of 20,000 ft^2 or larger (Slothower, 2021). To ensure clients and contractors are best prepared for all seasons, there needs to be more clarity on plant selection utilized for the wet season. Currently, the most recent ecoroof manual focuses on plant selection for drought conditions (City of Portland & BES, 2020). A lack of selection and research for more water-efficient species hinders the reduction of runoff from roof systems.

Acknowledgments

Thank you to the Home Ecology Research Lab, led by Dr. Olyssa Starry, and the PSU Ecohydrology Lab, led by Dr. Samantha Hartzell, for making this research possible. I am grateful for the project I was entrusted with and the flexibility to learn many skills. Special thanks to the support of the NIH-funded BUILD EXITO program and its wonderful staff for this undergraduate research experience. Support by the NSF CBET-2139003 grant made this collaborative research possible. Extended thanks to the 2022 senior environmental capstone team who constructed and installed the ecoroof trays. Additional thanks to Dr. James Mickley from the College of Agricultural Sciences at OSU for plant identification support.

Appendix

<u>ImageJ instructions</u>

In ImageJ, a cropped photo specifying the edge of the tray is opened. The length of the entire image is measured using the straight line tool to measure its known distance. To label the known distance of the image, go to **> Analyze > Set scale** and set the known distance as 78.74 (considering 4ft length), with inches for the unit of length. The lasso and paintbrush tools are used to remove any large segments of non-plant material. **> Image > Adjust > Color Threshold** estimates the plant coverage to the pixel count based on the hue, saturation, and brightness of the image. Then **> Process > Binary > Make Binary** converts the color threshold selection into a binary image. Cleanup of the image is accomplished by using the **> Process > Noise > Despeckle/ Remove Outlier** to remove outliers. Lastly, binary data is measured by **> Analyze > Measure** for the final coverage result.

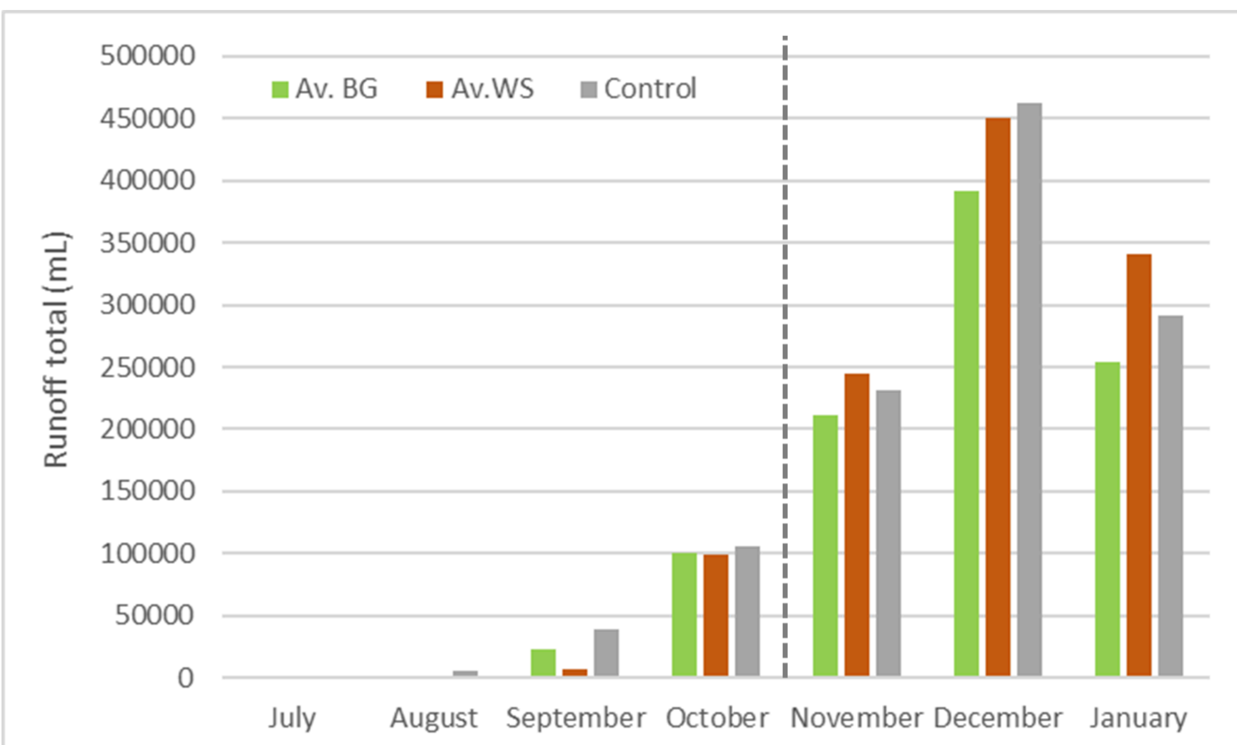


Figure 9. Average precipitation per month between White Stonecrop (WS) and buffalograss (BG) trays. Data prior to November omits trays with sensor issues. Watering events were subtracted from the total precipitation prior to averaging results.

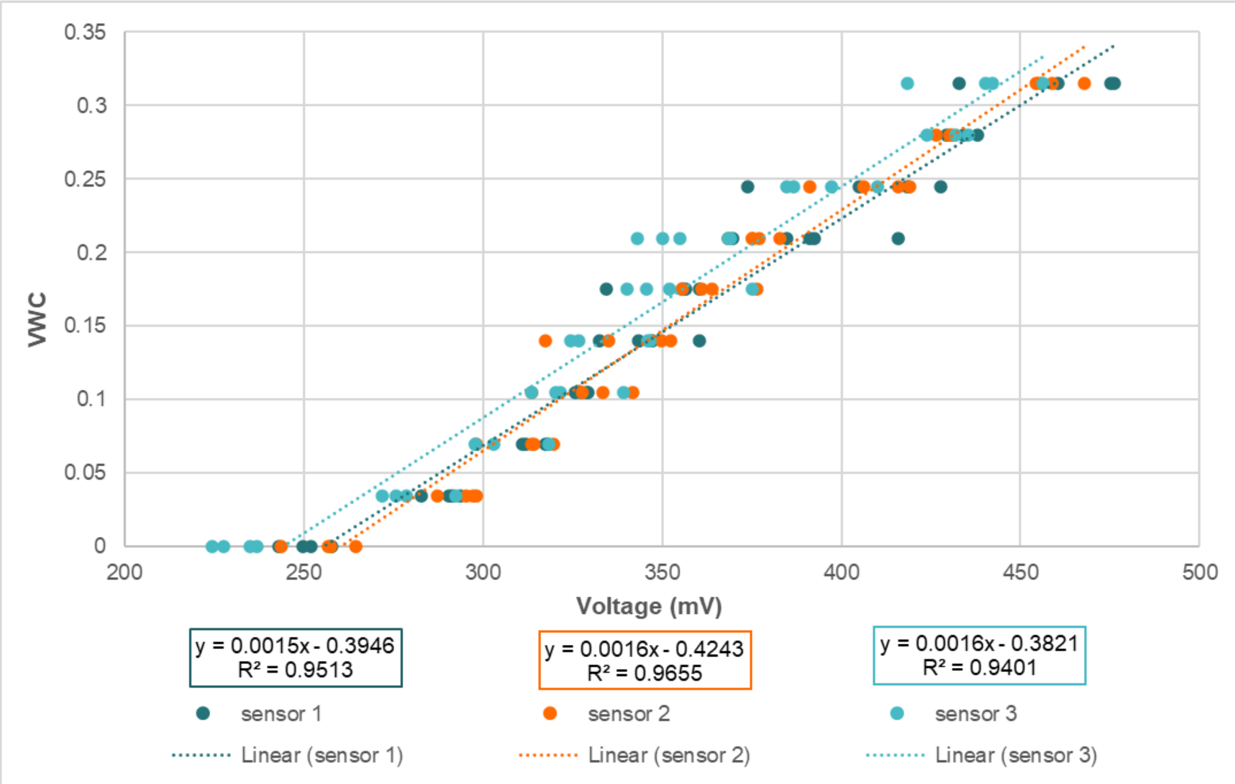
Figure 10. Photos of two moss species that dominated trays during the winter.

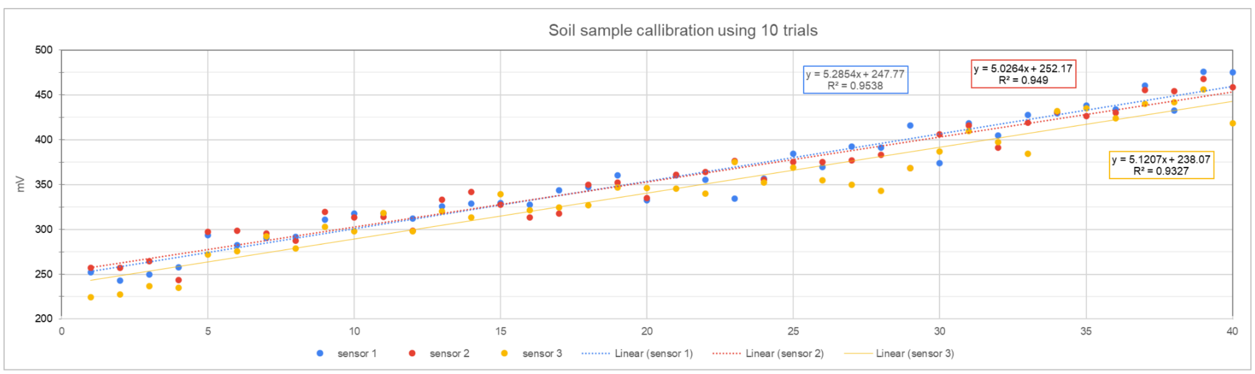
Table 5. The total count of all species identified within all trays including the control tray.

Scientific Name	Common Name	Total Count	Season With Highest Count	Root Type (Simplified)
Prunella/ Epilobium ciliatum	Heal-all/ fringed willowherb	56	Fall	Fibrous
Gamochaeta ustulata	Pacific cudweed	10	Fall	Fibrous
Sonchus oleraceus	Common sowthistle	38	Fall	Taproot
Hypochoeris radicata	Common catsear	6	Fall	Fibrous
Stellaria media	Chickweed	74	Fall	Fibrous
Vicia	Vetches	20	Fall	Taproot
Poaceae	Grass	21	Spring	Fibrous
Taraxacum officinale	Dandelion	4	Fall	Taproot
Geranium robertianum	Herb robert	32	Fall	Fibrous
Lotus corniculatus	Bird's foot trefoil	6	Fall/ Spring	Taproot
Cardamine hirsuta	Hairy bittercress	24	Fall	Taproot
Veronica filiformis	Heath speedwell	2	Fall/ Spring	Fibrous
Lythrum salicaria	Purple loosestrife	2	Fall	Taproot
Trifolium repens L.	Clover	1	Fall	Stolons
Unidentified	Tree sapling	1	Spring	Fibrous

__Soil sensor calibration__

Instructions are replicated from the ECH20 soil moisture sensor calibration manual (Cobos & Chambers, n.d.). With gloves, four empty 500 mL beakers labeled 1-4 are weighed before 200 mL of oven dried ecoroof growing media is added. The weight of the jar and soil is weighed before the voltage is taken with the EC5 Soil Moisture Sensor. Water is added at 17.5 mL intervals measured in a 40mL graduated cylinder. After each measurement, the weight is taken before the soil is mixed until uniform in respectively labeled beakers. The mixed soil is placed back into the beakers, with the voltage measured before repeating the process. Data are taken in google sheets and LoggerNet. Water is continuously added in 17.5 mL intervals until soil saturation based on visual estimation.





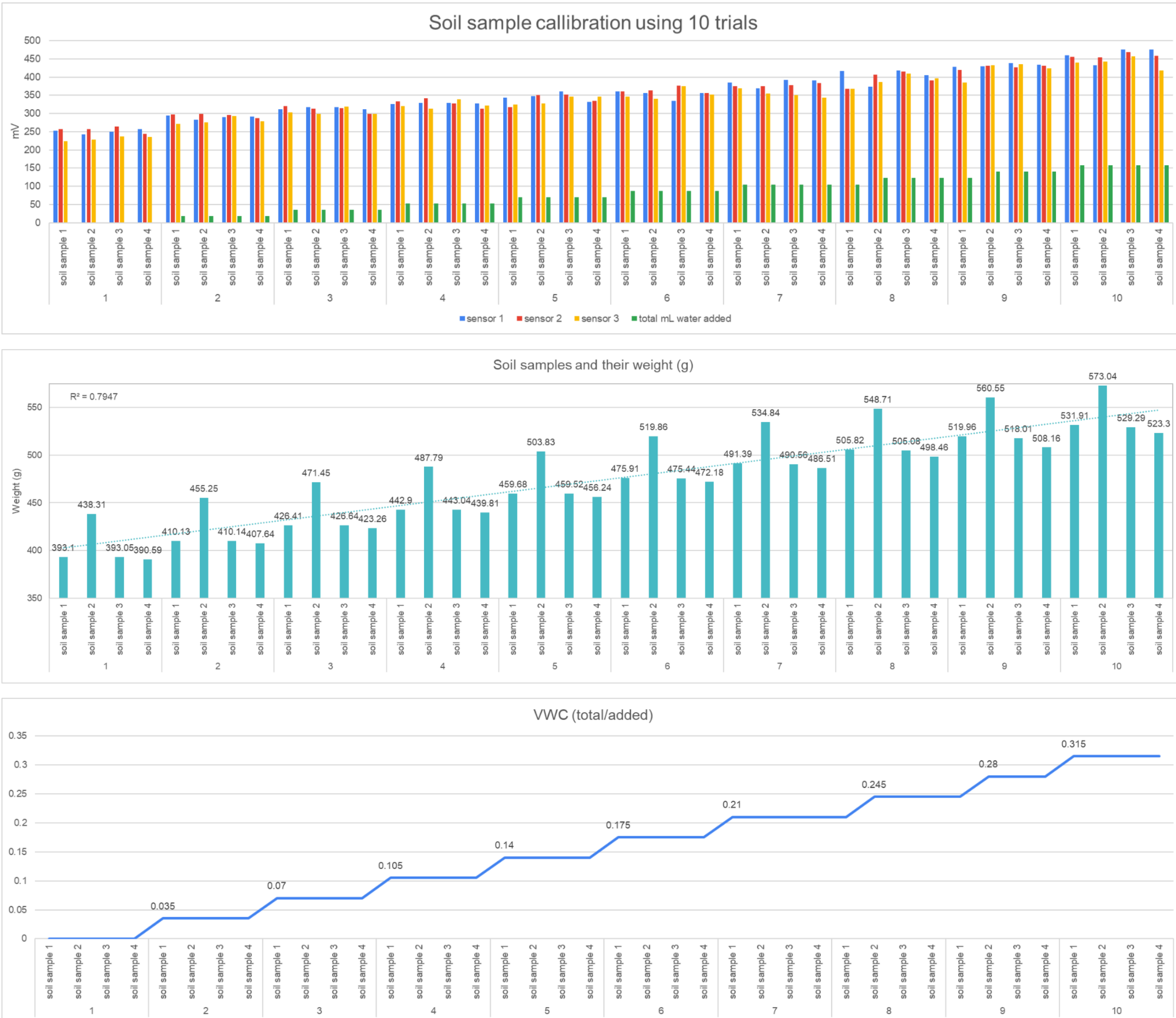


Figure 11. Soil calibration graph comparing voltage (mV) and volumetric water content (vwc). Different chart types were used to compare the relationship in broad and specific ways.

Table 6. ecoroof media analysis by Agricultural Analytical Services Laboratory from The Pennsylvania State University. The German Landscape Research, Development and Construction Society (FLL) standards are included to compare results to ideal standards within the ecoroof industry. All results are within the range of these standards. Results were sampled on 1/11/2021 and completed on 1/25/2021 and are simplified to include important measurements.

Analysis	Units	Result	FLL standard
pH		6.8	6.0-8.5
Soluble salts (water, 1:10, m:v)	g (KCl)/L	0.69	<3.5g (KCl)/L
Organic matter content	Mass %	8.1	<40 g/L

Nitrate + Ammonium ($CaCl_2$)	mg/L	33.4	<80 mg/L
Magnesium, Mg ($CaCl_2$)	mg/L	104.5	<200 mg/L
Phosphorus, P_20_5 (CAL)	mg/L	132.0	<200 mg/L
Potassium K_2O (CAL)	mg/L	415.5	<700 mg/L

Biomass measurements

Table 7. Biomass measurements of white stonecrop (SEDALBX) and buffalograss (BOUDACX) before the start of the experiment. Weight samples are taken after the plant is cleared of the leftover growing media. Samples are then dried for 24 hours at 105 C and weighed.

	wet weight total (g)	wet weight roots (g)	wet weight shoots (g)	dry weight total (g)	dry weight roots (g)	dry weight shoots (g)
SEDALB1	10.07	4.07	5.71	0.87	0.47	0.39
SEDALB2	10.98	5.12	5.33	0.9	0.54	0.36
BOUDAC1	3.35	2.1	0.88	0.49	0.21	0.28
BOUDAC2	3.12	2.25	0.68	0.49	0.28	0.2
BOUDAC3	3.9	2.82	0.81	0.62	0.39	0.23

Table 8. Biomass measurements of white stonecrop (WS) and buffalograss (BG).

Season	Tray type	Average wet weight (g)	Average dry weight (g)
Summer	BG	4.00	0.82
	WS	15.91	1.25
Fall	BG	3.71	1.18
	WS	13.97	1.97
Winter	BG	14.62	0.86
	WS	20.27	1.49
Spring	BG	6.68	2.07
	WS	30.85	3.34

References

Anderson, M., Lambrinos, J., & Schroll, E. (2010). The potential value of mosses for stormwater management in urban environments. Urban Ecosystems, 13(3), 319–332. https://doi.org/10.1007/s11252-010-0121-z

Bans, A. (2020). A Seasonal Study of Ecoroof Metal and Nutrient Dynamics and Associated Drivers in an Ecoroof on a Commercial Building in North Portland Oregon. *Dissertations and Theses*. https://doi.org/10.15760/etd.7449

Bergahge, R. (2007). *Quantifying evaporation and transpirational water losses from greenroofs and greenroof media capacity for neutralizing acid rai*.

Breen, P. (2023). *USDA Hardiness Zone Maps of the United States | Landscape Plants | Oregon State University*. https://landscapeplants.oregonstate.edu/usda-hardiness-zone-maps-united-states

Bureau of Environmental Services. (2013). *Greening the Rooftops and Growing the Local Economy | City Green Blog | The City of Portland, Oregon*. https://www.portlandoregon.gov/bes/article/445573

Cao, J., Hu, S., Dong, Q., Liu, L., & Wang, Z. (2019). Green Roof Cooling Contributed by Plant Species with Different Photosynthetic Strategies. *Energy and Buildings*, *195*. https://doi.org/10.1016/j.enbuild.2019.04.046

City of Portland. (2021). *Appeals | Portland.gov*. https://www.portlandoregon.gov/bds/appeals/index.cfm?action=entry&appeal_id=24932

City of Portland. (2023a, August 25). *About Our Sewer and Stormwater System | Portland.gov*. https://www.portland.gov/bes/resource-recovery/about-sewer-stormwater

City of Portland. (2023b, December 5). *About the Big Pipe Project | Portland.gov*. https://www.portland.gov/bes/about-big-pipe

City of Portland. (2024). *Stormwater strategies | Portland.gov*. https://www.portland.gov/bps/climate-action/scg/scg-dashboard/stormwater-strategies

Climate Check. (n.d.). *Portland, Oregon Climate Change Risks and Hazards: Precipitation, Heat*. Retrieved May 20, 2024, from https://climatecheck.com/oregon/portland

City of Portland, & Bureau of Environmental Services. (2020). *2020 Stormwater Management Manual*.

Cobos, D. D., & Chambers, C. (n.d.). *Calibrating ECH2O Soil Moisture Sensors Application Note*.

De Buyck, P.-J., Matviichuk, O., Dumoulin, A., Rousseau, D. P. L., & Van Hulle, S. W. H. (2021). Roof runoff contamination: Establishing material-pollutant relationships and material benchmarking based on laboratory leaching tests. *Chemosphere*, *283*, 131112. https://doi.org/10.1016/j.chemosphere.2021.131112

Dunnett, N., Nagase, A., Booth, R., & Grime, P. (2008). Influence of vegetation composition on runoff in two simulated green roof experiments. *Urban Ecosystems*, *11*(4), 385. https://link.springer.com/article/10.1007/s11252-008-0064-9

Editors, B. D. (2017, September 8). C3, C4 and CAM Plants—Comparison Chart. *Biology Dictionary*. https://biologydictionary.net/c3-c4-cam-plants/

FLL. (2004). *Guideline for the planning, execution and upkeep of green-roof sites* (1st ed). Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau e.V.

Galliot, L. (2012, April 24). There's No One-Size-Fits-All Green Roof, Studies Show. *State of the Planet*. https://news.climate.columbia.edu/2012/04/24/theres-no-one-size-fits-all-green-roof-studies-show/

Hartzell, S., Bartlett, M. S., & Porporato, A. (2018). *Unified representation of the C3, C4, and CAM photosynthetic pathways with the Photo3 model*.

iNaturalist. (2023a). *Buffalograss (Bouteloua dactyloides)*. iNaturalist. https://www.inaturalist.org/taxa/288038-Bouteloua-dactyloides

iNaturalist. (2023b). *White Stonecrop (Sedum album)*. iNaturalist. https://www.inaturalist.org/taxa/79025-Sedum-album

Johnson, A. J., Davidson, C. I., Cibelli, E., & Wojcik, A. (2023). Estimating leaf area index and coverage of dominant vegetation on an extensive green roof in Syracuse, NY. *Nature-Based Solutions*, *3*, 100068. https://doi.org/10.1016/j.nbsj.2023.100068

King County. (2018). *King County Noxious Weed Alert*. https://your.kingcounty.gov/dnrp/library/water-and-land/weeds/Brochures/Herb_Robert_Factsheet.pdf

Kluge, M., & Ting, I. P. (1978). *Crassulacean Acid Metabolism* (Vol. 30). Springer. https://doi.org/10.1007/978-3-642-67038-1

Lady Bird Johnson Wild Flower Center. (2023). *Bouteloua dactyloides (Buffalograss) | Native Plants of North America*. https://www.wildflower.org/plants/result.php?id_plant=BODA2

Matsuoka, T., Tsuchiya, K., Yamada, S., Lundholm, J., & Okuro, T. (2019). Value of *Sedum* species as companion plants for nectar-producing plants depends on leaf characteristics of the *Sedum*. *Urban Forestry & Urban Greening*, *39*, 35–44. https://doi.org/10.1016/j.ufug.2019.02.003

McIntyre, J. K., Winters, N., Rozmyn, L., Haskins, T., & Stark, J. D. (2019). Metals leaching from common residential and commercial roofing materials across four years of weathering and implications for environmental loading. *Environmental Pollution*, *255*, 113262. https://doi.org/10.1016/j.envpol.2019.113262

Miceli, G. D., Iacuzzi, N., Licata, M., Bella, S. L., Tuttolomondo, T., & Aprile, S. (2022). Growth and development of succulent mixtures for extensive green roofs in a Mediterranean climate. *PLOS ONE*, *17*(6), e0269446. https://doi.org/10.1371/journal.pone.0269446

Micheletty, M. (2023, December 18). *Portland's Vulnerability to Flooding: Mitigation and Restoration Strategies*. Alpha Environmental Services | Portland, OR. https://alphaenvironmental.net/blog/portland-vulnerability-to-flooding-mitigation-and-restoration-strategies/

Missouri Botanical Garden (MBG)). (n.d.). *Sedum album—Plant Finder*. Sedum Album. Retrieved March 23, 2023, from https://www.missouribotanicalgarden.org/PlantFinder/PlantFinderDetails.aspx?taxonid=279379

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

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

National Oceanic and Atmospheric Administration, & National Integrated Drought Information System. (n.d.). *Oregon | Drought.gov*. Drought.Gov. Retrieved February 19, 2024, from https://www.drought.gov/states/oregon

Nowak, D. J., & Greenfield, E. J. (2020). The increase of impervious cover and decrease of tree cover within urban areas globally (2012–2017). *Urban Forestry & Urban Greening*, *49*, 126638. https://doi.org/10.1016/j.ufug.2020.126638

Perennial Obsessions. (2020). *Sedum album (Oregon Source)*. Perennial Obsessions. https://perennialobsessions.com/categories/ols/products/sedum-album-oregon-source

Okita, J., Poor, C., Kleiss, J., & Eckmann, T. (2018). Effect of Green Roof Age on Runoff Water Quality in Portland, Oregon. *Journal of Green Building*, *13*, 42–54. https://doi.org/10.3992/1943-4618.13.2.42

OregonFlora Home. (n.d.). Retrieved June 3, 2024, from https://oregonflora.org/

Oregon State University (OSU). (2018, June 1). *Bittercress*. https://horticulture.oregonstate.edu/weed/bittercress

Pallathadka, A., Sauer, J., Chang, H., & Grimm, N. B. (2022). Urban flood risk and green infrastructure: Who is exposed to risk and who benefits from investment? A case study of three U.S. Cities. *Landscape and Urban Planning*, *223*, 104417. https://doi.org/10.1016/j.landurbplan.2022.104417

Portland Nursery. (n.d.). *Sedum: Stonecrop | Portland Nursery*. Retrieved March 22, 2023, from https://www.portlandnursery.com/natives/sedum

Raghavendra, A. S. (2003). PHOTOSYNTHESIS AND PARTITIONING | C3 Plants. In B. Thomas (Ed.), *Encyclopedia of Applied Plant Sciences* (pp. 673–680). Elsevier. https://doi.org/10.1016/B0-12-227050-9/00094-6

Schrieke, D., Szota, C., Williams, N. S. G., & Farrell, C. (2023). Evaluating the effectiveness of spontaneous vegetation for stormwater mitigation on green roofs. *Science of The Total Environment*, *898*, 165643. https://doi.org/10.1016/j.scitotenv.2023.165643

Schroll, E., Lambrinos, J. G., & Sandrock, D. (2011a). An Evaluation of Plant Selections and Irrigation Requirements for Extensive Green Roofs in the Pacific Northwestern United States. *HortTechnology*, *21*(3), 314–322. https://doi.org/10.21273/HORTTECH.21.3.314

Schroll, E., Lambrinos, J. G., Righetti, T., & Sandrock, D. (2011b). The role of vegetation in regulating stormwater runoff from green roofs in a winter rainfall climate. *Ecological Engineering*, *37*(4), 595–600. https://doi.org/10.1016/j.ecoleng.2010.12.020

Schultz, I., Sailor, D. J., & Starry, O. (2018). Effects of substrate depth and precipitation characteristics on stormwater retention by two green roofs in Portland OR. *Journal of Hydrology: Regional Studies*, *18*, 110–118. https://doi.org/10.1016/j.ejrh.2018.06.008

Sherk, J. T., Fu, W., & Neal, J. C. (2020). Site Conditions, Maintenance Costs, and Plant Performance of 10 Extensive Green Roofs in the Research Triangle Area of Central North Carolina. *HortTechnology*, *30*(6), 761–769. https://doi.org/10.21273/HORTTECH04565-20

Shroll, E. (2009). *Plant selection, irrigation requirements and stormwater management of Pacific Northwest extensive green roofs*. Oregon State University.

Sivaram, A. K., Logeshwaran, P., Subashchandrabose, S. R., Lockington, R., Naidu, R., & Megharaj, M. (2018). Comparison of plants with C3 and C4 carbon fixation pathways for remediation of polycyclic aromatic hydrocarbon contaminated soils. *Scientific Reports*, *8*(1), Article 1. https://doi.org/10.1038/s41598-018-20317-0

Slothower, C. (2021, June 10). *Eco-roofs growing into urban role in Portland | Daily Journal of Commerce*. https://djcoregon.com/news/2021/06/10/eco-roofs-growing-urban-role-portland/

Snodgrass, E. C., & Snodgrass, L. L. (2006). *Green Roof Plants: A Resource and Planting Guide*. Timber Press.

Spolek, G. (2008). Performance monitoring of three ecoroofs in Portland, Oregon. *Urban Ecosystems*, *11*(4), 349–359. https://doi.org/10.1007/s11252-008-0061-z

Starry, O. (2013). *The comparative effects of three Sedum species on green roof stormwater retention*. http://hdl.handle.net/1903/14622

Starry, O., Lea-Cox, J. D., Kim, J., & van Iersel, M. W. (2014). Photosynthesis and water use by two Sedum species in green roof substrate. *Environmental and Experimental Botany*, *107*, 105–112. https://doi.org/10.1016/j.envexpbot.2014.05.014

Stovin, V., Poë, S., De-Ville, S., & Berretta, C. (2015). The influence of substrate and vegetation configuration on green roof hydrological performance. *Ecological Engineering*, *85*, 159–172. https://doi.org/10.1016/j.ecoleng.2015.09.076

Sutton, R. (2017). *Seeding Green Roofs for Greater Biodiversity and Lower Costs | 2017 ASLA Professional Awards*. American Society of Landscape Architects. https://www.asla.org/2017awards/298372.html

Tesemma, Z. K., Wei, Y., Peel, M. C., & Western, A. W. (2015). The effect of year-to-year variability of leaf area index on Variable Infiltration Capacity model performance and simulation of runoff. *Advances in Water Resources*, *83*, 310–322. https://doi.org/10.1016/j.advwatres.2015.07.002

The Bureau of Land Management. (2024). *Weeds and Invasives | Bureau of Land Management*. https://www.blm.gov/programs/weeds-and-invasives

United States Department of Agriculture. (n.d.). *USDA Plants Database*. Retrieved June 11, 2023, from https://plants.usda.gov/home/plantProfile?symbol=SEAL

United States Department of Agriculture. (2023). *USDA Plants Database*. Bouteloua Dactyloides (Nutt.) J.T. Columbus. https://plants.usda.gov/home/plantProfile?symbol=BODA2

Vanstockem, J., Somers, B., & Hermy, M. (2019). Weeds and gaps on extensive green roofs: Ecological insights and recommendations for design and maintenance. *Urban Forestry & Urban Greening*, *46*, 126484. https://doi.org/10.1016/j.ufug.2019.126484

Zaid, S., Zaid, L. M., Esfandiari, M., & Abu Hasan, Z. F. (2022). Green roof maintenance for non-residential buildings in tropical climate: Case study of Kuala Lumpur. *Environment, Development and Sustainability*, *24*(2), 2471–2496. https://doi.org/10.1007/s10668-021-01542-6

Zhang, H., Fan, X., Ren, L., Jiang, Y., Wu, J., & Zhao, H. (2021). Crassulacean plant succession over eight years on an unirrigated green roof in Beijing. *Urban Forestry & Urban Greening*, *63*, 127189. https://doi.org/10.1016/j.ufug.2021.127189

Zhou, L. W., Wang, Qi., Li, Y., Liu, M., & Wang, R. Z. (2018). Green roof simulation with a seasonally variable leaf area index. *Energy and Buildings*, *174*, 156–167. https://doi.org/10.1016/j.enbuild.2018.06.020