ROOTS THAT DIG DEEPER: WATER INFILTRATION IN LAWN ALTERNATIVES

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ABSTRACT

Ecosystem services, such as the regulation of the water cycle, are vital benefits provided by plants. Plants play a critical role in the water cycle as they influence water infiltration, contribute to groundwater replenishment, and reduce both stormwater runoff and soil erosion. However, the literature varies on the importance of plant versus soil factors in water infiltration. Urban and residential land has increased water runoff attributed to a reduction of diverse vegetation and an increase of impervious surfaces. Climate change will increase the likelihood of heavy downpours and flooding due to greater rainfall intensity and duration that will increase erosion in places lacking vegetation, such as urban and residential environments. The most common green spaces found in urban and residential areas are non-native turfgrass lawns, with root lengths averaging one to two inches. Lawn alternatives are low-growing plant species that offer a sustainable solution to turfgrass.

My study investigates the impact of lawn alternative plantings on water infiltration, runoff, and soil erosion through two experiments: a common garden field experiment and a greenhouse experiment. The field experiment, conducted at the Chicago Botanic Garden from summer 2023 to fall 2024, evaluated the effects of plant community treatment, installation method (pre-existing, seed, plug), season, and time since installation on infiltration. The greenhouse study, conducted at the University of Michigan–Flint, tested the influence of living plants versus 3D-printed artificial roots on infiltration, runoff, and erosion under controlled conditions. Results from the field experiment showed that installation method ($p = 0.0026$*), season ($p = <<<0.001$***), and their interaction ($p = 0.0027$*) had a significant impact on infiltration rate (ANOVA). Water infiltration increased over time in plug-installed treatments. The greenhouse experiment revealed that treatments with living plants had a trend of higher infiltration to runoff ratio when compared to the 3D printed artificial root treatments. These findings are increasingly relevant because of climate change and the growth of urban areas, as shifting rainfall patterns could exacerbate soil erosion and water runoff, making the use of lawn alternatives more crucial for environmental sustainability. My results provide valuable insights for implementing effective lawn alternatives that promote better water infiltration and reduce soil erosion and runoff, which are important for mitigating the impacts of climate change.

INTRODUCTION

Plants play a vital role in shaping ecosystems by providing habitat, supporting the food chain, performing photosynthesis, cycling nutrients, and regulating climate (Fisher and Turner, 2008; Costanza et al., 1997; Fernando, 2012). These essential ecosystem functions yield numerous benefits to humans, called ecosystem services (Costanza et al., 1997). Among the most critical of these services is the regulation of the water cycle, where plants influence water infiltration, contribute to groundwater replenishment, and reduce both stormwater runoff (precipitation flowing over land surface rather than absorbing into the soil) and soil erosion (Miedema Brown and Madhur, 2022). The literature varies on the importance of plant versus soil factors in water infiltration, with some studies attributing water infiltration rates to differences in soil structure (Sjöman & Gill, 2014; Peralta 2024), while others focusing on the role of plants (Zuazo & Pleguezuelo, 2008, Bochet et al., 1998), and some suggesting that both factors work together to enhance infiltration (Wood et al., 1987). However, a gap remains in understanding the complex relationship between soil and plants in regulating water infiltration. Here, I focus on the impact of plants, specifically the effect that plant matter above and below grounds has on water infiltration.

Infiltration

Infiltration is the flow of water from aboveground into the soil (Ferre and Warwick, 2005). Infiltration is extremely important as it plays many roles throughout the ecosystem, it replenishes groundwater, protects waterways, and filters and retains excess nutrients (Patterson and Haught, 2021). It is assumed that soil structure and compaction play the most important roles in water infiltration (Sjöman & Gill, 2014; Peralta 2024). For example, soils with a sandy texture have higher soil porosity than clay soils, allowing water to infiltrate at a faster rate (Basset et al.,

2023). In contrast, soil compaction limits water infiltration by decreasing soil porosity and creating a hard crust on the surface of the soil (Woltemade, 2010).

Plants impact water infiltration via above and belowground growth (Gyssels and Poesen, 2005). Aboveground, plant ground cover protects soil against erosion by reducing water runoff and increasing water infiltration (Rey 2003; Duran et al. 2008). The force of water hitting the soil directly causes the movement of topsoil at a high rate (Bochet et al., 1998). When there is a canopy of plant matter present, it physically protects the soil. The rainwater interacts with the above ground plant matter, which absorbs the force of the precipitation that would normally have been directly hitting the soil (Zuazo and Pleguezuelo, 2008). When vegetation is present and covering the soil, the force of rainwater is typically not an issue (Osterkamp and Friedman, 2000; Nunes et al., 2005).

Belowground, plant roots improve infiltration by creating channels in the soil to guide water downward (Ferre and Warwick, 2005). Roots are not only conduits for water to travel down, but they increase adhesion between soil particles, soil infiltration capacity, and soil absorbance, which will decrease soil erosion and runoff (Burak et al., 2021; Zuazo and Pleguezuelo, 2008). Infiltration and erosion rates change depending on what root type they have (fibrous, taproot, and shallow propagative) (de Baets et al., 2007; Reubens et al., 2007). For example, there is a decline of erosion as root length and root density increases (Mamo and Bubenzer, 2001; Gyssels et al., 2005; de Baets et al., 2007). Finally, roots absorb water through osmosis, with those having more root hairs offering a greater surface area and enhancing their ability to absorb water (Burak et al., 2021; Chapman et al., 2012). Plant and soil interactions decrease soil erosion (Singer et al., 1980).

Soil Erosion

More than 75 billion tons of soil are lost globally per year due to soil erosion, making it the most widespread form of land degradation (Zuazo and Rodríguez, 2008). Soil is being lost ten to twenty times faster than it can be naturally replaced (Atlavinyte, 1964). Soil erosion is caused by "rainfall energy," or the force of water breaking the adhesive bonds between soil particles (Laflen et al., 1991). Erosion can be prevented by plants, via aboveground and belowground structures, with roots aiding in infiltration and plant cover protecting the soil from precipitation (Gyssels and Poesen, 2005; Burak et al., 2021; Zuazo and Pleguezuelo, 2008; Osterkamp and Friedman, 2000; Nunes et al., 2005). Without the correct structure in place, erosion will cause irreversible soil loss, leading to reduction in plant biomass production, environmental productivity, ability of soil infiltration, and water cycle disruption (Zuazo and Pleguezuelo 2008).

Climate change will increase the likelihood of heavy downpours and flooding due to greater rainfall intensity and duration that will increase erosion in places lacking vegetation, such as urban and residential environments (Nearing et al. 2005; Nunes et al.2005). For example, within the Midwest, the volume of precipitation in the category of very heavy precipitation (characterized as the most extreme one percent of all daily occurrences) witnessed a 42% increase in the past 60 years (GLISA, 2016). Extreme rainfall events are projected to increase due to the warming atmospheres capacity to hold more water, resulting in a vigorous water cycle, not only increasing soil erosion but stormwater runoff (Morgan and Nearing, 2010).

Stormwater Runoff

Urban and residential land has increased water runoff attributed to a reduction of diverse vegetation (O'Driscoll et al., 2010). Development has resulted in natural landscape replacement with impermeable surfaces (EPA, 2024). When man-made surfaces increase, water infiltration decreases, and stormwater runoff is directed toward nearby bodies of water (Selbig and Balster, 2010). When heavy rainfall occurs in urban and residential areas, it can cause significant problems for residents and the ecosystem including elevated concentrations of nutrients and pollution in nearby waterways, decreased groundwater recharge, damage to infrastructures, and reduced biodiversity (Selbig and Balster, 2010). In urban and residential areas, concrete tunnels, bioswales, and reservoirs are commonly used to redirect stormwater runoff, but this infrastructure slows the recharge of groundwater. (EPA, 2024; Morash et al., 2019).

Instead of redirecting stormwater runoff, natural flood management (NFM) through green infrastructure is focused on increasing infiltration through natural practices (Gunnell et al., 2019). Natural Flood Management practices, such as installation of retention or detention ponds, planting street trees, and rain gardens hold and slowly release water back into the ecosystem, which decreases runoff and soil erosion (Gunnell et al., 2019; EPA, 2024). Retention and detention ponds are the most common implementations of NFM in the United States (Hosseinzadeh et al., 2023). Although retention and detention ponds are the most common NFMs, they require a large land area to install, which may not be feasible in some urban areas. Rain gardens are rising in popularity throughout the United States in both residential and urban areas. Rain gardens contain native, deep rooted, drought and flood resistant plants that capture and filter stormwater runoff (Sharma and Piyush, 2021). Finally, street trees can increase

infiltration by connecting water flow underground, enhance soil porosity with their roots, and reduce the compaction of soil with their aboveground plant cover (Revell et. al, 2022). These natural flood management practices improve water infiltration in urban and residential environments, but do not address the largest vegetated areas in urban and residential environments, lawns.

Lawns

The most common green spaces found in urban and residential areas are turfgrass lawns (Paudel and States, 2023). Approximately 62 million acres of the United States is covered in non-native turfgrass (Chawla et al., 2018). As the United States developed, turfgrass became the gold standard due to the rising popularity of the "clean, green carpet" aesthetic in the 1800s (Urmy, 2019). Due to this popularity, lawns have become the largest irrigated crop in the United States (Milesi et al., 2012). Although turf grass can perform some ecosystem services such as carbon sequestration and mitigation of soil erosion, the use of lawn chemicals, fertilization, and maintenance norms including frequent irrigation and mowing, can cause more harm than good (Robbins and Sharp, 2003; Robbins et al., 2001; Mayer et al., 1999).

The most common turfgrass species in the midwestern United States is Kentucky Bluegrass (*Poa pratensis*), which has shallow root systems averaging one to two inches (Chawla, 2018). In contrast, many native plant species in our region have long root systems, many over 10 feet, increasing water infiltration and groundwater restoration when compared to turfgrass (Selbig and Balster, 2012).

Lawn alternatives are low-growing plant species that can be the "happy medium" between full scale restorations and turf grasses. Not all current turfgrass lawns are feasible sites

for full-scale habitat restoration, as it could decrease visibility, increase unwanted wildlife, and may not be as aesthetically pleasing in all seasons (Fekete et al., 2024). Turfgrass could be replaced with lawn alternatives and the area could be used to support native plant communities and provide ecosystem services such as carbon and nitrogen sequestration, increased water infiltration, and pollinator support. Implementing lawn alternatives could also decrease maintenance efforts such as use of fertilizers, pesticides, lawn mowers, and irrigation.

My study aims to determine if plants influence water infiltration, runoff, and soil erosion with a focus on lawn alternative plant species. My study was split into two experiments, a common garden field experiment testing if lawn alternative plant community treatment, plant installation method, seasonality, or time since plant installation, significantly affected water infiltration and a greenhouse experiment controlling for installation method, season, and time since installation to test if plants significantly affected water infiltration, runoff, and soil erosion. My field experiment was completed at the Rethinking Lawns Experimental Research plots at the Chicago Botanic Garden in Glencoe, Illinois, where I collected water infiltration data four times in three seasons across two years (summer 2023, fall 2023, spring 2024, and fall 2024). There were eight experimental lawn alternative treatments installed in three ways: pre-existing, seeds, and plugs. I hypothesized 1) lawn alternative treatments 2) installation method 3) season and time since plant installation would all significantly impact water infiltration. Specifically, that lawn alternative treatments will have greater infiltration than non-native turfgrass, treatments that were plugged would have greater infiltration than other installation methods, the summer season would have the greatest infiltration rate, and the plants installed first would have greater infiltration than the plants installed later.

My ex-situ experiment was conducted in a temperature-controlled greenhouse at the University of Michigan-Flint, Flint, Michigan over one growing season (July-October 2024). I measured water infiltration, runoff, and soil erosion of six living plant treatments and three 3D printed artificial root treatments. 3D printed artificial root treatments were created to determine if living plants were aiding in water infiltration or if roots were only creating channels in the soil for water to travel down. I hypothesized that 1) Treatments with living plants will have significantly greater water infiltration, and less runoff and soil erosion than the 3D printed artificial root treatments. 2) Treatments with greater plant cover will have significantly greater water infiltration and less runoff and soil erosion than treatments with less plant cover. 3) Treatments with plant species that have longer roots will have significantly greater water infiltration and less runoff and soil erosion than treatments with shorter roots.

METHODS:

Field experiment:

Site description

I conducted this study in the Rethinking Lawns Research Plots at the Chicago Botanic Garden (GBG), Glencoe, Illinois. This experimental research garden area was established in 2022 in collaboration with the Chicago Botanic Garden, the Chicago Park District, and the University of Michigan-Flint. Experimental lawn alternative treatments were selected based on their low-growing characteristics as well as their popularity in public use as lawn alternatives (Barak, et al., 2022b).

My eight treatments included the following: turfgrass (negative control), white Dutch clover-turfgrass mix, fescue mix, white Dutch clover monoculture, sedge lawn, mini meadow-low

diversity, mini meadow-high diversity, and prairie (positive control-Figure 1A, Table 1A). The research plots were planted in three replicate blocks, each block contained one plot per treatment, split into three subplots, for a total of nine replicates per treatment (Figure 1F).

Lawn alternative treatments

The fescue mix and white Dutch clover monoculture treatments were installed by seed. The fescue mix treatment is a mix of four cultivars within two species of fine fescues (Figure 1B). The sedge lawn was installed by plug and includes three species (Figure 1C). The mini meadow-low and high diversity treatments include both low-growing sedge and forb species (Figure 1D). The mini meadow-low diversity treatment includes 9 species (2 sedge species and 7 species of forbs), while the mini meadow-high diversity includes 18 species (3 species of sedge and 15 forb species). The mini meadow plots were designed to look like low growing prairies, with the goal of providing ecosystem services similar to the native tallgrass prairie. The two levels of diversity within the mini meadow treatments were chosen to see the impact of ecosystem services as diversity increases. Both mini meadow treatments contain species native to the midwestern United States and were installed by plugs. The prairie treatment acts as the positive control and includes 18 tall grass prairie plants native to the midwestern United States (Figure 1E). The prairie treatment was installed by plugs.

The experimental lawn alternative treatments were installed depending on how quickly and reliably their germination and establishment occurred (Table 1B). The turfgrass used for the negative control and the white Dutch clover-turfgrass mix treatment has been established for over ten years (R. Barak, *personal communication*). The white Dutch clover-turfgrass mix was created by overseeding white Dutch clover seeds into pre-existing turfgrass. The seeded

treatments plant species mature and establish more quickly than those installed with plugs (Smith et al., 2010; Bush, 2005; Barak et al., 2022a). Specifically, the fescue mix and white Dutch clover monoculture germinate and establish rapidly, while treatments such as the sedge lawn, mini meadow-low diversity, mini meadow-high diversity, and prairie take three to five years to establish from seed, often with low survival rates (Barak et al., 2022a; Smith et al., 2010). Since establishment and germination is relatively low in these native prairie plants, they were installed by plug (Barak et al., 2022a). While planting native prairie species using plugs tends to be more successful, it is significantly more expensive—especially when aiming for a dense, lawn-like appearance (Barak et al., 2022a). Plug prices typically range from $2 to $11 per plant, whereas seeds are much more cost-effective for covering large areas (U.S. EPA, n.d.). For example, restoring a half-acre yard with native plants can cost around $750 using seed, compared to $21,780 when using plugs (Phillips-Mao, 2017).

Water infiltration tests

I measured water infiltration in the Rethinking Lawns Research Plots in June 2023, September 2023, April 2024, and September 2024 using a Turf-Tec Infiltrometer (Figure 1H & 1I). Infiltrometers are used to determine water infiltration rate through the downward flow from aboveground into the soil (Turf-Tec, 2020). The Turf-Tec infiltrometer is used by the Environmental Protection Agency (EPA) and the Department of Environmental Protection (DEP) in the United States to measure urban runoff for stormwater soil evaluations (Turf-Tec, 2020).

I divided each subplot into a grid with locations numbered one through nine and used a random number generator to assign the location to place the infiltrometer (Figure 1G). Next, I

positioned the infiltrometer into the subplot using the double ringed end to pierce the soil approximately four to five inches into the ground and I saturated twice by filling the infiltrometer's double rings with water until the inner ring was full (Figure 1G). Once all the water had infiltrated into the soil, I repeated the process again to saturate the soil before collecting the water infiltration data (Turf-Tec International, 2020).

After double saturation, I refilled the base of the infiltrometer with water and began recording how quickly water infiltrated into the soil (millimeters infiltrated) every minute for 15 minutes. I additionally recorded the complete infiltration time if water infiltrated before 15-minutes. Due to time constraints, if saturation took longer than 30 minutes, I would refill the infiltrometer and record mm infiltrated for a 15-minute time limit. I collected infiltration data at all 72 subplots per visit.

Soil texture

I collected one soil sample from each treatment plot per block to see if soil texture played a role in water infiltration rates. I collected soil using a bulb planter which reached approximately 4 inches into the ground. To ensure no bias, I used a random number generator with a grid overlay in each treatment plot for the location of the soil sample at each plot. After soil was collected, I performed the United States Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) soil texture jar analysis.

Each soil sample was dried and filtered through a soil sieve, to remove plant matter and rocks. I filled 16oz. mason jars with the filtered soil until they were approximately 1/3 full. I added one tablespoon of dawn dish soap and filled the jar with water until 2/3 full. I covered the jar and shook each one for five minutes to assure that the mixture was uniformly dispersed

throughout the jar and then let them settle for at least 24 hours before data collection. I measured each layer of sediment in the jar using a ruler and used the multipoint soil texture triangle to determine soil texture (USDA, NRCS, n.d.).

Statistical analysis

I performed all statistical analyses using R Version 2022.07 (RStudio Team, 2022). First, I calculated the infiltration rate (mm/hr) for each subplot as the response variable. These data were not normally distributed, so I used a logarithmic transformation. My first maximal linear regression model included infiltration rate as my response variable and plant treatments, installation method, season, and time since plant installation as my predictor variables.

I utilized a Variance Inflation Factor (VIF, car package) test for multicollinearity between predictor variables. Multicollinearity additionally existed between plant treatment and installation methods (VIF > 10), therefore I subset data by installation method for analysis. My final linear regression model was run independently for each installation method and consisted of infiltrate rate as my response variable and season, plant treatment, and time since plant installation as my predictor variables. I used an Analysis of Variance test (ANOVA) and backwards stepwise elimination to eliminate any non-significant predictors. Finally, I performed a Tukey's Post Hoc test to compare treatments after ANOVA indicated significant differences among predictors.

Greenhouse experiment:

Site Description

I conducted this study in the greenhouse at the University of Michigan-Flint, Flint, Michigan from June 2024 to October 2024. The greenhouse was temperature controlled, with open windows, fans, and heaters.

Treatment

The experimental treatments represent three categories: traditional common lawn species, lawn alternative species, and 3D printed artificial roots. Within each category, I divided treatments based on the root structure of the species: taproots, shallow propagative roots, or fibrous roots. The common lawn treatment species were dandelion (*Taraxacum officinale*; taproot), white Dutch clover (*Trifolium repens*; shallow propagative roots), and turfgrass (*Poa pratensis*; fibrous roots), the lawn alternative treatments species were purple prairie clover (*Dalea purpurea;* taproot), pussytoes (*Antennaria plantaginifolia*; shallow propagative roots) , and fescue mix (*Festuca rubra* and *Festuca ovina*; fibrous roots), and the 3D printed artificial roots treatments consisted of models representing taproots, fibrous roots, and shallow propagative roots (Table 2A)**.** I additionally tested monocultures of each common lawn treatment species, lawn alternative treatment species, and 3D printed artificial root treatments models with six replicates for each treatment. A plant community of all three root types was included for each category: common lawn, lawn alternative, and 3D printed artificial roots, but poor establishment did not allow for use in data collection.

3D Printed Artificial Root Design

I designed the 3D printed artificial root treatments based on observations of plant roots (Figure 2A). The species I used to create the 3D printed artificial root models were dandelions (taproot), white Dutch clover (shallow propagative roots), and turfgrass (fibrous roots). I pulled the plants carefully from the soil and measured their root lengths. I designed the 3D printed root models to represent the root lengths typically observed after 6 to 12 weeks of growth. The fibrous and shallow propagative 3D printed artificial root models were made using a 3Doodler Start+ 3D printer pen (Wobble Works Inc.). The length of fibrous and shallow propagative root models varied from 3 to 7 centimeters and with a consistent width of 1 millimeter. The taproot 3D printed artificial root models were made using a Creality Ender 3 and Creality Ender 5+ 3D printer (Shenzhen Creality 3D Technology Co., 2023). The length of the taproot models were 11.5 centimeters and a tapered width ranging from 1 to 4 millimeters. All models were made of polylactic acid (PLA) filament. To ensure no water was being absorbed by the filament, I weighed the 3D printed roots before and after submerging them in water for five minutes.

Experimental design

I used circular tree pots for this study, with a surface area of 200 sq inches and a height of 15 inches to establish treatment replicates in the greenhouse. I positioned the pots at a 5° angle at the base propping wood shims under one side of the pot to create a grade, in accordance with the Department of Energy's guidelines for grading soil away from buildings (USDE, 2021). The pots had seven 3 cm^2 holes at the bottom, which allowed for infiltrated water to flow through the pot and be captured. Finally, I cut a 10 x 9-inch rectangle into the side of the pot and placed a 2–3-foot tarp "slide" into the cut out to capture water runoff and soil erosion (Figure 2B). Standard

greenhouse soil was used in this study. I used a random number generator to determine the position of each treatment pot throughout the greenhouse and each treatment had six replicates, with a total of 54 pots being used for data collection.

Seeding:

The recommended seeding rates for each species within the common lawn and lawn alternative treatments differed. The turfgrass (The Scotts Company) and fescue mix (Prairie Moon Nursery) treatments recommended seeding rate were 3,000 seeds per pot and the white Dutch clover (rhizobia inoculated, Outsidepride Seed Source LLC) had a recommended seeding rate of 600-1200 seeds per pot, while the pussytoes (Prairie Moon Nursery), dandelion (Seed Needs LLC), and purple prairie clover (Prairie Moon Nursery) had a seeding rate of 1 seed per pot. Because of the large variety of seeding rates, I created a standard seeding rate to compare species. The common lawn and lawn alternative treatments were seeded at 200 seeds per pot for a rate of 1 seed per sq inch (Figure 2C). I added two treatments to compare turfgrass and fescue mix at their recommended seeding rate of 3,000 per pot (Figure 2C). I sowed the seeds into the soil and evenly distributed seeds throughout the surface area.

Watering:

All treatments were misted twice a day for the first two weeks after planting to ensure soil moisture availability for the young plants without disrupting the seeds, after this they were watered once every other day. I used a IRTOV soil moisture meter to determine how wet the soil was before and after watering to ensure each treatment received enough water. The soil moisture

meter readings were on a scale of dry>normal>wet>wet+. I watered the treatments until the soil moisture meter indicated a "wet" reading.

Weed interference:

Due to the pre-existing seed bank in the soil, crabgrass grew throughout all treatment pots within the first week and were removed by hand.

Implementation of 3D Printed Artificial Roots:

To ensure each living plant treatment had a direct 1:1 ratio comparison to the 3D printed artificial root treatments, I counted each plant within the common lawn and lawn alternative treatments and inserted the root models in at the exact number. I placed the root models into the soil four days before any data collection took place (Figure 2D).

Establishment of Treatments:

The planted treatments that established were turfgrass, fescue mix, white Dutch clover, dandelion, turfgrass 3k, and fescue mix 3k (Figure 2E & Figure 2F). The pussytoes, purple prairie clover, and the lawn alternative and common lawn plant communities did not establish well enough to utilize for data collection. I only used the dandelion and 3D artificial taproot model treatments in the 12-week trial because of low growth in the dandelion treatments in the first 6 weeks.

Data Collection:

The final treatments I used for data collection were dandelion, white Dutch clover, fescue mix, turfgrass, fescue mix 3k, turfgrass 3k, 3D printed taproots, 3D printed fibrous roots, and 3D printed shallow propagative roots. I collected data at 6 and 12 weeks of establishment. Specifically, I measured the weight of infiltrated water, water runoff, and soil erosion. I placed a bin underneath the treatment tub to catch infiltrated water, and a bucket at the end of the tarp "slide" to catch water runoff and soil erosion (Figure 2G). I watered the treatment tub for 30 seconds to simulate rainfall. I made the rainfall simulation using the shower setting on a hose with a consistent restricted release. Before rainfall simulation was used on the treatments, I conducted 10 trials, measuring 30 seconds of rainfall in each, to ensure a consistent volume of water was being released. I implemented the restricted release so the water pressure would not damage the treatments. I measured water runoff directly after rainfall simulation was complete. I separated the soil erosion from the water runoff using grade 100 cheesecloth and unbleached muslin fabric (Figure 2H). These soil samples were then left to dry before measuring weight. I left the infiltrated water underneath the treatment tubs for 20 minutes, giving the treatments a chance to infiltrate as much water as possible before removing to weigh. The water runoff and infiltrated weight was measured in grams.

Statistical Analysis:

I subset data based on root type, and statistical comparisons were made between the treatments within each root type group. The taproot group included the dandelion and 3D printed artificial taproot treatments. The fibrous root group included turfgrass, fescue mix, and 3D printed artificial fibrous root treatments. The shallow propagative root group included white

Dutch clover, and 3D printed artificial shallow propagative root treatments. The turfgrass 3k and fescue mix 3k treatments were compared to each other. My response variables were water infiltration, runoff, soil erosion, infiltration/runoff ratio, and plant cover. Plant cover was only tested as a response variable in the 3k Treatments because both treatments in the comparison contained living plants. I used t-tests to compare the response variables between turfgrass 3k and fescue mix 3k, an ANOVA to compare the fibrous root groups, a t-test and Mann-Whitney U test to compare the shallow propagative root groups, and a Mann-Whitney U test to compare the taproot groups.

RESULTS

Field experiment:

Installation method (p = 0.0026*), season (p = <<<0.001***), and the relationship between installation method and season (p = 0.0027*) had a significant impact on infiltration rate (ANOVA). Plant treatment (p = 0.78) and time since plant installation (p = 0.10) did not significantly alter infiltration rate when compared across installation methods (ANOVA). I found that plant treatments with the same installation method had similar infiltration rates (Figure 3A). Because of this, data were subset by installation method for remaining analyses. All soil samples had a sandy loam soil texture, so they were excluded from statistical analyses.

Pre-Existing treatments:

Season (ANOVA, df = 2, F-value = 5.7, p = 0.005, Figure 3C) was the only predictor that had a significant effect on infiltration rate within pre-existing plots of turfgrass and clover-

turfgrass mix. Plant treatment (ANOVA, df =1, F-value = 0.1, $p = 0.7$, Figure 3B) and time since plant installation (ANOVA, df = 1, F-value = 0.1, $p = 0.7$) were not significant predictors of water infiltration in pre-existing treatments. A Tukey's Post-Hoc performed showed that water infiltration in pre-existing treatments was significantly greater in summer compared to fall ($p = 0.01$) or spring ($p = 0.01$, Figure 3C).

Seeded treatments:

Season (ANOVA, df = 2, F-value = 12.8, $p <<< 0.001$, Figure 3E) was the only predictor that had a significant effect on infiltration rate within seeded plots of fescue mix and white dutch clover monoculture. Plant treatment (ANOVA, df = 1, F-value = 1.4, $p = 0.25$, Figure 3D) and time since plant installation (ANOVA, df = 1, F-value = 0.27, $p = 0.61$) were not significant predictors of water infiltration in seeded treatments. A Tukey's Post-Hoc performed showed that water infiltration in seeded treatments was significantly greater in fall ($p < 0.0010$) and summer ($p < 0.0010$) when compared to spring (Figure 3E).

Plugged treatments:

Season (ANOVA, df = 2, F-value = 48.5, $p = 2.2e\text{-}16$, Figure 3G) and time since plant installation (ANOVA, df = 1, F-value = 7.4, $p = 0.007$, Figure 3H) had significant effects on infiltration rate within plugged plots of sedge lawn, mini meadow-low diversity, mini-meadow high diversity, and prairie. Plant treatment (ANOVA, df = 3, F-value = 0.8, $p = 0.48$, Figure 3F) was not a significant predictor of water infiltration in plugged treatments. A Tukey's Post-Hoc performed showed that water infiltration in plugged treatments was significantly greater in fall ($p = 0$), summer ($p = 0$) when compared to spring (Figure 3G). The second visit had significantly

greater water infiltration than the fourth visit ($p = 0.04$, Figure 3H) in plugged treatments when comparing time since plant installation.

Greenhouse experiment:

3K Treatments:

I found the fescue mix 3k treatment had similar mean water infiltration (t-test, $t_{value} = 1.45$, df = 20.5, $p = 0.1$, Figure 4A) runoff (t-test, $t_{value} = -1.43$, df = 17.1, $p = 0.2$, Figure 4B), and soil erosion (t-test, $t_{value} = -1.7$, df = 12, $p = 0.1$, Figure 4C) compared to the turfgrass 3k treatment. The fescue mix 3k treatment had a nearly significant trend of higher infiltration/runoff ratio (t-test, $t_{value} = 1.9$, df = 11.66, $p = 0.06$, Figure 4D). The turfgrass 3k treatment had significantly higher percentage of plant cover (t-test, $t_{value} = -2.0$, df = 21.3, $p = 0.049$, Figure 4E)

Fibrous Root Treatments:

I found that the fescue mix and turfgrass treatments had significantly less soil erosion (ANOVA, df = 2, f-value = 5.0, $p = 0.0128$, Figure 5D) than the 3D printed artificial fibrous root treatments. I did not find a significant difference in water infiltration (ANOVA, df = 2, f-value = 1.5, $p = 0.2315$, Figure 5A), runoff (ANOVA, df = 2, f-value = 0.2, $p = 0.8267$, Figure 5B), and infiltration/runoff ratio (ANOVA, df = 2, f-value = 2.2, $p = 0.131$, Figure 5C).

Shallow Propagative Treatments:

I found that the white Dutch clover treatment had similar runoff (Mann-Whitney U test, U = 66.5, $p = 0.7$, Figure 6B) and soil erosion (Mann-Whitney U test, U = 57, $p = 0.6$, Figure

6D) than the 3D printed artificial shallow propagative root treatment. The White Dutch Clover had similar water infiltration (t-test, $t_{value} = 0.8$, df = 15.7, $p = 0.3$, Figure 6A) and infiltration/runoff ratio (Mann-Whitney U test, U = 73, $p = 0.6$, Figure 6C) when compared to the 3D Printed Artificial Shallow Propagative Root treatment.

Taproot Treatments:

I found that the dandelion treatment had similar water infiltration (Mann-Whitney U test, U = 4, p = 0.5, Figure 7A), significantly less runoff (Mann-Whitney U test, U = 33, p = 0.01, Figure 7B), and similar soil erosion (Mann-Whitney U test, U = 28, p = 0.1, Figure 7D) than the 3D printed artificial taproot treatment. The dandelion treatment had a nearly significant trend of higher infiltration/runoff ratio (Mann-Whitney U test, U = 5, p = 0.08, Figure 7C) than the 3D Printed Artificial Taproot treatment.

DISCUSSION

I investigated the impact of various factors including plant installation method, plant cover, root systems, soil texture, and temporal variation on water infiltration, water runoff, and soil erosion across different lawn alternative treatments in two experiments. In the field experiment, pre-existing treatments generally exhibited higher water infiltration rates compared to newly installed treatments (seed or plug). Additionally, plant cover, root systems, and soil compaction were found to play a significant role in enhancing infiltration and reducing runoff and soil erosion in both my experiments. Finally, temporal variation and time since plant establishment played significant roles in my field experiment, with time since plant establishment increasing water infiltration over time, while differing seasons, such as

significantly higher infiltration rates in the summer due to temperature increases and evaporation, and lower rates in the spring due to cooler temperatures and soil saturation, further influenced the results.

My findings are increasingly relevant because of climate change and the growth of urban areas, as shifting rainfall patterns could exacerbate soil erosion and water runoff, making the use of lawn alternatives more crucial for environmental sustainability (GLISA, 2016). My results provide valuable insights for implementing effective lawn alternatives that promote better water infiltration and reduce soil erosion and runoff, which are important for mitigating the impacts of climate change.

Installation Method

In my field experiment, the lawn alternative plant community treatment was not a significant predictor of water infiltration but, installation method (pre-existing, seeded, and plugged) was, supporting my hypothesis in part. Pre-existing treatments had a trend of higher water infiltration rates when compared to the other treatments, which could be attributed to the plants being established for over ten years before installation of the seeded and plugged treatments. Treatments installed by seed, the fescue mix, and white Dutch clover monoculture had a trend of greater infiltration when compared to the plugged treatments, and a lower infiltration when compared to the pre-existing treatments. Compared to the plugged treatments, the fescue mix and white Dutch clover monoculture plots were seeded at a higher rate and contained a greater number of individual plants. For example, the plugged treatments plots had 78 individual plants per plot, while the seeded treatments were overseeded at 2 to 3 times the recommended rate for fescue mix (approximately 573,000 seeds) and 8 to 10 times the rate

recommended for the white Dutch clover monoculture (approximately 776,000 seeds) per plot (St. John et al., 2012). Although the seeded treatments plant species are smaller than the plugged treatments, the different number of individual plants could have had an impact on water infiltration (Zhu, 2020).

Using plugs for the establishment of sedge lawn, mini meadow-low diversity, mini meadow-high diversity, and prairie treatments ensures higher survival rates and protection during critical germination periods but could also contribute to slower root growth and the lowest trend of infiltration rates when compared to pre-existing and seeded treatments. Installation by seed for these species is not as successful, for example, all the plugged treatments contained native prairie plants which can have a three to six times higher survival rate when installed by plugs vs seeds (Gallagher & Wagenius, 2015). These treatments not only have higher survival when established by plug, but they are protected during the germination stages, which is the most critical stage of establishment (Barak et al., 2022; Gallagher & Wagenius, 2015). Installation from seed would also take longer, with some native prairie plants taking three to five years to reach plug size, which will be further discussed below (Barak et al., 2022; Smith et al., 2010). Because the installation method was such a significant predictor in my field experiment, my greenhouse experiment eliminated this factor by installing all treatments by seed.

Plant Cover

Plant cover was an important predictor of water infiltration in both the field and greenhouse experiment. I directly tested this in the greenhouse experiment, with the turfgrass 3k treatment had a significantly higher percentage of plant cover than the fescue mix 3k treatment but had a nearly significantly trend of lower water infiltration to runoff ratio. The fescue mix

species used in their 3k treatment have blade widths that are smaller than the turfgrass species, which further shows the importance of root characteristics (Miller, 2022; New England Native Plant Trust, 2025).

The 3D printed artificial root treatments had no plant cover and had similar soil erosion rates when compared to all living plant treatments in my greenhouse experiment. I anticipated the absence of plant cover protection in these treatments would put all the force from rainwater onto the soil, causing the movement of topsoil at a high rate (Rey 2003; Duran et al. 2008; Bochet et al., 1998). The living plant treatments had a high percentage of bare soil, with plant cover ranging from only 5% to 80%. This limited vegetation may have reduced infiltration across all living plant treatments by creating a crust on the soil. Additionally, the standard seeding rates used (except in the 3k treatments) could have contributed to low infiltration. Higher seeding rates may have increased plant cover, improving infiltration and helping to reduce erosion and runoff.

Although plant cover was not directly tested across all treatments, the field experiment treatments with higher plant cover (pre-existing and seeded) had a trend of higher water infiltration, which is supported by Zuazo and Pleguezuelo, stating that a higher percentage of plant cover increases water infiltration rates (2008). The plugged treatments were frequently weeded, which decreased the amount of plant cover, leaving bare soil exposed. Plant cover protects the soil from the force of rainwater, by absorbing the force that would be directly exposed to the soil, without plant cover a hard crust on the soil can form, decreasing the infiltration rate (Bochet et al., 1998; Zuazo and Pleguezuelo, 2008).

Root Systems

All treatments with living plants had similar soil erosion to the 3D printed artificial root treatments in my greenhouse experiment. I hypothesized that roots would increase soil infiltration capacity and soil absorbance (Burak et al., 2021). Many factors work together to decrease soil erosion such as root surface area, root length density, root density, root diameter, and percentage of fine roots (Shit and Maiti 2012). The treatments with living plants had the advantage of having differing levels of these factors while the artificial roots did not. The 3D printed artificial roots had no root hairs, which can contain up to 90% of the surface area of living roots (Burak et al., 2021). Burak et al., studied the effects of soil erosion on plants with no root hairs vs root hairs and found that root hairs significantly decreased soil erosion.

The fescue mix 3k treatment had similar water infiltration than the turfgrass 3k treatment, but a nearly significant trend in a greater ratio of infiltration to runoff. This can be attributed to the fescue mix 3k plant species having longer roots averaging around 12 inches (Brown et al., 2010) than the turfgrass 3k treatment, which has root lengths averaging between 1-2 inches (Selbig and Balster, 2012). The longer roots of the fescue mix 3k treatments were able to infiltrate water at a faster rate (Morash et al., 2019). There is an increase of water infiltration as root length and densities increase (Wasson et al., 2012; Shit and Maiti 2012). I did not have an artificial root treatment for 3k because 3D printed artificial root treatments were placed into the soil at a one-to-one ratio. If treatments had more time to mature within treatment pots or a higher percentage of plant cover, the fescue mix 3k could have developed longer root systems, further distinguishing from the turfgrass 3k treatment.

The fibrous root treatments (fescue mix, turfgrass, & 3D printed artificial fibrous roots) did not significantly impact runoff (Figure 2B). This could be due to the similar root types throughout this group, including the artificial roots. These results show why diversity in root

systems are important (Leimer et al., 2021; Hooper & Vitousek, 1998; Liu, 2017). Plant communities with a more diverse root composition will capture water faster and decrease runoff (Leimer et al., 2021; Hooper & Vitousek, 1998). Higher species diversity leads to multiple types of root systems underground at different lengths in the soil that decrease runoff. Plant diversity stabilizes soil by increasing soil porosity which will enhance infiltration (Martin et al., 2010; Pohl et al., 2009; Leimer et al., 2021).

Although the plugged treatments contained plants with established root systems in my field experiment, they had the lowest infiltration rate, which could be because the plugged treatment plots contained compacted soil, the plugged species could have been root bound before installation, and the plugged species could have planted too closely. Root binding occurs when plants are grown in pots that restrict their root growth, and crowding of plants can lead to competition between neighboring plants (Schenk, 2006; Poorter, 2012). The plants were plugged into the soil 10 inches apart, which could be too close for these prairie species, Huddleston and Young found that plants plugged further apart were significantly more successful than those planted closer together (2004). The USDA recommends planting distance averages between 13 to 18 inches (2019). Since the plugged treatments included prairie plant species with long growing roots, the combination of these species' growth habits and the installation method could have interfered with root development before and after plugs were installed (Poorter, 2012; Weaver, 1915).

Soil

Soil texture and composition also plays a major role in water infiltration (Sjöman & Gill, 2014). Soils with differing textures will infiltrate water at different rates (Sjöman & Gill, 2014).

The soil samples collected from the Rethinking Lawns Research Plots were all sandy loam. The Chicago Stormwater Ordinance Manuals infiltration rates for USDA Soil Textures state that soil with sandy loam texture should have a infiltration rate no lower than 0.50 in/hr, only 1.8% of all infiltration rates fell below this standard in my field experiment (City of Chicago, 2024). Although soil texture was similar, soil compaction could have impacted water infiltration throughout the treatments, soil compaction occurs in highly trafficked areas where soil is disturbed, such as the Rethinking Lawn Research Plots (Woltemade, 2010). Compaction can be caused by many factors including frequently walking on the soil, weeding interference, and by bare soil being rained upon. Compaction inhibits further root growth, with limited infiltration abilities of plants (Peralta 2024). When soil has no above ground plant cover to protect it from rain, it can create a hard crust that water cannot infiltrate through quickly, which could be seen in the plugged treatment plots low water infiltration rates (Zuazo & Pleguezuelo, 2008). The plugged treatments were frequently weeded and walked upon throughout the entire spring-fall seasons, which could have led to high levels of soil compaction. To eliminate variability in soils, the same soil was used across treatments in my greenhouse experiment. All treatment pots were watered, even if treatments contained no living plants, to maintain the same soil moisture levels throughout.

Season and Time since plant installation

Season

I initially hypothesized that season would be a significant predictor or water infiltration in the lawn experiment treatment plot due to differences in rain frequency and temperatures across spring, summer, and fall in the Midwest (Huff & Angel, 1992). Specifically, I thought summer

would have the greatest infiltration rates across seasons, which had significantly higher water infiltration than the spring and fall seasons. In the Chicago area, summer has a higher percentage of rainfall when compared to the spring and fall season and increased average temperature of the season will interact to impact the infiltration rates (NOAA, 2020; Huff & Angel, 1992). Higher temperatures cause a greater water infiltration rate (up to 56%) due to lower soil moisture content and larger macropores within the soil (Braga et al., 2007; Cerdà, 1997). Season was a significant predictor throughout all the statistical analyses, plant water demands, and environmental conditions contribute to the variation in infiltration rates. The summer season's infiltration rate was the highest throughout all seasons. This is attributed to higher temperatures; the water in the soil will evaporate, making plants need a larger volume of water more frequently (Braga et al., 2007; Cerdà, 1997).

The spring season had significantly lower water infiltration rates when compared to summer and fall. This can be attributed to the rainfall and cooler temperatures throughout the spring season (Cerdà, 1997; Huff & Angel, 1992). Springtime has cooler temperatures, which explains the low infiltration rates throughout treatments, the soil will be saturated for longer periods of time due to the decrease of evaporation of water from soil due to temperature (Braga et al., 2007, Figure 2A). Fall fell between summer and spring when it came to infiltration rate due to cooler temperatures than summer and less rainfall than spring (Huff & Angel, 1992).

Time since plant installation

I initially hypothesized that time since plant installation would be a significant predictor of water infiltration in my field experiment, which is partially supported by the plugged treatment results. Visit was a significant predator of infiltration rate within the plugged

treatments. The second and fourth visits were significantly different from each other while all other visits were not. Both visits were in the fall seasons and infiltration rate increased throughout time (Figure 2H). This increased infiltration rate could be attributed to the maturation of the plugged plants throughout the full year in between data collection periods. As the plants mature, they are growing above and below ground, which will increase water infiltration rates (Zhu et al., 2020). These results could explain why the plugged treatments did not significantly impact water infiltration, as they are not fully established.

Native prairie plants can take five years to fully establish, but data was collected in the first and second year after installation (Smith et al., 2010). Since implementation of these species is most successful by plug, even with the inhibition of root growth in plug, this early-stage data still provides valuable insights into their performance in the first years of growth. Both pre-existing and seeded treatments had reached maturity (takes approximately four to eight weeks) and created a matrix of roots underneath the soil well before the plugged treatments (Larsen et al., 2004; Landschoot, 2022; Bush, 2005). My greenhouse experimental treatments were all planted on the same day in a temperature-controlled greenhouse to eliminate these variables.

Conclusion

Although the Rethinking Lawns Research Plot treatment identity was not a significant predictor of water infiltration throughout this study, various factors did significantly influence the infiltration rate. Season and installation methods of the treatments had the highest impact on water infiltration and should be kept in mind when implementing alternatives to turfgrass. The spring season has the second highest rainfall frequency and the lowest infiltration rates across all treatments, which is when cities have the highest flood risks (Huff & Angel, 1992). If the

plugged treatments plant species were mature and did not have soil compaction from disturbance, they would be able to have a substantially higher water infiltration rate than the pre-existing and seeded treatments. The plugged treatments were native prairie plants that have significantly longer root systems than the other treatments, which should have a higher infiltration rate (Weaver 1915; Zhu et al., 2020).

Although implementation of native prairie plants is more successful by plug, it is more expensive to create a carpeted "lawn" aesthetic using plugs (Barak et al., 2022a). Plug prices typically range from $2 to $11 per plant, whereas seeds are much more cost-effective for covering large areas (U.S. EPA, n.d.). For example, restoring a half-acre yard with native plants can cost around $750 using seed, compared to $21,780 when using plugs (Phillips-Mao, 2017). Even though native prairie plants can take longer to establish by seed, Barak et al., found that both installation methods had similar biodiversity outcomes (2022a).

Not all treatments with living plants had higher water infiltration than the 3D printed artificial root treatments, but living plant treatments tended to have a higher infiltration/runoff ratio in my greenhouse experiment. Based on these findings, I believe vegetation should be used to mitigate water runoff and soil erosion instead of manmade impervious surfaces.

Water infiltration, runoff, and soil erosion are becoming increasingly important in urban and residential ecosystems (Xu, et al., 2020). Within the midwestern United States, extreme weather rainfall events have increased 37% due to climate change since the 1960s (Chicago Metropolitan Agency for Planning, 2016). Mitigating the effects of this increased rainfall is especially pertinent in areas of decreased permeability, such as cities and suburbs (Zhang et al., 2018). Buildings, roads, and sidewalks are a few examples of the impermeable surfaces covering these urban ecosystems (USGS, 2018). When heavy rainfall occurs, it cannot infiltrate through

these surfaces and will runoff into nearby waterways, causing pollution, decreasing groundwater recharge, and damage to infrastructures (NIH, 2019).

Most green spaces throughout these urban areas are lawns, which are non-native turf grasses, that could be replaced with low-growing lawn alternatives that will be better equipped to handle this influx of rainfall events. This study aimed to find a lawn alternative for turfgrass that will have higher water infiltration, lower runoff, and lower soil erosion in a field and greenhouse experiment.

Future directions

To find the best method of implementation of lawn alternatives to mitigate runoff and soil erosion, I believe further studies need to study diversity within the treatments. Specifically, in my field experiment the sedge lawn, mini meadow-low diversity, mini meadow-high diversity, and prairie treatments all had similar infiltration rates in the plug installed treatments. However, there was a trend that treatments with higher species diversity had higher water infiltration rates (Figure 2F). Plant communities with a more diverse root composition will capture water faster and decrease runoff (Leimer et al., 2021; Hooper & Vitousek, 1998). This could be due to the prairie and mini-meadow high diversity treatments having 18 species each while the mini meadow-low diversity had 9 species, and the sedge lawn had 3 species. The higher species diversity could have led to multiple types of root systems underground at different lengths within the soil that could increase infiltration of water. Plant diversity stabilizes soil by increasing soil porosity which will enhance infiltration (Martin et al., 2010; Pohl et al., 2009; Leimer et al., 2021).

Plant maturation was an important factor in my field experiment and the treatments within my greenhouse experiment were only established for 12 weeks. A study focusing on water infiltration of plants throughout maturation would be beneficial especially for application of these lawn alternative plantings. If lawn alternative treatments at full maturation could have significantly higher infiltration, even in the spring season, it would help mitigate runoff and soil erosion in all environments, especially in urban and residential areas.

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Table 1A. The Rethinking Lawns Research Plots includes eight treatments and was installed in 2022 at the Chicago Botanic Garden, Glencoe, Illinois. The treatment not included is turfgrass (pre-existing turfgrass with encroaching weedy species).

Treatment	Species	Common Name
White Dutch clover monoculture & Clover-turfgrass mix	*Trifolium repens*	White Dutch clover
Fescue mix	*Festuca ovina*	Sheep fescue
	Festuca ovina	Hard fescue
	Festuca rubra	Chewings fescue
	Festuca rubra	Creeping red fescue
Sedge lawn	*Carex pensylvanica*	Penn sedge
	Eragrostis spectabilis	Purple love grass
	Juncus tenuis	Path rush
Mini meadow-low diversity	*Carex pensylvanica*	Penn sedge
	Eragrostis spectabilis	Purple love grass
	Ruellia humilis	Prairie petunia

Treatment	Species	Common Name
	Antennaria neglecta	Pussytoes
	Asclepias tuberosa	Butterfly weed
	Dalea candida	White prairie clover
	Eurybia macrophylla	Big leaf aster
	Geum trifolium	Prairie smoke
	Viola pedatifida	Prairie violet
Mini meadow- high diversity	*Carex pensylvanica*	Penn sedge
	Eragrostis spectabilis	Purple love grass
	Juncus tenuis	Path rush
	Allium cernuum	Nodding wild onion
	Antennaria neglecta	Pussytoes
	Asclepias tuberosa	Butterfly weed
	Dalea candida	White prairie clover
	Eurybia macrophylla	Big leaf aster
	Geum trifolium	Prairie smoke
	Viola pedatifida	Prairie violet
	Dalea purpurea	Purple prairie clover
	Scutellaria leonardii	Small skullcap
	Polemonium reptans	Jacob's ladder

Treatment	Species	Common Name
	Primula meadia	Shooting star
	Ruellia humilis	Prairie petunia
	Camassia scilloides	Wild hyacinth
	Symphyotrichum sericeum	Silky aster
Prairie	*Bouteloua curtipendula*	Side oats-grama
	Carex brevior	Plains oval sedge
	Elymus canadensis	Canada wild rye
	Schizachyrium scoparium	Little bluestem
	Allium cernuum	Nodding wild onion
	Asclepias tuberosa	Butterfly weed
	Chamaecrista fasciculata	Partridge pea
	Dalea candida	White prairie clover
	Dalea purpurea	Purple prairie clover
	Echinacea purpurea	Purple coneflower
	Eryngium yuccifolium	Rattlesnake master
	Liatris aspera	Rough blazing star
	Monarda fistulosa	Wild bergamot
	Penstemon digitalis	Foxglove beardtongue
	Ratibida pinnata	Yellow coneflower

Treatment	Species	Common Name
	Rudbeckia hirta	Black-eyed Susan
	Symphyotrichum laeve	Smooth blue aster
	Zizia aurea	Golden alexander

Table 1B. The Rethinking Lawns Research Plots includes eight treatments and was installed in 2022 at the Chicago Botanic Garden, Glencoe, Illinois.

Lawn Alternative Treatment	Installation Method
Turfgrass	Pre-existing
White Dutch clover-turfgrass mix	
White Dutch clover monoculture	Seeded
Fescue mix	
Sedge lawn	Plugged
Mini meadow-low diversity	
Mini meadow-high diversity	
Prairie	



Figure 1A. The Rethinking Lawns Research Plots includes eight treatments and was installed in 2022 at the Chicago Botanic Garden, Glencoe, Illinois.



Figure 1B. The fescue mix species in the Rethinking Lawns Research Plots. The Rethinking Lawns Research Plots includes eight treatments and was installed in 2022 at the Chicago Botanic Garden, Glencoe, Illinois.



Figure 1C. The sedge lawn treatment in the Rethinking Lawns Research Plots**.** The Rethinking Lawns Research Plots includes eight treatments and was installed in 2022 at the Chicago Botanic Garden, Glencoe, Illinois.



Figure 1D. The prairie and mini meadow treatment in the Rethinking Lawns Research Plots. The Rethinking Lawns Research Plots includes eight treatments and was installed in 2022 at the Chicago Botanic Garden, Glencoe, Illinois.



Figure 1E. The prairie treatment in the Rethinking Lawns Research Plots**.** The Rethinking Lawns Research Plots includes eight treatments and was installed in 2022 at the Chicago Botanic Garden, Glencoe, Illinois.

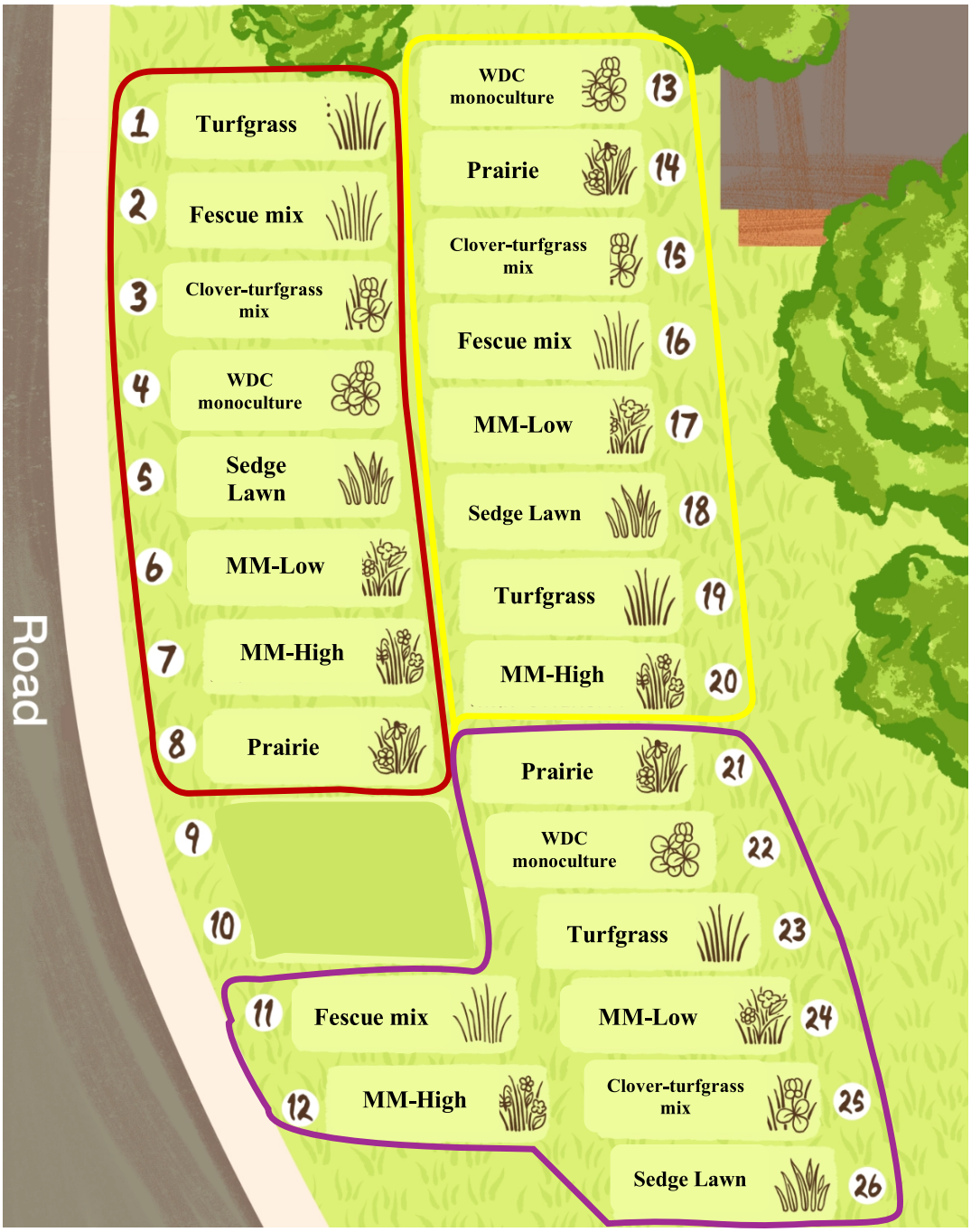


Figure 1F. The Rethinking Lawns Research Plots includes three blocks (A = red, B = yellow, C = purple) of eight treatment plots. Plots were approximately 115 square feet. Within each plot, data was collected from three subplots. Installed in 2022 at the Chicago Botanic Garden, Glencoe, Illinois. WDC = White dutch clover. MM = Mini meadow treatments.

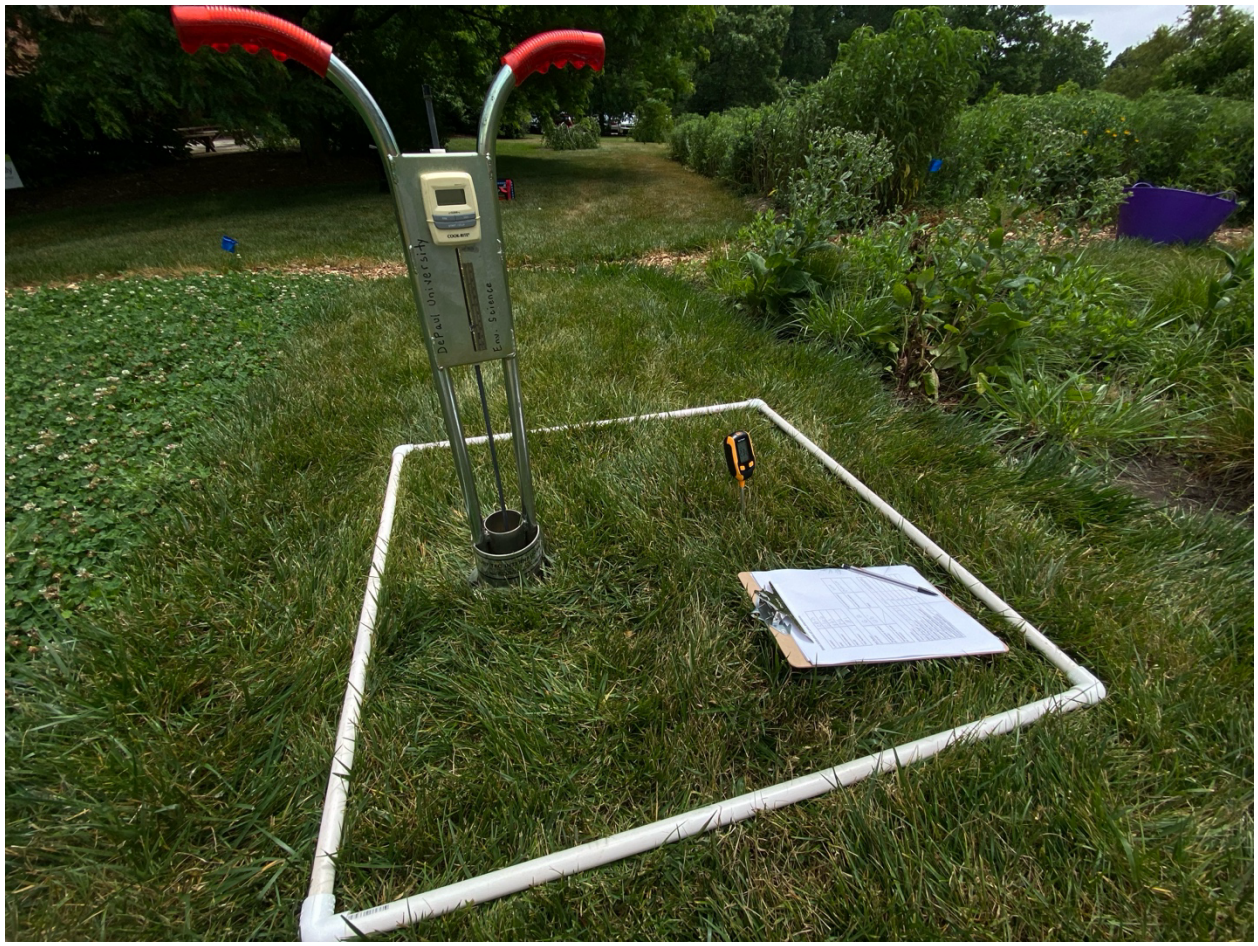


Figure 1G. The Turf-Tec Infiltrometer at Rethinking Lawns Research Plot. The infiltrometer was placed in the turfgrass subplot. The Rethinking Lawns Research Plots includes eight treatments and was installed in 2022 at the Chicago Botanic Garden, Glencoe, Illinois.



Figure 1H. The top of the Turf-Tec Infiltrometer at the Rethinking Lawns Research Plots. Including the timer, ruler (in mm), and infiltration indicator. The Rethinking Lawns Research Plots includes eight treatments and was installed in 2022 at the Chicago Botanic Garden, Glencoe, Illinois.



Figure 1I. The bottom of the Turf-Tec Infiltrometer at the Rethinking Lawn Research Plots. Including a double ring with hardened cutter blades, and a bulb in the inner ring as a float indicator. The Rethinking Lawns Research Plots includes eight treatments and was installed in 2022 at the Chicago Botanic Garden, Glencoe, Illinois.

Table 2A. Root types and Species of Common Lawn, Lawn Alternative, and 3D Printed Artificial Root Treatments.

Root Type	**Common Lawn**	**Lawn Alternative**	**3D Printed Artificial Root Models**
Taproot	Dandelion (*Taraxacum officinale)*	Purple prairie clover *(dalea purpurea)*	taproot model
Fibrous Root	Turfgrass *(Poa pratensis)*	Fescue mix *(Festuca ovina & Festuca rubra)*	fibrous root model
Shallow Propagative Roots	White Dutch clover *(trifolium repens)*	Pussytoes *(antennaria plantaginifolia)*	shallow propagative root model

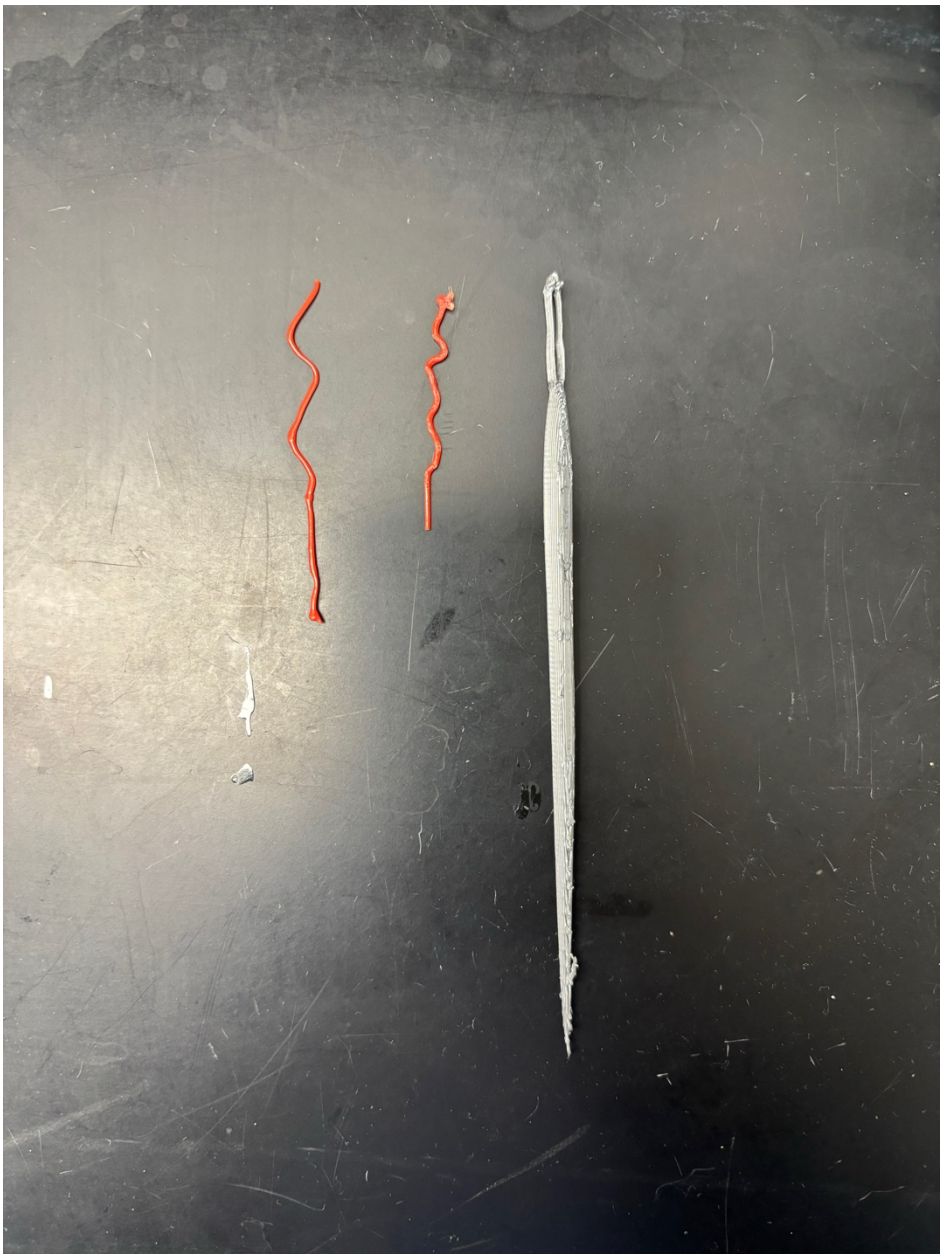


Figure 2A. Fibrous, shallow propagative, and taproot models used in 3D printed artifical root treatments. 3D printed artificial root models were placed into their treatment pots at a 1:1 ratio. Each plant was counted within the Common Lawn and Lawn Alternative treatment and root models were placed in pot at the exact number. Root models were placed into the soil four days before any data collection took place. University of Michigan-Flint, Flint, Michigan.

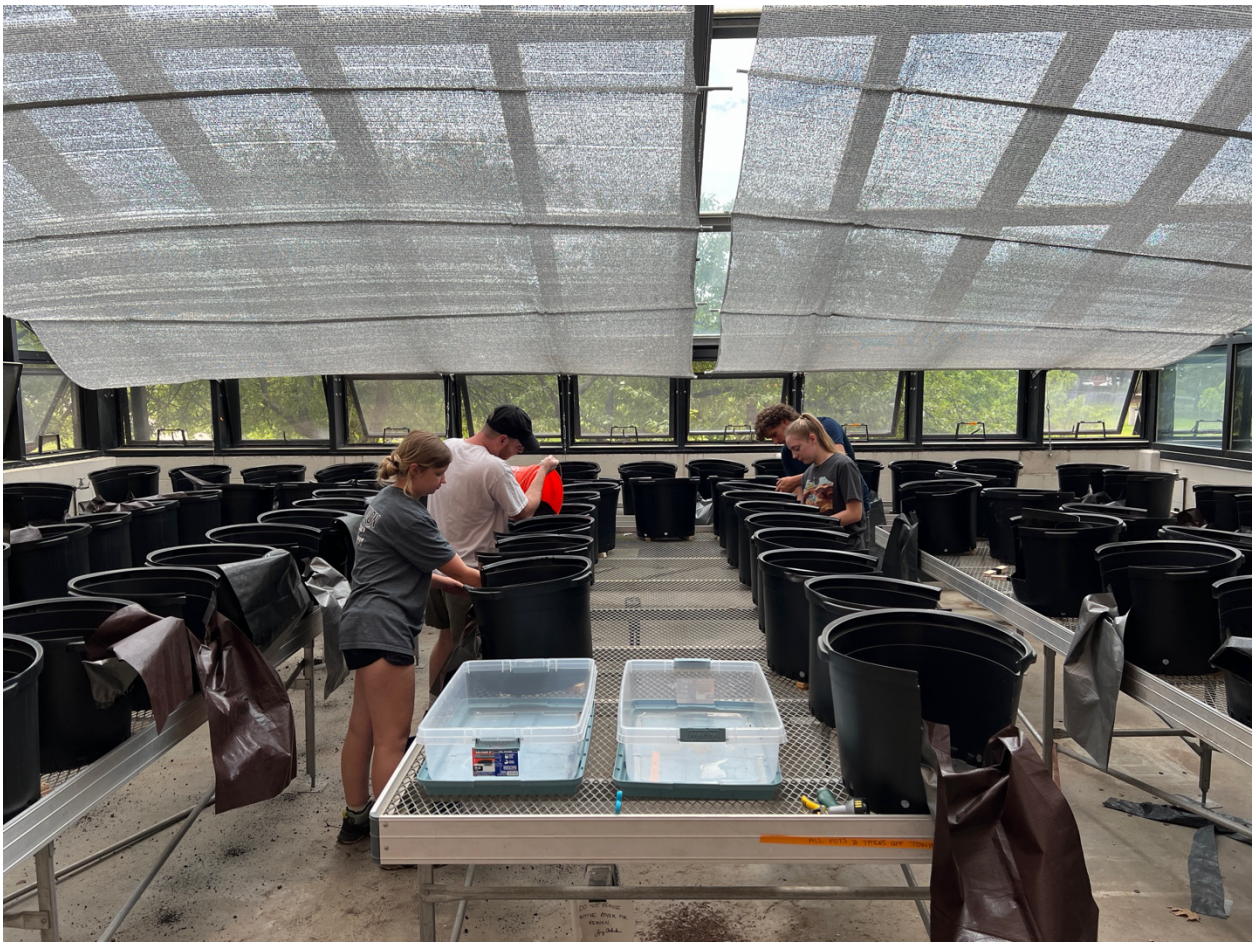


Figure 2B. Treatment pots were filled with soil to approximately 6 inches, tarp “slide” was used to capture runoff and soil erosion, and holes on the bottom of the pots were used to capture water infiltration. Six replicates of each treatment with data collection at 6 and 12 weeks. Established in greenhouse at the University of Michigan-Flint, Flint, Michigan.

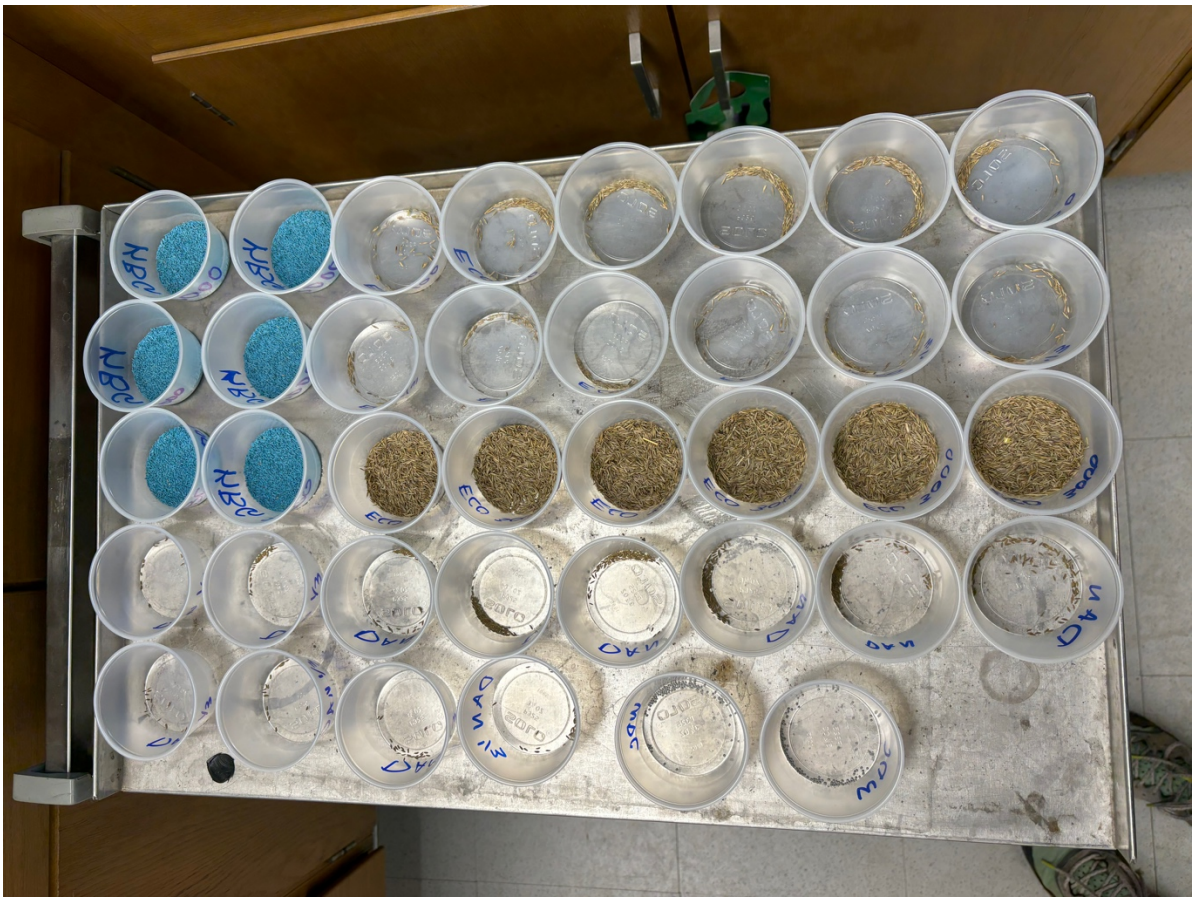


Figure 2C. Seeds used for Treatments. The standard seeding rate used in this experiment was 200 per pot. Turfgrass and fescue mix mix treatments recommended seeding rate was calculated at 3,000 per pot. Because of this discrepancy, two treatments were added (turfgrass 3k and fescue mix mix 3k).



Figure 2D. 3D printed artificial root models were placed into their treatment pots at a 1:1 ratio. Each plant was counted within the Common Lawn and Lawn Alternative treatment and root models were placed in pot at the exact number. Root models were placed into the soil four days before any data collection took place. University of Michigan-Flint, Flint, Michigan.



Figure 2E. Demonstration Pots of Dandelion, Fescue mix Mix, Turfgrass, and White Dutch Clover Treatments. Clear pots were used to determine root length throughout establishment. These pots were not used for data collection, but represent the treatments that were. Established in greenhouse at the University of Michigan-Flint, Flint, Michigan.



Figure 2F. Turfgrass 3K and Fescue mix Mix 3K Treatments in Experimental Pots at 6 Week Establishment. Six replicates of each treatment with data collection at 6 and 12 weeks. Established in greenhouse at the University of Michigan-Flint, Flint, Michigan.

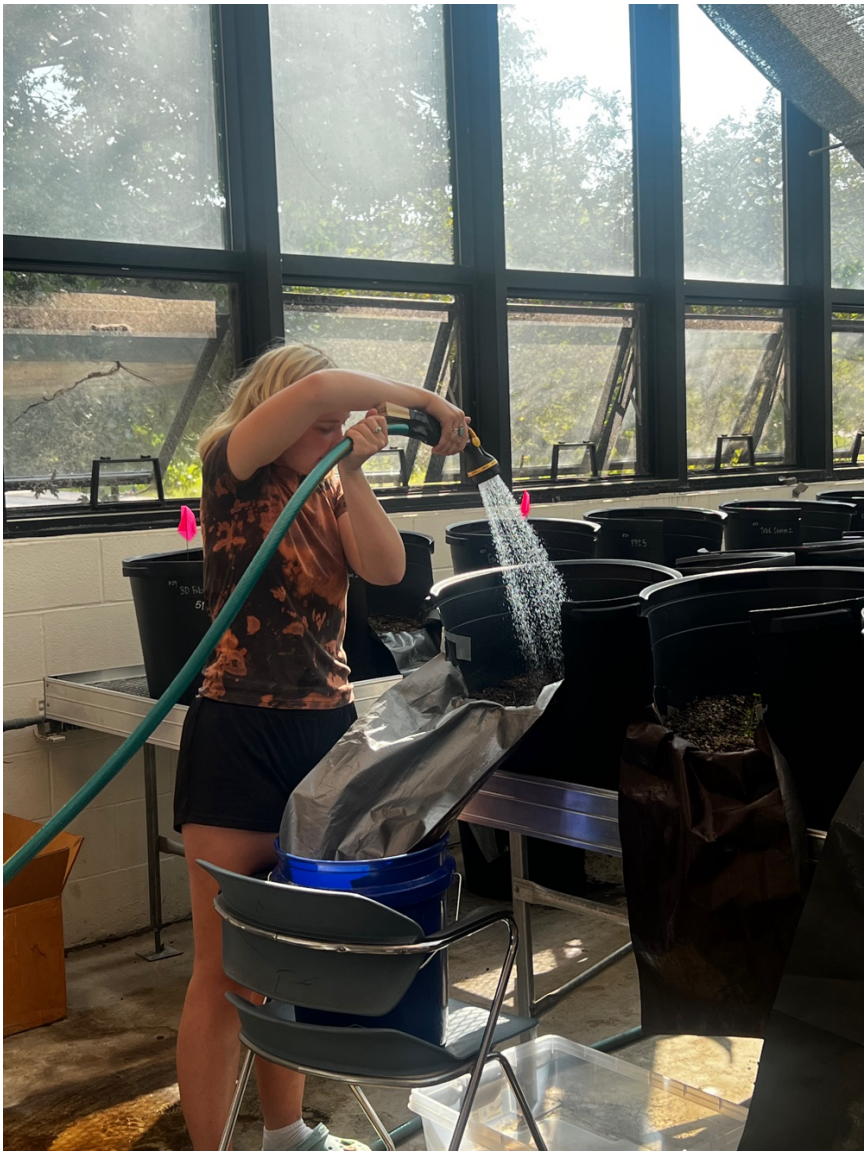


Figure 2G. The rainfall simulation was created by using the shower setting on a hose with a restricted release. A bin was placed underneath the treatment tub to catch infiltrated water, and a bucket at the end of the tarp “slide” to catch water runoff and soil erosion. The treatment was watered for 30 seconds to simulate rainfall of X inch per hour. Six replicates of each treatment with data collection at 6 and 12 weeks. Established in greenhouse at the University of Michigan-Flint, Flint, Michigan.



Figure 2H. Runoff was drained through a grade 100 cheesecloth (6 weeks) and white muslin (12 weeks) to capture soil erosion from each treatment and weighed (grams). After soil erosion was collected, it was dried and weighed (grams). University of Michigan-Flint, Flint, Michigan.

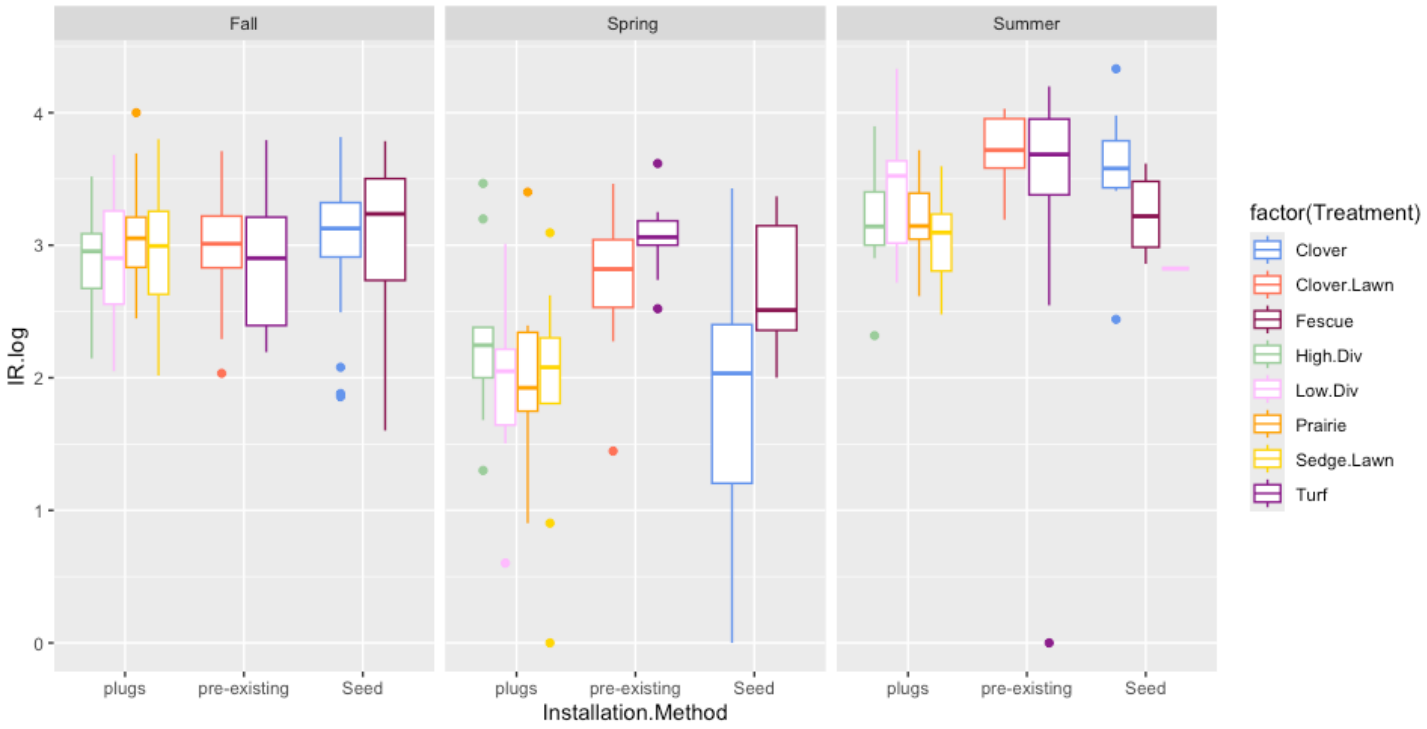


Figure 3A. The log of infiltration rate (mm/hour) of lawn alternative treatments based on installation method and season. The Rethinking Lawns Research Plots includes eight treatments: turfgrass, white Dutch clover-turfgrass mix, white Dutch clover monoculture, fescue mix, sedge lawn, mini meadow-low diversity, mini meadow-high diversity, and prairie. It was installed in 2022 at the Chicago Botanic Garden, Glencoe, Illinois.

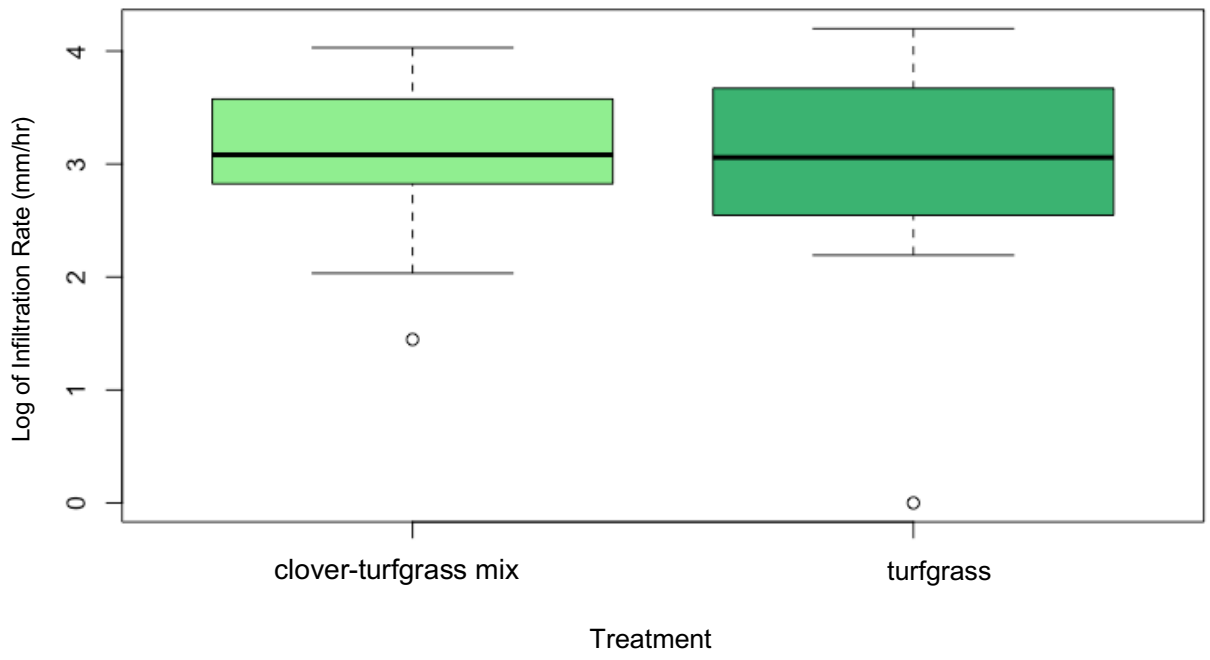


Figure 3B. The log of infiltration rate of pre-existing lawn alternative treatments (ANOVA, $p = 0.73$). White Dutch clover lawn and turfgrass vs the log of infiltration rate (mm/hour). Nine replicates of each treatment with data collected four times (June 2023, September 2023, April 2024, and September 2024) throughout three seasons (spring, summer, and fall). The Rethinking Lawns Research Plots were installed in 2022 at the Chicago Botanic Garden, Glencoe, Illinois

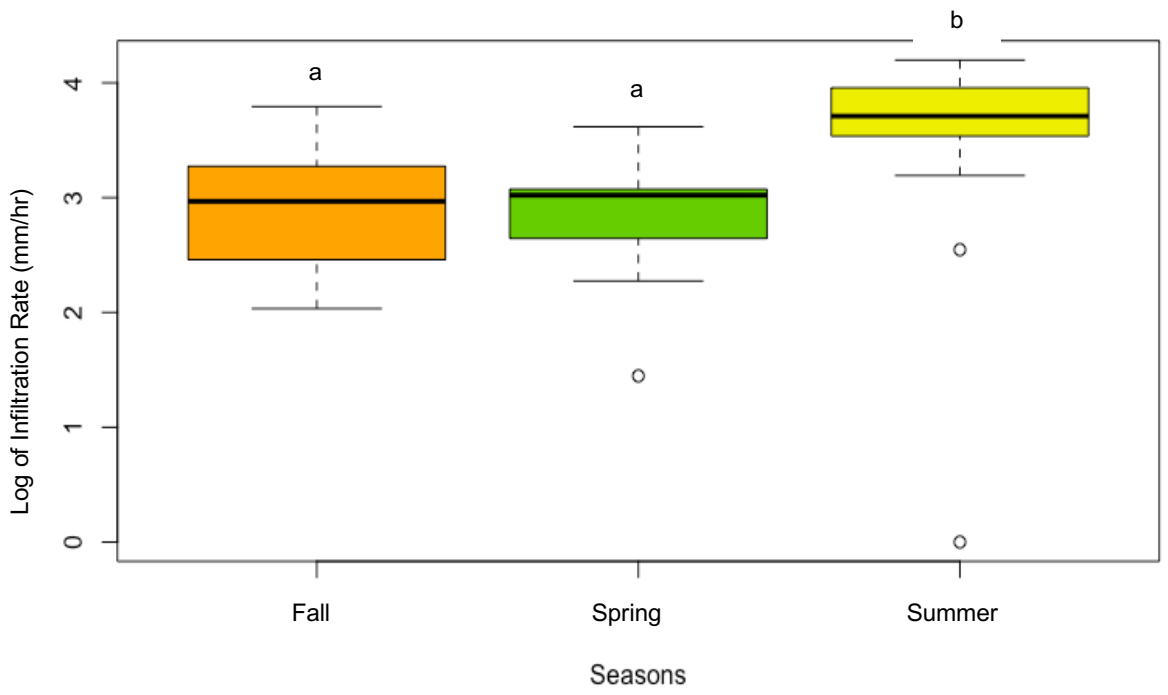


Figure 3C. The log of the infiltration rate of pre-existing treatments (ANOVA, $p = 0.005$) throughout seasons. Fall, spring, and summer vs the log of infiltration rate (mm/hour). Nine replicates of each treatment with data collected four times (June 2023, September 2023, April 2024, and September 2024) throughout three seasons (spring, summer, and fall). The Rethinking Lawns Research Plots were installed in 2022 at the Chicago Botanic Garden, Glencoe, Illinois. Lowercase letter indicates significant difference among seasons.

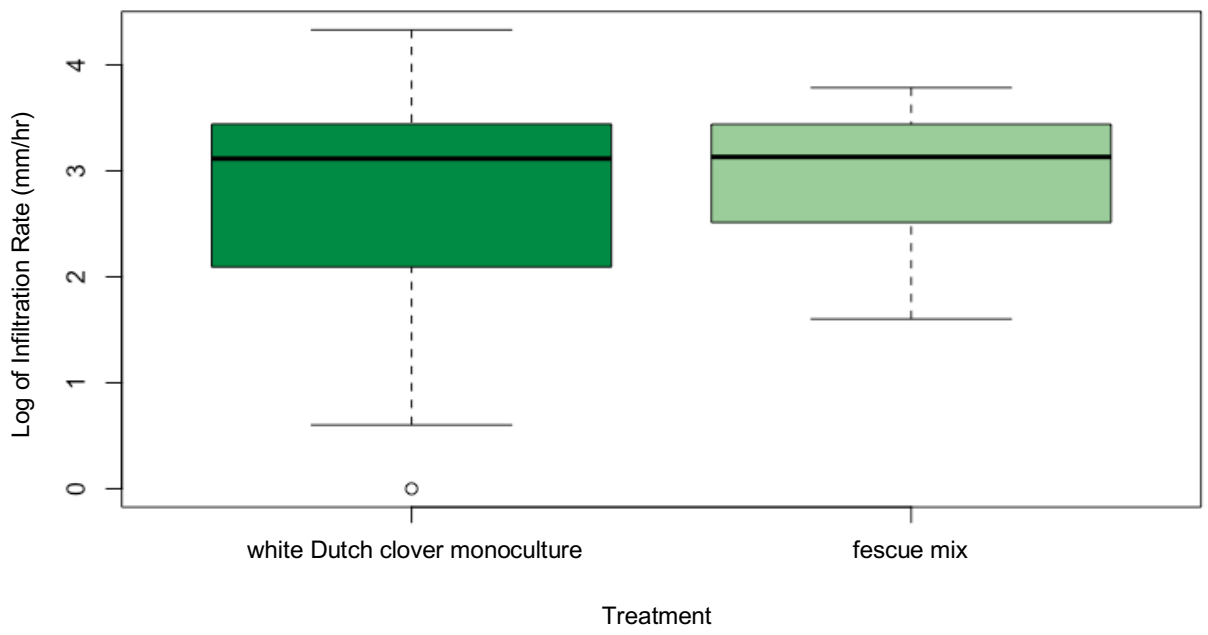


Figure 3D. Log of infiltration rate of seeded lawn alternative treatments (ANOVA, p = 0.25). White Dutch clover and fescue mix vs the log of infiltration rate (mm/hour). Nine replicates of each treatment with data collected four times (June 2023, September 2023, April 2024, and September 2024) throughout three seasons (spring, summer, and fall). The Rethinking Lawns Research Plots were installed in 2022 at the Chicago Botanic Garden, Glencoe, Illinois.

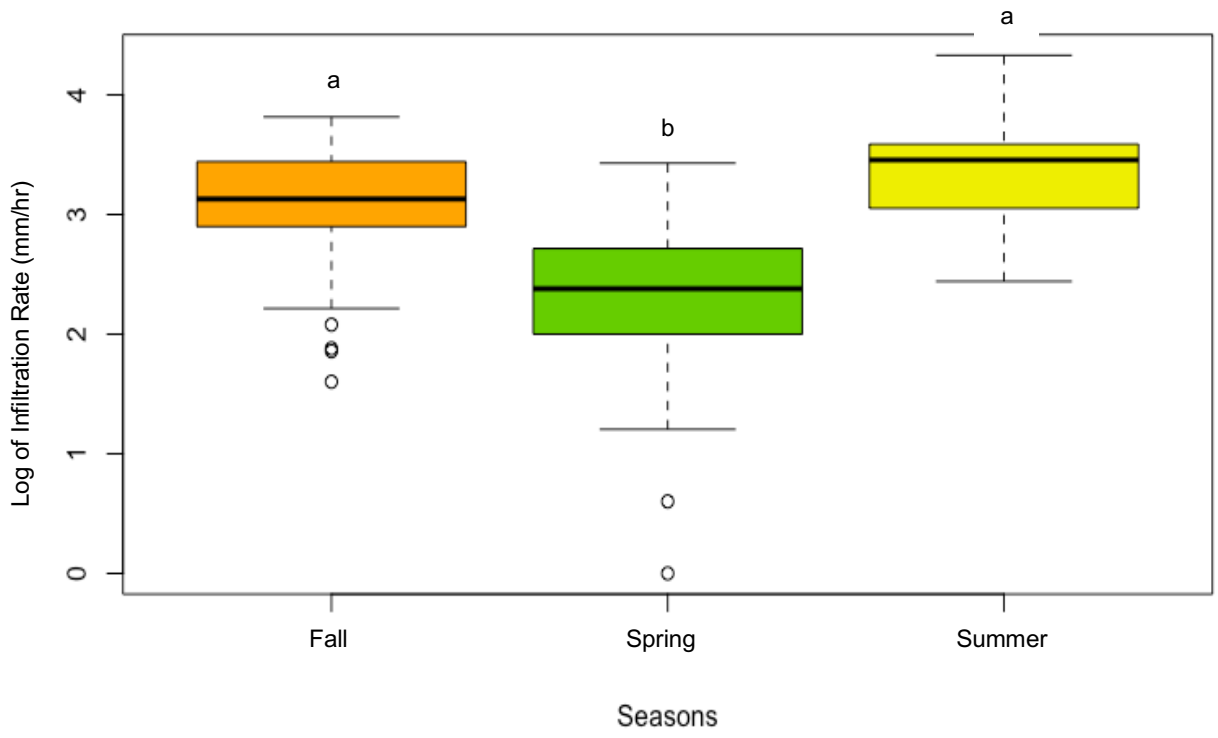


Figure 3E. The log of the infiltration rate of seeded treatments throughout seasons (ANOVA, p = 2.3e-05). fall, spring, and summer vs the log of infiltration rate (mm/hour). Nine replicates of each treatment with data collected four times (June 2023, September 2023, April 2024, and September 2024) throughout three seasons (spring, summer, and fall). The Rethinking Lawns Research Plots were installed in 2022 at the Chicago Botanic Garden, Glencoe, Illinois. Lowercase letter indicates significant difference among Season.

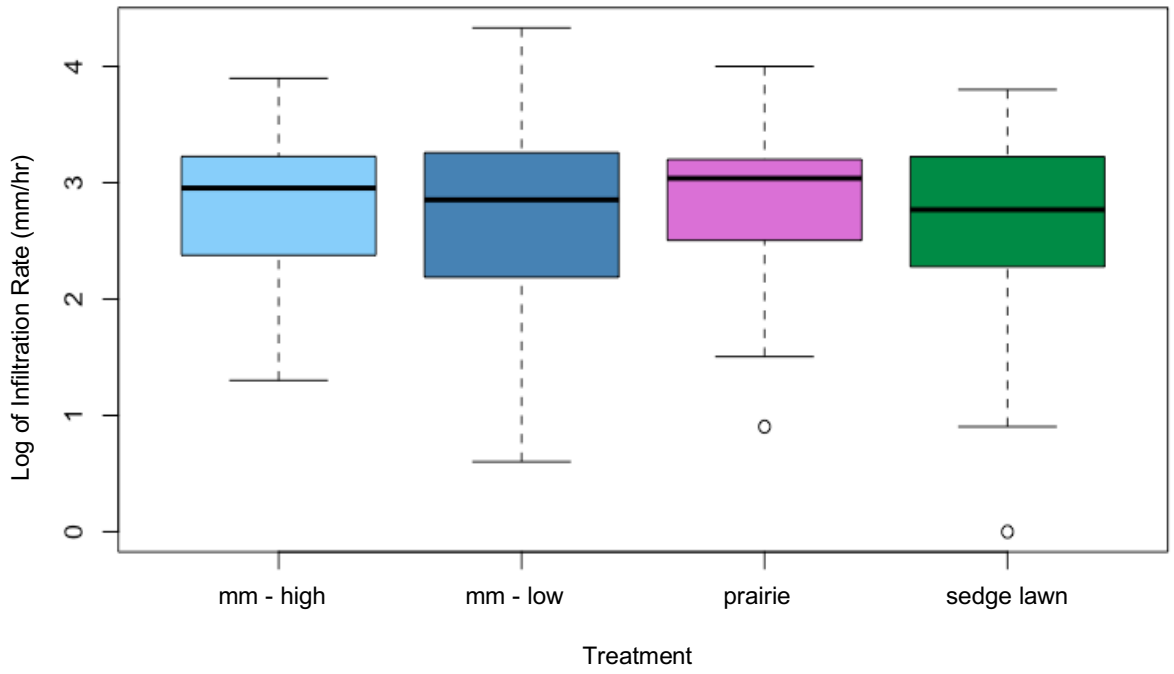


Figure 3F. The log of infiltration rate of plugged lawn alternative treatments (ANOVA, p = 0.48). Mini meadow-high diversity, mini meadow-low diversity, prairie, and sedge lawn vs the log of infiltration rate (mm/hour). Nine replicates of each treatment with data collected four times (June 2023, September 2023, April 2024, and September 2024) throughout three seasons (spring, summer, and fall). The Rethinking Lawns Research Plots were installed in 2022 at the Chicago Botanic Garden, Glencoe, Illinois.

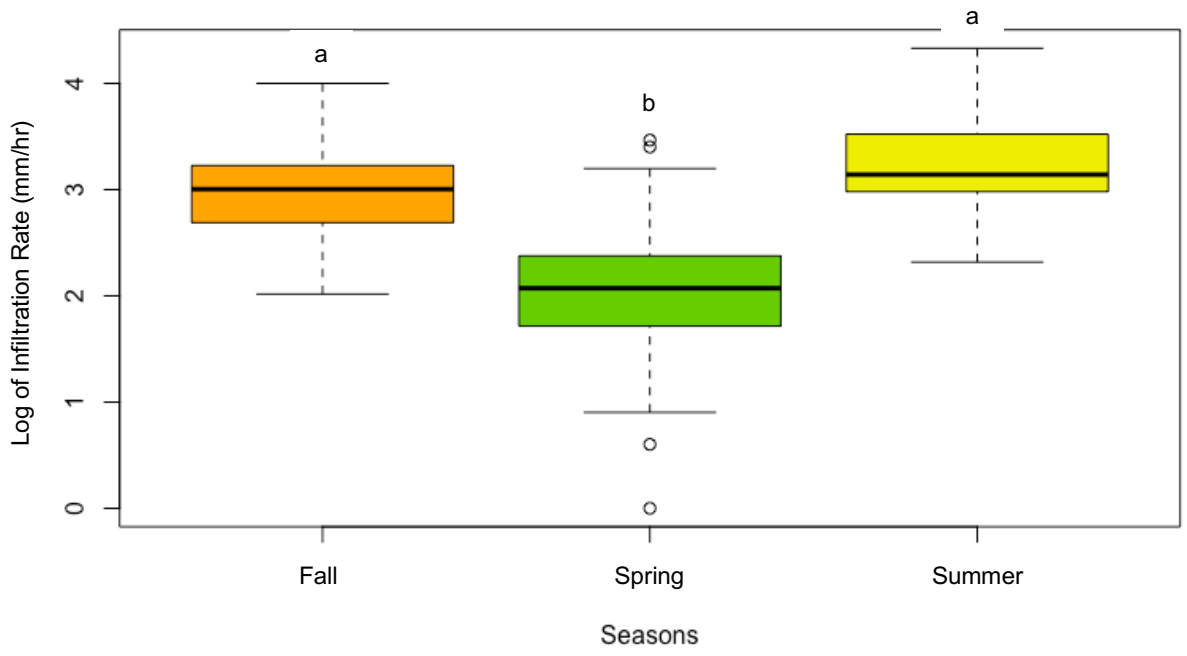


Figure 3G. The log of the infiltration rate of plugged treatments throughout season (ANOVA, p = 2.2e-16). Fall, spring, and summer vs the log of infiltration rate (mm/hour). Nine replicates of each treatment with data collected four times (June 2023, September 2023, April 2024, and September 2024) throughout three seasons (spring, summer, and fall). The Rethinking Lawns Research Plots were installed in 2022 at the Chicago Botanic Garden, Glencoe, Illinois. Lowercase letter indicates significant difference among Season.

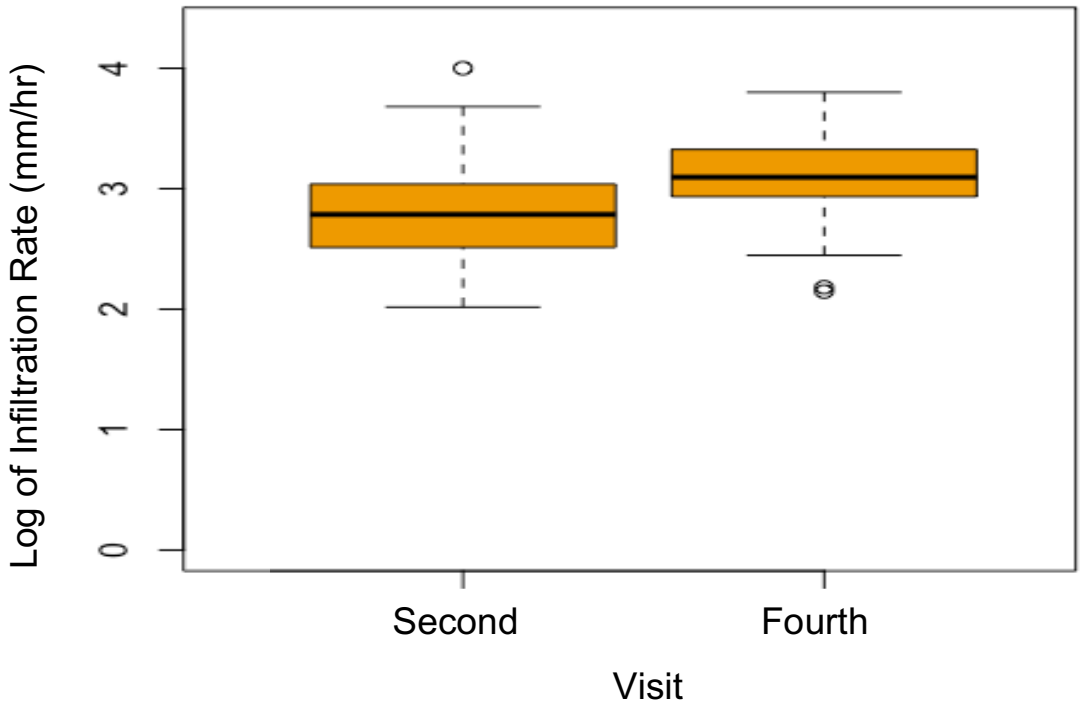


Figure 3H. The log of the infiltration rate of plugged treatments throughout one year (p = 0.01). The second and fourth visit (fall) vs the log of infiltration rate (mm/hour). Nine replicates of each treatment with data collected four times (June 2023, September 2023, April 2024, and September 2024) throughout three seasons (spring, summer, and fall). The Rethinking Lawns Research Plots were installed in 2022 at the Chicago Botanic Garden, Glencoe, Illinois. Lowercase letter indicates significant difference among visits.

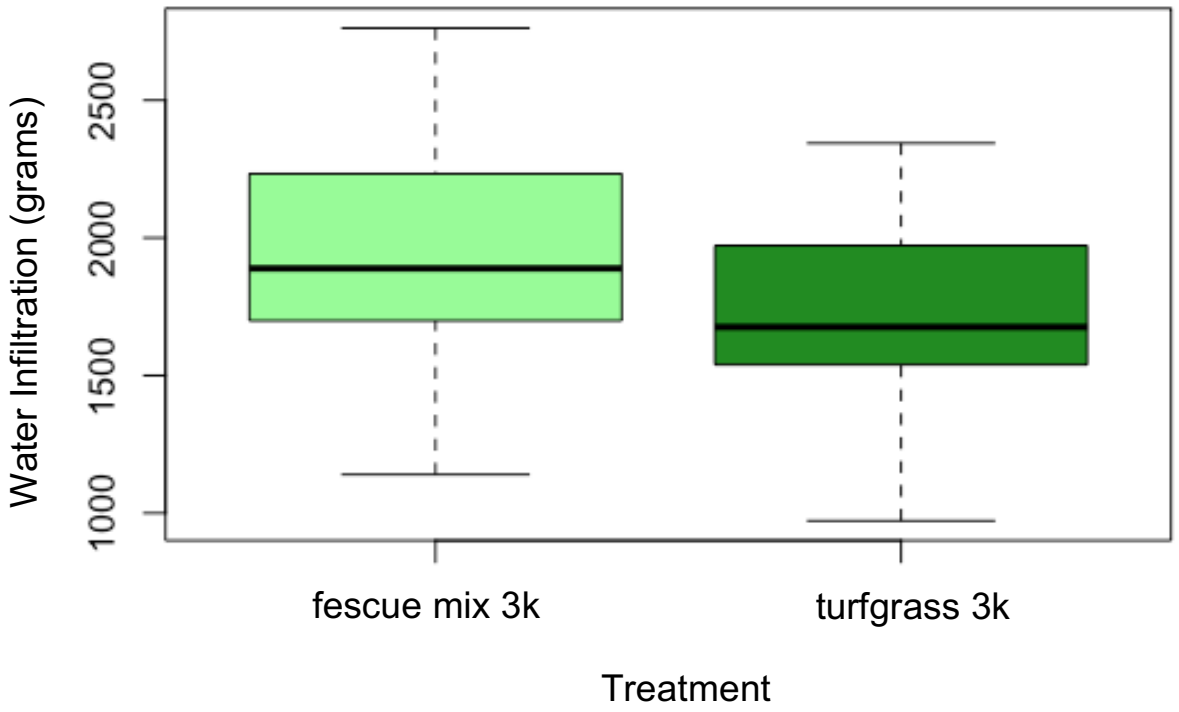


Figure 4A. The water infiltration of 3k treatments (t-test, $p = 0.1$). Fescue mix 3k and turfgrass 3k treatments vs the water infiltration (grams). Six replicates of each treatment with data collection at 6 and 12 weeks. Established in greenhouse at the University of Michigan-Flint, Flint, Michigan.

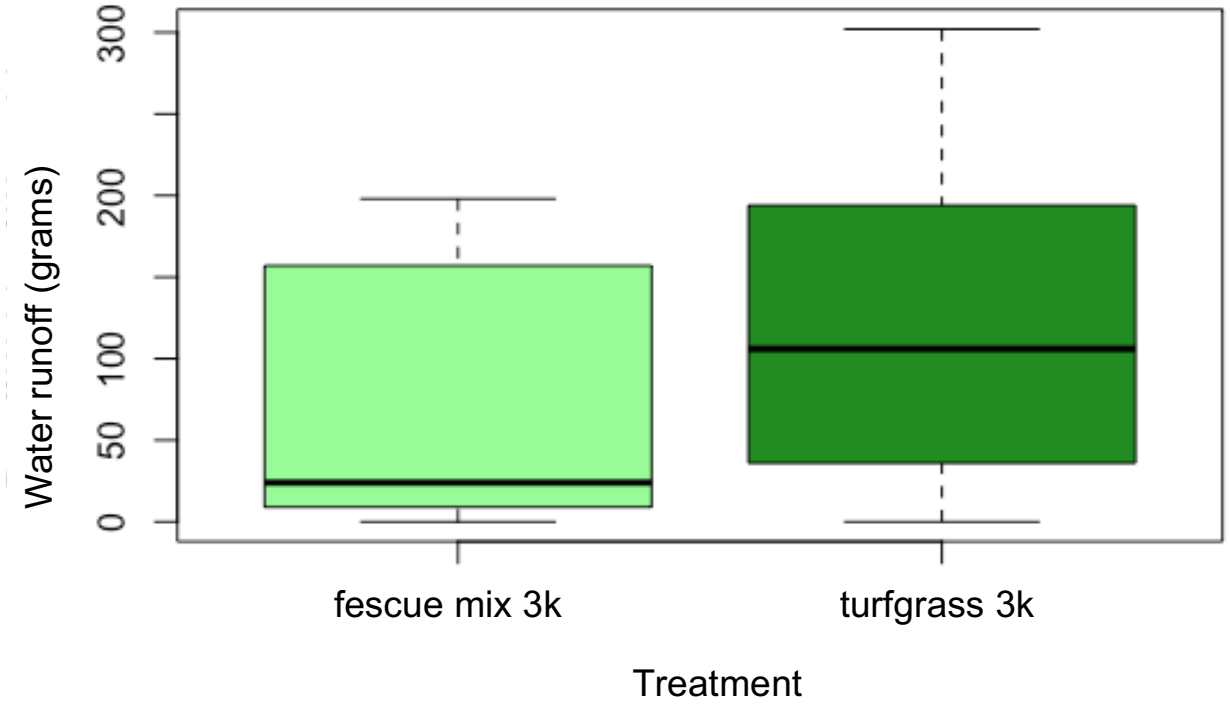


Figure 4B. The water runoff in 3k treatments (t-test, $p = 0.2$). Fescue mix 3k and turfgrass 3k treatments vs runoff (grams). Six replicates of each treatment with data collection at 6 and 12 weeks. Established in greenhouse at the University of Michigan-Flint, Flint, Michigan.

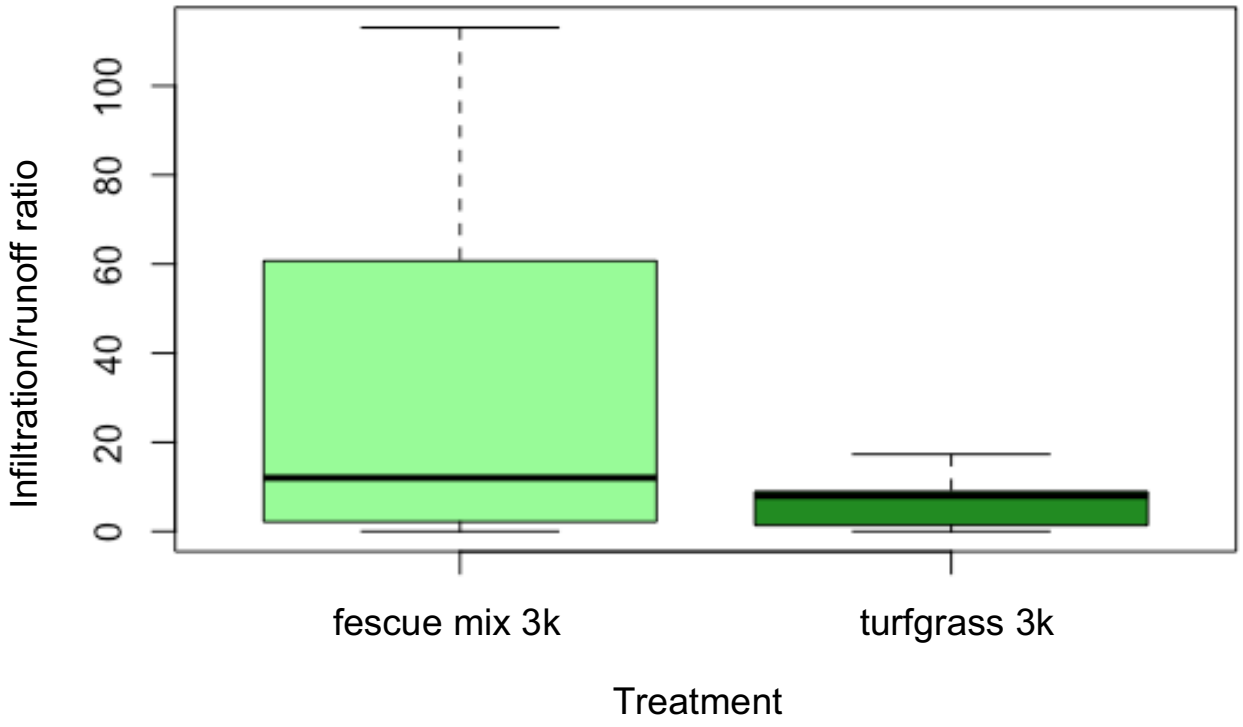


Figure 4C. The infiltration/runoff ratio in 3k treatments (t-test, $p = 0.1$). Fescue mix 3k and turfgrass 3k treatments vs the infiltration/runoff ratio. Six replicates of each treatment with data collection at 6 and 12 weeks. Established in greenhouse at the University of Michigan-Flint, Flint, Michigan.

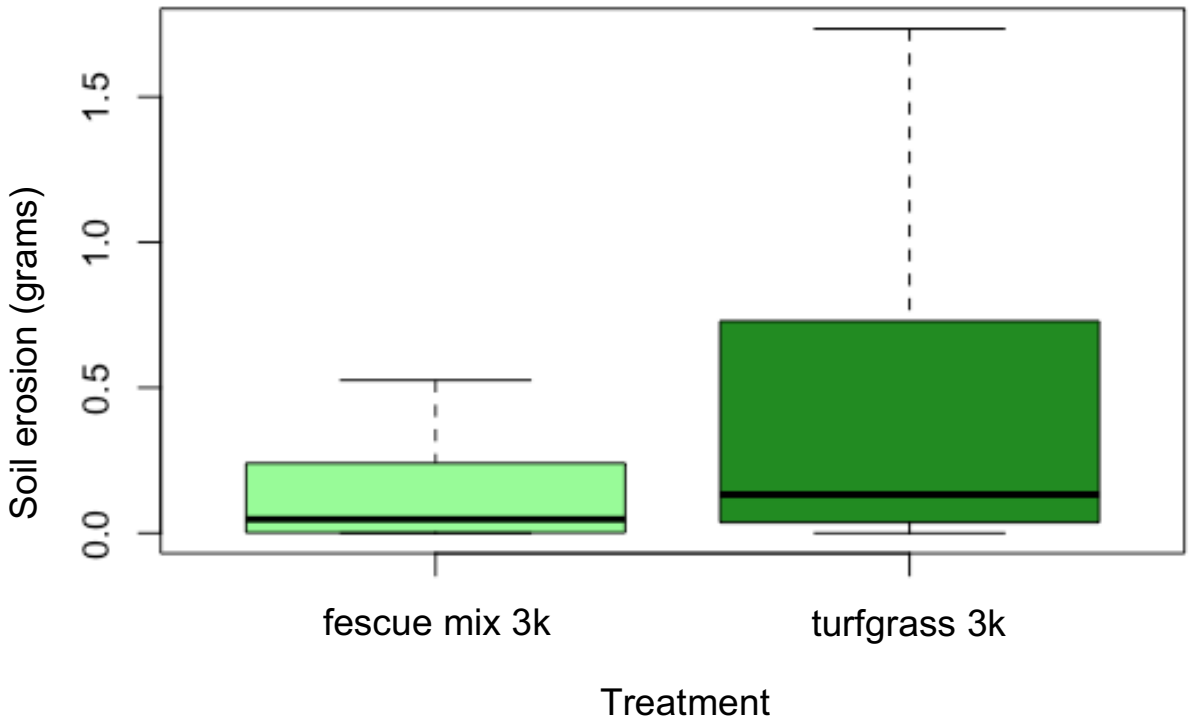


Figure 4D. The soil erosion in 3k treatments (t-test, p = 0.06). Fescue mix 3k and turfgrass 3k treatments vs soil erosion (grams). Six replicates of each treatment with data collection at 6 and 12 weeks. Established in greenhouse at the University of Michigan-Flint, Flint, Michigan.

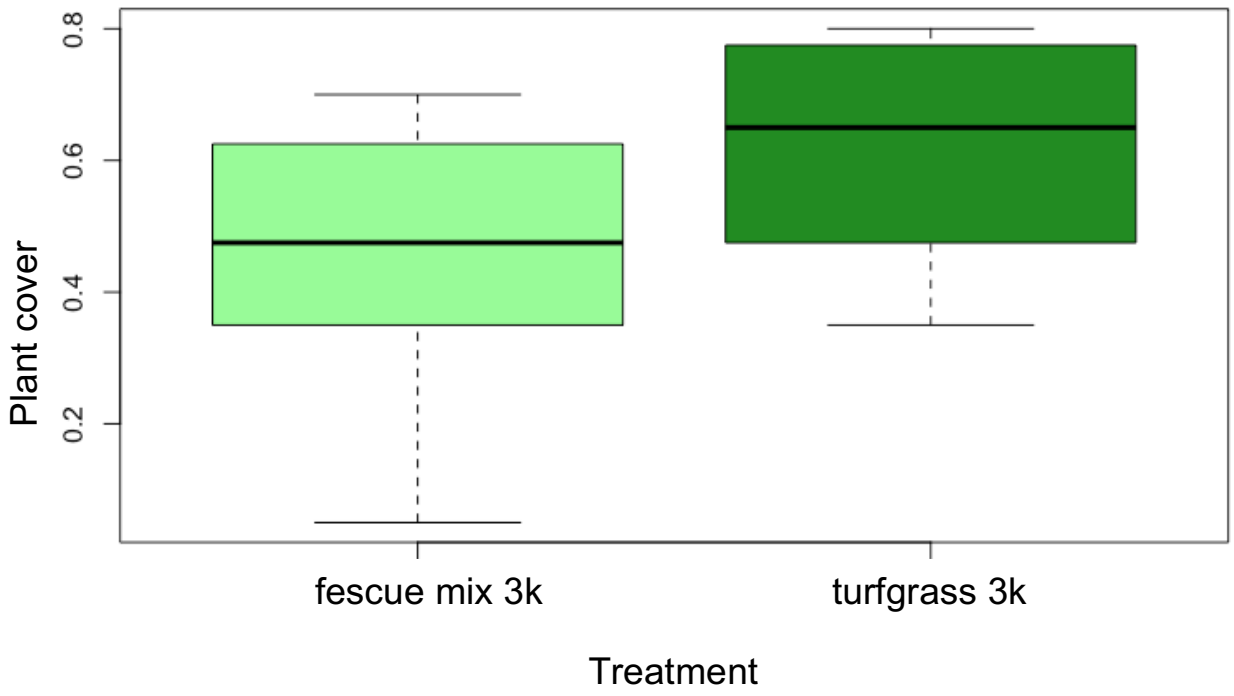


Figure 4E. The plant cover of 3k treatments (t-test, $p = 0.49$). Fescue mix 3k and turfgrass 3k treatments vs plant cover (%). Six replicates of each treatment with data collection at 6 and 12 weeks. Established in greenhouse at the University of Michigan-Flint, Flint, Michigan.

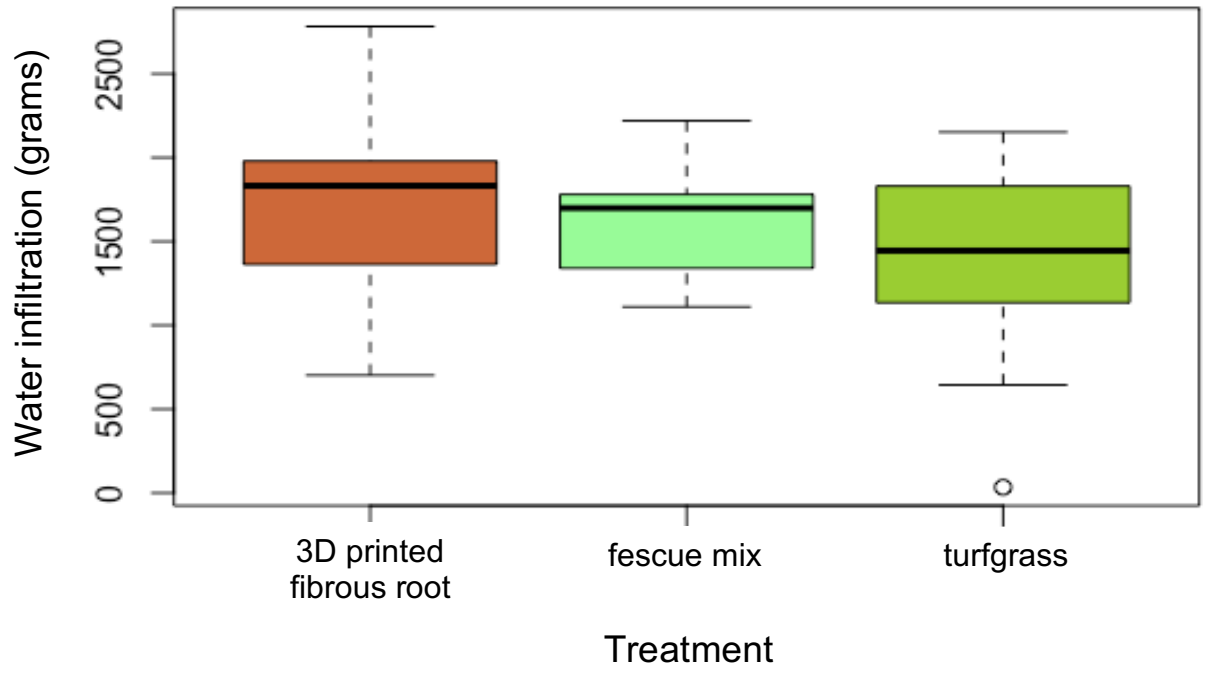


Figure 5A. The water infiltration of fibrous root treatments (ANOVA, p = 0.2). Fescue mix, turfgrass, and 3D printed artificial fibrous root treatments vs the water infiltration (grams). Six replicates of each treatment with data collection at 6 and 12 weeks. Established in greenhouse at the University of Michigan-Flint, Flint, Michigan.

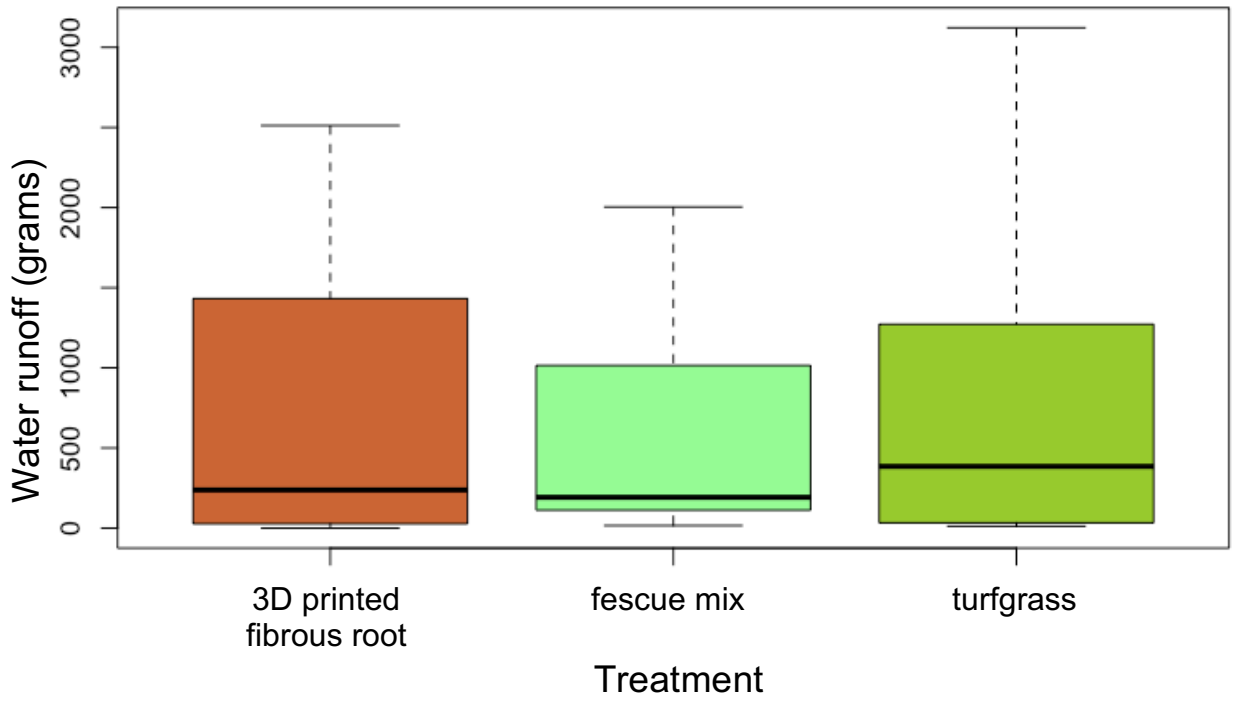


Figure 5B. The water runoff in fibrous root treatments (ANOVA, p = 0.8). fescue, turfgrass, and 3d printed artificial fibrous root treatments vs runoff (grams). Six replicates of each treatment with data collection at 6 and 12 weeks. Established in greenhouse at the University of Michigan-Flint, Flint, Michigan.

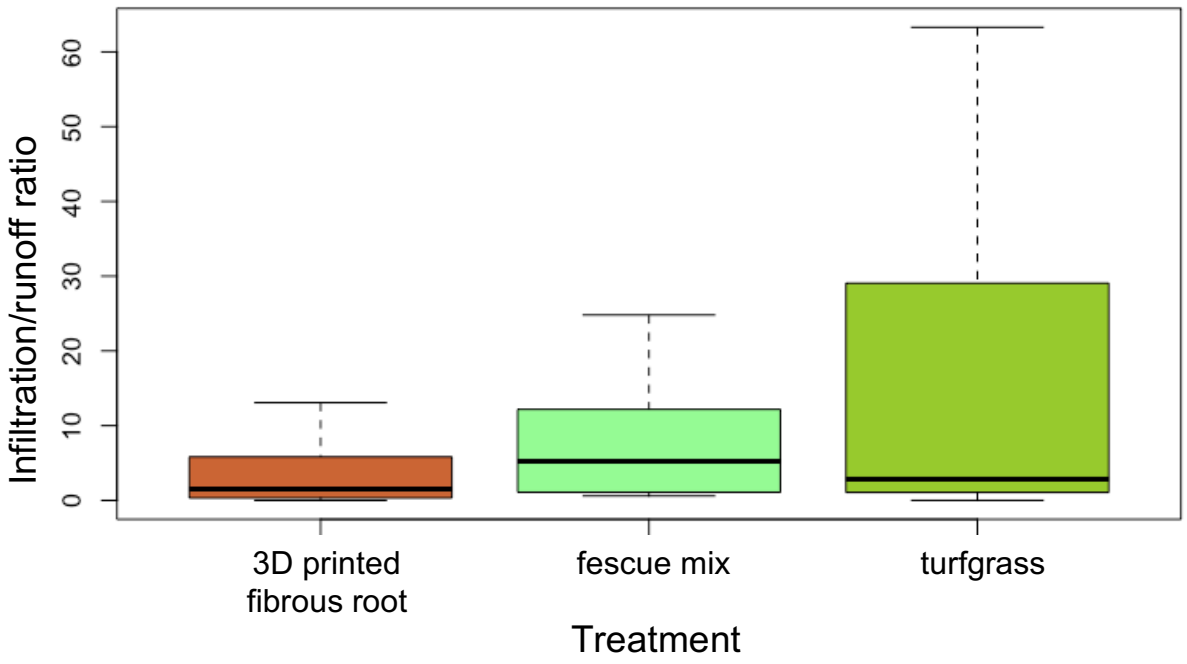


Figure 5C. The infiltration/runoff ratio in fibrous root treatments (ANOVA, $p = 0.1$). Fescue mix, turfgrass, and 3D printed artificial fibrous root treatments vs infiltration/runoff ratio. Six replicates of each treatment with data collection at 6 and 12 weeks. Established in greenhouse at the University of Michigan-Flint, Flint, Michigan.

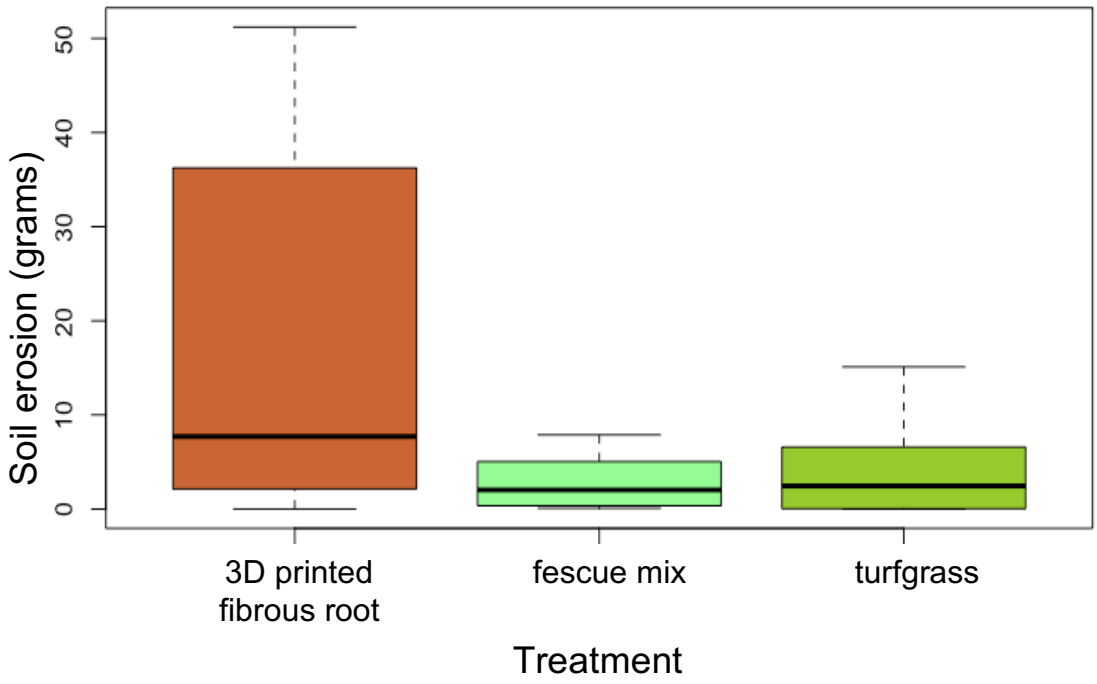


Figure 5D. The soil erosion in fibrous root treatments (ANOVA, $p = 0.01$*). Fescue mix, turfgrass, and 3D printed artificial fibrous root treatments vs soil erosion (grams). Six replicates of each treatment with data collection at 6 and 12 weeks. Established in greenhouse at the University of Michigan-Flint, Flint, Michigan.

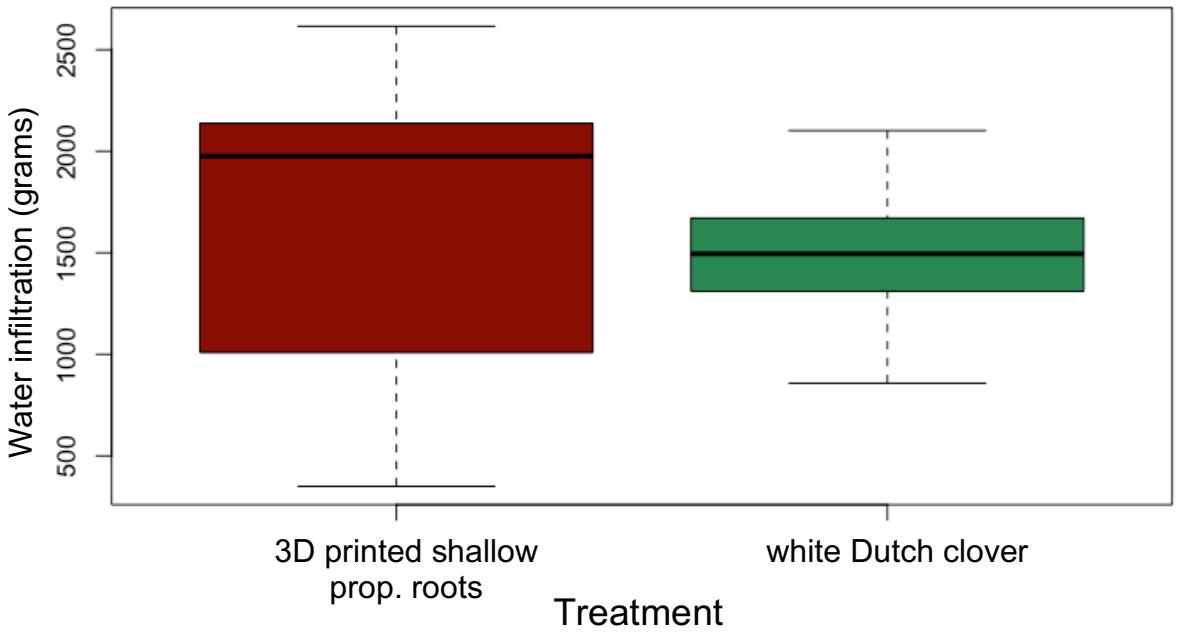


Figure 6A. The water infiltration of shallow propagative root treatments (t-test, $p = 0.6$). White Dutch clover and 3D printed artificial shallow propagative root treatments vs the water infiltration (grams). Six replicates of each treatment with data collection at 6 and 12 weeks. Established in greenhouse at the University of Michigan-Flint, Flint, Michigan.

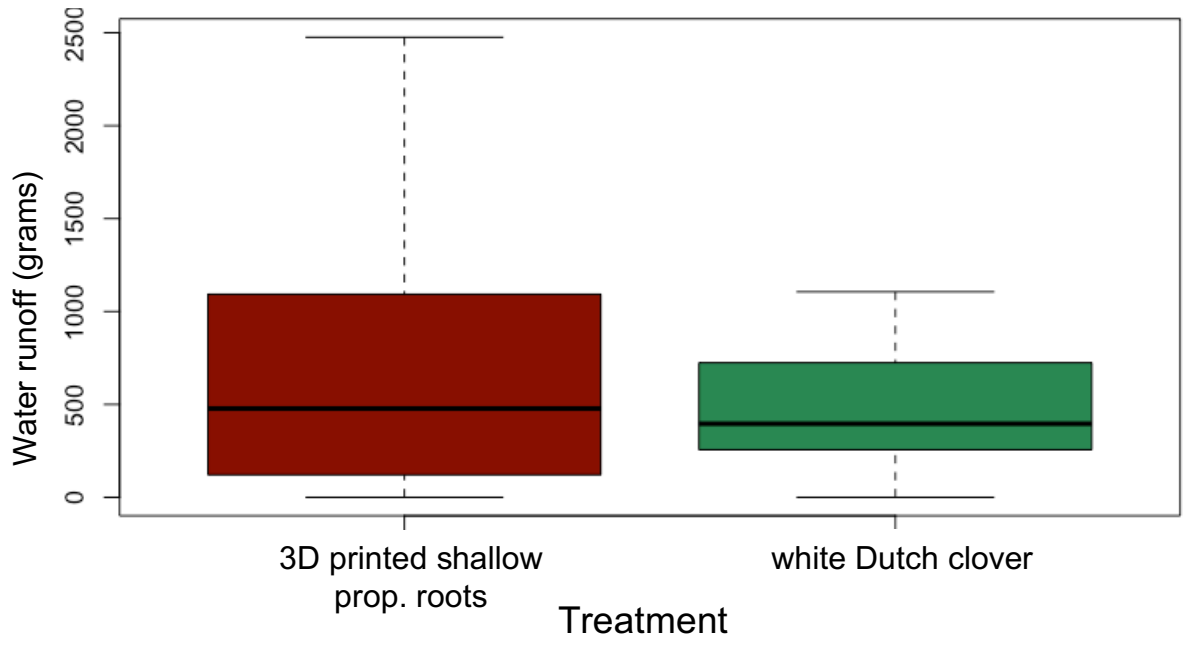


Figure 6B. The water runoff of shallow propagative root treatments (Mann-Whitney U test, p = 0.6). White Dutch clover and 3D printed artificial shallow propagative root treatments vs runoff (grams). Six replicates of each treatment with data collection at 6 and 12 weeks. Established in greenhouse at the University of Michigan-Flint, Flint, Michigan.

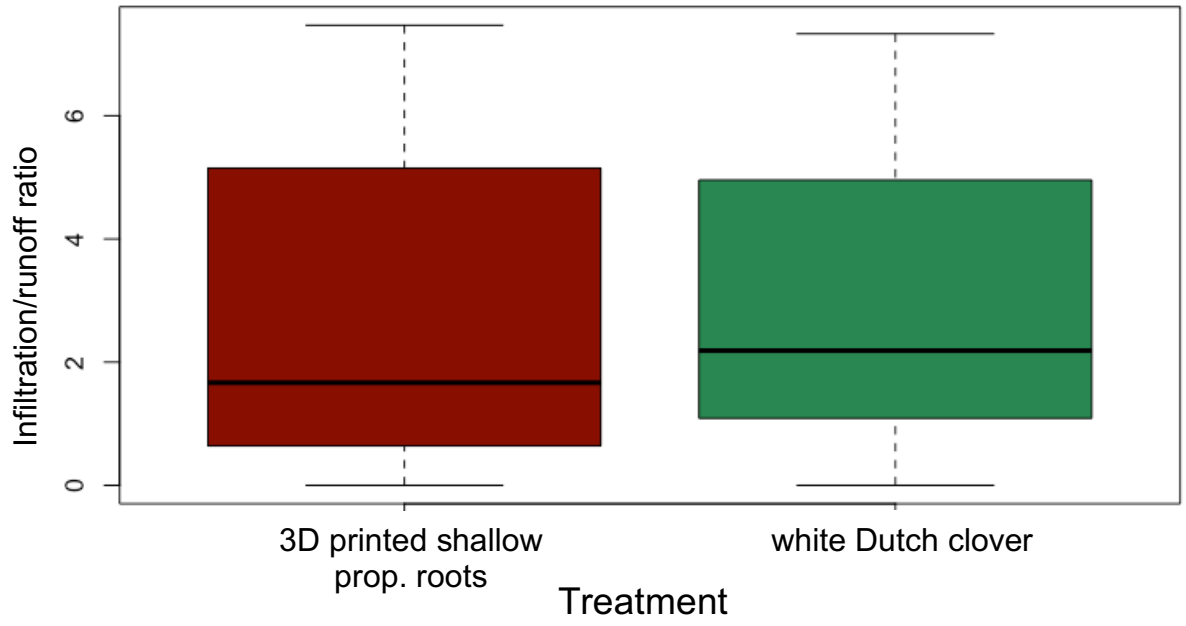


Figure 6C. The infiltration/runoff ratio in shallow propagative root treatments (Mann-Whitney U test, $p = 0.6$). White Dutch clover and 3D printed artificial shallow propagative root treatments vs the infiltration/runoff ratio. Six replicates of each treatment with data collection at 6 and 12 weeks. Established in greenhouse at the University of Michigan-Flint, Flint, Michigan.

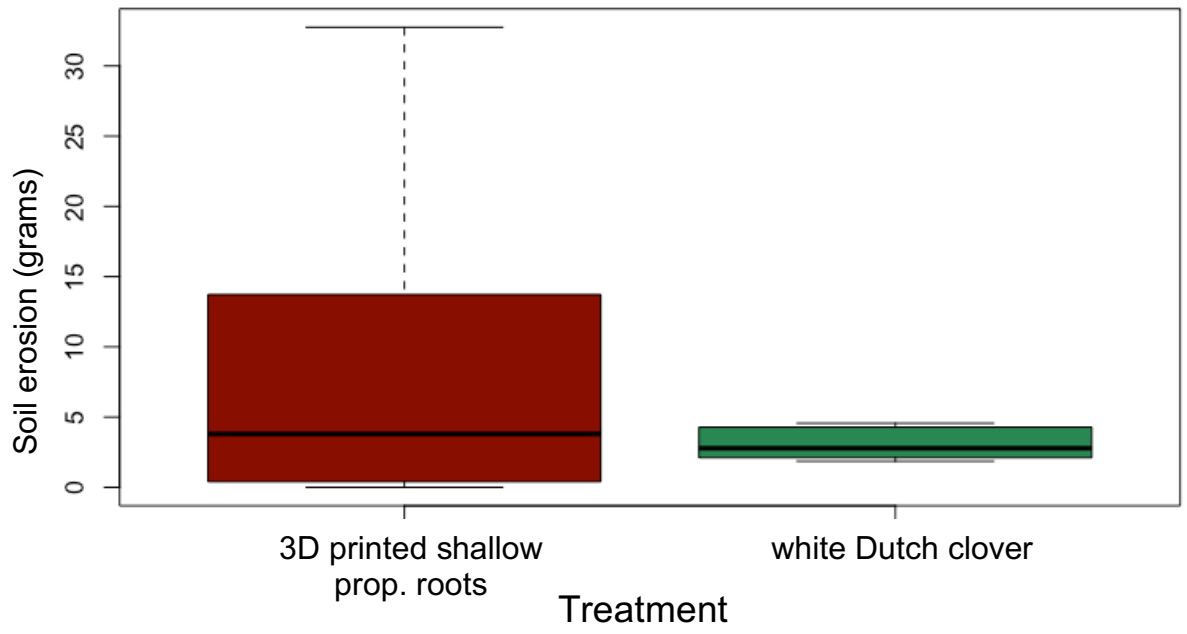


Figure 6D. The soil erosion in shallow propagative root treatments (Mann-Whitney U test, p = 0.6). White Dutch clover and 3D printed artificial shallow propagative root treatments vs the soil erosion (grams). Six replicates of each treatment with data collection at 6 and 12 weeks. Established in greenhouse at the University of Michigan-Flint, Flint, Michigan.

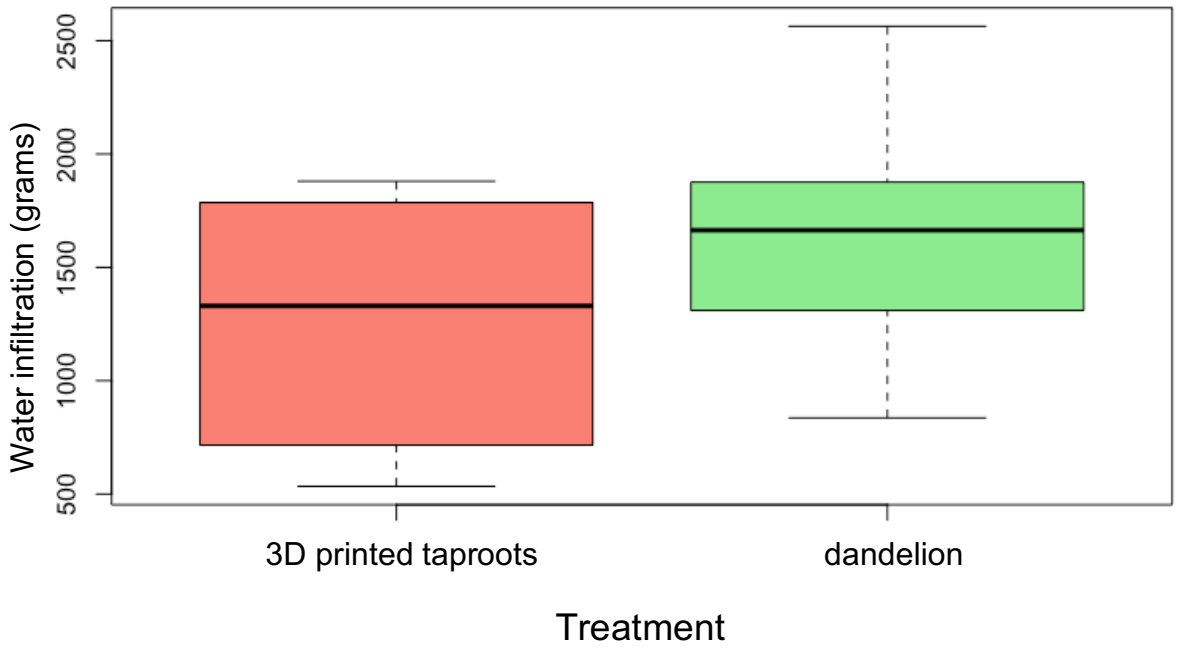


Figure 7A. The water infiltration in taproot treatments (Mann-Whitney U test, $p = 0.5$). Dandelion and 3D printed artificial taproot treatments vs the water infiltration (grams). Six replicates of each treatment with data collection at 6 and 12 weeks. Established in greenhouse at the University of Michigan-Flint, Flint, Michigan.

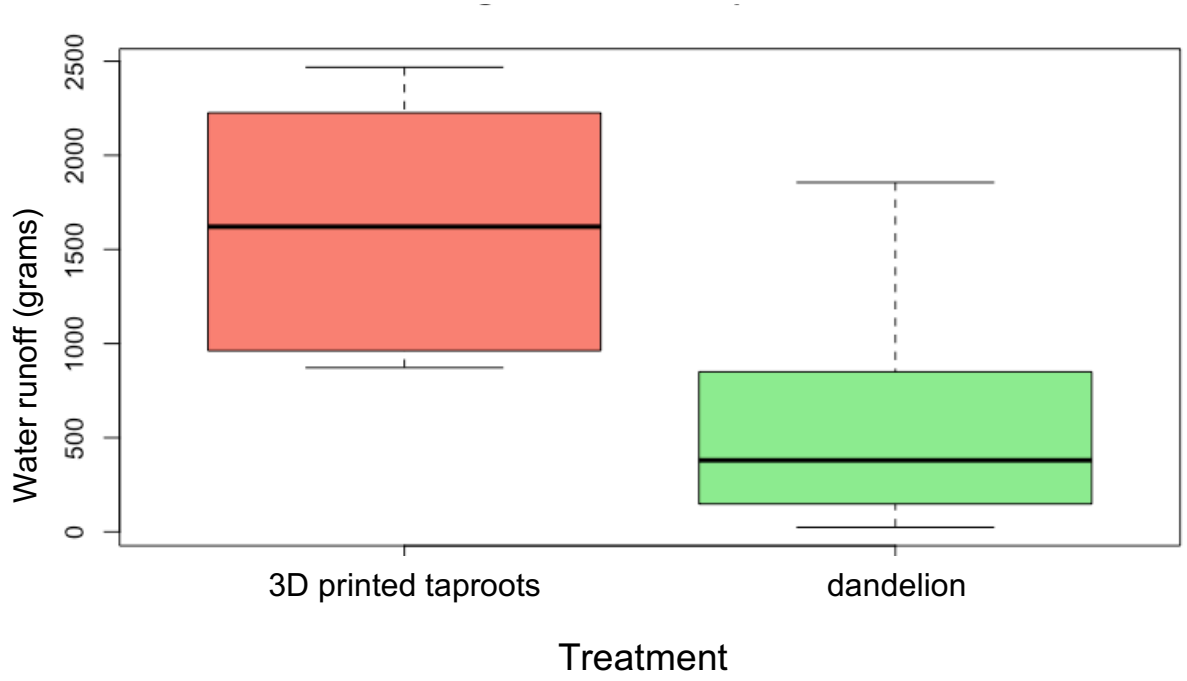


Figure 7B. The water runoff in taproot treatments (Mann-Whitney U test, $p = 0.01$). Dandelion and 3D printed artificial taproot treatments vs the runoff (grams). Six replicates of each treatment with data collection at 6 and 12 weeks. Established in greenhouse at the University of Michigan-Flint, Flint, Michigan.

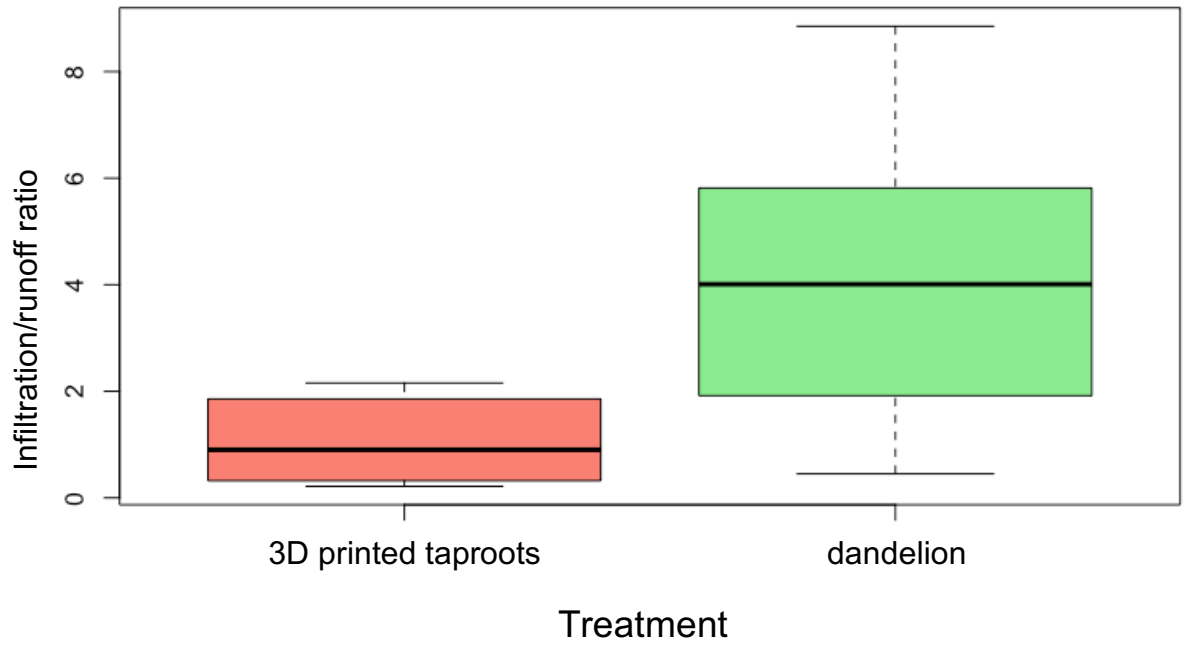


Figure 7C. The infiltration/runoff ratio in shallow taproot treatments (Mann-Whitney U test, p = 0.1). Dandelion and 3D printed artificial taproot treatments vs the infiltration/runoff ratio. Six replicates of each treatment with data collection at 6 and 12 weeks. Established in greenhouse at the University of Michigan-Flint, Flint, Michigan.

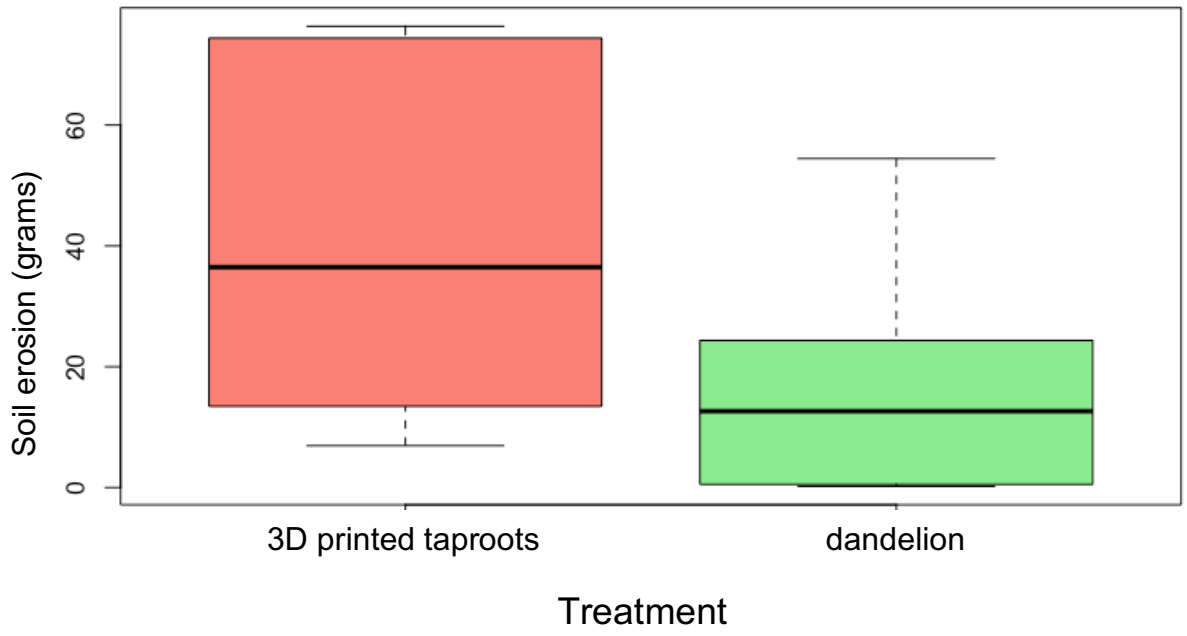


Figure 7D. The soil erosion in taproot treatments (Mann-Whitney U test, $p = 0.08$). Dandelion and 3D printed artificial taproot treatments vs soil erosion (grams). Six replicates of each treatment with data collection at 6 and 12 weeks. Established in greenhouse at the University of Michigan-Flint, Flint, Michigan.