

Initial Performance of Trees in an Urban Stormwater Bioretention System

Ethan Andrew Apisa

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P. Eric Wiseman, Chair

John R. Seiler

Daniel L. McLaughlin

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ABSTRACT

Stormwater runoff is an issue in urban areas as impervious surfaces increase. Various bioretention systems that incorporate trees have been developed but are expensive, technically complex, and require large amounts of space, which limits their widespread use as a stormwater solution. This study investigated a novel design for a bioretention system that is less complex and may hold promise as an inexpensive approach to capturing runoff and growing trees near impervious surfaces. The system comprises a large bed of gravel surrounding a trench of topsoil planted with trees. The gravel bed captures and retains stormwater from adjacent hardscapes. Roots extending outward from the topsoil into the gravel bed absorb and recycle captured water through transpiration. A full-scale field prototype of this system was constructed adjacent to a parking lot on the campus of Virginia Tech in Blacksburg, VA in spring 2020. The system was planted with three London planetree (*Platanus × acerifolia* ‘Morton Circle’), which were compared to three control trees of the same species planted concurrently in nearby native control soil. The purpose of this study was to monitor stormwater capture by the bioretention system and evaluate tree growth and physiological function during the second growing season following planting. Because the topsoil in the gravel bed was of better quality than the native control soil, trees in the gravel bed exhibited greater water use efficiency and had larger and denser crowns during the study period. Under prevailing precipitation conditions, the gravel bed rarely captured runoff exceeding its volume capacity, and the residence time of water in the system rarely lasted more than 48 hours before draining via deep infiltration into the underlying subsoil.

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CHAPTER 1 – INTRODUCTION

1.1 Background and Rationale of Project

The US population has been growing as people continue to move to low-density, vehicle-dependent, suburban areas (Kahn, 2000). The tendency of the middle-class to live in suburban areas has been reinforced over the years with vehicle and travel innovations (Mieszkowski and Mills, 1993). Construction of these neighborhoods and roads removes soil and tree cover from previously undisturbed land. Removal and disturbance of the natural environment can have negative effects on the microclimate and surrounding ecosystems. This often is not taken into consideration during the planning and construction of new development. The rapid expansion of urban areas has been termed “urban sprawl” (Frumkin, 2002), which can be defined as low-density, dispersed, and auto-dependent (Hasse and Lathrop, 2003). The auto-dependency of these suburban areas creates more hardscapes for streets and parking. Part of the reason for auto-dependency is the zoning laws that keep different land uses, such as housing, retail, offices, and public spaces separate from each other (Frumkin, 2002).

Hardscape development is often associated with removing tree cover, vegetative ground cover, and permeable topsoil, then replacing it with impermeable surfaces, which makes it impossible for stormwater to enter the groundwater system. Low-density residential and commercial developments typically have much more total impervious surface area than that of higher-density developments on a regional scale (Afield et al., 2011). Impervious surfaces can include streets, sidewalks, driveways, and other surfaces that do not allow water to pass through them. These surfaces cause water from storm events to build up and create the potential for flooding. Poorly planned urban areas make the area more vulnerable to floods (Jha et al., 2011).

The combination of increasing infrastructure and construction along with a forecasted increase in precipitation intensity due to climate change in many parts of the country results in a greater risk of potential flooding (Petit-Biox et al., 2017). In the US, flooding causes more than \$2.5 billion in damages and 1,254 deaths per year (Rodriguez et al., 2009). The more impervious surface there is, the more complications that occur during large precipitation events. Some economic consequences include damage to gray infrastructure, roads, and greenways. This can cause soil erosion and degradation of streams. When there is more inflow than sewers can hold, the gray infrastructure system can overflow, causing stormwater and untreated sewage waste to spill over into nearby waterways (Berland et al. 2017). This is nonpoint source pollution that is a major threat to the quality of drinking water and is linked to chronic and acute illness (Afield et al., 2011). This pollution also leads to environmental issues. Waste and pollution that contaminate natural waterways disturb the ecosystem. There are ways to use nature-based solutions to help mitigate these negative effects from stormwater runoff.

Nature-based solutions are systems that incorporate green infrastructure such as plants and engineered soils into urban areas to address environmental issues caused by urbanization and impervious surfaces. These solutions bring value-added services to stormwater retention systems because they provide ecosystem services in addition to stormwater control, such as shade and air filtration, that benefit the residents of urban areas (Ulmer et al., 2016). Escobedo et al. (2011) define these services as “the components of urban forests that are directly enjoyed, consumed, or used to produce specific, measurable human benefits.” They bring many benefits to the community as well as mitigate issues caused by urbanization, such as the urban heat island, crime, and carbon sequestration. Trees mitigate the urban heat island effect and can help achieve energy savings in the temperature-reduced area (Memnon et al., 2007). A study done by Kondo

et al. (2015) showed a significant decrease in narcotic manufacturing and burglaries within a half-mile radius of newly constructed green stormwater infrastructure in the city of Philadelphia.

Tree canopy cover is a key element of many of the services the urban forest provides (Nowak and Greenfield, 2020). Nature-based solutions that implement trees utilize the tree canopy and root system of these plants and their role in the urban water cycle by giving their roots direct access to stormwater runoff. Urban tree canopies reduce stormwater runoff directly through canopy interception of precipitation (Li et al., 2017). Because of these value-added ecosystem services of trees, there has been an explosion of research and technology development of bioretention systems that incorporate trees to mitigate stormwater runoff. However, incorporating green infrastructure for bioretention around impervious surfaces can be challenging due to size, expense, and complexity. Furthermore, these systems require ongoing maintenance to perform properly and not adversely affect surrounding land use. Urban environments create harsh growing conditions for trees due to limited soil volumes and access to water, resulting in poor growth and mortality (Grey et al., 2018a).

1.2 Scope and Aim of Project

The scope of this project was a demonstration and pilot test of a new concept for a tree-based stormwater bioretention system that might be cheaper and less complex than other bioretention technology that currently exists. For this study, we used a novel design first imagined by colleagues at the US Forest Service and the University of Tennessee. A prototype of this system was constructed in 2020 adjacent to a 0.18-ha parking lot on the Virginia Tech campus in Blacksburg, Virginia. This system comprises a belowground gravel bed surrounding a trench filled with topsoil in which trees are planted. The gravel bed provides both stormwater runoff storage and space for root systems to anchor trees and absorb water. This system utilizes

the role of trees in the water cycle and their ability to absorb water with their roots to mitigate the volume of stormwater runoff. The goal of this design is to retain water for tree growth, as opposed to it becoming runoff and causing harm downstream.

The aim of this project was to gather preliminary data on growth and development of the trees planted into the bioretention system and to monitor stormwater runoff captured by the system. This is the first stage of a long-term observation of the system to evaluate its effectiveness for growing trees and capturing runoff. The objectives of this study were:

- 1) To measure tree growth and physiological responses to conditions in the gravel bed system.
- 2) To compare soil conditions and tree performance between the gravel bed system and a nearby typical landscape setting serving as a control.
- 3) To monitor and describe water retention and outflow events of the gravel bed system under ambient weather conditions.

CHAPTER 2 – LITERATURE REVIEW

2.1 Stormwater Runoff

Stormwater runoff is becoming more prevalent as cities expand into rural areas. Americans are attracted to urban areas because it has created opportunities for a higher level of housing and land ownership (Nechyba et al., 2004). Extensive roads, parking lots, and other impervious surfaces need to be constructed for the residents of suburbs to shop or go to work (Frumkin, 2002). The impervious surface area has a positive correlation with stormwater runoff volume. While many conventional stormwater management practices, such as retention ponds, are effective at reducing peak flow and extending flow during storm events (Hancock et al., 2010), they have drawbacks compared to green stormwater infrastructure, which utilizes vegetation to achieve the goal of stormwater mitigation. Adding vegetation to these retention systems provides more ecosystem services and serves as a method of low-impact development (LID), which is a management strategy that retains and treats stormwater on-site (Rippy et al., 2022). Some LID systems include green roofs, pervious pavers, rainwater cisterns, and bioswales. LIDs are considered more ecologically sensitive than conventional piping and retention ponds (Chen et al., 2016). Traditional stormwater runoff management practices have human health consequences associated with them (Gaffield et al., 2003). A study done by Irwin et al. (2008) showed that stormwater ditches, retention ponds, and detention ponds accounted for 84% of mosquito larvae collected from urban wet environments in the upper Midwest.

2.2 Trees as Stormwater Bioretention Systems

Coupled with expanding impervious surfaces, environmental issues are magnified by the urban setting. Trees play a vital role in mitigating these issues in a variety of ways. Tree crowns

and leaves provide ecosystem services directly related to the hydrological cycle. Precipitation interception by tree canopies is very important when the ground cover below is impervious. The canopies of urban trees intercept rainfall and reduce the amount of water that reaches the ground below (Livesley et al., 2016). Urban tree canopy cover is one metric used to quantify the benefits of urban forests because many urban forest ecosystem services are directly related to canopy size and healthy leaves (Nowak et al., 2012). Stormwater running across impervious surfaces picks up pollutants and toxins that are a threat to water quality. Yet trees can be used as biofiltration systems to improve the quality of stormwater by removing pollutants and waste (Xiao et al., 2016). A study by Denman et al. (2016) showed oxidized nitrogen concentration in stormwater was reduced in an experimental street tree biofiltration system. The goals of stormwater management vary across municipalities and their local characteristics, but should all focus on sustainable opportunities to improve environmental conditions (Barbosa et al., 2012).

2.3 Other Types of Bioretention Systems

While the focus of this paper is on a tree-based bioretention system, there are other systems that have similar objectives and work in concert with tree-based systems for a holistic approach to stormwater green infrastructure. Some are based strictly on hardscape materials while others incorporate various forms of woody and non-woody vegetation. Bioswales are an alternative to conventional retention ponds that incorporate hydric vegetation to filter and transpire stormwater that is conveyed from adjacent hardscapes into the swale. The key component of these systems is vegetation, which absorbs runoff and pollutants (Hatt et al., 2009). There is a wide variety of vegetation that can be used, such as grasses, trees, and shrubs (Scharenbroch et al., 2016). The plants utilize their below-ground biomass and act as a biofilter. Another form of vegetation-based bioretention systems are rain gardens. They are an effective

LID system and have been recommended as a best management practice (Dietz and Clausen, 2005). They improve infiltration rates by incorporating vegetation into a depressed, mulched area to capture rainwater. A study done by Dietz and Clausen (2005) used three shrub species (chokeberry, winterberry, and compact inkberry) in two raingardens to test flow retention and pollutant concentrations impacts. They found that 98% of the water that entered the raingarden left as subsurface flow. Their conclusion was that rain gardens provided runoff control but poor water quality renovation.

Pervious pavers are a LID system that can be used to increase stormwater infiltration into the soil. The space between the pavers is filled with a washed and graded stone that allows water to be filtered by the several bedding layers below (Rowe et al., 2009). A study completed by Chen et al. (2014) showed that pervious pavers were most effective at removing pollution and runoff compared to a bioretention cell and grass swale. While pervious pavers have shown to be very effective at mitigating stormwater, they do not provide the value-added ecosystem services of green infrastructure such as cooling, air cleansing, and wildlife habitat. Another common issue with urban hardscapes not addressed by pervious pavers is compact soil, which limits water infiltration and storage in the soil—both are important for minimizing runoff as well as sustaining landscape trees planted nearby (Bartens et al., 2008). Compaction also makes root growth and water and nutrient access difficult for trees, leading to stunted growth and lower vitality. Trees need a robust root system to become established in the landscape. Soil compaction comes from urban infrastructure development and use (Day et al., 2010). A LID solution to inadequate soil volume for water storage and root growth is suspended pavement, which transmits the weight load from vehicles and pedestrians to a compact subbase (Tirpak et al., 2019). The pavement is suspended by pillars extending between the subsoil and the surface

concrete, leaving an uncompacted layer of soil in between. The design of these systems relieves topsoil compaction that typically occurs in an urban setting, creating a more natural soil setting for the tree roots. Studies have shown that trees growing in uncompacted soil volume grow faster, are healthier in appearance, and have larger canopies compared to trees growing in compact urban soils (Page 2016; Smiley et al., 2006).

2.4 Prior Studies on Trees and Stormwater Bioretention

Some similar studies have been done focusing on stormwater control measures involving trees in urban areas. Many of these studies investigate different species and their ability to function in LID and nature-based systems. A study by Scharenboch et al. (2016) examined tree growth and condition and their effects on the urban water cycle in bioswales adjacent to a parking lot in the Morton Arboretum main parking lot. They looked at trees in bioswales compared to trees in the native soil in control areas of the arboretum. This study included seven different species, three replicates of each species and environment, totaling 42 trees. The soil in the bioswales consisted of a sandy loam with a pH from 5.5 to 7.5. The most significant difference was in the bioswale soil, which had much less organic matter and lower soil moisture. They concluded that species with high stomatal conductance and large mature form are likely to contribute best to bioswale function (Scharenboch et al., 2016). This study puts an emphasis on how important species selection is for nature-based solutions in order to provide the greatest amount of ecosystem services. Another similar study by Grey et al. (2018b) compared the growth of *Acer campestre* (L.) within five different treatments. After 18 months, the trees in treatments irrigated with stormwater with an underdrain showed double the growth compared to the control trees. Their results suggest that irrigating establishing trees with stormwater can be highly beneficial to their growth (Grey et al., 2018b).

CHAPTER 3 – MATERIALS AND METHODS

3.1 Site Details

The study site was located on the campus of Virginia Tech in Blacksburg, Virginia. Blacksburg is in the valley and ridge physiographic region of Virginia, sitting about 633 meters above sea level (Fig. 1.). The Blacksburg area has a mean annual precipitation rate of 110.8 cm with May, June, and July being the wettest months (United States -- National Weather Service, 1999). The site chosen for the bioretention installation was adjacent to a 0.18 ha parking on the south portion of campus (37.214113, -80.417650). This location allows for the potential capture of stormwater runoff as well as public access for educational purposes (Fig. 1).



Figure 1. A map of Virginia Tech's campus in Blacksburg, Virginia showing the study site and adjacent parking lot outlined in red near bottom-center of map (from Sprouls, 2020).

3.2 Description of Gravel Bed System and Installation

The gravel bed bioretention system was designed and installed in early 2020 during an initial study aimed at finding a suitable location for a long-term demonstration area, examining the design and feasibility of the system, and selecting appropriate tree species to plant in the system (Sprouls, 2020). The design for the gravel bed system included three trees planted in a mineral soil bed surrounded by gravel (Fig. 2 and Fig. 3), as well as three control trees of the same species planted adjacent to the system in the native soil, which was previously disturbed from its natural state during construction of the parking lot several decades ago. The gravel in this system has a high porosity, allowing water to flow through it quicker than typical soil and allowing the pit to fill up with water. While the water slowly drains out of the system, it can then be absorbed by the tree roots. The gravel bed measures 14.6 m long x 5.5 m wide x 1.8 m deep (48' x 18' x 6'), and the mineral soil trench surrounded by gravel measures 12.2 m long x 1.3 m wide x 1.3 m deep (40' x 4' x 4'). The system has a 4" PVC pipe perforated underdrain that controls the depth of water accumulation during rain events so that the upper 45cm of soil does not stay saturated and asphyxiate tree roots near the surface of the gravel bed and mineral soil. The underdrain connects to a subsurface outflow pipe that delivers overflow water captured by the gravel bed to an earthen swale located downslope from the gravel bed. Construction of the system and planting of trees were completed in May 2020 (Fig. 4).

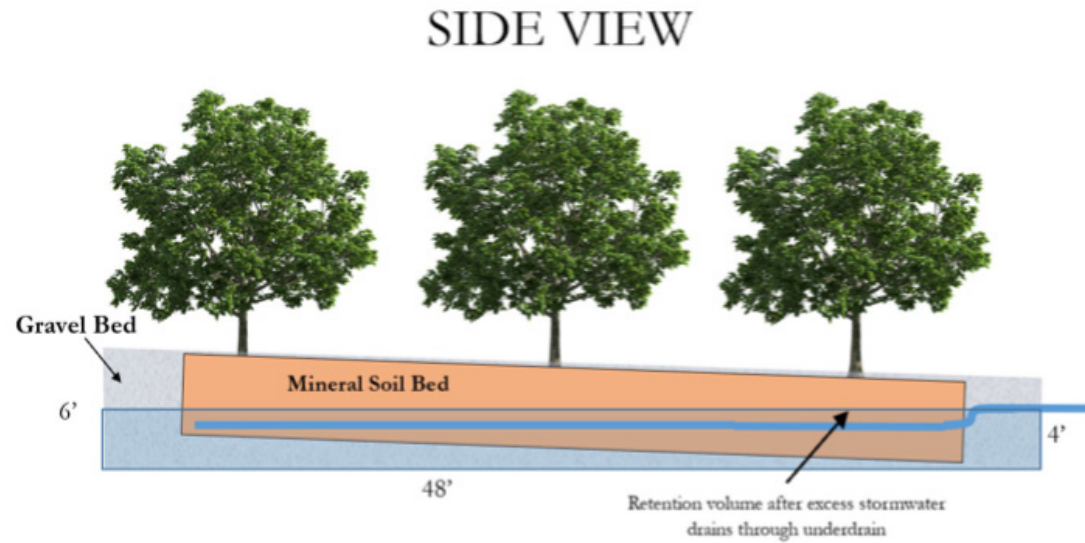


Figure 2. A side-view schematic of the gravel bed bioretention system from west to east aspect (from Sprouls, 2020).

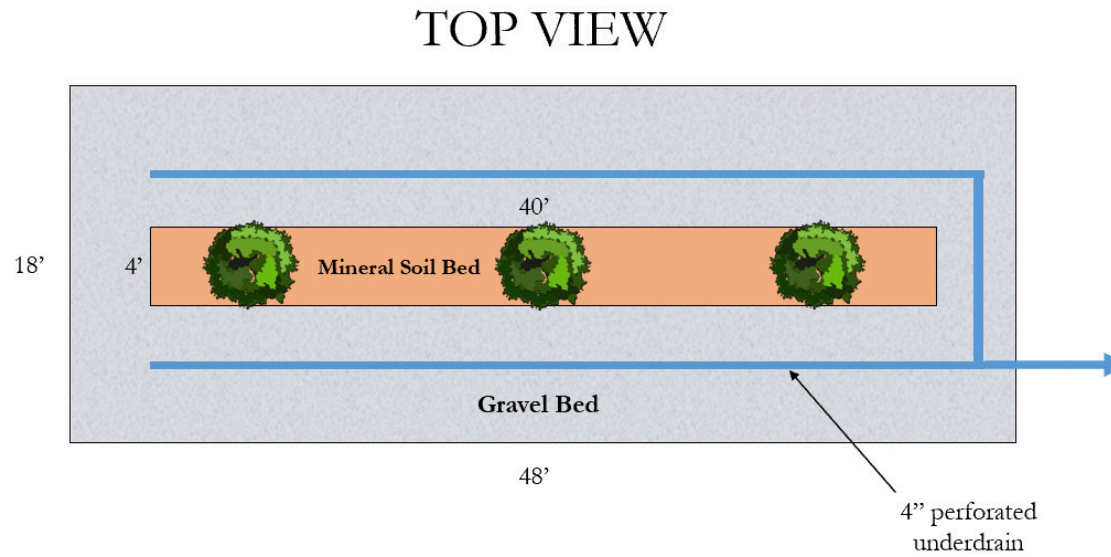


Figure 3. A top-view schematic of the gravel bed bioretention system from west to east aspect (from Sprouls, 2020).



Figure 4. View of gravel bed trees (top) and native soil control trees (bottom) looking toward the study site from the southwest in April 2022.

An extensive literature review of tree physiology and water relations was completed by Sprouls (2020) to select appropriate tree species to plant in the system. Based on the review, *Platanus x acerifolia* ‘Morton Circle’ was chosen for this site because of its physiological traits and availability in the nursery trade. It has rapid growth, so it will quickly fill in the gravel matrix with its fibrous root system (Sprouls, 2020). The trees had an average 5.1 cm trunk caliper and 61 cm diameter root ball (field-grown, balled-and-burlapped) at the time of planting in May 2020.

3.3 Soil and Root Measurements

Multiple soil and root attributes were measured around the trees growing in the native control soil and gravel bed soil during 2021 (Table 1). Bulk density and soil nutrients were measured in July of 2021. A slide hammer soil core sampler was used to extract samples for the bulk density test. The soil cores were extracted in metal cylinders measuring 5 cm long and 5 cm diameter. Each core extracted 98.2 cm³ of soil at a depth interval of 0 cm to 10 cm below the surface. Each tree had three soil core sampling locations, one to the north, one to the southeast, and one to the southwest, all 1.22 m out from the trunk (Fig. 5).

Table 1. Soil and root measurements collected around trees at the study site in 2021.

Measurement	Start and End Dates	Frequency
Soil Bulk Density	July 2021	Once
Soil Nutrient Analysis	July 2021	Once
Soil Moisture (Vol.)	July 2021 – October 2021	Weekly
Root Core Extraction	December 2021	Once

Each sample location had two cores taken at different depths, one right below the first. The first sample was taken at 0-5 cm, and the second sample was taken at 6-10 cm. The fresh weight of the samples was taken before being dried in an oven at 30° C for 48 hours. After the drying was complete, the final weight was taken for the bulk density calculation. The samples were then sieved through a 2 mm sieve to sort the coarse fragments, coarse woody debris, and fine earth fraction of soil. Each component was then weighed separately and volume calculated using water displacement in a graduated cylinder.

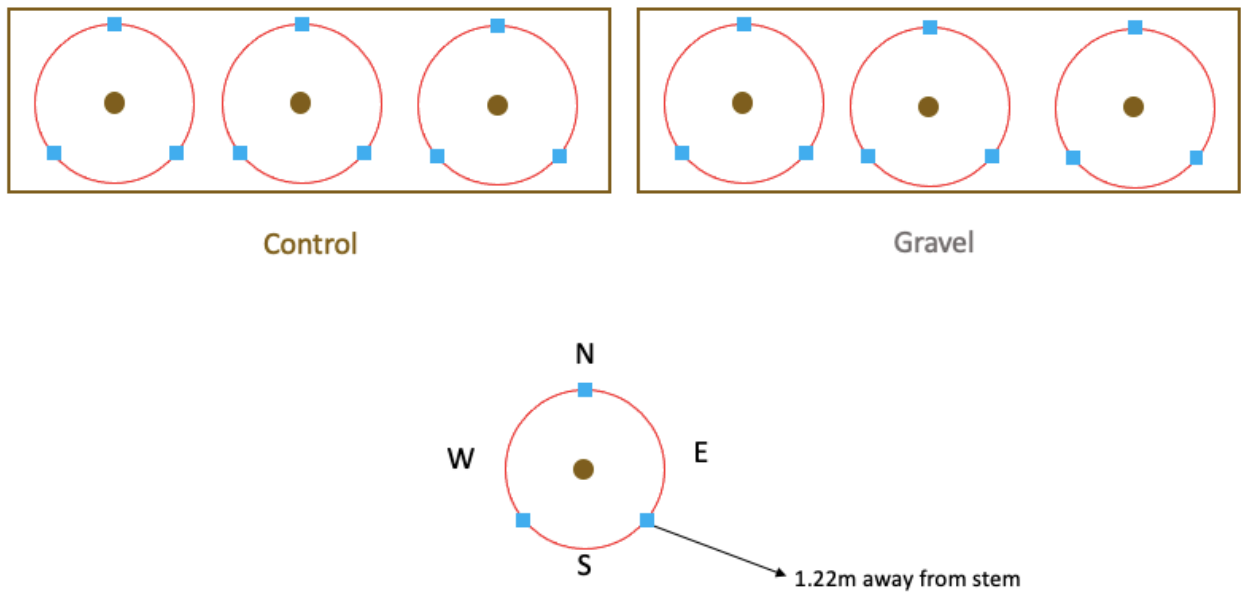


Figure 5. The sampling schematic for the bulk density samples for the control and gravel bed trees taken in July 2021.

A bucket augur was used to gather soil samples from the root zone of each tree for a fertility analysis performed by the Virginia Tech Soil Testing Laboratory. Offset from the location of the bulk density core extractions, the bucket augur was used to extract three sub-samples of soil to a depth of 20 cm at a distance of 1.22 m from the trunk. The sub-samples for each tree were placed into a bucket, thoroughly mixed, and a single composite sample was used for the fertility analysis of each tree.

After the growing season was over in December 2021, root core samples were extracted to compare root growth between control trees and gravel bed trees. The samples were extracted with a metal cylinder measuring 18 cm long and 10 cm diameter with a volume of 1414 cm³. Six samples were taken at each tree around two concentric circles at 38.1 cm and 76.2 cm from the trunk, totaling three sub-samples at each distance. The sub-samples were taken in three pairs to the north, southwest, and southeast (Fig. 6).

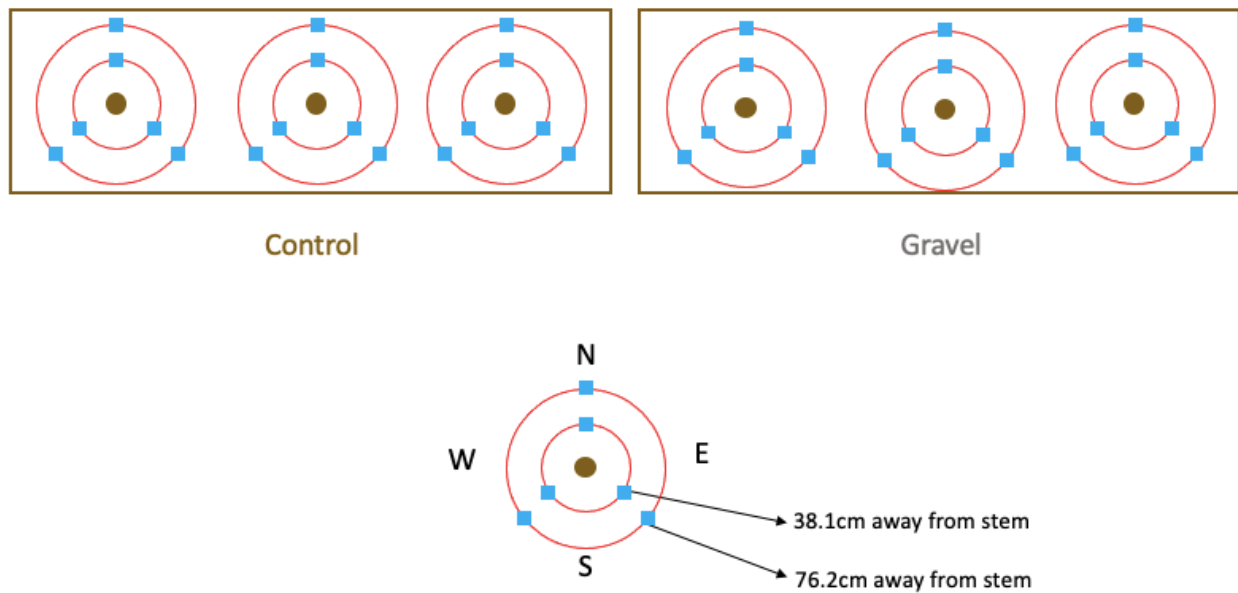


Figure 6. The sampling schematic for the soil root cores extracted from the control and gravel bed site in December 2021.

Each sample was placed into a gallon Ziploc bag and refrigerated at 6.5° C until manual processing to extract roots from the core. The soil was gently passed through a 2 mm sieve into a pan to break apart aggregates. Roots accumulating on the sieve and the pan below were carefully recovered with tweezers and placed in a 1:1 water-ethanol mixture for preservation. The samples were then scanned for length, surface area, projected area, volume, and average diameter using a

flatbed scanner and WinRhizo software. After being scanned, the root samples were weighed for fresh weight, dried at 65° C for 72 hours, and weighed for dry weight.

Soil moisture from 0 to 11.4 cm depth was measured weekly during summer 2021 using a HydroSenseII moisture meter. Each tree had 12 subsamples, three in each cardinal direction (Fig 7). The three samples in each direction were taken at 35 cm, 70 cm, and 105 cm away from the trunk. The mulch was removed before probe placement into the soil to ensure full soil contact.

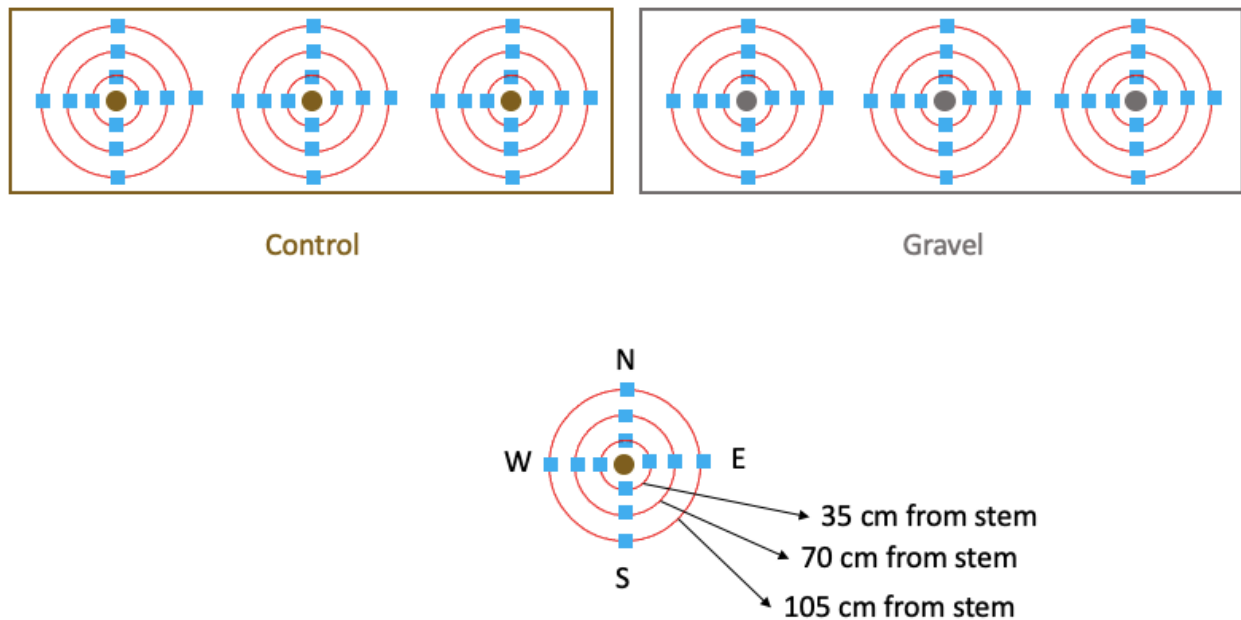


Figure 7. The sampling schematic for the weekly soil moisture measurements with the HydroSenseII that was completed from July to October of 2021.

3.4 Hydrological Measurements of the Gravel Bed

The hydrology of the gravel bed was monitored to observe how stormwater runoff and precipitation interacted with the gravel matrix. The gravel bed system had three vertical observation wells incorporated into the underdrain. They went to the bottom of the gravel bed and emerge 1 m above the gravel. Two of the wells each contained two HoboWare pressure

transducers and one well had a single transducer. For the wells with two devices, there was one device at the top of the well and one at the bottom, while the well with one device had it at the bottom. These were used to measure air and water pressure to monitor water depth in the gravel bed during and after rainstorm events. Outflow events were measured by a moisture sensor located in the outflow pipe of the drainage system. The outflow sensor recorded when there was moisture in the pipe, signaling there was outflow from the gravel bed. The transducers constantly recorded data. Their recording began when the site finished construction in May 2020. Precipitation was measured by a bucket gauge that is located at the northeastern corner of the gravel pit. Precipitation data was also downloaded from a Weather Underground Personal Weather Station (PWS), labeled “Boxwood”, located at the Virginia Tech Montgomery Executive Airport (<https://www.wunderground.com/dashboard/pws/KVABLACK54>).

3.5 Physiological Measurements of the Trees

A series of leaf physiological measurements were performed during summer 2021, the second growing season of the trees (Table 2). Repeated measurements of stomatal conductance and photosynthesis were always randomized across the control trees and gravel bed trees on data collection dates to avoid biasing the data by fluctuations in time of day, temperature, humidity, and light intensity.

Stomatal conductance was measured weekly using the LI-COR LI-600 porometer. These measurements were completed over the course of July to October 2021. Each tree had 12 leaves sampled, three in each cardinal direction. Only fully mature and healthy leaves from perimeter of crown were measured. This same device also functions as a fluorometer, measuring the efficiency of photosystem II through fluorescence index.

Table 2. Tree physiology measurements collected at the study site during the summer 2021.

Measurement	Start and End Dates	Frequency
Stomatal conductance	July 2021 – October 2021	Weekly
Fluorescence	July 2021 – October 2021	Weekly
Photosynthesis	July 2021 – September 2021	Monthly
Transpiration	July 2021 – September 2021	Monthly
Chlorophyll content	July 2021 – September 2021	Monthly
Specific leaf area	August 2021	Once
Crown dimensions	July 2021	Once
Tree growth	May 2020-March 2022	Yearly

Leaf gas exchange was measured three times from July to September 2021 using the LI-COR LI-6800 and LI-6400. Each tree had four subsamples, one in each cardinal direction. The leaf chamber was set to relative humidity of 55%, ambient CO₂ of 410 ppm, temperature of 25° C, and ambient light of 1500 $\mu\text{mol m}^{-2} \text{s}^{-1}$. Chlorophyll levels were measured immediately after the photosynthesis measurements on the same leaf. Five different subsamples were taken on the same leaf, four leaves per tree in each cardinal direction. A chlorophyll content meter (Opti-Sciences CCM-300) was used for these measurements.

Specific leaf area was measured during July 2021. Three leaves were picked from each cardinal direction on each tree, totaling 12 sub-samples per tree. The leaves picked were fully formed mature leaves without abnormalities, collected from the upper $\frac{1}{2}$ to $\frac{3}{4}$ of the canopy. The leaves were stored in plastic Ziploc bags with a moist paper towel on ice so they would retain their fresh size and weight. The samples were scanned individually with a LI-COR LI-3100 Area Meter for surface area. They were immediately weighed afterward to record fresh weight. The leaves were then dried at 60° C for 72 hours. Using this data, gravimetric water content and specific leaf area were calculated.

Crown dimensions (canopy volume, density, transparency, height, diameter, and live crown ratio) were measured using photographic analysis in the UrbanCrowns software (Winn et al., 2011). Two photos per tree were taken, one at a 135° azimuth from the tree and the other at a 225° azimuth from the tree. They were taken at a distance of two times the tree height, at approximately solar noon. The photos were taken with a camera on a tripod. The angle from the camera to the base of the trunk and the top of the canopy were recorded for the software. The angle was set using a clinometer and the distance was set using a laser hypsometer. A white cloth backdrop was held behind the trees to screen out background clutter in the photos. It was created by using a 3.66 m by 5.49 m canvas, zip-tied to two measuring poles. After the photos were uploaded to the software, a “digital lasso” was manually traced around the tree crown. The software then tightly delineated the perimeter of the crown to calculate crown transparency and physical dimensions of the crown (Fig 8).

Physical dimensions of the trees were measured manually in May 2020, March 2021, and March 2022 to determine annual growth. A height pole was used to measure the tree height, a caliper was used to measure the trunk diameter at 1.4 m above the ground, and a measuring tape was used to measure the crown spread. Trunk diameter and crown spread were measured in both north to south and east to west directions and averaged for a single value.



Figure 8. Screen capture from UrbanCrowns software of a processed photo of a control tree showing the computer-aided tracing of the crown perimeter. Photos of trees were taken in July 2021.

3.6 Statistical Analysis

The experiment was a completely randomized design with three trees each ($n=3$) randomly assigned to the control soil growing environment and the gravel bed growing environment, respectively. All calculations and statistical analyses of the data were performed in Microsoft Excel. Raw data for sub-samples of each response variable were examined with histograms and boxplots to identify extreme outliers, which were removed prior to further analysis. Experimental unit data for each response variable were tested for homogeneity of variance between control trees and gravel bed trees using the F -test for equality of two variances. Means comparisons for each response variable were performed with a two-sample t -test, using a two-tailed distribution and either equal (homoscedastic) or unequal (heteroscedastic) variance adjustments based on the result of the F -test. All tests were conducted at alpha level of 0.05 for type I error.

CHAPTER 4 – RESULTS

4.1 Soil and Root Measurements

The results from the bulk density and nutrient analysis tests in July 2021 showed multiple statistically significant differences between the gravel bed soil and the native control soil (Table 3, Appendix A). The gravel bed soil had lower bulk density, higher nutrient content, higher cation exchange capacity, higher organic matter, and lower soil salinity. The native control soil showed a deficiency in phosphorus and potassium. The soil pH was the only variable between treatments that did not statistically differ.

Table 3. Soil properties for control and gravel bed soil (n=3 each) calculated from soil core samples collected in July 2021.

	Control		Gravel		p-value
	Mean	Std. Error	Mean	Std. Error	
Bulk Density (%)	1.36	0.07	1.30	0.06	.07
pH	7.70	0.17	7.73	0.03	.86
CEC (meq/100g)	6.47	0.44	15.83	0.12	.0003
Phosphorus (ppm)	7.00	1.26	23.00	0.50	.003
Potassium (ppm)	24.65	1.10	98.65	2.90	.00002
Calcium (ppm)	963.50	50.49	2444.00	31.86	.00002
Magnesium (ppm)	191.65	21.99	412.35	4.43	.0006
Zinc (ppm)	1.19	0.09	2.62	0.30	.01
Manganese (ppm)	14.29	0.93	20.00	0.64	.007
Copper (ppm)	0.24	0.04	0.32	0.02	.09
Iron (ppm)	4.24	0.29	12.94	0.44	.00008
Organic matter (%)	2.83	0.03	4.23	0.07	.00005
Soil salinity (ppm)	174.70	33.31	77.00	0.00	.04

Soil moisture content was similar in the native soil and gravel bed soil throughout summer 2021, with the native soil trending slightly higher than the gravel bed soil (Fig. 9). There were only a few dates where there was a marginally significant difference between the two. Soil

moisture for each treatment followed similar trends from June 2021 to September 2021 with no statistically significant differences.

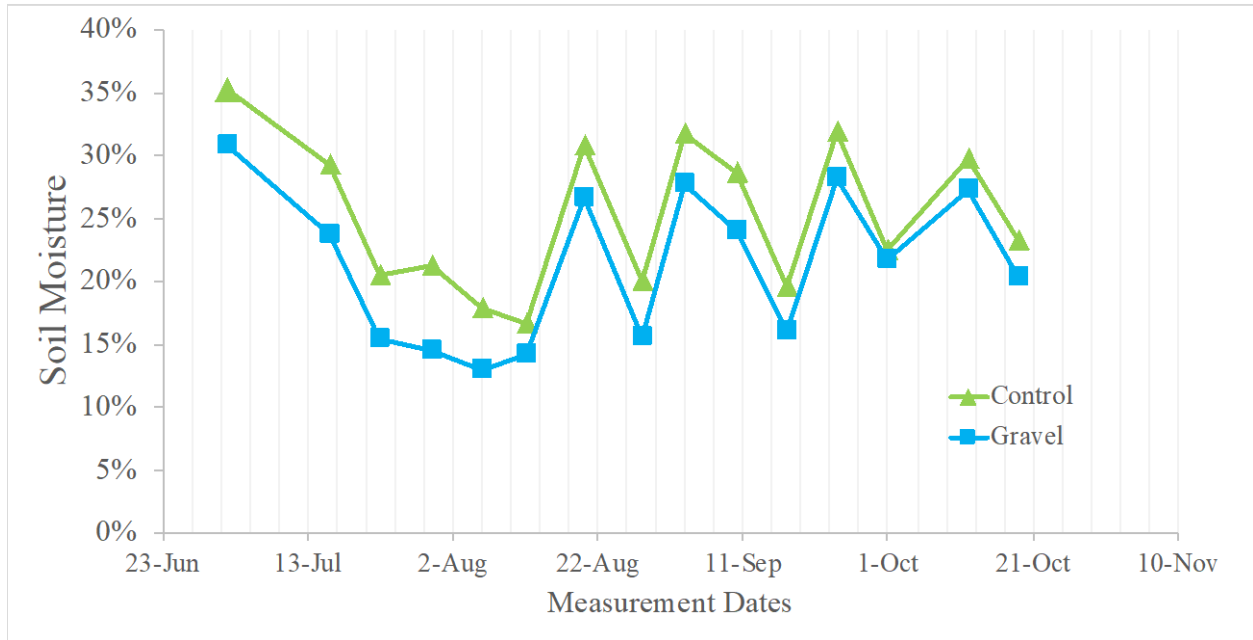


Figure 9. Volumetric soil moisture within the root zone of trees growing in control and gravel bed soil (n=3 each) measured with a HydroSenseII meter to 11.4 cm depth during summer 2021.

Control tree roots had about 48% more total length per soil core on average than the gravel trees, which was statistically significant both for all diameter classes combined and for the diameter classes less than 4.5 mm (Table 4). The control tree roots showed more volume than the gravel bed tree roots only for the diameter class less than 4.5 mm. No significant differences were observed in root relative water content or specific root length.

Table 4. Root traits of trees growing in control soil and gravel bed soil (n=3 each) calculated from soil core samples collected in December 2021. The samples were extracted with a metal cylinder measuring 18 cm long and 10 cm diameter with a volume of 1,414 cm³. Root mass, relative water content, and specific root length were not measured separately for the root diameters < 4.5 mm.

	All Root Diameters					Root Diameters < 4.5 mm				
	Control		Gravel		p-value	Control		Gravel		p-value
	Mean	Std. Error	Mean	Std. Error		Mean	Std. Error	Mean	Std. Error	
Root length (cm)	926.80	178.20	626.80	215.70	.03	921.20	175.50	621.30	215.00	.03
Root vol. (cm ³)	4.83	6.77	3.48	4.20	.69	2.42	0.83	1.36	0.61	.002
Root mass (g)	2.78	3.46	3.13	3.04	.86	-	-	-	-	-
RWC ^a (g/g)	3.15	0.80	4.62	2.69	.37	-	-	-	-	-
SRL ^b (cm/g)	1391.20	705.24	2609.52	2394.01	.37	-	-	-	-	-

^aRWC: relative water content

^bSRL: specific root length

4.2 Hydrological Measurements of the Gravel Bed

Multiple rainstorm events were recorded at the study site over the summer of 2021 (Fig. 10). The pressure transducers in the gravel matrix showed that the water level would rise during these events, but never enough to reach the outflow pipe of the gravel bed. No outflow events were recorded between May 2021 and October 2021. The greatest water level in the gravel bed occurred on July 1st, 2021 when the sensor measured a depth of 0.66 m. The rain event that caused this happened from June 30th to July 2nd, with a total of 11.1 cm of precipitation (8.9 cm on July 1). The water in the pit was gone by July 4th. Because the bottom of the gravel bed was not sealed, accumulated water would drain deeper into the soil profile quickly after most rain events.

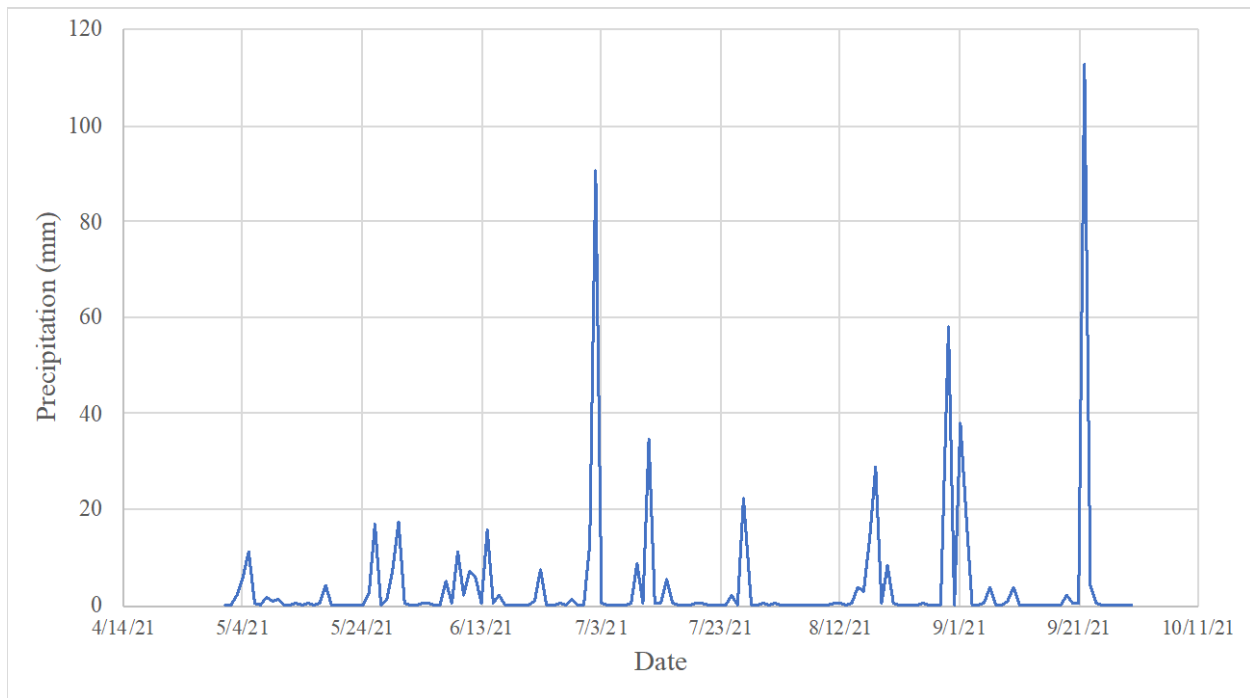


Figure 10. Precipitation amounts recorded at National Weather Service Station at Blacksburg, Virginia from May 1st, 2021, to September 30th, 2021. Data portal weblink: (<https://www.weather.gov/wrh/Climate?wfo=rnk>).

4.3 Physiological Measurements of the Trees

The results from weekly stomatal conductance measurements in summer 2021 showed similar trends in the gravel bed and control trees (Fig. 11). Stomatal conductance ranged from a low of $0.061 \text{ mol m}^{-2} \text{ s}^{-1}$ in the control trees and $0.014 \text{ mol m}^{-2} \text{ s}^{-1}$ in the gravel bed trees to a high of $0.404 \text{ mol m}^{-2} \text{ s}^{-1}$ in the control trees and $0.338 \text{ mol m}^{-2} \text{ s}^{-1}$ in the gravel bed trees. Average stomatal conductance of control trees was $0.225 \text{ mol m}^{-2} \text{ s}^{-1}$, which was 30% higher than gravel bed average of $0.173 \text{ mol m}^{-2} \text{ s}^{-1}$. However, eight out of thirteen weekly measurements were not significantly different between groups, and only one week showed a statistical significance when the p-value was less than .05. The stomatal conductance rates followed a very similar trend in comparison to the soil moisture of both the gravel bed soil and native control soil. Chlorophyll fluorescence was not significantly different between groups throughout the 2021 growing season (Fig. 12). Average fluorescence of gravel bed trees was 0.649, which was 9% higher than control soil average of 0.597.

Photosynthesis results showed no significant differences between the two groups on any dates in summer 2021 (Fig. 13a). The control trees averaged $11.17 \text{ } \mu\text{mol m}^{-2} \text{ s}^{-1}$ while the gravel bed trees averaged slightly higher at $11.54 \text{ } \mu\text{mol m}^{-2} \text{ s}^{-1}$. The control trees averaged a slightly higher, but non-significant, transpiration rate than the gravel bed trees, averaging 0.0034 and $0.0030 \text{ mol m}^{-2} \text{ s}^{-1}$, respectively (Fig. 13b). Chlorophyll content results showed that the gravel bed trees had statistically significantly higher content levels on every measurement date (Fig. 14a). The gravel bed trees averaged 25% higher levels than the control trees, with a p-value of 0.0001. Stomatal conductance measured on those same dates did not significantly differ between groups, averaging $0.16 \text{ mol m}^{-2} \text{ s}^{-1}$ and 0.13 in control trees and gravel bed trees, respectively (Fig. 14b).

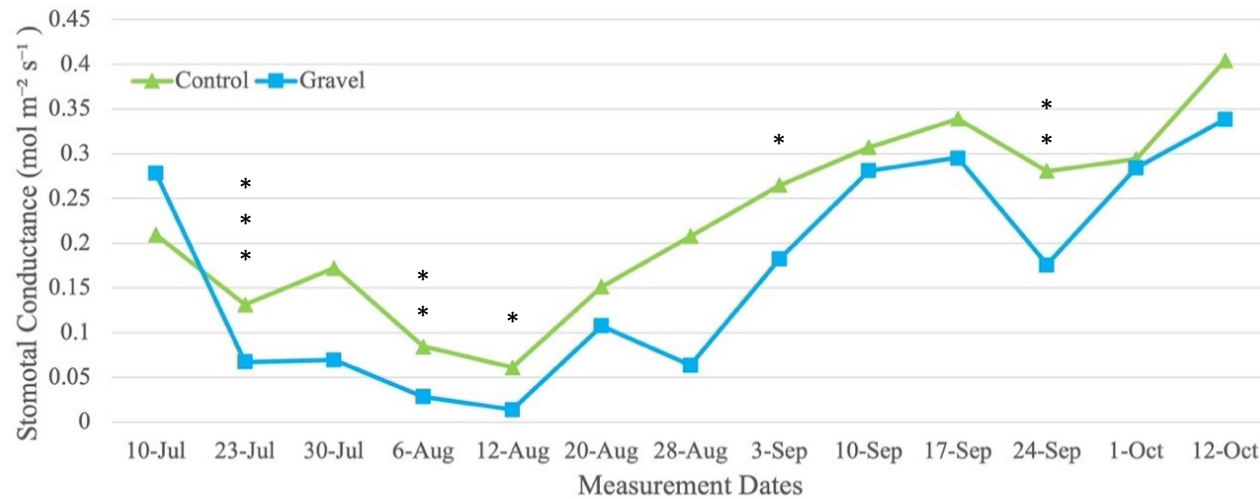


Figure 11. Stomatal conductance of trees growing in control and gravel bed soil (n=3 each) measured with LI-COR LI-600 during summer 2021. Asterisks denote dates with means comparisons having p-value <.1 (*), <.075 (**), <.05 (***)

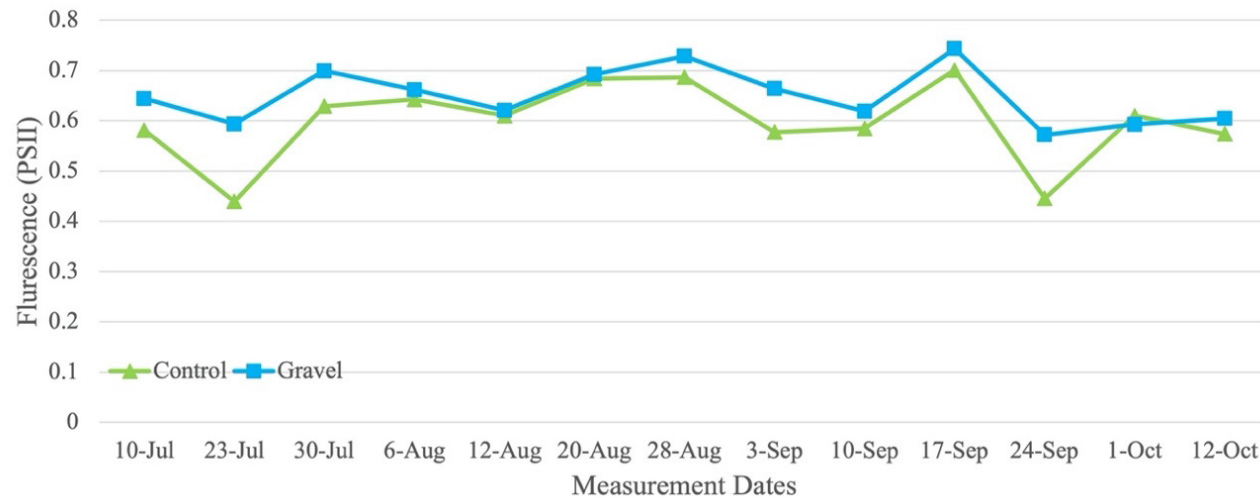


Figure 12. Chlorophyll fluorescence of trees growing in control and gravel bed soil (n=3 each) measured with LI-COR LI-600 during summer 2021.

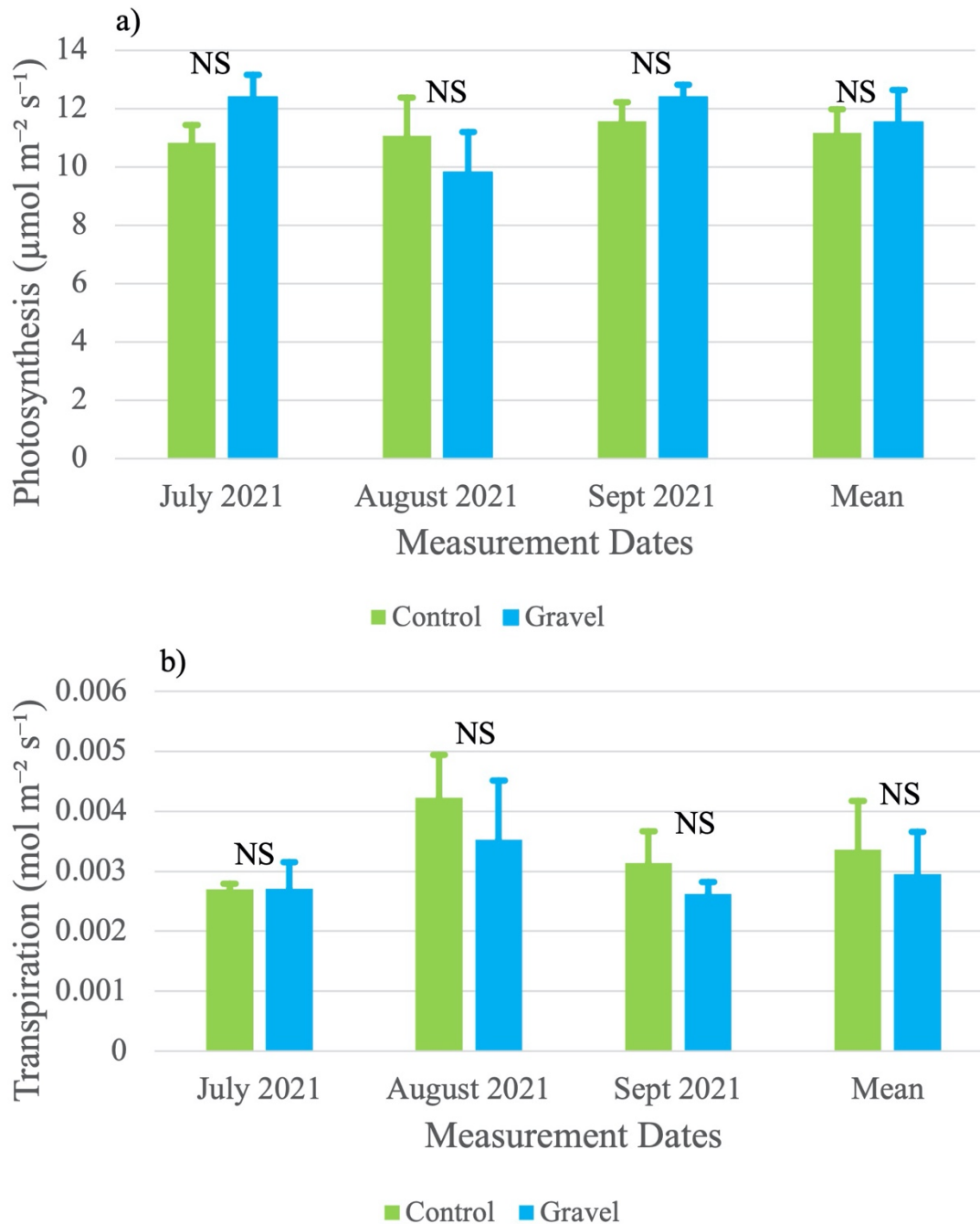


Figure 13. Photosynthesis (a) and transpiration (b) of trees growing in control soil and gravel bed soil (n=3 each) measured on three dates during the 2021 growing season. Overall mean of all dates also shown. Error bars are standard error of mean. Data was collected using the LI-COR LI-6800 and LI-6400. NS indicates no statistically significant difference at $\alpha=.05$.

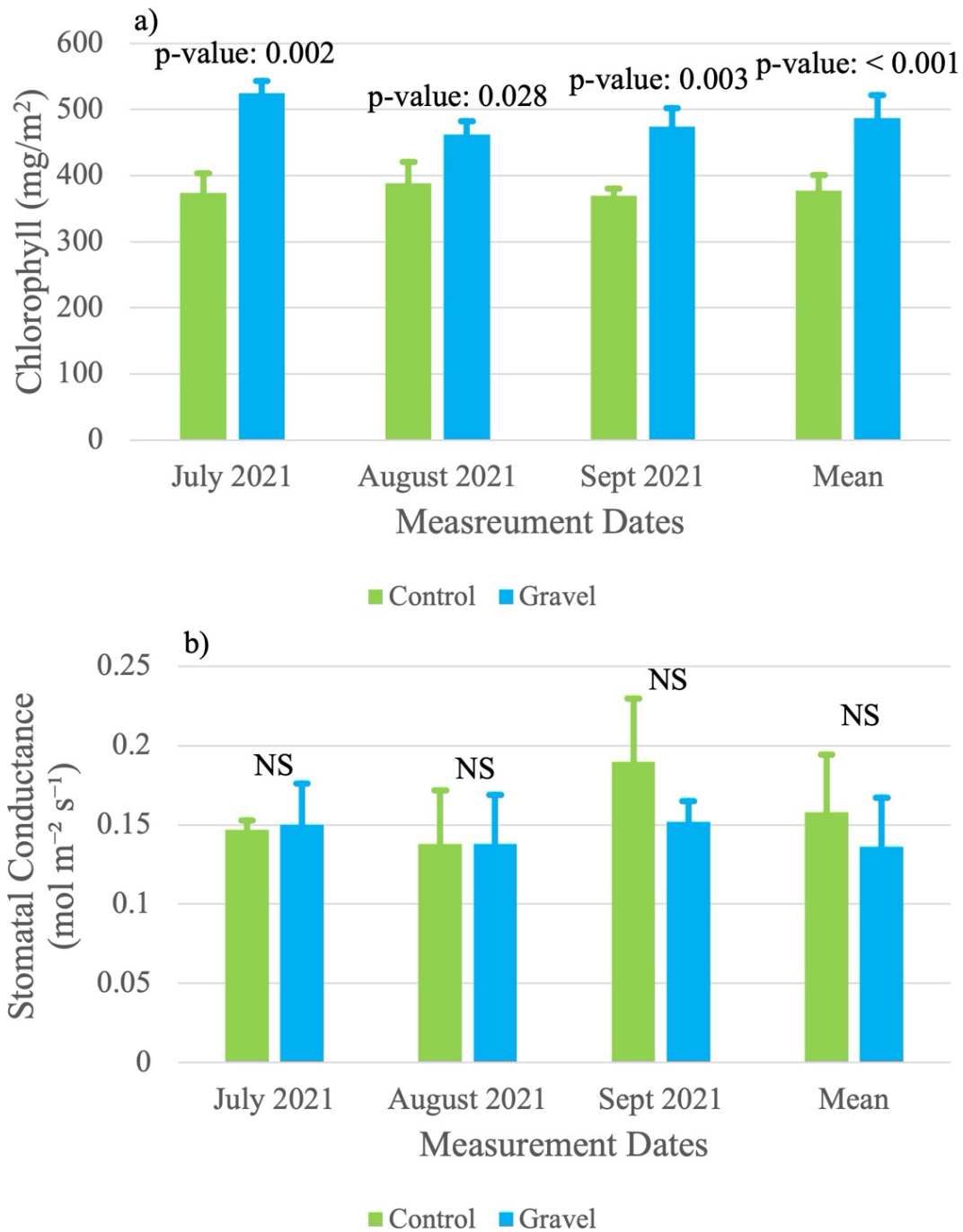


Figure 14. Chlorophyll content (a) and stomatal conductance (b) of trees growing in control soil and gravel bed soil (n=3 each) measured on three dates during the 2021 growing season. Overall mean of all dates also shown. Error bars are standard error of mean. Chlorophyll data was collected using the Opti-Sciences CCM-300. Stomatal conductance data was collected using the LI-COR LI-6800 and LI-6400. NS indicates no statistically significant difference at $\alpha=.05$.

Water use efficiency was calculated using photosynthesis and transpiration measurements during summer 2021. The gravel bed trees had a higher water use efficiency on every occasion (Fig. 15a). All but one measurement date produced a statistically significant difference between groups. On average, the water use efficiency of gravel bed trees was 16% higher than the control trees. The stomatal limitation was calculated using the internal carbon dioxide and ambient carbon dioxide measurements (Fig. 15b). Overall, the gravel bed trees averaged slightly higher than the control trees, with the gravel bed trees averaging 17% higher than the control trees. Two of the three measurement dates yielded non-significant differences.

The average values of specific leaf area, fresh weight, dry weight, and area were all higher in the gravel bed trees (Table 5). The leaves of gravel bed trees were on average 21% larger than the control tree leaves. However, the *t*-tests for the variables did not give any values below 0.05 for the p-value, making none of them statistically significant. Based on the UrbanCrowns analysis, the gravel bed trees produced larger and denser crowns than the control trees (Table 6). The crowns of gravel bed trees had 84% more volume on average compared to the control trees (Fig. 16).

Control trees and gravel bed trees had no statistically significant differences in their size at the time of planting in May 2020. After one year of growth, it was apparent the gravel bed trees were growing more quickly because they had a greater increase in height, trunk diameter, and crown width compared to the control trees based on the measurements taken after the 2020 growing season. However, there were still no statistical differences at that time. The measurements after the 2021 growing season showed significantly greater crown width and trunk diameter for the gravel bed trees. The gravel bed trees had almost a 17% larger trunk diameter than the control trees (Table 7).

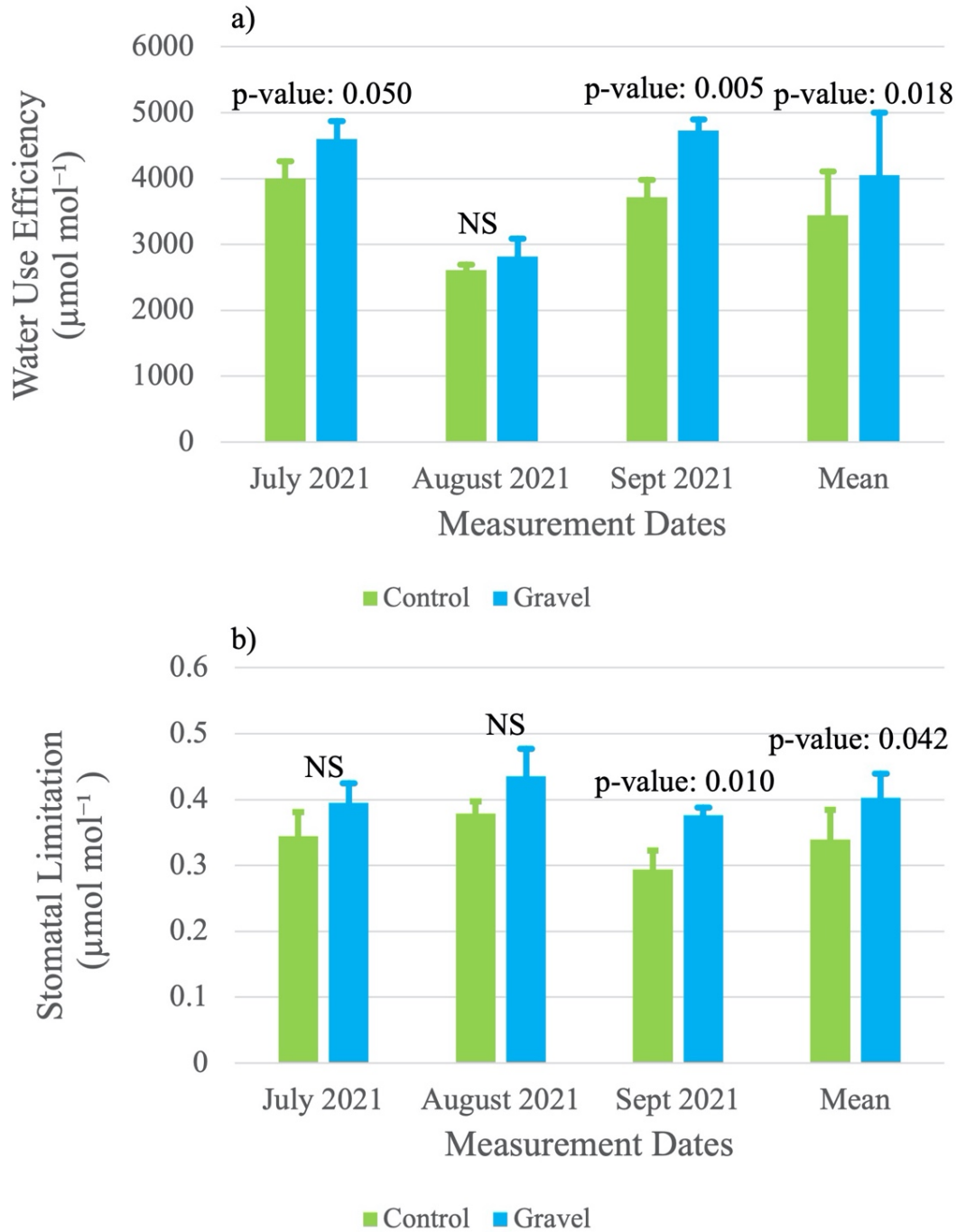


Figure 15. Water use efficiency (a) and stomatal limitation (b) of trees growing in control soil and gravel bed soil (n=3 each) measured on three dates during the 2021 growing season. Overall mean of all dates also shown. Error bars are standard error of mean. Data was collected using the LI-COR LI-6800 and LI-6400. NS indicates no statistically significant difference at $\alpha=.05$.

Table 5. Leaf traits of trees growing in control and gravel bed soil (n=3 each) calculated from a canopy sample of upper-crown, full sun leaves in July 2021.

	Control		Gravel		p-value
	Mean	Std. Error	Mean	Std. Error	
Leaf Area (cm ²)	127.76	26.19	157.95	23.53	.30
RWC ^a (g/g)	1.44	0.06	1.46	0.06	.56
SLA ^b (cm ² /g)	109.42	4.76	115.85	7.31	.24

^aRWC: Relative water content

^bSLA: Specific leaf area

Table 6. Physical dimensions of tree crowns growing in control and gravel bed soil (n=3 each) computed from digital analysis of field photographs using UrbanCrowns software in July 2021.

	Control		Gravel		p-value
	Mean	Std. Error	Mean	Std. Error	
Crown density (%)	82.04	1.80	85.28	1.04	.02
Crown volume (m ³)	7.41	0.89	13.66	1.61	.02
Crown height (m)	3.40	0.10	4.17	0.14	.01
Crown diameter (m)	3.05	0.20	3.44	0.20	.13
Live crown ratio	0.72	0.02	0.82	0.01	.01

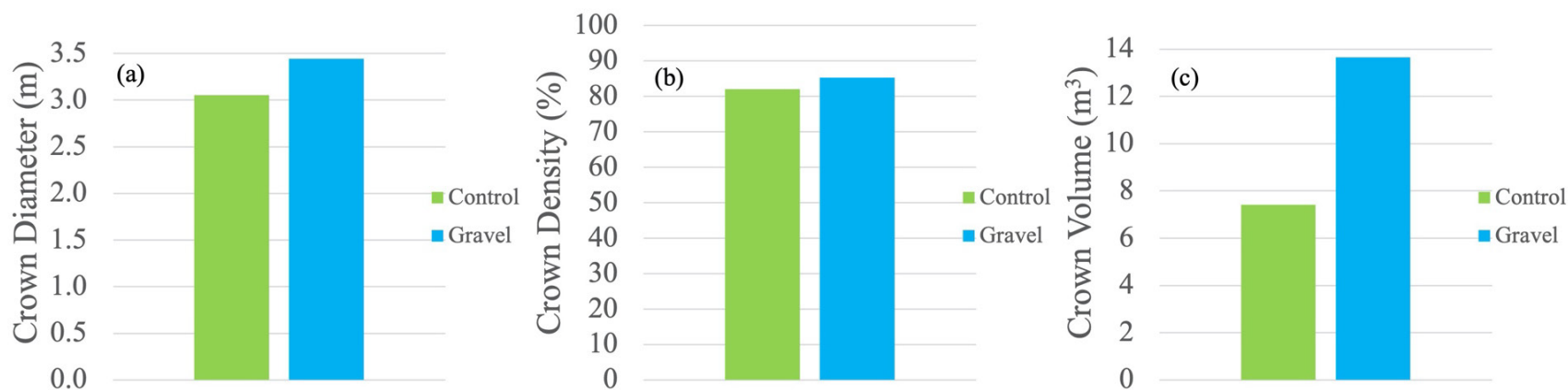


Figure 16. Crown diameter (a), crown density (b), and crown volume (c) of trees growing in control and gravel bed soil (n=3 each) computed from digital analysis of field photographs using UrbanCrowns software in July 2021.

Table 7. Size of trees growing in control soil and gravel bed soil (n=3 each) calculated from field measurements on three dates.

	At Planting					After 2020 Growing Season					After 2021 Growing Season				
	Control		Gravel		p-value	Control		Gravel		p-value	Control		Gravel		p-value
	Mean	Std. Error	Mean	Std. Error		Mean	Std. Error	Mean	Std. Error		Mean	Std. Error	Mean	Std. Error	
Tree Height (m)	4.17	0.14	4.24	0.09	.69	4.50	0.10	4.68	0.05	.18	5.33	0.06	5.45	0.08	.31
Crown Width (m)	1.68	0.13	1.63	0.10	.75	2.15	0.08	2.26	0.03	.27	2.77	0.11	3.10	0.03	.04
Trunk Diameter (mm)	37.44	1.19	38.07	1.36	.75	44.33	2.60	46.74	1.64	.48	56.67	1.09	67.17	2.61	.02

CHAPTER 5 – DISCUSSION

5.1 Soil and Root Measurements

Soil quality plays a large role in tree growth, especially while the tree is becoming established in the first couple of years after transplanting. The topsoil installed in the gravel bed into which the trees were planted came from a stockpile maintained by the university for grading and landscape projects (Sprouls, 2020). Therefore, the soil had higher quality than the typical native soil found around campus, which is heavily impacted by construction grading and compaction. Based on this, the results from the soil analyses supported our hypothesis that gravel bed soil is of better quality than native control soil. The gravel bed soil had better quality for every characteristic of the analysis, except for pH, in which there was no significant difference. This was to be expected because the gravel bed had topsoil while the native landscape soil has been disturbed from previous construction. The trends observed in the soil characteristics are factors that greatly influence the physiology of the trees.

5.2 Hydrological Measurements of the Gravel Bed

After rain events, the water level would rise in the gravel bed for a few hours depending on the amount of precipitation and during the event. However, since the gravel bed was not lined, the water would seep through the soil before ever making it to the outflow pipe. Because of this, the water would seep into the soil from the bottom and sides of the pit. This was not an issue for the gravel bed tree in the 2021 growing season because their roots are currently only in the mineral soil. Since the water did not get deep or stay in the pit for very long, the trees will likely struggle to get enough water to thrive once their root systems populate the gravel matrix.

5.3 Physiological Measurements of the Trees

Based on the results from the gas exchange measurements the gravel bed trees are using water more efficiently than the control trees. The weekly stomatal conductance measurements followed a similar trend to the soil moisture levels in both the control trees and gravel bed trees. The gravel bed trees had statistically significantly higher water use efficiency levels than the control trees. This allowed them to produce larger canopies with more leaf area, as demonstrated by the physical dimension measurements of the trees because they used less water per leaf area. Results of the photographic analysis of the trees also showed that the gravel bed trees produced larger, more dense crowns than the control trees. These major differences are most likely caused by the differences we found in the soil between groups. The gravel bed soil was much richer in nutrients causing the gravel bed trees to have larger, healthier crowns with leaves containing much higher levels of chlorophyll. As these trees mature and leaf area increases, we foresee their performance trends to change. .

5.4 Study Limitations

We recognize this study has its limitations. There was a very limited amount of statistical power due to the low replication of treatments. These trees are still young and becoming established in their environments. Future monitoring is recommended to evaluate tree performance once the tree roots have populated the gravel matrix.

CHAPTER 6 – CONCLUSION

In this study, we have found that this tree based bioretention system has the potential to be an effective and simple stormwater mitigation design. The gravel bed trees produced large and healthy crowns. However, the trees in this system are young and their roots have not populated the gravel bed matrix. The system showed it can retain water when heavy precipitation events occur. The gravel bed system is a long-term observation project that is going to be studied further in the future. The same measurements should be done in the future to compare the further establishment and growing trends of the control trees and gravel trees as they mature and fill out the gravel bed system. The tree's performance is expected to change as they grow into the gravel bed. The observation of their water stress and root elongation is going to be a key element in the future of this study and the success of this design. As the roots populate the gravel matrix, it will be crucial to observe their turnover rate and growth patterns.

As urbanization continues, the challenge of stormwater runoff will continue to grow and the implementation of bioretention systems will become more important. The study and research of green infrastructure as a stormwater management practice must continue as more pervious surfaces are covered with streets, sidewalks, and parking lots. The ecosystem services provided by trees are invaluable in the urban environment. They continue to help offset the issues caused by the creation of hardscapes through their role in the urban water cycle.

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APPENDIX A

Results of nutrient content analysis by Virginia Tech soil testing lab for soils samples collected in root zones of experimental trees in July 2021. Sample ID numbers shown on reports are labeled as follows: control trees west to east (CON01, CON02, CON03), gravel bed trees west to east (GRA01, GRA02, GRA03).

Lab ID: 21-32858

2021-07-09

MONTGOMERY / 121

Virginia Cooperative Extension Soil Test Report

Questions? Contact:
Montgomery County Office
755 Roanoke Street, Suite 1G
Christiansburg, VA 24073
540-382-5790

Virginia Tech Soil Testing Laboratory
145 Smyth Hall (0465)
185 Ag Quad Ln
Blacksburg, VA 24061
www.soiltest.vt.edu

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BLACKSBURG, VA 24061

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SAMPLE HISTORY

Sample ID	Field ID	LAST CROP		LAST LIME APPLICATION		SOIL INFORMATION				
		Name	Yield	Months Prev.	Tons/Acre	SMU-1 %	SMU-2 %	SMU-3 %	Yield Estimate	Productivity Group
CON01				---	None applied.					

LAB TEST RESULTS (see Note 1)

Analysis	P (lb/A)	K (lb/A)	Ca (lb/A)	Mg (lb/A)	Zn (ppm)	Mn (ppm)	Cu (ppm)	Fe (ppm)	B (ppm)	S.Salts (ppm)
Result	20	51	2086	408	2.7	29.9	0.6	9.5	0.4	179
Rating	M-	L	B+	VH	SUFF	SUFF	SUFF	SUFF	SUFF	L

Analysis	Soil pH	Buffer Index	Est.-CEC (meq/100g)	Acidity (%)	Base Sat. (%)	Ca Sat. (%)	Mg Sat. (%)	K Sat. (%)	Organic Matter (%)
Result	8.0	6.60	7.0	0.0	100.0	74.9	24.2	0.9	2.8

FERTILIZER AND LIMESTONE RECOMMENDATIONS

Crop: TREES. (246)

619. Lime recommendations: NONE NEEDED.

261. FERTILIZER RECOMMENDATIONS: See Note 20.

991. "Explanation of Soil Tests, Note 1" and other referenced notes are viewable at www.soiltest.vt.edu under Report Notes.

677. Soluble Salts are not high enough to cause salt injury.

APPENDIX A, CONTINUED

Lab ID: 21-32859

2021-07-09

MONTGOMERY / 121

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Questions? Contact:
Montgomery County Office
 755 Roanoke Street, Suite 1G
 Christiansburg, VA 24073
 540-382-5790

Virginia Tech Soil Testing Laboratory
 145 Smyth Hall (0465)
 185 Ag Quad Lu
 Blacksburg, VA 24061
www.soiltest.vt.edu

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SAMPLE HISTORY

Sample ID	Field ID	LAST CROP		LAST LIME APPLICATION		SOIL INFORMATION				
		Name	Yield	Months Prev.	Tons/Acre	SMU-1 %	SMU-2 %	SMU-3 %	Yield Estimate	Productivity Group
CON02				---	None applied.					

LAB TEST RESULTS (see Note 1)

Analysis	P (lb/A)	K (lb/A)	Ca (lb/A)	Mg (lb/A)	Zn (ppm)	Mn (ppm)	Cu (ppm)	Fe (ppm)	B (ppm)	S.Salts (ppm)
Result	12	52	1740	298	2.3	30.9	0.4	7.5	0.4	230
Rating	M-	L	H	VH	SUFF	SUFF	SUFF	SUFF	SUFF	L

Analysis	Soil pH	Buffer Index	Est.-CEC (meq/100g)	Acidity (%)	Base Sat. (%)	Ca Sat. (%)	Mg Sat. (%)	K Sat. (%)	Organic Matter (%)
Result	7.7	6.60	5.6	0.0	100.0	77.0	21.8	1.2	2.9

FERTILIZER AND LIMESTONE RECOMMENDATIONS

Crop: TREES. (246)

619. Lime recommendations: NONE NEEDED.

261. FERTILIZER RECOMMENDATIONS: See Note 20.

991. "Explanation of Soil Tests, Note 1" and other referenced notes are viewable at www.soiltest.vt.edu under Report Notes.

677. Soluble Salts are not high enough to cause salt injury.

APPENDIX A, CONTINUED

Lab ID: 21-32860

2021-07-09

MONTGOMERY / 121

Virginia Cooperative Extension Soil Test Report

Questions? Contact:
Montgomery County Office
 755 Roanoke Street, Suite 1G
 Christiansburg, VA 24073
 540-382-5790

Virginia Tech Soil Testing Laboratory
 145 Smyth Hall (0465)
 185 Ag Quad Ln
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SAMPLE HISTORY

Sample ID	Field ID	LAST CROP		LAST LIME APPLICATION		SOIL INFORMATION				
		Name	Yield	Months Prev.	Tons/Acre	SMU-1 %	SMU-2 %	SMU-3 %	Yield Estimate	Productivity Group
CON03				---	None applied.					

LAB TEST RESULTS (see Note 1)

Analysis	P (lb/A)	K (lb/A)	Ca (lb/A)	Mg (lb/A)	Zn (ppm)	Mn (ppm)	Cu (ppm)	Fe (ppm)	B (ppm)	S.Salts (ppm)
Result	13	45	1955	444	2.1	24.9	0.4	8.4	0.4	115
Rating	M-	L	H+	VH	SUFF	SUFF	SUFF	SUFF	SUFF	L

Analysis	Soil pH	Buffer Index	Est.-CEC (meq/100g)	Acidity (%)	Base Sat. (%)	Ca Sat. (%)	Mg Sat. (%)	K Sat. (%)	Organic Matter (%)
Result	7.4	6.60	6.8	0.0	100.0	72.1	27.0	0.9	2.8

FERTILIZER AND LIMESTONE RECOMMENDATIONS

Crop: TREES. (246)

619. Lime recommendations: NONE NEEDED.

261. FERTILIZER RECOMMENDATIONS: See Note 20.

991. "Explanation of Soil Tests, Note 1" and other referenced notes are viewable at www.soiltest.vt.edu under Report Notes.

677. Soluble Salts are not high enough to cause salt injury.

APPENDIX A, CONTINUED

Lab ID: 21-32861

2021-07-09

MONTGOMERY / 121

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Questions? Contact:
Montgomery County Office
 755 Roanoke Street, Suite 1G
 Christiansburg, VA 24073
 540-382-5790

Virginia Tech Soil Testing Laboratory
 145 Smyth Hall (0465)
 185 Ag Quad Ln
 Blacksburg, VA 24061
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SAMPLE HISTORY

Sample ID	Field ID	LAST CROP		LAST LIME APPLICATION		SOIL INFORMATION				
		Name	Yield	Months Prev.	Tons/Acre	SMU-1 %	SMU-2 %	SMU-3 %	Yield Estimate	Productivity Group
GRA01				---	None applied.					

LAB TEST RESULTS (see Note 1)

Analysis	P (lb/A)	K (lb/A)	Ca (lb/A)	Mg (lb/A)	Zn (ppm)	Mn (ppm)	Cu (ppm)	Fe (ppm)	B (ppm)	S.Salts (ppm)
Result	44	187	4936	834	4.4	37.9	0.6	24.4	1.1	77
Rating	H-	H-	VH	VH	SUFF	SUFF	SUFF	SUFF	SUFF	L

Analysis	Soil pH	Buffer Index	Est.-CEC (meq/100g)	Acidity (%)	Base Sat. (%)	Ca Sat. (%)	Mg Sat. (%)	K Sat. (%)	Organic Matter (%)
Result	7.8	6.60	16.0	0.0	100.0	77.0	21.5	1.5	4.3

FERTILIZER AND LIMESTONE RECOMMENDATIONS

Crop: TREES. (246)

619. Lime recommendations: NONE NEEDED.

261. FERTILIZER RECOMMENDATIONS: See Note 20.

991. "Explanation of Soil Tests, Note 1" and other referenced notes are viewable at www.soiltest.vt.edu under Report Notes.

677. Soluble Salts are not high enough to cause salt injury.

APPENDIX A, CONTINUED

Lab ID: 21-32862

2021-07-09

MONTGOMERY / 121

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Questions? Contact:
Montgomery County Office
755 Roanoke Street, Suite 1G
Christiansburg, VA 24073
540-382-5790

Virginia Tech Soil Testing Laboratory
145 Smyth Hall (0465)
185 Ag Quad Ln
Blacksburg, VA 24061
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SAMPLE HISTORY

Sample ID	Field ID	LAST CROP		LAST LIME APPLICATION		SOIL INFORMATION				
		Name	Yield	Months Prev.	Tons/Acre	SMU-1 %	SMU-2 %	SMU-3 %	Yield Estimate	Productivity Group
GRA02				---	None applied.					

LAB TEST RESULTS (see Note 1)

Analysis	P (lb/A)	K (lb/A)	Ca (lb/A)	Mg (lb/A)	Zn (ppm)	Mn (ppm)	Cu (ppm)	Fe (ppm)	B (ppm)	S.Salts (ppm)
Result	47	207	4753	833	6.4	42.3	0.6	25.8	1.1	77
Rating	H-	H-	VH	VH	SUFF	SUFF	SUFF	SUFF	SUFF	L

Analysis	Soil pH	Buffer Index	Est.-CEC (meq/100g)	Acidity (%)	Base Sat. (%)	Ca Sat. (%)	Mg Sat. (%)	K Sat. (%)	Organic Matter (%)
Result	7.7	6.60	15.6	0.0	100.0	76.3	22.1	1.7	4.3

FERTILIZER AND LIMESTONE RECOMMENDATIONS

Crop: TREES. (246)

619. Lime recommendations: NONE NEEDED.

261. FERTILIZER RECOMMENDATIONS: See Note 20.

991. "Explanation of Soil Tests, Note 1" and other referenced notes are viewable at www.soiltest.vt.edu under Report Notes.

677. Soluble Salts are not high enough to cause salt injury.

APPENDIX A, CONTINUED

Lab ID: 21-32863

2021-07-09

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Questions? Contact:
Montgomery County Office
755 Roanoke Street, Suite 1G
Christiansburg, VA 24073
540-382-5790

Virginia Tech Soil Testing Laboratory
145 Smyth Hall (0465)
185 Ag Quad Ln
Blacksburg, VA 24061
www.soiltest.vt.edu

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BLACKSBURG, VA 24061

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SAMPLE HISTORY

Sample ID	Field ID	LAST CROP		LAST LIME APPLICATION		SOIL INFORMATION				
		Name	Yield	Months Prev.	Tons/Acre	SMU-1 %	SMU-2 %	SMU-3 %	Yield Estimate	Productivity Group
GRA03				---	None applied.					

LAB TEST RESULTS (see Note 1)

Analysis	P (lb/A)	K (lb/A)	Ca (lb/A)	Mg (lb/A)	Zn (ppm)	Mn (ppm)	Cu (ppm)	Fe (ppm)	B (ppm)	S.Salts (ppm)
Result	47	198	4951	807	4.9	39.8	0.7	27.4	1.1	77
Rating	H-	H-	VH	VH	SUFF	SUFF	SUFF	SUFF	SUFF	L

Analysis	Soil pH	Buffer Index	Est.-CEC (meq/100g)	Acidity (%)	Base Sat. (%)	Ca Sat. (%)	Mg Sat. (%)	K Sat. (%)	Organic Matter (%)
Result	7.7	6.60	15.9	0.0	100.0	77.6	20.9	1.6	4.1

FERTILIZER AND LIMESTONE RECOMMENDATIONS

Crop: TREES. (246)

619. Lime recommendations: NONE NEEDED.

261. FERTILIZER RECOMMENDATIONS: See Note 20.

991. "Explanation of Soil Tests, Note 1" and other referenced notes are viewable at www.soiltest.vt.edu under Report Notes.

677. Soluble Salts are not high enough to cause salt injury.