Studying the soil-strength effects of vegetation for slope stabilization and erosion control along streambanks and roadside slopes.

By:

Victoria Niedzinski

A thesis submitted to the Graduate Faculty of
Auburn University
in partial fulfillment of the
requirements for the Degree of
Master of Science

Auburn, Alabama
August 7, 2021

Keywords: Stream Restoration, Bio-Engineering, Erosion Control, Construction Management

Approved by:

Dr. Frances C. O’Donnell, Chair, Assistant Professor of Civil and Environmental Engineering
Dr. Michael A. Perez, Assistant Professor of Civil and Environmental Engineering
Dr. Jack Montgomery, Assistant Professor of Civil and Environmental Engineering

Abstract

Vegetative covers are a common solution used for erosion control and slope stabilization for a variety of applications. Studies were conducted to look at two applications of vegetation for erosion control, stream restoration and roadside slopes, by studying root traits, plant establishment, and run-off analysis. The first part of this experiment created simulated streambank microcosms in the Auburn Plant Research Center that contained live stakes of two common riparian species, black willow (*Salix nigra)* and silky dogwood (*Cornus Amomum*). The vegetation growth was monitored and various root trait were analyzed after a 4- and 8-month growing period. The results suggest that the black willow is able to develop a much larger biomass belowground that creates a stronger hydrologic effect on the surrounding soil. The dogwood develops more slowly so it had less overall biomass but the roots developed had significantly higher tensile strength than the black willow at a 90% confidence level.

The second part of this experiment studied the use of vegetative covers along a roadside slope. Erosion that occurs during and after construction projects is a leading source of sediment loading in surface waters and vegetation is an easy and natural solution to decrease soil movement. This study looked at four species of plants, Parson's juniper (*Juniperus chinensis "Parsoni")*, vetiver grass (*Vetiveria zizaniodies*), maidenhair fern (*Adiantum pedatum),* and hairy vetch (*Vicia villosa Roth*) in comparison to a control, fescue grass (*Lolium arundinaceum*), to monitor their establishment and growth in test plots along the NCAT test track in Opelika, AL. The maidenhair fern and hairy vetch were not able to be successfully established for the duration of this study but both the juniper shrubs and vetiver grass were able to grow successfully and decrease sediment movement in the test plots under standard roadside conditions in comparison

to the fescue grass. The quantitative methods of run-off analysis proved to have large margins of error that created uncertainty in the results but the general trends showed that the juniper shrubs had the lowest sediment yield and the lowest volume of run-off coming off the plot. The vetiver grass did not perform as well but it also showed a general trend of less overall sediment yield and volume movement as compared to the fescue grass control.

Acknowledgements

I would like to thank my advisor, Dr. Frances C O'Donnell for her guidance and patience throughout the research and writing process and giving me the opportunity to work on a variety of projects. I would also like to thank Dr. Jack Montgomery and Dr. Michael Perez for their expertise and assistance while working on the project at NCAT. Additionally, I would like to thank Dr. Eve Brantley for providing the live stakes that were used during the greenhouse experiments, as well as Hannah Crosson and Jessica Calhoun who helped start the project. I would like thank Guy Savage, Jason Nelson, and Jennifer Dukes at NCAT for all of their assistance and their commitment to safety at the test track. I also would like to thank Han Xiao, Ross Ellis, Michael Kiernan, and Ashton Babb for all their work helping to construct and establish the entire test site at NCAT. I would also like to thank Homayra Asima and Zoe Hilliard-Shepard for assistance with site monitoring and who are now continuing this work. I would also like to thank the university and the Department of Civil Engineering for giving me this opportunity. Finally, I would like to thank my family for their unwavering support and belief in me.

Table of Contents

List of Tables

List of Figures

1. Introduction

1.1 Background

Urbanization is a wide-spread phenomenon that has increased the amount erosion and sediment movement in developed watersheds and construction projects. A majority of urban and highway erosion is due to exposed soil along construction sites and this soil is often carrying pollutants (Messer, 2007). The U.S. EPA reports that this construction-induced erosion is the largest non-point source of sediment loading into surface water (U.S. EPA, 2000). This sediment movement can accumulate and interfere in stormwater management systems, decrease water quality of surrounding surface water, and degrade streams (Messer, 2007; Puno, 2019; Walsh et al., 2005). The urbanization of a watershed is also a leading cause for stream degradation that results in bank failures, flow regime changes, and a decrease in aquatic habitat quality (Meyer, 2005; Puno, 2019; Walsh, 2005).

Vegetation is a common method of decreasing erosion along construction sites and in stream restoration projects as it provides both mechanical and hydrological benefits to the surrounding soil and slope (Morgan and Rickson, 1995; Simon and Collison, 2002; Wells, 2002). The vegetative cover acts as a protective barrier between the surface and the atmosphere by slowing precipitation, decreasing run-off flow, and intercepting wind while the root systems can decrease soil moisture, provide stabilization, and help resist shearing forces within the soil (Dingman, 2002; Morgan and Rickson, 1995; Simon and Collison, 2002). However, every plant has different traits that define how they interact with their environment and acquire resources. To explain this variation in plant traits, an economic approach has been defined that suggests plants must allocate resources to either one purpose or another (Bloom, 1985; Givnish, 1986; Wright, 2004).

This resource allocation comes with trade-offs as each plant species determines what type of growth provides the best chance of survival in its designated niche. Wright et al., 2004, suggests that there are two major strategies for resource allocation, fast growth and slow growth. A plant species that allocates its resource to quick growth can provide benefits in the short-term to help prevent slope failures and erosion following construction. However, this fast growth is generally associated with lower quality in traits such as the density and durability of plant tissue. A plant species with slow resource allocation, requires more time to become established but generally survives longer and through more intense disturbance due to an investment in higher quality traits. This suggests that slower growing species may promote long-term slope stability and erosion control.

In stream restoration, projects that use vegetation are at risk for bank failure and erosion if a major storm event occurs before the plants are fully established (Logar and Scianna, 2005). Many riparian species are suitable in streambank restoration but black willow trees (*Salix nigra*) are the most common species used in the Southeastern United States (Hunolt, 2013). Hunolt et al., 2013, compared the black willow with three other common riparian species to determine which species grows root biomass most quickly as well as the best methods for ensuring the survival of live stake planted. Their study found that the silky dogwood (*Cornus amomum*) developed the largest belowground biomass in the growth period but they did not perform an in-depth analysis of individual root traits as a part of this study. Simon and Collison, 2002, performed an analysis to quantify the mechanical and hydrologic effects of mature riparian vegetation on streambank stability. This work found that riparian tree roots were able to increase soil strength and improve overall slope stability but they looked at mature tree species already established within a streambank. Little work has been done quantifying the hydrologic and mechanical effects of newly planted black willow and silky dogwood live stakes within a streambank environment.

Shallow-slope failure are fairly common occurrence along roadsides in Alabama. Steeper slopes are naturally more prone to sediment movement, faster run-off velocity, and more extreme sun conditions. Repairing these landslides is costly to ALDOT and requires extra time and effort to reestablish the area. Vegetative covers are a permanent solution to this but establishing and maintaining vegetative covers along steeper slopes near roadsides can be more challenging than along flatter, less extreme terrain. Alabama currently uses a grass mix to cover slopes which provide minimal deeper root structure and requires mowing to maintain it. This maintenance can actually add to the risk of slope failure as machine-induced rutting creates areas of exposed slope. Little work has been done to study other potential vegetative covers; studying other species that provide quick establishment, less maintenance, and deeper soil stability can provide long-term slope stability and can drive down the costs of landslide repair and grass maintenance.

1.2 Research Objectives

This research aims to study how vegetation grow and utilize different strategies to improve soil strength and slope stability in a simulated streambank environment and along a roadside slope. The results can then be utilized to improve streambank restoration and roadside construction projects. The research objectives of this study are:

- Quantify hydrologic and mechanical soil-strength effects of contrasting riparian tree species used in streambank restoration.
- Identify and assess alternate vegetation species that can be beneficial for roadside erosion control.

- Establish pilot plots along the NCAT test track to understand installation requirements and field performance of each species.
- Determine the best methods to quantify the effects of vegetation on sediment and water movement on a roadside slope.

1.3 Research Scope

This research is primarily concerned with how vegetation utilizes various growth strategies on sloped or unstable surfaces to increase both soil strength and decrease sediment movement. The first set of experiments were conducted in a simulated streambank microcosm environment, differences between the microcosm and a natural environment are assumed but not quantified. The microcosms are an idealized growing area without any extreme weather events to disrupt growth, as a result, the ability of the plants to weather extreme situations were not included in the scope of this study. Mechanical and hydrologic root traits were the primary area of interest; aboveground traits were noted but minimal analysis was performed.

The roadside-slope experiment was performed in a more ‘natural’ environment so vegetation was exposed to all the natural events that occurred during the test period. These events created more error in the results but also provided information on how the vegetation can withstand such events. However, unlike the microcosm experiment, this research was primarily concerned with aboveground traits (i.e., sediment and water movement). As this was the initial stage of a longer-term study, measurement of root traits, which requires destructive sampling was not included in this thesis.

1.4 Thesis Organization

This thesis contains 6 chapters, organized as follows:

Chapter 1: Introduction provides background information on how vegetation can be used to improve slope quality using different growth strategies. This includes the general hypotheses studied and the motivation to perform the work. A statement of the intended research objectives and the scope of the study are the final part of this chapter.

C*hapter 2: Literature Review* provides a more in-depth analysis of the current research that has been conducted in the field. This chapter provides information on the three main areas of interest of this study: root impacts on soil stability, vegetation used for streambank stability, and vegetation use for roadside erosion control.

Chapter 3: Methodology outlines the experimental procedures that were used for both experiments. This includes site/microcosm creation, site-monitoring process, as well as the various equations, error propagation, and statistical analysis performed.

Chapter 4: Greenhouse Microcosm Results describes and discusses the results from the experiment performed studying the simulated streambank microcosms. This section explains the results, how they relate to the Plant Trait Economic spectrum, and what future work can be done to improve the knowledge.

Chapter 5: Roadside Slope Results describes and discusses the results from the pilot plot study along the roadside slope. This section explains the growth results and run-off analysis as well as providing in-depth analysis of the error associated with the results. How these results can be applied to the Plant Trait Economic Spectrum as well as what future work should be performed to improve the study is also discussed.

Chapter 6: Conclusions contains a summary of all the conclusions that were drawn from both experiments and future work that should be pursued. This section also contains a discussion of the outcomes of each research objective. Following Chapter 6 are all the references cited in this work and supplementary information that was used to create the results.

2. Literature Review

2.1 Root contributions to soil stability

Vegetation is used as a way to increase slope stability along roadsides and streambanks due to hydrologic and mechanical effects the roots have on increasing soil strength as well as slowing overall sediment mass movement (Morgan and Rickson, 1995; Simon and Collison, 2002; Wells, 2002). It can act as a buffer between the soil and atmosphere by intercepting precipitation, absorbing wind and water energy, decreasing soil loss, and transferring water from the soil to the atmosphere (Dingman, 2002; Morgan and Rickson, 1995). When a plant is transpiring, water is evaporating from the leaf surface creating a potential-energy gradient that moves water through a plant's vascular system from the roots to the leaves to make up this water loss. This gradient subsequently draws water out from the soil into the roots, thereby decreasing the surrounding soil-water content (Dingman, 2002).

Unsaturated soil is characterized by having negative pressure relative to atmospheric pressure and this creates tension or suction forces between soil grains (Dingman, 2002). As the amount of water within a specified pore space decreases, the tension will increase as if a pseudo-vacuum is created (Dingman, 2002). Therefore, having a root system within soil that reduces the pore-water content will increase the matric suction of the soil and improved overall slope stability (Morgan & Rickson, 1995; Simon & Collison, 2002).

Plants can reduce the incidence of soil failure by drying the soil through transpiration. When water is not removed it can create increased slope instability due to additional weight as well as decreasing the effective stress between soil grains (Nelson, 2013). Water weighs more than air, so when water infiltrates the pore-space the weight of that same unit of soil will increase. When this occurs, there is a higher load placed on the same area which can cause slope failure. Oversaturation of soil can also lead to decreased effective stress between soil grains which decreases the strength of the soil.

Plant root systems also can provide a primary structural component within a slope by mechanically reinforcing the soil (Simon & Collison, 2002; Wells, 2002). Multiple root traits can influence the overall stabilizing effect of vegetation including size, distribution, and density (Stokes, 2009). Roots are strong in resisting tension forces while soil is strong in resisting compression forces (De Baets, 2008) so root-permeated soil creates a mixed material that can withstand both forces (Simon, 2004). Large, thick roots act as a passive stabilizing stakes that anchor the plant to the soil and also determine the position for associated thinner roots to grow. The thinner roots then provide wide spreading tensile strength that can resist shearing forces if they traverse into potential failure zones (Stokes, 2009). In shearing events, the stresses within the soil matrix are transferred to the root fibers by friction or tensile resistance (De Baets, 2008).

A well-developed root system with high biomass density (dry mass of roots per volume of soil) provides more soil stabilization while also helping to increase the likelihood of overall plant survival (Hunolt, 2013). In both woody and grass vegetation, the root area ratio (fraction of area of shear surface occupied by roots) tends to be more important for increasing soil shear strength than individual root strength (Simon and Collison, 2002). De Baets, 2008 concluded that generally, smaller diameter root systems had higher tensile strength, indicating that plants with dense fibrous root systems can successfully improve soil stability. Woody vegetation tends to form lateral root mats from dense root systems which provide increased stability within the upper planes of soil and decrease mass wasting along the surface (Stokes, 2009). Although they have deep taproots as well, the density of roots decreases dramatically past a 1-2 m depth so any soil stabilizing benefits end past that depth (Stokes, 2009).

Aboveground, vegetation can intercept rainfall and wind, increase surface roughness, and bind or block loose soil particles (Greenway, 1987). During rain and wind events, foliage will act as a barrier that breaks the velocity at which water and wind will reach the ground surface. Roots and stems will increase soil infiltration and surface roughness. The increased infiltration capacity of the soil is important on slopes as water that reaches the ground will be more likely to infiltrate the soil instead of moving sediment downslope. The volume of water that does run off of the slope will be reduced and the velocity will be decreased by the roughness of the vegetated surface. Roots and stems at the ground surface can also bind to loose soil particles and provide a physical barrier for sediment being moved down the slope by wind, water, or gravity (Greenway, 1987). Vegetation is used as a method for slope stability and erosion control along artificial slopes like dikes, roadsides, cut slopes, and mining tailings (ASWCC, 2018; Lobmann, 2020) as well as along natural slopes like streambanks, hills, and mountain slopes (Hunolt, 2013; Lobmann, 2020). This work focused particularly on the role of vegetation in streambank reinforcement and roadside erosion control to prevent shallow slope failure.

2.2 Stream Restoration

Human activity along streams and rivers has resulted in a growing problem of streambank degradation (Walsh, 2005). One of the leading causes of streambank degradation has been the urbanization of watersheds which increases the imperviousness of surrounding areas and intensifies stormwater peak flows (O’Driscoll, 2010). Most degradation is in the form of bank erosion, deeper channels, bank undercutting, and excessive sedimentation. These changes along the rivers have caused decreased water quality, storage, and flow rate which in turn has negative impacts on the surrounding ecosystems (Meyer, 2005; Walsh, 2005). Stream restoration has increasingly been a common response to these changes as a properly restored stream can improve the geomorphology of the area and restore an ecosystem to its former, natural condition (Shields, 2011; Thompson, 2018).

One major goal of stream restoration is to create long-term bank stabilization. Streambank failures are generally caused by stream-induced erosion that can undercut the streambank material, geotechnical failures within the bank due to increased moisture, or a combination of the two (Fischenich, 1989). Vegetation growing in a streambank counteracts these forces by decreasing soil moisture and mechanically reinforcing the bank with the root system (Simon and Collison, 2002). However, in order to achieve this long-term stabilization, vegetation needs to have adequate time to be established within the bank before major storm events occur to prevent plant mortality and subsequent bank failure due to lack of established stability (Logar and Scianna, 2005).

Planting live stakes is the most common way to establish native woody, riparian species for restoration projects. Native species are preferred as they are already adapted to local streambank conditions and are generally resistant to known stresses like flooding and drought cycles (Correll, 2005; DuBois, 2009; Hoag, 2009). Live stakes are branch cuttings of deciduous hardwood species, harvested during their dormant season and installed within a few days of collection (Gray & Sotir, 1996; Hunolt, 2013). The stakes are inserted vertically into the streambank; they are typically 0.5 to 1 m in length and 1 cm to 10 cm in diameter (Hunolt, 2013). As opposed to seeds, the larger size allows for a decreased chance of the live stakes being swept or washed away during establishment and, they immediately provide passive support within the bank. The roots of the stakes will then have a chance to grow and create longer-lasting soil stability within the bank by controlling shallow mass movement and drying the soil through transpiration (Gray and Sotir, 1996; Hunolt, 2013). The live stakes also create a more natural streambank aesthetic and are able to decrease nonpoint pollution by intercepting potentially contaminated sediment (Logar & Scianna, 2005).

In a given area, many acceptable native species may be available for live staking. Determining which species or mix of species will provide the best short- and long-term bank stability is difficult due to the inherent challenges associated with measuring root traits. Traditional methods of measuring root traits, such as root tensile strength, tend to be highly time consuming, destructive to the plant, and don't allow for successive measurements of individual plant growth over time (Greenway, 1987; Muhlich, 2008). Roots traits like density, orientation, and diameter need to be measured by exposing the soil face and measuring each root individually. To measure tensile strength, the root pull-out test is a common method (Schwarz, 2011; Wu, 1979), this is done by physically gripping exposed roots with a clamp and measuring the force required to pull it from the soil toward the plant. However, different root traits have various responses to the surrounding soil characteristics (Kramer-Walker, 2016) and tensile strength can vary within species depending on the growing environment, season, and root orientation (Greenway, 1987). These methods in root trait analysis limit the number of individuals that can be tested, so it is not feasible to assess the root traits of the native species in all regions where stream restoration is performed. Therefore, there is a need to develop a method to explain a plant's ecological niche so that belowground traits (i.e., root traits) can be correlated to aboveground traits (Kramer-Walter, 2016; Shen, 2019; Wright, 2004).

The plant trait economic spectrum (PTES) is a way to explain plant traits and the ecological strategies for acquiring and using different resources, such as light, water, and nutrients (Kramer-Walter, 2016). The PTES predicts that functional leaf, stem, and root traits of a species are correlated (Shen, 2019; Wright, 2014). It can be used to improve understanding of how ecosystems function at large (Westoby & Wright, 2006) as well as predict trait variation within species (Wright, 2004). Shen, 2019, found a strong correlation between aboveground plant traits (specific leaf area, nitrogen and phosphorus content, dry matter) and certain root traits (root tissue density and specific root length). These aboveground plant traits could potentially be used as indicators for root traits that promote soil stability without requiring the direct, destructive, root analysis.

A core principle of the PTES is that there is a trade-off between how quickly a plant is able to uptake resources and how well it can survive a low-resource or high-disturbance environment (Reich, 2014). Fast-growing species would be more abundant in resource-rich environments as they tend to acquire resources more quickly and outcompete slow-growing species. Slow-growing species invest resources in traits that allow better survival rates under stressful conditions and would dominate in resource-depleted environments or following disturbance (Kramer-Walter, 2016; Reich, 2004; Shen, 2019). In stream restoration projects, fast-growing species may be beneficial to ensure quick establishment but these plants are not investing as much in root tissue that withstands stress. It could be predicted that their roots have lower tensile strength and are likely to fail in extreme weather events. Slow-growing species contrarily would not be able to establish quickly enough to provide immediate bank stability benefits but may invest more resource in their roots. In this case, these plants may develop stronger roots systems that could survive the more extreme storm events and keep the streambank intact. Mixing fast and slow-growing species during restoration projects could provide both benefits and increase the overall success of the project.

Two common species used in streambank projects are the black willow (*Salix nigra)* and silky dogwood (*Cornus amomum*) (Hunolt, 2013; Simon & Collison, 2002). Black willows and silky dogwood are commonly planted from live stakes in riparian corridors of the southeast due to their ability to grow and establish root systems very quickly (Hunolt, 2013; Li, 2006; Pezeshki, 2005). Hunolt, 2013, found that harvesting live stakes of both species during the dormant season (February-March) resulted in 100% survival as long as the stakes weren't allowed to dry out before being planted. The species in this study developed large root systems but the black willow was found to grow quickly initially before plateauing out after 6 months while the silky dogwood continued to increase its biomass over the entire 9-month study. The Hunolt, 2013, study focused on live stake establishment and overall biomass growth (plant height, above and belowground mass, and stem diameter) while not looking at root traits. Our work applied the establishment principles that they determined worked best for live stakes and instead studied the root area, root strength, and soil moisture to determine the impact these species have on soil strength.

2.3 Roadside Slope Stability

Roadside shoulders are a known area for frequent erosion and sediment movement due to the creation of large areas that have exposed soil and/or steep slopes (Liu, 2014). Although loose earth and slope destabilization along roadsides causes only minor landslides and erosion, the consequences can cause major economic and social disruption (Morgan and Rickson, 1995; Montgomery, 2019). Many factors can impact roadside erosion like rain, slope gradient, rutting caused by lawn maintenance equipment, roadside construction, soil type, and type of vegetative cover (ASWCC, 2018; Montgomery, 2019).

The roadside slopes near construction sites run the risk of increased erosion as surrounding vegetation is removed, bare soil is exposed, and heavy equipment compacts the soil which can decrease infiltration so subsequent rain/wind events will have compounding negative effects (ASWCC, 2018). Currently, the most common species used in Alabama as a vegetative erosive control is tall fescue grass, specifically the Kentucky-31 cultivar (*Lolium arundinaceum*) as it can germinate within 6-8 days, tolerates full sun and poor soil conditions, is fairly drought resistant, and can endure regular foot traffic (AWSCC, 2018; USDA, 2021). The root systems are well-developed and can reach close to a 3-foot depth which can provide adequate soil stabilization (Cook, 2005). While fairly low maintenance, fescue grass tends to grow in bunches. This can lead to uneven distribution with bare patches of soil exposed and repeat visits required to re-seed bare areas (Cook, 2005; USDA, 2021). The grass also needs to be mowed and large-scale mowing operations can create long, deep ruts in the slope (Cook, 2005; Montgomery, 2019). These ruts and gaps in vegetation compound to increase the amount of soil that is exposed and lead to larger slope failures (Montgomery, 2019). Replacing fescue grass with a species that requires less maintenance but still develops deep roots systems that improve slope stability would decrease the costs associated with both maintenance and repair of road-side slopes. Several vegetation types present potential options based on previous literature.

Vetiver grass (*Vetiveria zizaniodies)* is a common grass native to southeast Asia that has been used for decades to improve slope stability, streambank establishment, and decreased sediment run-off in agricultural areas (Dalton, 1996; Kemper, 1993, USDA, 2021). The sunshine variety is used most commonly in the United States as it is more readily available (U.S. ACE, 2011). Compared to the India variety, the Sunshine variety of vetiver grass is shorter but with a base area that is bushier (U.S. ACE, 2011) which could be beneficial in areas where visibility is a factor. The grass is planted as a slip rather than as a seed and is generally sold sterile so it will not flower and be invasive to the surrounding native flora (Truong, 2000; U.S. ACE. 2011). The grass grows to be about 6 feet tall but occasional trimming can keep it at a height of 15-20 inches

(USDA, 2021). The roots stretch down as deep at 15-25 feet and when it is planted in hedgerows, the grass creates a physical barrier that prevents sediment movement and slows run-off (Shariff, 2000; Truong, 2000; USDA, 2021).

Juniper shrubs are also used often for erosion control along slopes and embankments; there are several varieties available but *Juniperus communis, Juniperus conferta,* and *Juniperus chinensis "Parsoni"* are common varieties used (USDA, 2021). Juniper shrubs grow relatively slowly but can reach a spread of 10' and root systems that reach close to 3' deep after 2 years of growth (Cherrylake, 2021; USDA, 2021). This creates a physical boundary at the ground surface that can block sediment movement as well as anchor deep soil. The shrubs also intercept precipitation and take up much of the water that flows down the stem. This can decrease the overall water running down the slope and creating a drier soil area but as a result they can out-compete other tree/shrub species (Lyons, 2009). Junipers are very drought-resistant, can grow in full sunlight, require minimal maintenance, and are able to grow in a variety of soil conditions along steep slopes (Cherrylake, 2021).

Ferns are also useful in erosion control practices as they create dense, long-lasting ground cover and naturally grow in disturbed areas with low nutrient and moisture access (Chau, 2017). Ferns are fairly slow growing, but they help increase erosion control by developing wide-spreading rhizome mats and fronds that rest on the ground and bind with surface level sediment (Knouse, 2017). Chau, 2017, found fern cover to significantly decrease sediment movement once they reach about 80% cover. Maidenhair fern (*Adiantum pedatum*) is native to the southeast and is able to develop large colonies of rhizome mats that block sediment movement and is able to grow on near vertical faces (Knouse, 2017; Prairie Nursery, 2021).

Hairy Vetch (*Vicia villosa* Roth) is a winter-active legume species used for erosion control and often used as a cover crop for agriculture due to its ability to fix large amounts of nitrogen (USDA, 2021). Weismeier, 2015, found that planting hairy vetch in steppe soil decreased the amount of sediment movement and increased overall soil organic carbon. The vetch developed high above- and belowground biomass which increased the soil structure and blocked above ground sediment movement. Power, 1991, also found that hairy vetch has a tendency to draw out large amounts of water from the soil, this is beneficial for soil strength but when grown with other species, could limit the growth of other nearby plants. Hairy vetch grows best when planted in the fall so can be beneficial for fall/winter construction projects when other species are typically dormant (USDA, 2021).

This research focused on developing test plots to analyze the field performance of each of these species as well as develop methods of analysis for sediment yield and runoff. The plot design was based on work done by Liu, 2014. Their work was based in rural China, but their conditions were more extreme than the area of concern in Alabama (highway-280 corridor roadside slopes between Auburn and Alexander City) as the roadside conditions were steeper and there was more exposed soil areas. They used 5m x 2m runoff plots with a 1,000 L runoff storage container for each test species and measured runoff, soil detachment, soil shear strength, aboveground biomass, surface cover, and root weight density. The plots used in this research has a similar shape but are smaller (1.5 m x 3 m) and used 68-liter capacity runoff collection container. TSS of runoff was measured to determine weekly sediment movement as well as calculate total sediment yield. Run-off volume and flow rate were measured using depth measurements and water level loggers. General plant health and establishment were monitored to ascertain how well each species can grow under these conditions.

Each species was grown individually but one aspect of this study was to understand the plant traits and, much like the stream restoration project, identify fast and slow-growing species and applying their traits to the PTES to create more robust stability in roadside slopes. Fast initial growth is necessary along roadsides to minimize soil movement after a disturbance caused by construction or other activity (Grace, 2002) but that growth may come with weaker root systems that will not survive subsequent disturbance events. If mixed with a species that provides stronger and deeper soil strength, roadside slope stability would be improved both short and long-term with minimal maintenance required.

3. Methodology

3.1 Experiment Overview

Two separate experiments were performed from February 2019 to March 2021 for the scope of this research. To assess vegetative stabilization for stream restoration projects, microcosms simulating a riparian water table were built and kept in the Auburn Plant Science Research Center greenhouses. Two common riparian species, black willow (*Salix nigra*) and silky dogwood (*Cornus amomum*), were studied from March 2019 to December 2019. The second portion of this research studied vegetation growth and stabilization along roadsides. Five test plots were built along the National Center of Asphalt Technology (NCAT) test track with five separate species of vegetation studied from May 2020 to March 2021.

3.2 Streambank Microcosm Experiment

Live stakes of black willow (*Salix nigra*) and silky dogwood (*Cornus amomum*) were harvested in February of 2019. The stakes were harvested from a stream near Hickory Dickory Park in Auburn, Alabama (32.635887N, -85.487130E) and kept soaking in a bin until planting. Hunolt et al. 2013 determined that harvesting live stakes during the dormant season had the highest chance of survival as long as they were kept wet.

The microcosms were created in 64x44x49 cm plastic bins with drainage holes 10 cm above the base so they are saturated from the bottom to simulate a riparian water table (following Hunolt et al., 2013). The microcosm bins were filled with hand-compacted native soil from the Piedmont physiographic province of Alabama to approximate a recently restored stream bank. Eight live stakes were planted into 2 bins per species on March 9, 2019 (Figure 1). The silky dogwood was marked as D-A1-4 and D-B1-4, while the black willow was marked as W-A1-4 and W-B1-4. The bins containing D-B1-4 and W-B1-4 were used in the four-month root analysis, while the bins containing D-A1-4 and W-A1-4 were used in the eight-month root analysis. D-A1 and D-A3 were replaced on May 10th, 2019 so initial stem diameter values were not noted. The final bin was left unplanted as a control with only soil kept inside. The five bins were left to grow in the Auburn Plant Research greenhouses and cared for by the staff of the greenhouse where they were watered three times a week and treated with standard pesticide and fertilizer as per greenhouse schedule.

Figure 1. Initial Live Stake Planting (3/9/19)

On a weekly basis, the stem diameter at a marked location near the base of each plant was measured using digital calipers to the nearest hundredth of a millimeter. The overall health of each plant was assessed qualitatively and pictures of each microcosm were taken. Weeding of any intrusive plants was done as necessary to keep the soil in each bin clear.

After both a four- and eight-month interval post-planting, one bin containing each plant species was analyzed for root tensile strength using a root pull-out test (modifying Wu et al., 1979). Each bin was cut in half to expose the root system (Figure 2). Individual roots were selected and their diameter was measured using the digital calipers. The location within the soil was noted using a grid overlay (4 cm x 4 cm) (Figure 3) and depth from the top of the soil was measured.

Figure 2. Exposed Soil Face

Figure 3. Grid Overlay

The root was then secured using a variety of clamps depending on size (Irwin 1 ½” C-Clamp; 1” spring clamp). The clamps had sandpaper attached to the contact area and a plastic zip-tie loop attached to the other end. A digital force gauge (Extech Model #475040) with data logging capabilities was attached to the plastic zip-tie. A steady force pulling in the direction that would be normal to each roots’ live stake stem was applied by hand until the root was pulled out of the soil while logging data. The peak force in Newtons required to pull the root out of the soil was recorded. The root tensile strength in MPa was determined by dividing peak force by the cross-sectional area of the root, which was determined using the diameter measurements and standard equation for the area of a circle.

Roots were selected based on size and location within the square of exposed soil. A variety of sizes was attempted however larger roots (>3.5mm) were often so well embedded that the clamps were not strong enough to hold the root without slipping off and very thin roots

(~<0.5mm) would break at the clamp rather than be pulled out. Certain roots also were unable to be used as they were still attached to the live stakes. The pull-out test was performed to test the strength of the roots pulling toward the plant so any roots still attached to the main stem were not able to be tested.

Following a previous study of mature riparian trees (Pollen and Simon, 2005), an exponential equation of the form:

$$y = a\,x^b \qquad \text{(Eq. 1)}$$

was fit to the data where x is the root diameter (mm) and y is the root tensile strength (MPa). The 95% confidence intervals of the model parameters (a and b) and R^2 were determined to assess goodness of fit. A t-test for two-samples with unequal variance was performed to determine if there were differences between the two species in root tensile strength. Curve fitting was performed in Matlab R2020a (Mathworks). Other statistical analyses were performed in Excel V16.48 (Microsoft).

Soil moisture measurements during a soil dry down were done in the microcosm bins to assess species level differences in the rate of soil drying. A bin containing each species was watered to field capacity and left undisturbed for 10 days at both the four- and eight-month interval. A time domain reflectometry soil moisture probe (Campbell-Scientific CS655) was calibrated using an internal calibration software and inserted into the soil in the root zone (15 cm depth). The volumetric water content (%) was then recorded at five-minute intervals over the course of the ten-day drying period. The crop coefficient of evapotranspiration was determined for each species as an indicator of its capacity to improve soil stability through rapid drying. The crop coefficient (K_c) relates crop evapotranspiration under well-watered conditions (ET_c) to reference evapotranspiration (ET_0) by the following relationship (Allen et al., 1998):

$$ET_c = K_c\, ET_0 \qquad \text{(Eq. 2)}$$

ET_c (mm/day) was estimated by multiplying the change in volumetric water content over the first 24 hours after the bins were watered to field capacity by the rooting depth determined during pull-out tests. ET_0 was calculated from meteorologic conditions recorded in the greenhouse and the standard method recommended by the Food and Agriculture Organization of the United Nations (Allen et al., 1998).

3.3 Roadside Slope Experiment

This experiment design was based on Liu et al. 2014 and Grace, 2002. The land and plots were all prepared and built in May 2020. The area of land used for the experiment was located along the National Center for Asphalt Technology (NCAT) Test Track in Opelika. AL (32.595390N, -85.296363E). The area has a 25-30° slope at its most extreme angle (S1). The land along the track was first treated with Round-Up herbicide several days before clearing. Any vegetation remaining within the designated area was first scraped using a small excavator then removed manually and tilled using a mechanical rototiller.

Figure 4. Initial Land Preparation (May, 2020)

Each plot consisted of a 1.5m x 3m wooden frame built from pressure-treated 2x4s (Figure 5). The outlet of each plot was tapered to a 45 cm exit to create a total surface area of 5.23 m^2. The four corners of all the frames had rebar installed to keep the plots stable on the slope and maintain the shape of the 45 cm outlet. The planks at the end of all the frames were wrapped with plastic sheeting and the ground between them had sheeting shingled under the earth to create a smooth path.

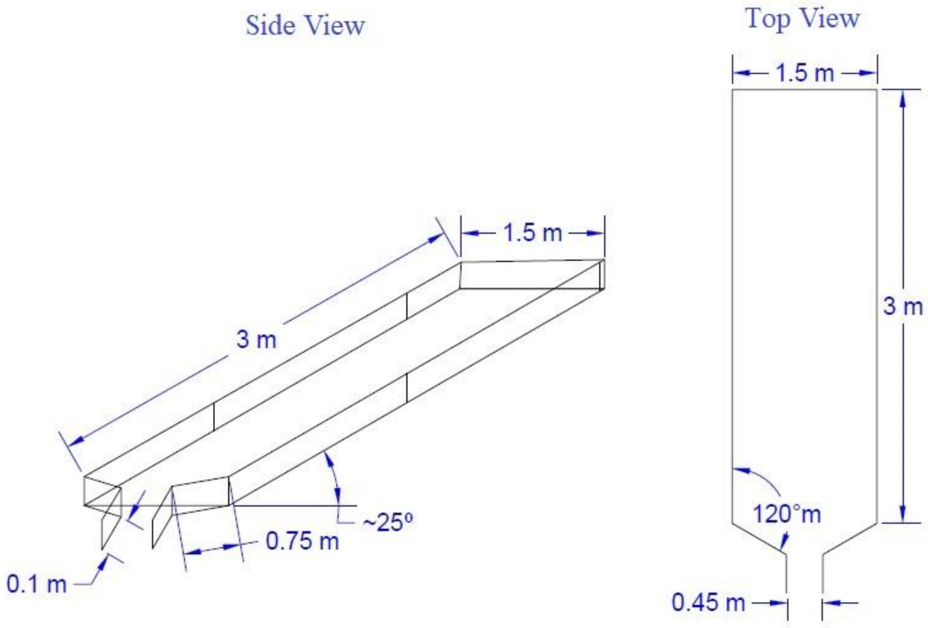


Figure 5. General Test Plot Design

Below each outlet, a 45 cm x 75 cm x 45cm hole was dug to accommodate 68-liter plastic bins. Along the lowest point of the slope, below the holes for the bins, a trench was dug along the entire length of the plot of land to divert any rainwater away from the collection bins. Another trench was dug 6 feet above the frames creating a berm directly above the plot to divert water away from the frames. The berm was covered with plastic sheeting and secured using garden stakes. An erosion fence was erected at the top of the frames and below the berm to catch any potential sediment movement from the slope above the plots. The erosion fence was finally fortified with a length of straw wattle that was laid along the base of the fence (Figure 6).

Figure 6. Completed plot installation

The vegetation was planted May 16-18, 2020 (Figure 7). On May 16th the juniper shrubs (*Juniperus chinensis 'Parsoni'*), fescue grass (*Lolium arundinaceum*), and maidenhair ferns (*Adiantum pedatum*) were planted and on May 18th the hairy vetch (*Vicia villosa* Roth) and vetiver grass (*Vetiveria zizaniodies)* were planted. Vegetation types were randomly assigned to the plots. The Parson's Juniper require a 4-foot spacing between each plant (Cherrylake, 2021) so 6 potted plants were planted within the first frame. The second frame contained the vetiver grass; these are planted in hedge rows with 2.5 feet of separation between each row. A 6" spacing distance is required between each slip (ORCDC, 2012) so every hedge row had 9 slips planted. The plot had four full rows planted and a final fifth row was planted right at the outlet of the plot with 3 slips. In total, 39 slips of the vetiver grass were installed. The third plot contained KY-31 fescue grass; this served as the control plot. The grass seed was applied to the prepared soil in an even layer using a broadcast spreader (Scott's Turfbuilder). Any bare areas within the plot were filled in by hand. The fourth plot was planted with potted maidenhair fern which require a 12" spacing so 15 individual ferns were planted within the plot. The final plot contained the hairy vetch. The vetch is planted from seeds scattered by hand on the soil. All five of the plots and surrounding area were covered with seeding straw (Pennington) to retain moisture, minimize sediment loss, and prevent weed growth while the plants established in the soil.

Figure 7. Test plots with all vegetation planted

After initial planting, the plants were watered multiple times a week, depending on weather conditions, to ensure proper establishment. After three weeks, on June 8th, 2020, the supplemental watering stopped and the monitoring of run-off and sediment loss began. Five 68-liter plastic bins (Centrex, model# 831522) were installed in the holes at the base of each plot. The bins were positioned with the plastic sheeting at the base of each plot flowing into the bins. Bins were partially covered with lids to minimize water loss due to evaporation.

On July 13th, 2020, extensive weed growth was removed and on August 3rd, 2020, a mesh screen was added to the opening to prevent any large leaves or animals from falling inside

(Figure 8). In each bin a U20L HOBO water logger was suspended from the lids using static electric wire (Figure 9) and submerged in water. The loggers were initially deployed on July 13th, 2020, they were set to record pressure (psi) and temperature (°F) every 15 minute.

Figure *8*. Collection bin with mesh covering

Figure *9*. Water logger suspended from lid

3.4 Roadside Slope Monitoring

Weekly site visits occurred from June 8th to March 26th for data collection and site monitoring. The plants growing were monitored for health and overall establishment. Water depth within the collection bins was measured using a tape measure to the nearest 1/8th of an inch. The water depth was measured after a week of collection then the bins were emptied, cleaned out, and refilled to a level that kept the water logger submerged. The water depth after cleaning and refilling was measured again so that total volume accumulated each week could be determined. The volume was determined as follows:

$$Vol_{tot}(L) = \frac{final\ depth(in) \times 256\ in^2}{61.024} \quad \text{(Eq. 3)}$$

$$Vol_{acc}(L) = \frac{\left(final\ depth\ (in) - initial\ depth\ (in)\right) \times 256\ in^2}{61.024} \qquad \text{(Eq. 4)}$$

Where the depth measurements were collected with an error +/- 0.0625 inches. The 256 in^2 was determined as an averaged area of the collection bin face using ImageJ software. The 61.024 is a conversion factor for volume between in^3 and liters. The error for both measurements is +/- 16 in^3 or +/-0.26 L.

A dilution factor had to be accounted for as each collection period started with a substantial volume of clean water. The factor was determined as follows:

$$Dilution\ factor = \frac{Vol_{tot}}{Vol_{acc}} \qquad \text{(Eq. 5)}$$

As both variables in this equation have their own error, the error associated with the dilution factor was determined using standard error propagation:

$$\Delta DF = \sqrt{\left(\frac{\partial DF}{\partial Vol_{tot}} \Delta Vol_{tot}\right)^2 + \left(\frac{\partial DF}{\partial Vol_{acc}} \Delta Vol_{acc}\right)^2} \qquad \text{(Eq. 6)}$$

$$\Delta DF = \sqrt{\left(\frac{1}{Vol_{acc}} \Delta Vol_{tot}\right)^2 + \left(\frac{-Vol_{tot}}{{Vol_{acc}}^2} \Delta Vol_{acc}\right)^2} \qquad \text{(Eq. 7)}$$

3.5 Run-off Collection Analysis

Water samples of the runoff were collected from the collection bins using round, wide mouth 500 mL HDPE sampling bottles, weekly or biweekly, depending on precipitation. TSS analysis was conducted on these samples onsite at the NCAT laboratory. Turbidity measurements were also taken on the same samples to provide a method of verifying the TSS values.+

Turbidity was analyzed using a Hach 2100Q turbidimeter. The meter was calibrated weekly using 800, 100, 20, and 10 NTU standards using an internal calibration software.

Samples were transferred into 16 ml containers and the turbidity was measured twice for each sample to the nearest 0.01 NTU. The average of these values was then multiplied by the dilution factor to obtain an accurate understanding.

$$Turbidity = NTU \times Dilution\ Factor \qquad \text{(Eq. 8)}$$

TSS was measured using EPA method 160.2. Glass microfiber filters (LabExact, 4.7 cm, model # LSS-AH4700) were soaked with filtered water then dried using a Gast (Model 1HAB-2524M-00X) vacuum pump. Each filter was placed on a metal weigh boat and allowed to dry out in a Despatch Lab Series oven at ~108° C for an hour. Once dried, each filter + weigh boat was weighed using a Mettler Toledo (ME204E) scale to the nearest 0.0001 g. Each water sample was then pushed through a filter using the same vacuum pump set up. The filters were put back into the oven for another hour to dry and reweighed. The total sediment weight was determined by subtracting the final weight from the initial. TSS was determined by dividing the total weight by the volume of water collected in the sample bottle and multiplied by the dilution factor.

$$TSS\ (\frac{mg}{L}) = \frac{mass}{volume} \times DF \qquad \text{(Eq. 9)}$$

Error associated with the TSS is dependent on error with the sediment mass, the volume, and the dilution factor.

$$\Delta TSS = \sqrt{\left(\frac{\partial TSS}{\partial m}\Delta m\right)^2 + (\frac{\partial TSS}{\partial DF}\Delta DF)^2 + \ (\frac{\partial TSS}{\partial Vol}\Delta Vol)^2} \qquad \text{(Eq. 10)}$$

$$\Delta TSS = \sqrt{(\frac{DF}{Vol}\Delta m)^2 + (\frac{m}{Vol}\Delta DF)^2 + (\frac{-m}{Vol^2}\Delta Vol)^2} \qquad \text{(Eq. 11)}$$

Sediment yield was then determined in grams using both the TSS values and the accumulated volume measurements where:

$$Sediment\ Yield\ (g) = \frac{TSS \times Vol_{acc}}{1000} \quad \text{(Eq. 12)}$$

The error associated with this is depended on both the TSS and volume measurements so the error value is determined by:

$$\Delta Yield = \sqrt{\left(\frac{\partial Yield}{\partial TSS}\Delta TSS\right)^2 + (\frac{\partial Yield}{\partial Vol_{acc}}\Delta Vol_{acc})^2} \quad \text{(Eq. 13)}$$

$$\Delta Yield = \sqrt{(\frac{Vol_{acc}}{1000}\Delta TSS)^2 + (\frac{TSS}{1000}\Delta Vol_{acc})^2} \quad \text{(Eq. 14)}$$

Cumulative sediment yield was determined by simply adding each consecutive sediment yield value.

$$Cumulative\ Yield = Y_n + Y_{n+1} + Y_{n+2} + \cdots \quad \text{(Eq. 15)}$$

The error associated was determined the same way:

$$\Delta Cumulative\ Yield = \sqrt{(\frac{\partial CY}{\partial Y_n}\Delta Y_n)^2 + (\frac{\partial CY}{\partial Y_{n+1}}\Delta Y_{n+1})^2 + \cdots} \quad \text{(Eq. 16)}$$

$$\Delta Cumulative\ Yield = \sqrt{(\Delta Y_n)^2 + (\Delta Y_{n+1})^2 + \cdots} \quad \text{(Eq. 17)}$$

The amount of sediment that moved per liter of water was also determined using both the cumulative yield and cumulative volume collected for the plots:

$$Sediment\ per\ liter\ volume\ (\frac{g}{L}) = \frac{Cumulative\ Yield\ (g)}{Cumulative\ Volume\ (L)} \quad \text{(Eq. 18)}$$

The associated error with these values was determined as follows:

$$\Delta Sediment/vol = \sqrt{\left(\frac{\partial S/V}{\partial CY}\Delta CY\right)^2 + \left(\frac{\partial S/V}{\partial CV}\Delta CV\right)^2} \quad \text{(Eq. 19)}$$

$$\Delta S/V = \sqrt{(\frac{1}{CV}\Delta CY)^2 + (\frac{-CY}{CV^2}\Delta CV)^2} \qquad \text{(Eq. 20)}$$

3.6 Run-off Flow Data Analysis

Meteorologic data (atmospheric pressure and precipitation) was obtained from the NCAT weather station and additional precipitation data was obtained from visualcrossing.com for Opelika, AL using the Auburn-Opelika A AL, KAUO weather station. A water level logger was suspended from a post at the site on October 12th, 2020, to collect atmospheric pressure data to provide a more accurate conversion of logger data from pressure to water depth than was obtained with weather station data.

The water level logger data was unloaded using a HOBO waterproof shuttle (part # U-DTW-1) fitted with a U20L coupler (part # COUPLER2-C) onto the HOBOware software version 3.7.22 during each weekly or bi-weekly monitoring visit. The data was then converted to an Excel .csv file for analysis. The pressure data was precise to 0.0001 psi. The pressure values of the logger suspended in air was subtracted from the pressure values of the loggers in the collection bins. Prior to October 12th, 2020, when the atmospheric logger was added, pressure data from the NCAT weather station was used. However, due to equipment malfunctioning, many values were either not recorded or inaccurate, so flow data is not available for the first few months of analysis.

All of the pressure values were analyzed in Excel using the PivotTable option. The pressure values were converted into a volume using the following formula:

$$Logger\ Volume\ (L) = \frac{\frac{Pressure\ (psi)}{0.4335\ (psi\ per\ foot)} \times (12\frac{in}{ft}) \times 256\ in^2}{61.024} \qquad \text{(Eq. 21)}$$

Where 0.4335 is a conversion factor from psi to depth in feet (AllWaterRights, 2019). The 12 in/ft converts to a depth in inches and 256 in^2 converts it to a volume in in^3. The 61.024 again is a conversion factor for volume in in^3 to liters. As all the other values associated with this formula are constants/known exactly the only source of error is the logger error (0.0001 psi) so the error associated with the volume is +/- 0.01 L.

4. Greenhouse Microcosm Results

4.1 Vegetation Establishment and Growth

The dogwood and willow were analyzed at both the four and eight-month growing period. Both species successfully took root and grew substantially in the microcosms within a few weeks. By April, 2019, the plants were already developing substantial leaves (Figure 10).

Figure 10. Plant Status on 04/05/19

After the first four-month growth period, both species had a very visible increase in growth (Figure 11 and 12).

Figure 11. Silky Dogwood, July, 2019

Figure 12. Black Willow, July, 2019

By the eight-month growth period, both plants would be in a dormant period in a natural environment, so leaf coloring was reflective of that change. But overall plant growth continued and both plants were healthy during the final experiment.

Figure 13. Dogwood, November 2019

Figure 14. Willow, November 2019

4.2 Root Size and Distribution

	Average Root Cross-Sectional Area		Cumulative Root Area	
	7/15/2019	12/5/2019	7/15/2019	12/5/2019
Dogwood	1.46 mm^2	0.52 mm^2	46.72 mm^2	13.06 mm^2
Willow	1.13 mm^2	1.66 mm^2	31.64 mm^2	50.00 mm^2

Table 1. Average cross-sectional area of individual roots and cumulative root area within the 0.28 m^2 soil cross-section calculated during each test period.

Table 1 shows that the average cross-sectional area of individual roots area and cumulative root area for both species. The dogwood's average area was smaller for the measurements in July than December while the willow tree had larger values for both the average size and cumulative area. The dogwood had two stakes replanted in May, which could be creating this variation in root size. The growth for the willow is consistent with the findings from Hunolt, 2013, where they saw a steady growth for the black willow over the first 6 months of their growing period.

The location of each root was mapped on the grid overlay (Figure 3) during the December root analysis and the root distribution is shown in Figure 15. The willow roots are distributed throughout the root zone, while the dogwood roots are more concentrated within the upper few centimeters of the soil. These results show that the dogwood roots tend to stay more clustered to the bottom of the live stake creating a dense, horizontal layer of roots within the soil. The willow roots are less densely packed within a single location but instead create a larger area where a root-soil matrix is created. This is further visualized when comparing the cumulative root area to the depth of the root location (Figure 16), the willow is able to develop overall more root area deeper in the soil in an 8-month growing period than the dogwood.

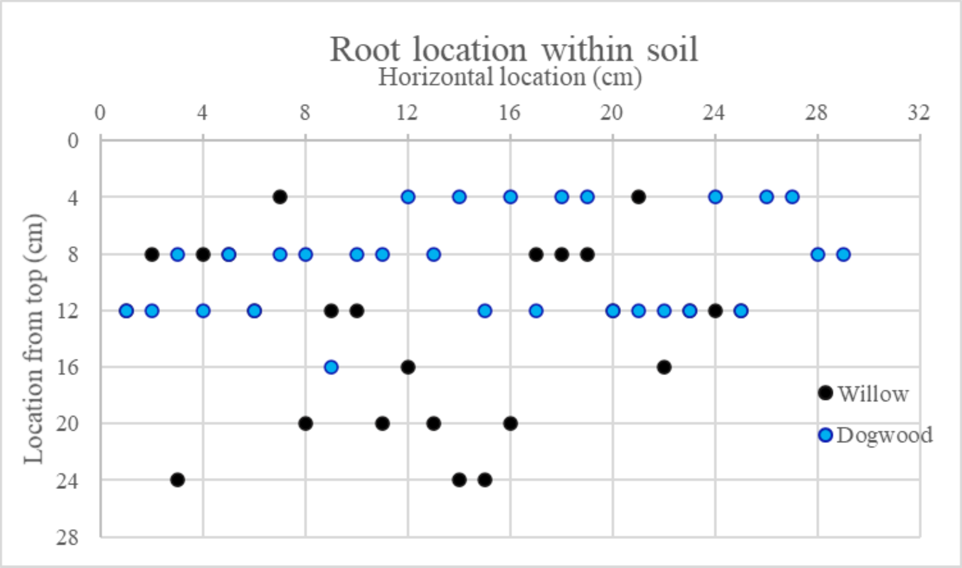


Figure 15. Root distribution of each plant during 12/5/19 testing period determined using the grid overlay seen in Figure 3

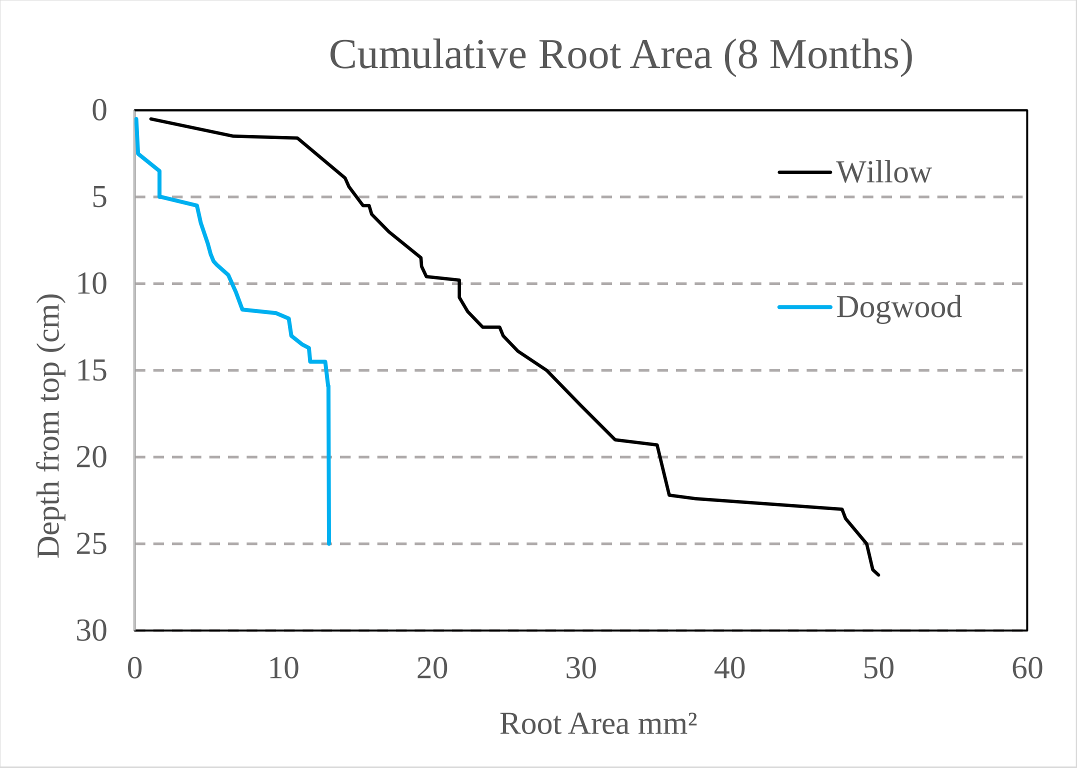


Figure 16. Cumulative root area of both plant species plotted against the successive depth from the top. Analysis done during the testing period that occurred after an 8-month growth period.

Figure 17. Dogwood Root

Figure 18. Willow Root

Visual analysis of the roots shows that the dogwood (Figure 17) has smaller, uniform roots developing into a branching configuration while the willow (Figure 18) has different widths of roots coming out of the single length. The morphology is consistent with the results in Figures 15 and 16, the willow has a single, primary root where smaller roots are emerging from. The willow prioritizes growing this primary root so that it can reach deeper soil layers and the roots that branch out of it are distributed along its entire length. The dogwood doesn't appear to have such a clearly defined primary root and instead is growing all of its roots uniformly, in a branching method that develops laterally rather than vertically.

4.3 Root Tensile Strength

The force required to pull the roots out of the soil was measured in Newtons. The tensile strength was calculated by dividing the force by the root area. $MPa = \frac{N}{mm^2}$ (Figure 19).

Root Tensile Strength

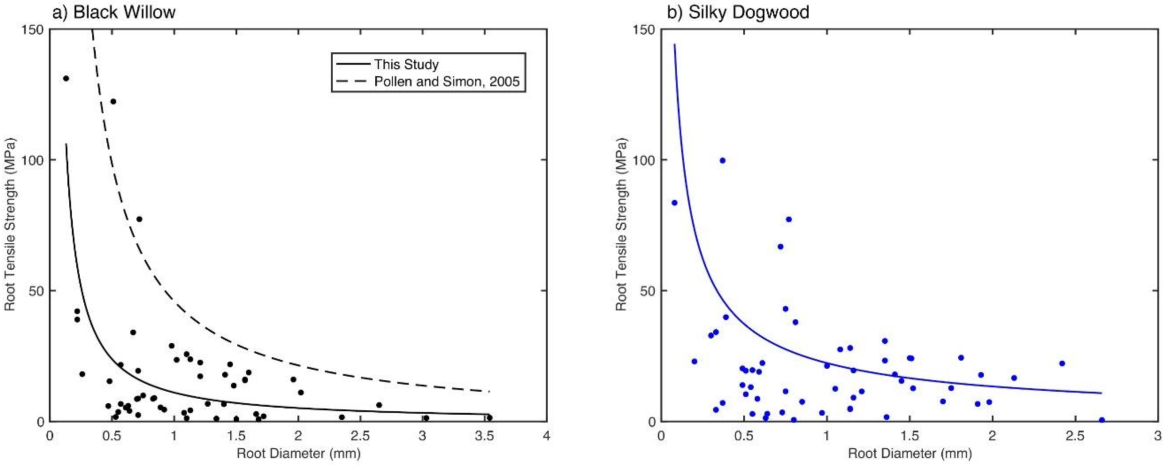


Figure 19. Root tensile strength of each plant species converted into MPa plotted against each individual root diameter. Results from Pollen and Simon, 2005 paper also added as a reference point for how mature black willow plants behave.

The root tensile strength data followed an exponential trend, given by the equations and coefficients in Table 2.

	Coefficients (95% CI)		
	a	*b*	**R^2**
Black Willow	11.03 (5.45, 16.61)	-1.11 (-1.44, -0.78)	0.39
Silky Dogwood	22.29 (10.51, 34.08)	-0.74 (-1.08, -0.40)	0.22

Table 2. Coefficients with 95% confidence intervals and R^2 of the exponential equation of the form y=a x^b fit to data for two species where x is root diameter (mm) and y is root tensile strength (MPa).

	Silky Dogwood	**Black Willow**
Mean (MPa)	29.6	18.0
Variance (MPa^2)	2455	676
N	51	56
***t* Statistic**	1.53	
***p* Value**	0.065	

Table 3. Results of a t-test for two samples with unequal variance comparing the tensile strength of Black Willow and Silky Dogwood.

Root tensile strength was consistent within each species between four months and eight months, so the results are analyzed together. The *t*-test results (Table 3) show that silky dogwood had higher root tensile strength than black willow at the 10% confidence level. There was a large amount of scatter in the diameter-tensile strength relationship for both species, resulting in low confidence in estimation of the exponential fit parameters (Table 2). Pollen and Simon, 2005, performed a similar root-tensile strength test on black willows in Mississippi (Figure 19). Their tensile strength values were higher for the willow but the experiment was performed on fully grown willows in a natural environment. This suggests that the tensile strength would still increase with a longer growing period. However, this could also suggest that a microcosm environment may not provide an environment that fully mimics a natural growing environment.

4.4 Soil Moisture Analysis

Soil moisture data was collected at both growth intervals using the Campbell-Scientific Soil Moisture probes, however the greenhouse conditions in December, with cool temperatures and low incident radiation, led to overall low evapotranspiration rates. The data from July showed a clear difference between the two species.

Soil Moisture Test

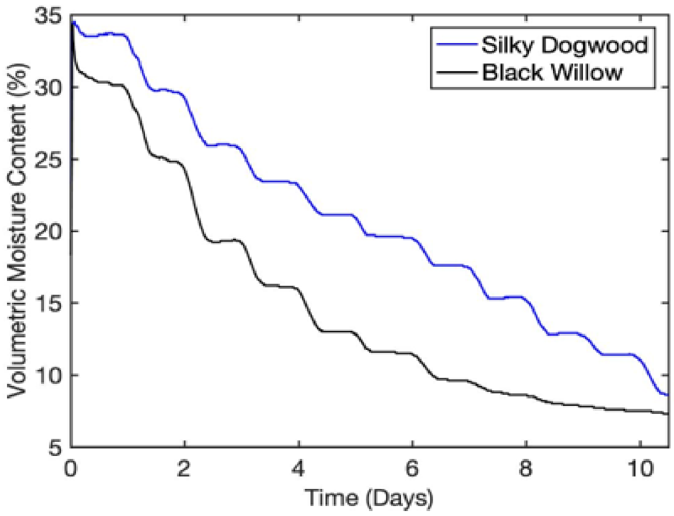


Figure 20. Soil moisture values given in volumetric water content over the course of a 10 day drying period for both species.

The willow immediately began drying out the soil more quickly than the dogwood and over the course of the 10 days, reached a lower final moisture content. The evapotranspirative crop coefficent (K_C) was determined for both species using this data and the following values were calculated (Table 4). These values show that the willow tree has a higher transpiration rates and water demand than the dogwood which indicates that the willow has a larger hydrologic effect on the surrounding soil.

	Crop Coefficient Values (K_c)
Dogwood	1.2
Willow	1.6

Table 4. Kc values determined for each species using soil moisture results and Eq. 2

These soil moisture results are consistent with the root area values, the black willow will require more water to maintain the larger root biomass so it will draw out moisture much quicker. The dogwood conversely, had less root biomass so it would not require as much water but the roots it does grow are stronger and are providing more mechanical strength to the soil in the long-term.

4.5 General Growth Patterns

Aboveground traits were also examined by measuring the stem diameters of each individual plant (Figure 21). The willows showed the same trend of increasing stem diameter over the eight-month growth period as their root area. The dogwood had more variation within the stem diameter readings, showing minimal or decreased growth in some individual's cases which mimics what was occurring with the dogwood's root area.

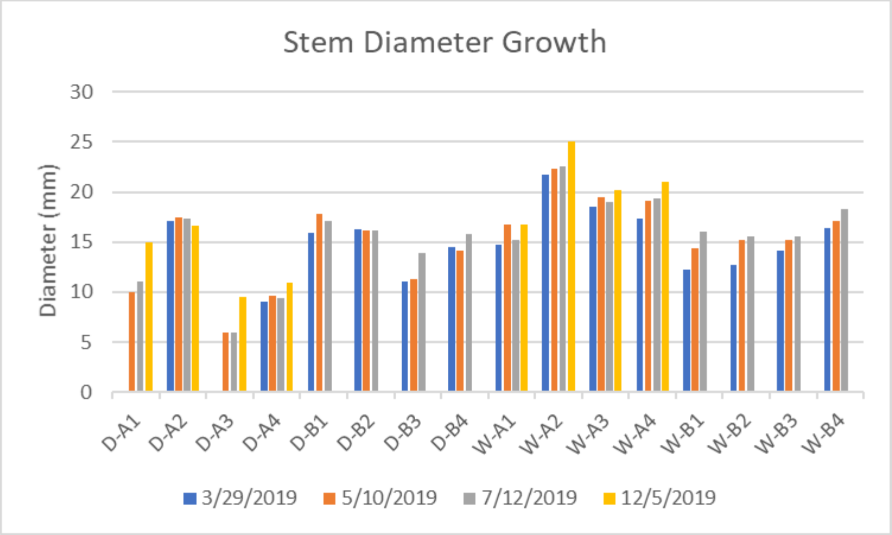


Figure 21. Stem diameter growth of each individual plant over the course of the study period.

The difference in growth between these two species is fairly consistent above and below ground. The aboveground measurements were limited to verifying that the plants were established successfully within the microcosms but more work could be done to measure different aboveground variables like leaf area index, branch growth, plant height, etc. and determine a relationship to belowground root traits. Establishing this correlation can provide a non-destructive method of plant analysis which can allow for more longitudinal studies of plant establishment.

The PTES spectrum suggests that ecological traits for a plant are functionally coordinated (Shen, 2019) and that different plants will invest their energy differently depending on their growth strategy. This work suggests that the willow will invest energy producing lots of overall biomass (both above and belowground) on the trade-off that what is grown is lower quality. The dogwood will do the opposite where it will invest more energy in developing higher quality features (stronger roots) but with the trade-off that it will develop less and require more time to develop these features.

5. Roadside Slope Results

5.1 Vegetation Establishment and Growth

The vegetation was all planted by May 18th, 2020 and after 3 weeks of watering, the plants were left unattended to begin run-off collection. Initially, all five of the plant species were able to grow and establish successfully (Figure 21).

Figure 21. All test plots, June 8th, 2020

However, native weeds and plants in the surrounding area began to encroach and quickly took over the plots (Figure 22) and weeding was required on all of the plots.

Figure 22. All test plots July 10th, 2020, prior to weeding

After the weeding, the two plots containing the vetch and fern were overwhelmed by the disturbance. The fern (Figure 23) was still visible but would often appear dormant (leaves were brown, little growth) while the vetch completely disappeared from the plot for much of the remaining time (Figure 24). The plots were instead overtaken by fescue grass that encroached from the adjacent plot, as well as white clover (*Trifolium repens*) and ground-ivy (*Glechoma hederacea*).

Figure 23. Fern plot, November 30th, 2020

Figure 24. Vetch plot, November 30th, 2020

The intended vegetation for both of those plots remained dormant during much of the testing period. The fern plants were able to survive the entire test period but they were primarily dormant and only re-emerged briefly under ideal circumstances. The plants themselves did not grow or spread out in any significant way that would alter sediment movement within the plot. Any decreases in sediment movement would have been due to the invasive weeds that took over the plot. The vetch did begin to return by the end of March 2021 (Figure 25) and began outcompeting other plants that were previously growing there as well as spreading to adjacent plots. Vetch is generally used as a winter cover crop so it could be useful for quick establishment on construction projects that occur in winter or early spring.

Figure 25. Vetch Plot March 29th, 2020

Figure 26. Fescue Grass March 15th, 2020

The plot containing the fescue grass control (Figure 25) remained consistent throughout the entire test period and grew well as long as it had direct sunlight. After the initial weeding in July, the plot was resistant to most invasive weeds. The same species that were present in the vetch and fern plots (clover and ground-ivy) did occur in the control plots but the grass remained the dominant species. The grass behaved as expected but the erosion fence that was installed above the plot cast a shadow along the top half of the plot and the grass in that area was sparser.

The plots containing the vetiver and juniper plants were the most successful at general establishment (Figure 27 & 28). The area surrounding the junipers was overgrown by similar weeds as the other plots (fescue grass, clover, and ground-ivy), however, these surrounding plants did not impact the growth of the juniper as the juniper shrubs were able to grow successfully. The vetiver grass also performed similarly, by September 2020, the grass was nearly at its full height (2 meters) and the hedgerows developed an almost impenetrable layer that was resistant to invasive plants. In November, 2020, the grass reverted to a dormant stage where the blades of grass turned brown, but the overall plant remained healthy and performed the same as it did while not dormant.

Figure 27. Juniper plot, March 15th, 2021

Figure 28. Vetiver grass plot, March 15th, 2021

Overall, the plots containing the juniper shrubs and vetiver grass performed the best in terms of growing and adapting to surrounding conditions. After all invasive plants were removed in July, these plants were the most resistant to invasive species, grew the most consistently, and the vetiver developed the most visible aboveground biomass. The control plot was also fairly resistant to native weeds and, except for requiring direct sunlight, required minimal maintenance but this could have been due to the plot's location in the middle of the test site. The plots containing the fern and vetch fared the worst. The fern was able to survive but it did little else, these plants were the least weed resistant and did not noticeably grow. The vetch completely vanished after July, so the plot simply had native weeds growing for much of the test period. However, when it re-emerged in March, the vetch was highly aggressive out-competing other weeds. It could still potentially be a useful species paired with plants that grow during the late summer/fall period as it does grow quickly and does not require any maintenance once it is planted. Both the fern and vetch species were dormant for most of the testing period so the run-off analysis collected for those plots are not accurately representing the plants' ability to stabilize sediment.

5.2 TSS and Turbidity Analysis

The TSS and turbidity values are plotted in Figure 29 for all five plant species. The values that were collected don't show any clear trends or patterns occuring between the species or between the two methods of analysis. There is also no species that was tested that provided consistent results after any rain event and there were large discrepencies between the two methods of analysis. Vetch had a large spike in TSS in mid-September that did not have a corresponding spike in turbidity while the fern had a large spike in turbidity mid-August that is not reflected to the same degree in the TSS values.

The initial turibidity values are also much higher than the initial TSS values comparatively, the four plants that are off the chart in Figure 29 all have values between 1500-3000 NTU while their TSS values are all below 1000 mg/L. The same dilution factor was added to both values to account for the addition of clean water but this dilution would have different effects on each method of analysis as the TSS simply dealt with overall mass per unit volume while turbidity looks at the amount of light that is able to pass through the sample.

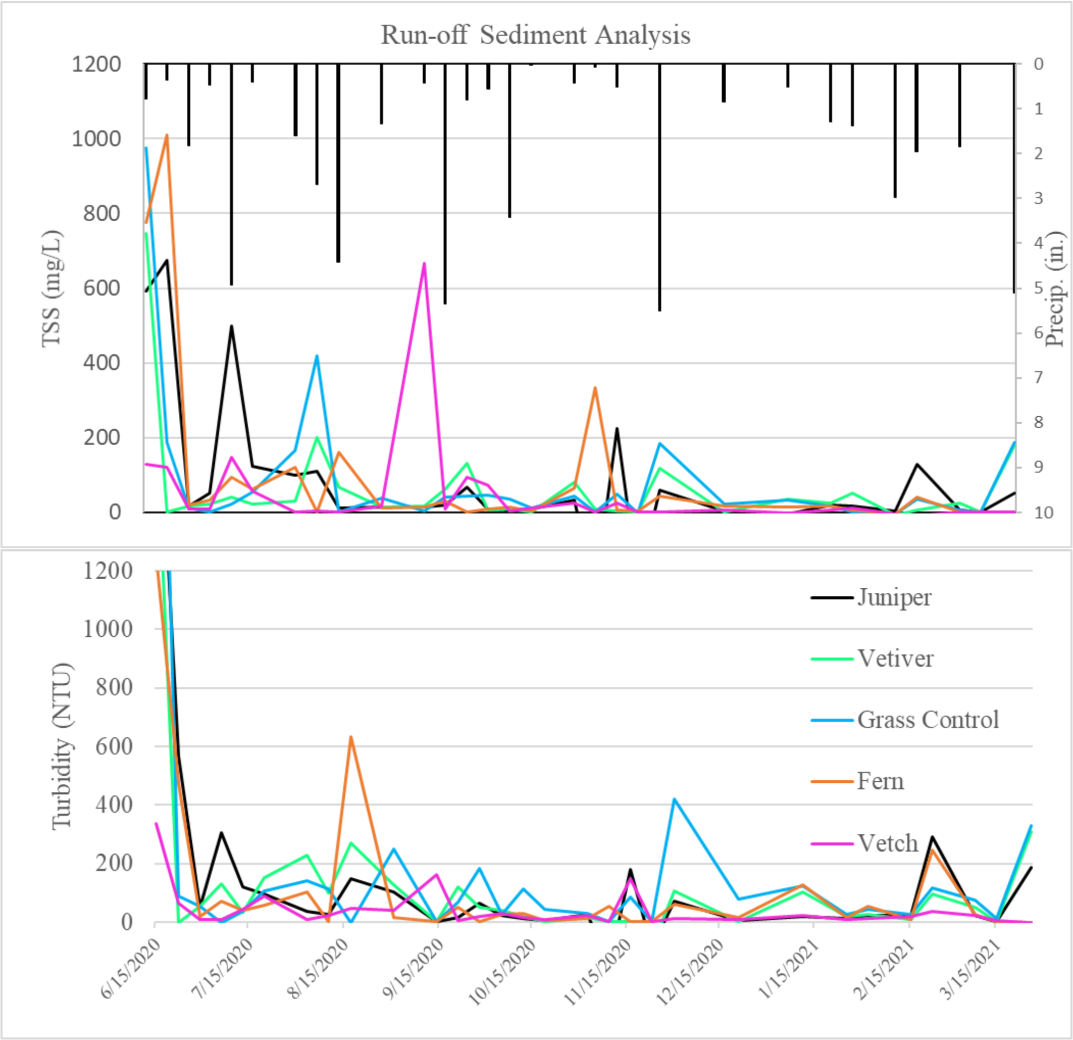


Figure 29. TSS and turbidity values calculated with added dilution factor of the course of the 9-month test period

Hannouche, 2011 confirmed that a strong linear relationship between these two these parameters exists and that TSS could be determined based on a turibidity value. Since both TSS and turbidity were analyzed using the same sample bottles, a linear relationship should be expected. The values of this experiment were plotted against each other (Figure 30) to validate the results where a linear relationship would indicate that the values are accurate but the two graphs show that was no such relationship observed for the values collected. A theoretical 1:1 line was added to the chart to show where values tended to lay with respect to the two methods of analysis. The values are highly scattered but many points tend to occur above the theoretical

1:1 line. This suggests that either the turbidity values are overestimating the amount of sediment or that the TSS values are underestimating the amount. This could be due to how dilute the water samples or how small the amount of sediment collected within the sample bottles was but it indicates that this method of analysis has low precision.

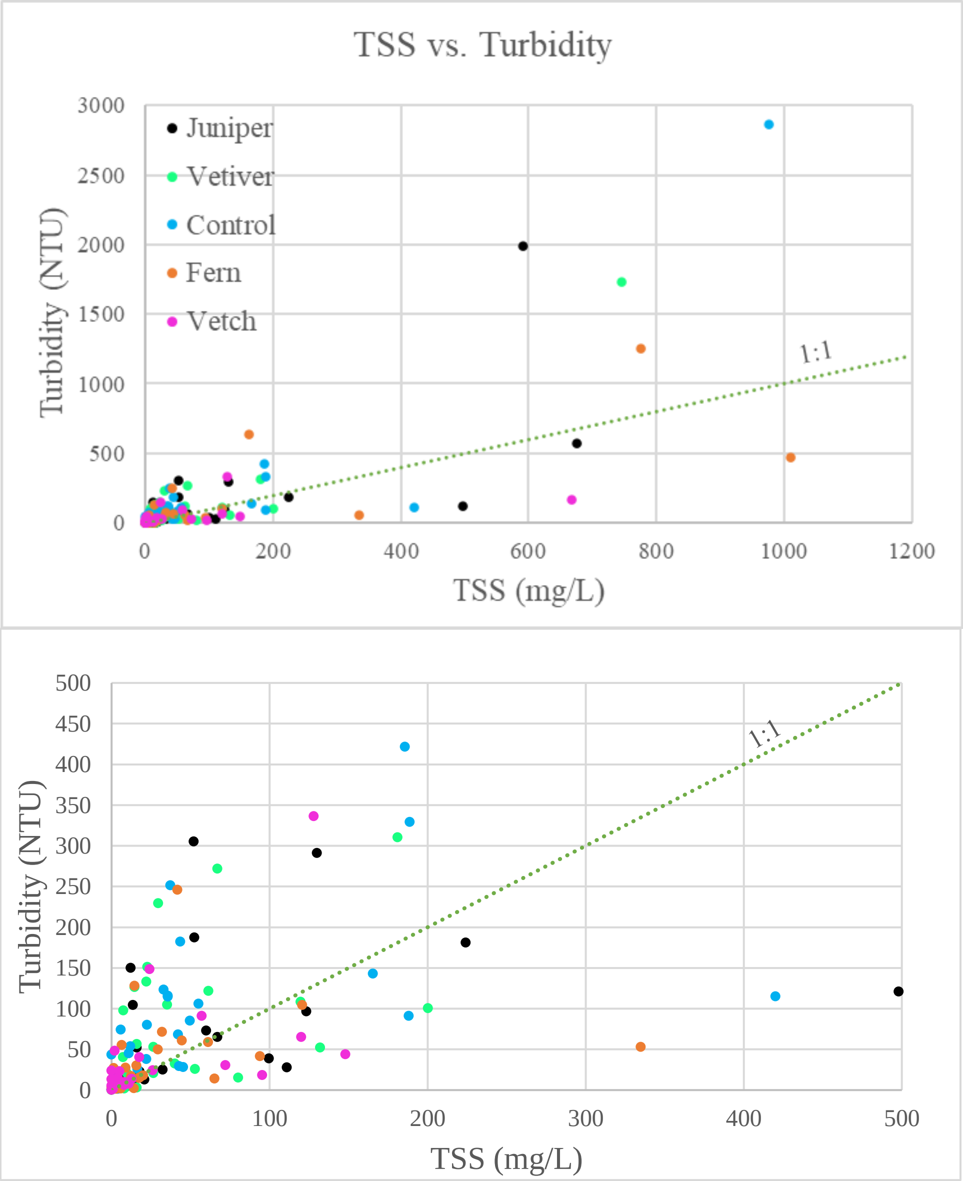


Figure 30. TSS vs. turbidity; both plots show the same value, the lower plot is limited to values below 500 NTU and 500 mg/L to better display the smaller values. Theoretical 1:1 line is added as a reference point.

5.3 Sediment Yield

The cumulative sediment yield was deterimined for only the three species of interest (juniper, vetiver, grass control); the fern and vetch were excluded from this analysis as they were mainly dormant. Figure 31 shows the total sediment yield. The grass control had the largest amount of sediment movement over the course of the nine-months while the juniper shrubs had the least and the vetiver grass was about in the middle of the two. The initial spike in sediment yield in June was collected 1 month after planting and shows that the grass provided the least amount of initial surface-soil stabilization. Over the course of the study-period the juniper had a much gradual increase in sediment. All three species showed similar spikes in sediment during rain events at the end of November and the end of March. The grass control had much more extreme jumps in movement with minimal increases in between rain events while the juniper also had jumps but the movement overall was very gradual throughout the nine-month period. This suggests that the juniper can provide a more stabilizing effect during more extreme weather while the grass performs better during milder/no weather.

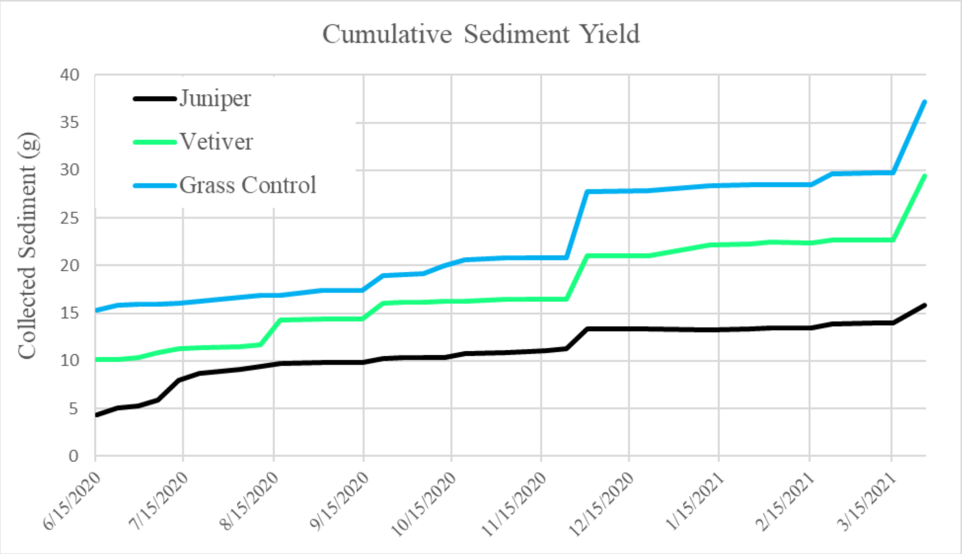


Figure 30. Cumulative sediment yield of the juniper, vetiver, and control plots over the course of the 9-month period, determined using TSS values and accumulated volumes.

The total sediment accumulated was compared with the total run off volume accumulated (Table 6) to see how much sediment is moving per liter of run-off. The grass control had the highest sediment accumulation while the vetiver had the highest volume accumulated. While looking at the values for sediment per liter of volume, the vetiver and juniper had very similar values while the grass control value is much higher. The vetiver had nearly double the sediment yield as the juniper but much more water coming through as well which suggests that the run-off coming off the vetiver plot is much less concentrated. This could be the hedgerows preventing sediment movement but simultaneously creating an area of land that is more impervious to water infiltration. The juniper had both low sediment and low volume which points to better surface stabilization and ground that allows more water infiltration. However, the error that is associated with the values over the course of this test period is very high for both sediment yield and sediment per volume. These values can provide a good baseline for information but additional testing in the future should be performed to validate these results. The control had the lowest error values, but it is still almost half of the total accumulated value. While the juniper error values for sediment yield are larger than the actual value.

	Cumulative Sediment Yield (g)	Total Volume (L)	Sediment per 1 liter run-off (g/L)
Juniper	15.6 ± 20 g	262 ± 90 L	0.077 ± 0.07 g/L
Vetiver	29.5 ± 20 g	343 ± 90 L	0.086 ± 0.07 g/L
Grass Control	37.2 ± 20 g	305 ± 90 L	0.12 ± 0.06 g/L

Table 5. Cumulative values for the three species of interest as well as comparison of amount of sediment per 1 liter run-off to quantify the relationship between sediment and water movement.

5.4 Run-Off Movement

The run-off movement into the collection bins during two large rain events are plotted in Figures 32 and 33. The initial volume values for each chart are dependent on how much clean water was added during each weekly reset, as a result each bin had slightly different starting volumes of water. During the November rain event (Figure 32), the juniper overall had the lowest volume of water moving down slope. The vetiver had a similar starting value as the juniper but its volume jumped much higher during the first spike in precipitation. The control plot had a higher starting value than the other two but its jump in volume during the first day of precipitation is also larger than that of the juniper. These values are consistent with what was shown in Table 6. The vetiver has the most amount of water movement of all three plots but less sediment as compared to the control. The juniper had the lowest water movement during this rain event which suggests the ground may be the most pervious of the three plots and the juniper exerts some hydrologic drying effect.

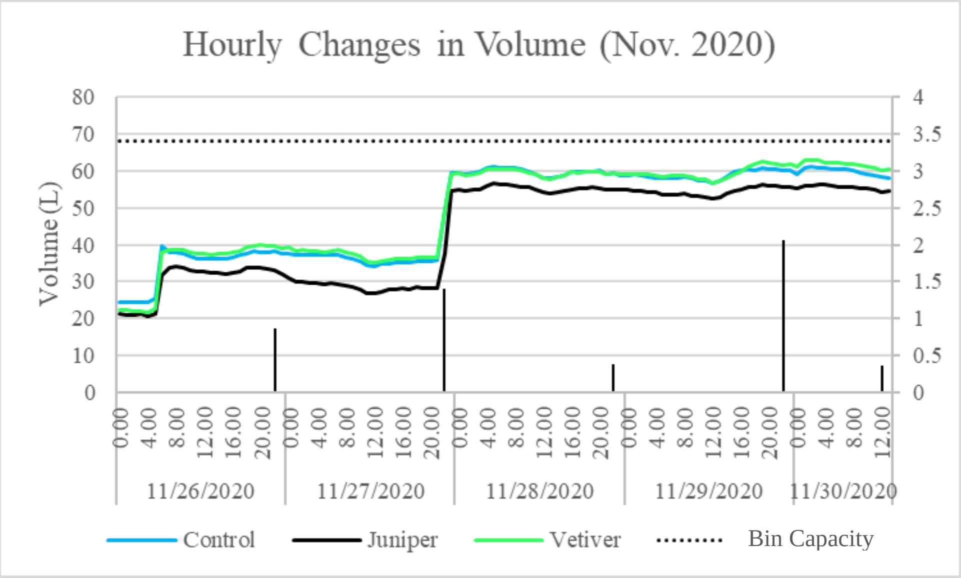


Figure 29. Run-Off volume changes during 11/26/2020 rain event

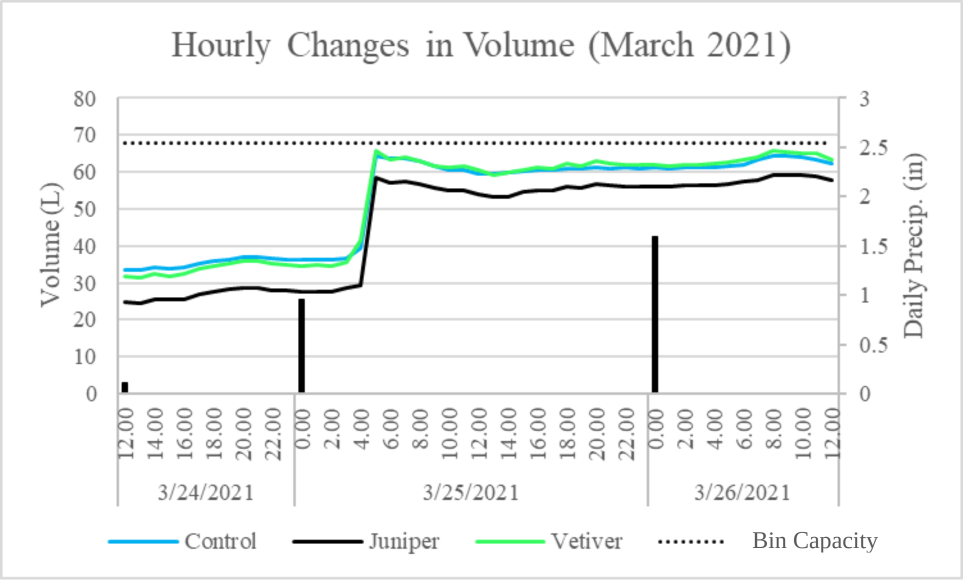


Figure 30. Run-Off volume changes during 3/24/2021 rain event

During the March rain event, the juniper's initial volume is the lowest and it stays the lowest throughout, but comparative to the other two bins, the change in volume is fairly consistent. The vetiver seems to have a slightly larger increase in volume as compared to the control, but the difference is much smaller as compared to the difference in change during the November event. This suggests that after a longer growth period, all three plots are behaving fairly similarly when it comes to their effect on run-off.

Overall, the plot containing the juniper shrubs performed the best in terms of both sediment and water movement, especially during the initial few months of growth. This conclusion comes with the consideration that there was a significant amount of error associated with many of the calculations. Over the course of the entire test period, there was only about 52 inches of precipitation with many weeks having less than 1 inch total, if any. This resulted in most samples being highly dilute and the mass of sediment collected during TSS analysis being less than 1 mg total with a scale that has a precision of 0.1 mg. This applies to the run-off volume collection as well since there was minimal water flowing into the collection bins during weeks of little precipitation.

The interface between the plot outlet and the collection bin is another area of potential error as the bins would occasionally be displaced by flooding below the plots. Water would come up from below the bins so the plot outlet would not fully align with the bin opening. This resulted in some of the run-off not being collected. This occurred sporadically and would not impact the bins equally so certain weeks could have lower values of run-off than what would have actually been. Future work with these types of plots could build a more secure plot to ensure the bins are securely attached to the outlet to prevent any loss in collection. Liu et al. 2014, used prefabricated concrete plots and collection areas to ensure the two elements were fully connected at all times. However, for the scope and size of this project, other methods of analysis could be more useful to yield better results in slope stability and erosion control.

More work should be done to develop different methods of analysis to verify the results of this experiment. Above and belowground analysis of the plant species to measure biomass and root characteristics would provide quantifiable measures of how the plant is directly impacting the soil. Liu et al. 2014 performed in-situ shear tests that measure the shear strength of soil using a vane tester as a quick measure of instantaneous soil strength. Erosion pins are also a quick method of showing surface and sub-surface sediment movement which could be used in the place of the TSS analysis with potentially less error.

6. Conclusions

6.1 Research Conclusion

This study aimed to look at how vegetation can be used to increase slope stability and reduce erosion in two different applications. The main objective of the streambank microcosm was to quantify and compare the hydrologic and mechanical effects of silky dogwood and black willow roots. The results suggest that the black willows utilize the fast growth pattern and silky dogwoods use a slow growth pattern that Wright et al. 2004 propose. In our work, the black willow developed a much larger root system in a shorter time period and exerted a larger hydrologic effect on the soil than the silky dogwood. The silky dogwood developed less root area but the roots developed were higher quality and they had significantly higher tensile strength than the black willow. When planted together in a restoration project the willow could provide the short-term stability to ensure initial bank establishment and the dogwood could provide the long-term stabilization that is required for the streambank to remain stable.

The roadside experiment had three major objectives. The first two were to identify and assess alternate species that could be used that require less maintenance but provide similar or better erosion control than the current grass used. Both the juniper and vetiver grass performed extremely well in this regard while the hairy vetch had mixed results. It was dormant for most of the experiment like the maidenhair fern, but it did begin to reemerge during the end of the study period which could warrant more experiments. The maidenhair fern was not able to be established to a point where it provided any soil-strength benefits so it is not recommended for any future work.

The final objective was to determine methods of analysis that can accurately quantify how the different vegetative covers decrease sediment movement and increase slope stability.

TSS analysis of the collected run-off proved to have far too much error to be considered accurate. The volume of run-off provides more accurate analysis of run-off flow but this doesn't provide any information regarding slope stability. Overall, the roadside experiment was successful in establishing test plots and identifying several species that could be used for future work but the methods of analysis will require more work.

6.2 Cost Analysis

The streambank microcosm project used live stakes that were collected from a local streambank. For use in stream restoration projects, the only cost that would be associated with using these plants is labor to harvest the stakes and then having them installed. Using live stakes from local streambanks also ensures that the plant species you are using are known to grow and establish in a similar environment which can provide additional verification to potential stakeholders that the project will be successful.

The cost breakdown per square foot of area for the five species is in Table 6 below. The two seeded mixes, the fescue grass and hairy vetch, had the lowest cost per square foot which is expected. Of the non-seeded plant species tested, the juniper is the most cost-effective species again, the other two species both had substantial increases in prices but these are all based on retail prices rather than wholesale which could drive the cost down for larger-scale prices. The vetiver grass was planted with the distance between hedgerows being at the absolute minimum, under different slope conditions (i.e., less steep), the distance between the hedgerows could be increased which would require less plants.

The seed-mix comes with much easier installation requirements as well but adding some form of straw, hay, or mat to prevent seeds from just being blown off by the wind would need to be factored into the cost. Conversely, the non-seeded plant species would have more laborinduced costs to install the plants but adding a straw or other stabilizing mat would not be a necessity to ensure plant survival.

	Price per square foot
Juniper Shrubs	$1.07
Vetiver Grass	$2.16
K-31	$0.01
Maidenhair Fern	$3.30
Hairy Vetch	$0.02

Table 6. Price per square foot of each tested plant species at retail price

6.3 Recommendations for Future Work

The streambank microcosms focused more on analyzing root traits directly and did little with the aboveground traits. This provided good information for the two growing periods but due to the destructive manner of this analysis, only provided a cross-sectional look at plant life. The Plant Trait Economic Spectrum is an emerging area study that is not being utilized enough for engineering practices. Future work that correlates above and belowground traits of riparian vegetation can be used to develop a system to measure field performance without destructive research. A non-destructive experiment could then be used to perform a longitudinal study that quantifies long-term riparian vegetation establishment starting from a live stake and better serve stream restoration projects.

Unlike the streambank microcosms, the roadside experiment focused entirely on aboveground behavior of the plants and run-off. Creating isolated microcosm like the streambank experiment could provide information on belowground traits which can provide a more quantitative analysis of the soil-strength effects of the roots. In-situ work can also be done to study the sub-surface like using soil-moisture probes, soil-conductivity probes, and erosion pins. These all provide a more direct measurement of how the soil is behaving near each vegetative cover and would minimize the large error propagation of the TSS analysis. In addition, this study looked at each vegetation type individually but combining multiple species in the same plot could provide a more stable surface by drawing on different traits that each species has. The vegetation studied in this experiment could benefit from being analyzed using the PTES to determine where on that spectrum they lay to better predict what combination of vegetation can provide both short- and long-term benefits.

Using other biomaterials and geosynthetics were not in the scope of this research but could be another potential area of study. In this case, these materials could provide the role of short-term surface-soil stabilization and be combined with a plant species that provides the long-term slope stabilization. This could be a quick method to overcome the seasonal growth patterns that many fast-growing plants have.

7. References

Alabama Department of Transportation (2018). Section 665 Temporary Soil Erosion and Sediment Control. ALDOT, Special Provision No. 18-0699(2). https://www.dot.state.al.us/publications/Construction/pdf/Specifications/2018/ProposedGASPSummary/18-0699(2).pdf.

Alabama Soil and Water Conservation Committee (2018) Alabama Handbook for Erosion Control and Stormwater Management on Construction Sites and Urban Areas. Alabama Department of Transportation. https://www.dot.state.al.us/dsweb/divped/Stormwater/pdf/AlabamaHandbookforErosionControl.pdf.

AllWaterRights (2019). Converting Logger Pressure to Depth & Storage/Flows. Rights to Water Engineering, Inc. https://allwaterrights.com/2019/02/24/converting-logger-pressure-to-depth-storage-flows/.

Armstrong, A., Sousa, L. R., Haggerty, C., Fischer, C., & Wagenlander, W. (2013). An Integrated Approach to Sustainable Roadside Design. Federal Highway Administration, Department of Transportation produced by Parsons Brinckerhoff; Report Number: FHWA-WFL/TD-13-001. https://www.fhwa.dot.gov/clas/pdfs/IntegratedApproachtoSustainableRoadsideDesign.pdf**.**

Bloom, A. J., Chapin, F. S., & Mooney, H. A. (1985). Resource Limitation in Plants-An Economic Analogy. Annual Review of Ecology and Systematics, 16(1), 363–392. https://doi.org/10.1146/annurev.es.16.110185.002051.

Caltrans (2010). Green Technologies for Reducing Slope Erosion. Caltrans Division of Research and Innovation produced by CTC & Associates LLC. https://dot.ca.gov/-/media/dot-media/programs/design/documents/f0005886-green-infrastructure-preliminary-investigation.pdf.

Chau, N. L., & Chu, L. M. (2017). Fern cover and the importance of plant traits in reducing erosion on steep slopes. Catena, 151: 98-106. https://doi.org/10.1016/j.catena.2016.12.016.

Cherrylake (2021). Juniper Parsoni. https://cherrylake.com/resource/shrubfactsheets/juniper_parsoni.pdf.

Cook, T. (2005). Tall Fescue. OSU Horticulture Department. https://agsci.oregonstate.edu/sites/agscid7/files/horticulture/beaverturf/TallFescue-1-5-05V.pdf.

Cope, J. T., Alvord, B. F., & Drake, A. E. (1962). Rainfall distribution in Alabama. Auburn University, Progress Report Series No. 84.

Correll, D.L. (2005). Principles of planning and establishment of buffer zones. Ecological Engineering 24:433-439. https://doi.org/10.1016/j.ecoleng.2005.01.007.

Dalton, P. A., Smith, R. J., & Truong, P. N. V. (1996). Vetiver grass hedges for erosion control on a cropped flood plain: hedge hydraulics. Agricultural Water Management, 31(1-2), 91-104. https://doi.org/10.1016/0378-3774(95)01230-3.

De Baets, S., Poesen, J., Reubens, B., Wemans, K., De Baerdemaeker, J., & Muys, B. (2008). Root tensile strength and root distribution of typical Mediterranean plant species and their contribution to soil shear strength. Plant Soil, 305, 207-226. https://doi.org/10.1007/s11104-008-9553-0.

Dingman, L. S. (2002). *Physical Hydrology*. 2nd edition. Waveland Press.

DuBois, L., Latimer, J., Appleton, B., and Close, D. (2009). America's Anniversary Garden: Native Plants. Blacksburg, VA: Virginia Cooperative Extension. https://vtechworks.lib.vt.edu/bitstream/handle/10919/48226/426-223_pdf.pdf?sequence=1&isAllowed=y.

Ellis, J. R. (2020). Developing a practical tool for integrating green infrastructure into cost-effective stormwater management plans. Thesis submitted to Auburn University. https://etd.auburn.edu//handle/10415/7287.

Federal Interagency Stream Restoration Working Group. (2001). Stream Corridor Restoration. National Engineering Handbook, USDA-Natural Resources Conservation Service. Part 653.

Fischenich, J. C. (1989). Channel erosion analysis and control. In Proceedings of the Symposium on Headwaters Hydrology. American Water Resources Association, Bethesda Maryland. Vol. 1989, p. 101-109.

Givnish, T. J. (1986). On the economy of plant form and function: Proceedings of the Sixth Maria Moors Cabot Symposium (Vol. 6). Cambridge University Press.

Grace III, J. M. (2002). Effectiveness of vegetation in erosion control from forest road sideslopes. Transactions of the ASAE, 45(3), 681. doi: 10.13031/2013.8832.

Gray, D. H., & Sotir, R. B. (1996). Biotechnical and soil bioengineering slope stabilization: a practical guide for erosion control. John Wiley & Sons.

Greenway, D. R. (1987). Vegetation and slope stability. Slope stability: geotechnical engineering and geomorphology/edited by MG Anderson and KS Richards, p. 187-230. Wiley.

Hannouche, A., Chebbo, G., Ruban, G., Tassin, B., Lemaire, B. J., & Joannis, C. (2011). Relationship between turbidity and total suspended solids concentration within a combined sewer system. Water Science Technology, 64(12): 2445-2452. doi: 10.2166/wst.2011.779.

Hoag, C.J. (2009). Vertical Bundles: A Streambank Bioengineering Treatment to Establish Willows and Dogwoods on Streambanks. Technical Note, USDA Natural Resources Conservation Service. Plant Material No. 53. Boise, ID and Salt Lake City, UT: USDA Natural Resources Conservation Service.

Hunolt, A. E. (2012). Survival and Growth of Black Willow (Salix nigra), Silky Willow (Salix sericea), Silky Dogwood (Cornus amomum), and Virginia Sweetspire (Itea virginica) Live Stakes. Thesis submitted to Auburn University. https://etd.auburn.edu/bitstream/handle/10415/3053/FINAL%20THESIS%20After%20defense%205%20mom.pdf?sequence=4&isAllowed=y.

Hunolt, A. E., Brantley, E. F., Wright, A. N., & Wood, C. W. (2013). Comparison of native woody species for use as live stakes in streambank stabilization in the southeastern United States. Journal of Soil and Water Conservation, 68(5), 384-391. https://doi.org/10.2489/jswc.68.5.384.

Kemper, W. D. (1993). Vetiver grass: A thin green line against erosion. Journal of Soil and Water Conservation, 48(5), 426-427.

Knouse, J. A. (2017). Ferns as conservation agents. https://www.jaknouse.athens.oh.us/ferns/ferncons.html.

Kramer-Walter, K. R., Bellingham, P. J., Millar, T. R., Smissen, R. D., Richardson, S. J., & Laughlin, D. C. (2016). Root traits are multidimensional: specific root length is independent from root tissue density and the plant economic spectrum. Journal of Ecology, 104(5), 1299-1310. https://doi.org/10.1111/1365-2745.12562.

Li, S., S.R. Pezeshki, and F.D. Shields. (2006). Partial flooding enhances aeration in adventitious roots of black willow (Salix nigra) cuttings. Journal of Plant Physiology 163:619-628. https://doi.org/10.1016/j.jplph.2005.06.010.

Liu, Y. J., Wang, T. W., Cai, C. F., Li, Z. X., & Cheng, D. B. (2014). Effects of vegetation on runoff generation, sediment yield and soil shear strength on road-side slopes under a simulation rainfall test in the Three Gorges Reservoir Area, China. Science of the Total Environment, 485, 93-102. https://doi.org/10.1016/j.scitotenv.2014.03.053.

Lobmann, M. T., Geitner, C., Wellstein, C., & Zerbe, S. (2020). The influence of herbaceous vegetation on slope stability – a review. Earth-Science Review, 209: 103328. https://doi.org/10.1016/j.earscirev.2020.103328.

Logar, R., & Scianna, J. (2005). Improving the Establishment of Willow Cuttings in Riparian Areas. Forestry Technical Note No. MT-25. United States Department of Agriculture. NRCS. https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs144p2_051418.pdf.

Lyons, R. K., Owens, M. K., & Machen, R. V. (2009). Juniper Biology and Management in Texas. AgriLife Communications, The Texas A&M System.

Messer, R. C. (2011). Evaluating Maintenance Techniques for Long-term Vegetation Establishment on Disturbed Slopes in Alabama. Thesis submitted to Auburn University. https://etd.auburn.edu/bitstream/handle/10415/2648/Thesis%20Final%2007.pdf?sequence=2&isAllowed=y.

Meyer, J. L., Paul, M. J., & Taulbee, W. K. (2005). Stream ecosystem function in urbanizing landscapes. Journal of the North American Benthological Society, 24(3), 602-612. https://doi.org/10.1899/04-021.1.

Mickovski, S. B., & van Beek, L. P. H. (2009). Root morphology and effects on soil reinforcement and slope stability of young vetiver (*Vetiveria zizaniodies*) plants grown in semi-arid climate. Plant and Soil, 324: 43-56. https://doi.org/10.1007/s11104-009-0130-y.

Montgomery, J., Knights, M., Xuan, M., & Carcamo, P. (2019). Evaluation of Landslides along Alabama Highways. Alabama Department of Transportation, 930-931.

Monti, A., & Zatta, A. (2009). Root distribution and soil moisture retrieval in perennial and annual energy crops in Northern Italy. Agriculture, Ecosystems & Environment, 132(3-4), 252-259. https://doi.org/10.1016/j.agee.2009.04.007.

Morgan, R. P. C. 1., & Rickson, R. J. (1995). Slope stabilization and erosion control: A bioengineering approach. London ; New York: E & FN Spon.

Mΰhlich, M., Truhn, D., Nagel, K., Walter, A., Scharr, H., & Aach, T. (2008). Measuring Plant Root Growth. Pattern Recognition 30th DAGM Symposium, 497-506. https://doi.org/10.1007/978-3-540-69321-5_50.

Nelson, S. A. (2013). Slope Stability, Triggering Events, Mass Movement Hazards. EENS 3050, Natural Hazards, Tulane University. http://www.tulane.edu/~sanelson/Natural_Disasters/slopestability.htm.

Oahu Resource Conservation and Development Council (2012). Vetiver Installation Guide. USDA Natural Resource Conservation Service (NRCS) Pacific Islands Area. https://www.vetiver.org/USA_Vetiver%20Installation%20Guide_2012.pdf.

O’Driscoll, M., Clinton, S., Jefferson, A., Manda, A., & McMillan, S. (2010). Urbanization Effects on Watershed Hydrology and In-Stream Processes in the Southern United States. Water, 2: 605-648. https://doi.org/10.3390/w2030605.

Pezeshki, S.R., C.E. Brown, J.M. Elcan, and F.D. Shields. (2005). Responses of non-dormant black willow (Salix nigra) cuttings to preplanting soaking and soil moisture. Restoration Ecology 10:1-7. https://doi.org/10.1111/j.1526-100X.2005.00001.x.

Prairie Nursery. (2021). Maidenhair Fern: *Adiantum pedatum.* https://www.prairienursery.com/maidenhair-fern-adiantum-pedatum.html.

Pollen, N., & Simon, A. (2005). Estimating the mechanical effects of riparian vegetation on stream bank stability using a fiber bundle model. Water Resources Research, 41(7). https://doi.org/10.1029/2004WR003801.

Power, J. F., Doran, J. W., & Koerner, P. T. (1991). Hairy Vetch as Winter Cover Crop for Dryland Corn Production. Journal of Production Agriculture, 4(1): 62-67. https://doi.org/10.2134/jpa1991.0062.

Puno, R. C. C., Puno, G. R., & Talisay, B. A. M. (2019). Hydrologic responses of watershed assessment to land cover and climate change using soil and water assessment tool model. Global Journal of Environmental Science and Management, 5(1), 71-82.

Reich, P. B. (2014). The world-wide 'fast-slow' plant economics spectrum: a trait manifesto. Journal of Ecology, 102(2): 275-301. https://doi.org/10.1111/1365-2745.12211.

Schwarz, M., Cohen, D., and Or, D. (2011). Pullout tests of root analogs and natural root bundles in soil: Experiments and modeling. Journal of Geophysical Research, Vol. 116, F02007. https://doi.org/10.1029/2010JF001753.

Sharif, M. (2000). US Army experience: Cold tolerance and seed viability characteristics of vetiver. In Proc. Second Intern. Vetiver Conf.

Shen, Y., Gilbert, G. S., Li, W., Fang, M., Lu, H., & Yu, S. (2019). Linking Aboveground Traits to Root Traits and Local Environment: Implications of the Plant Economics Spectrum. Frontiers in Plant Science, 10: 1412. https://doi.org/10.3389/fpls.2019.01412.

Shields, F. D. Jr., Copeland, R. R., Klingeman, P. C., Doyle, M. W., & Simon, A. (2003). Design for Stream Restoration. Journal of Hydraulic Engineering, 129(8). 575-584. https://doi.org/10.1061/(ASCE)0733-9429(2003)129:8(575).

Simon, A., Bennet, S. J., & Neary, V. S. (2004). Riparian Vegetation and Fluvial Geomorphology: Problems and Opportunities. Riparian Vegetation and Fluvial Geomorphology, Water Science and Application 8, American Geophysical Union.

Simon, A., & Collison, A. J. C. (2002). Quantifying the mechanical and hydrologic effects of riparian vegetation on streambank stability. Earth Surface Processes and Landforms, 27(5), 527-546. https://doi.org/10.1002/esp.325.

Stokes, A., Atger, C., Bengough, A. G., Fourcaud, T., & Sidle, R. C. (2009). Desirable plant root traits for protecting natural and engineered slopes against landslides. Plant Soil, 384, 1-30. https://doi.org/10.1007/s11104-009-0159-y.

Thompson, J., Pelc, C. E., Brogan III, W. R., & Jordan, T.E. (2018). The multiscale effects of stream restoration on water quality. Ecological Engineering, 124: 7-18. https://doi.org/10.1016/j.ecoleng.2018.09.016.

Truong, P. (2000, May). Vetiver grass system: Potential applications for soil and water conservation in northern California. In Invited paper presented at the STIFF GRASS TECHNOLOGY Seminar, sponsored by the Yolo County Flood Control & Water Conservation District and Family Water Alliance at Woodland on (Vol. 9).

U.S. Army Corp of Engineers (2011). Army Critical Area Revegetation Establishment Strategies (Army Cares). Public Works Technical Bulletin 200-1-72.

USDA, NRCS. (2021). The PLANTS Database. National Plant Data Team, Greensboro, NC 27401-4901 USA. http://plants.usda.gov.

USDA, NRCS. (2021). Tall Fescue: *Lolium arundinaceum*. Plant Guide, National Plant Data Team, Greensboro, NC 27401-4901. https://plants.usda.gov/plantguide/pdf/pg_loar10.pdf.

USDA, NRCS. (2021). 'Sunshine' Vetivergrass: *Chrysopogon zizanioides.* Plant Guide, National Plant Data Team, Greensboro, NC 27401-4901. https://plants.usda.gov/plantguide/pdf/pg_chzi.pdf.

USDA, NRCS. (2021). Shore Juniper: *Juniperus conferta.* Plant Guide, National Plant Data Team, Greensboro, NC 27401-4901. https://plants.sc.egov.usda.gov/factsheet/pdf/fs_juco12.pdf.

USDA, NRCS. (2021). Hairy Vetch: *Vicia villosa* Roth. Plant Guide National Plant Data Team, Greensboro, NC 27401-4901. https://plants.usda.gov/factsheet/pdf/fs_vivi.pdf.

U.S. EPA (2000). Bosque Watershed doesn't waste manure. Nonpoint Source News-Notes 63: 21-22. https://www.epa.gov/sites/production/files/2016-02/documents/2003_03_31_info_NewsNotes_pdf_63_issue.pdf.

Walsh, C. J., Fletcher, T. D., & Ladson, A. R. (2005). Stream restoration in urban catchments through redesigning stormwater systems: looking to the catchment to save the stream. Journal of the North American Benthological Society, 24(3), 690-705. https://doi.org/10.1899/04-020.1.

Wells, G. W. (2002). Biotechnical Streambank Protection: The use of plants to stabilize streambanks. Agroforestry Notes, USDA-NAC, 23. https://digitalcommons.unl.edu/agroforestnotes/23.

Westoby, M., & Wright, I. J. (2006). Land-plant ecology on the basis of functional traits. Trends in Ecology & Evolution, 21(5), 261–268. https://doi.org/10.1016/j.tree.2006.02.004.

Wisconsin Department of Natural Resources (2009). Streambank Erosion Factors, Mechanisms, and Causes. Companion Document 580-4. EFH Notice 210-WI-119. https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs142p2_025096.pdf.

Wright, I. J., et al. (2004). The worldwide leaf economics spectrum. Nature, 428: 821-827. https://doi.org/10.1038/nature02403.

Weismeier, M., Lungu, M., Hubner, R., & Cerbari, V. (2015). Remediation of degraded arable steppe soil in Moldova using vetch as green manure. Solid Earth, 6: 609-620. doi:10.5194/se-6-609-2015. https://doi.org/10.5194/se-6-609-2015.

Wu, T. H., McKinnell III, W. P., & Swanston, D. N. (1979). Strength of tree roots and landslides on Prince of Wales Island, Alaska. Canadian Geotechnical Journal, 16(1), 19–33. https://doi.org/10.1139/t79-003.

Wu, T. H. (2013). Root reinforcement of soil: review of analytical models, test results, and applications to design. Canadian Geotechnical Journal, 50(3), 259–274. https://doi.org/10.1139/cgj-2012-0160.

8. Supplementary Information

Dogwood			Willow		
4 Months			4 Months		
Diam (mm)	Force (N)	Strength (MPa)	Diam (mm)	Force (N)	Strength (MPa)
2.13	59.14	16.59710081	0.57	1.7	6.662072102
0.63	0.4	1.283184222	1.48	23.54	13.68337239
0.64	0.94	2.921985283	0.47	1.02	5.879150456
1.16	20.6	19.49222252	0.64	1.3	4.041043477
1.81	62.62	24.33694341	0.92	3	4.512900088
0.55	4.66	19.61420257	0.83	4.68	8.649674945
0.85	4.26	7.507267073	1.45	36.02	21.81312171
1.21	13.18	11.46185179	1.08	3.02	3.296625022
1.35	33.28	23.2501575	0.7	3.3	8.574878567
1.41	28.06	17.97047514	1.96	48.34	16.02155341
1.98	22.78	7.398325893	0.22	1.48	38.9337712
1.52	22.96	12.65303841	0.98	21.8	28.90110587
1.91	19.12	6.673155916	1.57	30.4	15.70306388
0.8	0.3	0.596831037	0.61	1.54	5.269521362
0.55	0.68	2.862158315	1.72	4.58	1.97114559
0.72	27.2	66.80577858	0.51	24.98	122.2819063
1.16	9.6	9.083754184	0.75	4.38	9.914291922
0.54	3	13.09917227	1.41	27.86	17.84238907
1.14	28.64	28.05908015	1.6	37.58	18.69075863
0.27	15.7	274.2093395	0.71	3.46	8.739156566
1.45	25.56	15.47871713	1.27	8.54	6.741562225
1.51	43.12	24.07880758	1.4	10.14	6.587065808
1.5	42.8	24.21984556	0.26	0.96	18.08150833
2.42	101.92	22.1584206	0.67	12	34.03625426
1.93	51.98	17.76772304	0.22	1.6	42.09056346
0.75	19	43.0072024	0.89	3.34	5.368791919
1.08	25.2	27.50826177			
1.36	2.4	1.652127437			
1.14	4.78	4.683044801			
0.61	6.52	22.30992161			
0.58	2.28	8.629566474			
8 Months			8 Months		
0.75	5.08	11.4987678	1.66	6.12	2.827778347
0.97	2.4	3.247714855	2.02	35.36	11.03366099
0.33	2.92	34.1401237	0.72	31.48	77.31786433
1	16.66	21.21217082	0.48	2.78	15.36287298
1.05	10.82	12.49564796	0.57	5.52	21.63214

0.51	2.12	10.3778079	1.68	1.8	0.812015016
0.81	19.54	37.91967795	2.35	6.96	1.604662242
0.33	0.38	4.44289281	1.02	19.24	23.54587547
0.49	2.62	13.89374264	0.63	1.86	5.966806634
0.08	0.42	83.55634512	1.13	4.24	4.227845305
0.77	35.96	77.22329909	3.54	13.76	1.398047826
0.59	5.18	18.94679932	1.13	23.82	23.75171584
0.49	3.82	20.25728888	1.5	1.5	0.848826363
1.75	30.62	12.73031669	1.34	1.5	1.063632946
1.7	17.3	7.621814576	0.71	0.96	2.424737082
0.39	4.76	39.84628687	0.55	0.86	3.619788458
0.3	2.32	32.82128604	1.1	24.42	25.69628899
0.73	1.44	3.440542211	1.21	19.84	17.25365246
0.2	7.88	250.8281903	0.71	7.66	19.3473813
0.2	0.72	22.91831181	1.21	25.88	22.5062765
1.14	4.98	4.878988098	2.65	34.42	6.240641528
0.37	0.76	7.068386077	1.57	31	16.01299277
1.35	44.02	30.75336338	0.53	0.38	1.722431566
0.37	10.72	99.70144572	0.13	1.74	131.0909354
0.51	3.96	19.38496193	0.84	4.96	8.950209952

SI Table 1. Measurements from 4 and 8-month root analysis

	Juniper		Vetiver		Grass Control		Fern		Vetch	
Date	TSS mg/L	TSS Error	TSS mg/L	TSS Error	TSS mg/L	TSS Error	TSS mg/L	TSS Error	TSS mg/L	TSS Error
6/15/2020	592	0.5920	1492	0.7460	976	1.4640	776	0.7760	128	0.0640
6/22/2020	676	0.3380	0	0.0000	188	0.0940	1010	0.5050	120	0.0600
6/29/2020	16	0.0082	16	0.0082	12	0.0063	20	0.0102	8	0.0045
7/6/2020	52	0.0261	22	0.0112	0	0.0000	32	0.0161	8	0.0045
7/13/2021	498	0.2490	40	0.0201	22	0.0112	94	0.0470	148	0.0740
7/20/2021	123.2	0.0094	22.63	0.0018	55.11	0.0083	61.16	0.0048	57.04	0.0108
8/3/2021	99.56	0.0085	29.44	0.0050	165.33	0.0192	120.72	0.0168	1.07	0.0011
8/10/2021	110.99	0.0143	200.19	0.0541	420	0.2145	1.48	n/a	5.01	0.0267
8/17/2021	12.12	0.0007	66.93	0.0034	0	0.0000	161.47	0.0098	1.97	0.0005
8/31/2021	13.6	0.0011	14.57	0.0011	37.2	0.0021	12.4	0.0013	17.52	0.0012
9/14/2021	15.2	n/a	16	n/a	4	0.0960	14.2	0.1101	667.4	0.3356
9/21/2021	20.06	0.0012	61.34	0.0032	42.03	0.0022	29.36	0.0016	8.03	0.0006
9/28/2021	67	0.0184	132	0.0341	43.5	0.0065	0.4	0.0108	95.33	0.0095
10/5/2021	8.64	0.0030	7.2	0.0025	45.36	0.0057	8.96	0.0014	72	0.0084
10/12/2021	6.94	0.0012	9.87	0.0014	35.53	0.0019	15.8	0.0013	3.984	0.0007
10/19/2021	9.2	0.0005	0.4	0.0002	11	0.0006	2.6	0.0002	11	0.0006
11/2/2021	32.45	0.0053	80.24	0.0093	42.71	0.0035	65.1	0.0055	26.13	0.0032
11/9/2021	3.6	0.1056	8	0.2000	1.6	0.0424	334.8	0.1686	0.4	n/a
11/16/2021	224.2	0.1133	4.4	n/a	49.5	0.0138	5.8	0.1537	24	0.0170
11/23/2021	6.2	0.0478	0	0.0108	0	0.0168	3	0.0214	1	0.0265
11/30/2021	59.95	0.0031	119.69	0.0061	185.63	0.0085	44.52	0.0025	0	0.0005
12/21/2021	3.2	0.1024	1.8	0.0144	22.4	0.0044	18	0.0027	7.7	0.0012
1/11/2022	0	0.0009	35.2	0.0018	33	0.0018	14.48	0.0016	-1.23	0.0006
1/25/2022	20.80	0.0023	26.43	0.0033	16.32	0.0014	17.49	0.0025	6.02	0.0011
2/1/2022	17.87	0.0020	52.9	0.0056	0	0.0011	6.4	0.0033	12.8	0.0025
2/15/2022	4.47	0.0009	-6.11	0.0013	-3	0.0010	0	0.0012	-4.44	0.0008
2/22/2022	130	0.0128	7.51	0.0005	35.51	0.0018	41.6	0.0037	-8.4	0.0013
3/8/2022	6.78	0.0014	26.4	0.0043	5.79	0.0007	1.4	0.0014	0	0.0013
3/15/2022	0.2	0.0023	0	0	1.2	0.0050	0	0.011	0	0.0067
3/26/2022	52.34	0.0027	180.88	0.0152	188.64	0.0315		0		0

SI Table 2. TSS values and error

Date	Juniper			Vetiver			Control		
	Accum. Vol. (L)	Dilution Factor	DF Error	Accum. Vol. (L)	Dilution Factor	DF Error	Accum. Vol. (L)	Dilution Factor	DF Error
6/15/2020	7.341	2.000		6.817	2.000		5.244	3.000	
6/22/2020	1.049	1.000		0.524			2.622	1.000	
6/29/2020	12.061	1.000		11.536	1.000		9.963	1.000	
7/6/2020	12.585	1.000		24.646	1.000		0.000		
7/13/2021	4.195	1.000		8.390	1.000		5.768	1.000	
7/20/2021	5.244	7.700	0.388	7.341	4.429	0.162	2.098	15.500	1.942
8/3/2021	4.195	7.000	0.442	2.098	13.250	1.661	2.622	12.000	1.204
8/10/2021	3.146	9.667	0.810	1.049	23.500	5.880	0.524	54.000	27.005
8/17/2021	26.219	2.020	0.023	38.280	1.699	0.014	-27.792	1.000	n/a
8/31/2021	10.488	4.000	0.103	9.439	3.833	0.110	14.158	3.000	0.059
9/14/2021	0.000	1.000	0.000	0.000	1.000	0.000	-0.524	1.000	24.005
9/21/2021	18.878	2.639	0.039	26.744	1.941	0.021	36.182	1.812	0.015
9/28/2021	1.049	33.500	8.379	1.049	27.500	6.880	2.098	14.500	1.817
10/5/2021	2.622	14.400	1.443	2.622	12.000	1.204	2.622	12.600	1.264
10/12/2021	7.341	5.786	0.210	6.293	6.167	0.260	25.170	2.167	0.025
10/19/2021	41.426	1.000	0.009	38.280	1.000	0.010	54.012	1.000	0.007
11/2/2021	2.098	14.750	1.848	2.622	11.800	1.184	4.719	6.889	0.387
11/9/2021	-0.524	1.000	n/a	-0.524	1.000	n/a	-0.524	1.000	n/a
11/16/2021	0.524	59.000	29.504	0.000	1.000	0.000	1.049	27.500	6.880
11/23/2021	-1.049	1.000	n/a	-0.524	1.000	n/a	-0.524	1.000	n/a
11/30/2021	34.609	1.909	0.016	38.280	1.740	0.014	37.231	1.789	0.014
12/21/2021	0.524	1.000	32.004	1.049	1.000	8.004	2.098	16.000	2.004
1/11/2022	9.963	4.368	0.118	32.512	2.000	0.018	16.780	2.750	0.046
1/25/2022	4.195	8.000	0.504	3.146	10.167	0.851	7.866	4.800	0.163
2/1/2022	4.719	7.444	0.417	3.146	11.500	0.962	6.817	5.385	0.211
2/15/2022	7.866	4.467	0.153	4.719	6.111	0.344	7.341	5.000	0.182
2/22/2022	3.146	10.000	0.837	34.085	1.877	0.016	33.036	1.889	0.017
3/8/2022	4.719	6.778	0.381	2.098	12.000	1.505	14.683	2.893	0.055
3/15/2022	-2.622	1.000	n/a	0.000	1.000	0.000	0.000	-19.250	2.409
3/26/2022	36.182	1.768	0.015	37.231	1.803	0.015	39.329	1.747	0.013
Cumulative:	262.192			342.947			304.667		

SI Table 3. Accumulated Volume, Dilution Factor and Associated Error for Juniper, Vetiver, and Grass Control Plots

Date	Fern			Vetch		
	Accum. Vol. (L)	Dilution Factor	DF Error	Accum. Vol. (L)	Dilution Factor	DF Error
6/15/2020	7.866	2.000		11.012	1.000	
6/22/2020	1.049	1.000		1.049	1.000	
6/29/2020	12.061	1.000		12.061	1.000	
7/6/2020	22.024	1.000		15.207	1.000	
7/13/2021	4.719	1.000		6.817	1.000	
7/20/2021	5.244	6.400	0.324	1.573	18.333	3.060
8/3/2021	2.098	13.250	1.661	5.768	4.818	0.224
8/10/2021	0.000	1.000	n/a	1.783	13.529	1.995
8/17/2021	7.866	4.667	0.159	19.402	2.459	0.036
8/31/2021	6.293	5.167	0.219	9.963	3.368	0.092
9/14/2021	-1.049	1.000	n/a	0.524	47.000	23.505
9/21/2021	24.646	2.128	0.025	18.878	2.361	0.036
9/28/2021	-0.524	1.000	n/a	3.146	9.167	0.768
10/5/2021	5.244	6.400	0.324	2.622	12.000	1.204
10/12/2021	8.915	4.647	0.140	13.110	3.320	0.069
10/19/2021	39.329	1.000	0.009	44.573	1.000	0.008
11/2/2021	4.195	7.750	0.488	3.146	9.333	0.782
11/9/2021	0.524	54.000	27.005	0.000	1.000	n/a
11/16/2021	-0.524	1.000	n/a	0.524	60.000	30.004
11/23/2021	-1.049	1.000	n/a	-0.524	1.000	n/a
11/30/2021	12.061	3.478	0.079	21.500	2.293	0.031
12/21/2021	3.146	10.000	0.837	6.293	5.500	0.233
1/11/2022	6.293	6.583	0.277	14.683	3.071	0.058
1/25/2022	3.671	9.714	0.698	7.446	5.014	0.180
2/1/2022	2.098	16.000	2.004	3.146	10.667	0.893
2/15/2022	5.768	6.000	0.276	10.488	3.700	0.096
2/22/2022	4.195	8.000	0.504	5.768	6.000	0.276
3/8/2022	4.195	7.000	0.442	5.454	6.673	0.324
3/15/2022	-0.524	1.000	n/a	-1.049	1.000	n/a
3/26/2022	0.000	0.000	0.009	0.000	0.000	0.009
Cumulative:	189.827			244.363		

SI Table 4. Accumulated Volume, Dilution Factor and Associated Error for Fern and Vetch Plots.

	Juniper		Vetiver		Control	
Date	Sediment Yield (g)	Yield Error (g)	Sediment Yield (g)	Yield Error (g)	Sediment Yield (g)	Yield Error (g)
6/15/2020	4.346	9.476	10.171	23.872	5.118	15.616
6/22/2020	0.709	10.816	0.000	0.000	0.493	3.008
6/29/2020	0.193	0.256	0.185	0.256	0.120	0.192
7/6/2020	0.654	0.832	0.542	0.352	0.000	0.000
7/13/2021	2.089	7.968	0.336	0.640	0.127	0.352
7/20/2021	0.646	1.971	0.166	0.362	0.116	0.882
8/3/2021	0.418	1.593	0.062	0.471	0.433	2.645
8/10/2021	0.349	1.776	0.210	3.203	0.220	6.720
8/17/2021	0.318	0.194	2.562	1.071	0.000	0.000
8/31/2021	0.143	0.218	0.137	0.233	0.527	0.595
9/14/2021	0.000	0.000	0.000	0.000	-0.002	0.064
9/21/2021	0.379	0.321	1.640	0.981	1.521	0.672
9/28/2021	0.070	1.072	0.138	2.112	0.091	0.696
10/5/2021	0.023	0.138	0.019	0.115	0.119	0.726
10/12/2021	0.051	0.111	0.062	0.158	0.894	0.569
10/19/2021	0.381	0.147	0.015	0.006	0.594	0.176
11/2/2021	0.068	0.519	0.210	1.284	0.202	0.683
11/9/2021	0.004	0.058	-0.004	0.128	-0.001	0.026
11/16/2021	0.118	3.587	0.000	0.000	0.052	0.792
11/23/2021	0.006	0.099	0.000	0.000	0.000	0.001
11/30/2021	2.075	0.959	4.582	1.915	6.911	2.970
12/21/2021	0.002	0.051	0.002	0.029	0.047	0.358
1/11/2022	0.000	0.001	1.144	0.563	0.554	0.528
1/25/2022	0.087	0.333	0.083	0.423	0.128	0.261
2/1/2022	0.084	0.286	0.166	0.846	0.000	0.000
2/15/2022	0.035	0.071	-0.029	0.098	-0.022	0.048
2/22/2022	0.409	2.080	0.256	0.120	1.173	0.568
3/8/2022	0.032	0.108	0.055	0.422	0.085	0.093
3/15/2022	0.000	0.003	0.000	0.000	0.001	0.019
3/26/2022	1.894	0.837	6.734	2.894	7.419	3.019

Cumulative	15.582	17.358	29.447	24.553	26.920	18.111

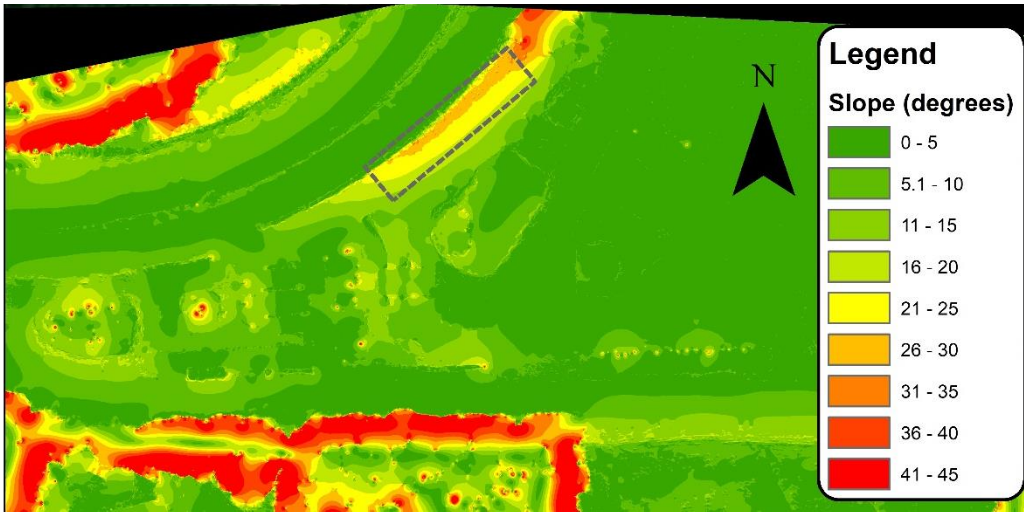
SI Table 5. Sediment Yield and Associated Error for Juniper, Vetiver, and Grass Control Plots

Date	Juniper	Vetiver	Control	Fern	Vetch
6/15/2020	1988.00	1728.00	2868.00	1256.00	336.00
6/22/2020	569.00	0.00	90.90	473.00	65.10
6/29/2020	51.90	56.20	53.70	18.00	8.51
7/6/2020	305.00	133.00	0.00	71.40	9.78
7/13/2021	120.67	32.43	37.97	41.33	43.63
7/20/2021	96.51	151.01	106.02	58.67	90.99
8/3/2021	38.68	229.23	142.80	104.48	8.19
8/10/2021	27.79	100.35	114.75	2.13	23.00
8/17/2021	149.88	271.78	0.00	634.67	47.96
8/31/2021	104.40	126.50	251.10	17.10	40.08
9/14/2021	3.92	3.02	1.33	2.19	163.09
9/21/2021	17.27	121.42	68.21	49.79	6.26
9/28/2021	65.16	52.11	181.98	3.56	18.29
10/5/2021	24.62	40.32	27.97	27.39	30.48
10/12/2021	14.00	20.10	114.62	30.25	14.91
10/19/2021	4.62	2.09	45.00	4.81	7.56
11/2/2021	24.93	14.99	29.17	13.99	24.13
11/9/2021	n/a	1.69	1.41	52.92	0.97
11/16/2021	180.84	3.28	84.98	1.83	148.50
11/23/2021	n/a	n/a	1.72	1.29	1.37
11/30/2021	73.02	108.12	421.25	60.87	13.23
12/21/2021	5.53	3.06	79.84	15.45	8.50
1/11/2022	20.16	104.80	123.20	127.72	23.83
1/25/2022	12.60	20.64	25.90	14.81	8.32
2/1/2022	22.74	25.88	43.51	55.28	13.44
2/15/2022	21.44	9.26	25.93	9.90	19.18
2/22/2022	291.00	97.79	115.79	245.60	38.46
3/8/2022	21.96	52.68	73.91	26.78	23.92
3/15/2022	1.38	1.25	14.10	3.82	5.32
3/26/2022	187.42	310.08	329.25	0.00	0.00

SI Table 6. Turbidity Values (NTU) for all plots

Date	Weekly Precipitation Totals (inches)
6/15/2020	0.78
6/22/2020	0.35
6/29/2020	1.82
7/6/2020	0.46
7/13/2020	4.91
7/20/2020	0.39
8/3/2020	1.6
8/10/2020	2.67
8/17/2020	4.42
8/31/2020	1.33
9/14/2020	0.41
9/21/2020	5.35
9/28/2020	0.8
10/5/2020	0.55
10/12/2020	3.41
10/19/2020	0.01
11/2/2020	0.42
11/9/2020	0.06
11/16/2020	0.51
11/23/2020	0
11/30/2020	5.5
12/21/2020	0.85
1/11/2021	0.5
1/25/2021	1.28
2/1/2021	1.38
2/15/2021	2.97
2/22/2021	1.94
3/8/2021	1.84
3/15/2021	0
3/26/2021	5.1
	51.61

SI Table 7. Precipitation Totals



SI Figure 1. Slope of Test Site in NCAT (dashed box), processed from DTM by Dr. Jack Montgomery