Comparison of Vegetation Types for Prevention of Erosion and Shallow Slope Failure Along Roadways

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Abstract

Shallow slope failures due to erosion are common occurrences along roadways in Alabama due to the prevalence of high intensity rainfall in the region. The use of vegetative covers is a reasonable solution to stabilize newly constructed steep slopes or repair areas where shallow landslides have occurred. This research aims to evaluate and compare vegetation species that would provide low maintenance and economic slope stabilization and decrease shallow slope erosion at priority sites along roadways. Experiments were conducted to compare the applications of vegetation and to identify the most effective vegetation species for erosion control and stabilization of roadside slopes, by studying plant establishment, surface erosion, depth distribution of root biomass density and increased shear strength of soil due to roots.

For this study, five plots with different species were planted on a steep slope at the National Center for Asphalt Technology (NCAT) test track in Opelika, AL. A variety of shrub and grass species were tested and compared individually and in a mix: Parson's juniper (*Juniperus chinensis* "Parsoni"), vetiver grass (*Vetiveria zizaniodies*) and fescue grass (*Lolium arundinaceum*). The vetiver grass grew and established well. The plot with a juniper and fescue grass mix is also establishing well but has low weed resistance. Erosion pins were used to measure surface erosion and deposition in the shallow slope. Regression and ANOVA analysis have been performed on erosion pin data. In addition, the depth distribution of root biomass density and the increased shear stressed of soil due to roots were determined to evaluate the potential for slope stability. The grass control roots showed the highest average root tensile strength. However, vetiver roots had significantly higher root biomass and increased soil shear strength by a greater amount. This study suggests that vetiver is the most suitable species for slope stabilization. The results from this research will be used to identify suitable plant species that will meet the design objectives and low

maintenance requirements for shallow slope stabilization along roadways while also being appropriate for the climate and soil type of Alabama.

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1. Introduction

1.1 Background

Slope failures occur due to soil erosion and weakened self-retainability of the earth under the influence of water from rainfall or runoff. Erosion is the process by which the land surface is worn away by the action of water, wind, ice, or gravity. Water-related erosion is one of the main problems in areas of Alabama impacted by development (ASWCC 2018). Shallow slope failures due to erosion are common occurrences along roadway slopes in Alabama due to the prevalence of high intensity rainfall in the region (Knights et al. 2020). Both rain and surface water flow detach and move soil particles. (Foster et al. 1985). Strong wind can also cause surface soil erosion (He et al. 2008). Covering the soil using any types of groundcover can reduce soil erosion (Fryrear 1985). Plant leaves can reduce the force of rain on soil (Roundy 2019; Rousseva et al. 2002). Additionally, the root systems of plants help to stabilize the soil and hold the layers together.

Root systems also stabilize slopes by increasing soil shear strength (Chen et al. 2018; Ranjan et al. 2015; Reubens et al. 2007). Roots reinforce the soil due to their tensile strength and frictional properties. The overall mechanical effect of roots depends on both their strength and distribution (Ekanayake et al. 1997; Nilaweera and Nutalaya 1999). Roots that extend perpendicular to the soil surface reinforce the soil by increasing shear strength of the rooted soil mass on the sheared surface. Roots growing parallel to the soil surface reinforce the soil by increasing the in-plane tensile strength of the rooted soil zone (Zhou et al. 1998). Steeper slopes are more prone to erosion as there is greater potential for sediment movement and runoff. Alabama receives high amounts of precipitation throughout the year, which causes frequent shallow slope failures (Nobahar et al. 2020). There are many steep slopes along the highways of Alabama. When slope failures occur, repair is costly to Alabama Department of Transportation (ALDOT) and requires extensive time and labor (Montgomery et al. 2019).

The use of vegetative covers is a reasonable solution to stabilize newly constructed steep slopes or repair areas where shallow landslides have occurred. Establishing and maintaining vegetative covers along shallow slopes near roads can be challenging compared to flatter terrain. ALDOT has been using grass mixes to cover slopes, which provide minimal deep root structure and require mowing for maintenance (Messer 2011; Montgomery et al. 2019) This maintenance can add to the risk of slope failure as machine-induced rutting creates areas of exposed slope. Vegetation that has lower maintenance requirements and a larger and deeper root structure could produce greater long-term slope stability and lower the costs of landslide repair and maintenance. The soil characteristics are also a very important factor for vegetation growth and maintenance as vegetation can have different qualities in different types of soil (Levine et al. 1994; Raich and Tufekciogul 2000). The important research issue is identifying vegetation species that needs low maintenance and has deep root structure for slope stabilization and at the same time suitable for Alabama. This study compares different vegetation types to find out which species would be more ideal (to fulfil this goal) for erosion control and slope stabilization for roadside slopes of Alabama.

1.2 Research Objectives

This research study focuses on how different vegetation types establish, prevent erosion, and improve soil strength along a roadside slope. The results can be used to improve roadside construction projects. The research objectives of this study are:

- Determine the best methods to quantify the effects of vegetation on erosion and slope stability on a roadside slope.

- Evaluate and compare vegetation species that would provide low maintenance and economic erosion control.
- Among the vegetation types identified, compare the potential for slope stability by determining the depth distribution of root biomass density and the increase of soil shear strength.

1.3 Research Scope

A roadside-slope experiment was performed in a natural environment and vegetation was exposed to all natural rain events that occurred during the test period. This study focuses on the growth and stabilization of vegetation species under these natural circumstances. To expand on previous work (Niedzinski 2021), erosion pins were used to estimate soil loss from the roadside plots. Different types of vegetation (i.e., grasses, shrubs and a mix of species) were studied and compared to determine which species is most suitable to control soil loss and shallow slope failure. This study also characterizes the root system growth of different species by measuring the depth distribution of root biomass density. The result from this study is relevant to the climate zone and soil type of the study site.

1.4 Organization of Thesis

This thesis contains 5 chapters, organized as follows:

Chapter 1: Introduction provides background information on why roadside slope stabilization is necessary and how vegetation can be used to improve slope quality. This includes the general study goals 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.

Chapter 2: Literature Review provides a more in-depth analysis of current research that has been conducted in the field. This chapter provides information on the main areas of interest of this study: roadside slope failure, species used for roadside slope stability, and measurement of erosion and root biomass.

Chapter 3: Methodology outlines the experimental procedures that were used. This includes a description of the previous work on the roadside plots, the roadside plot design, erosion measurement, root biomass sampling, root biomass measurement, erosion pin data analysis, root biomass data analysis, root diameter, root tensile strength, increased shear strength due to roots, the equations used, and the statistical analyses performed.

Chapter 4: Results and discussion describes and discusses the results of the experiments. This section explains the conditions of the plant species, results from the erosion analysis, root biomass, root diameter, root tensile strength and increased shear strength due to roots.

Chapter 5: Conclusions contains a summary of all the conclusions that were drawn from the experiments, management implications, and future work that should be pursued in this area.

2. Literature Review

2.1 Roadside Slope Failure

Shallow slope failures due to erosion are common occurrences along roadway slopes in Alabama due to the prevalence of high intensity rainfall in the region. Local rainfall, soil characteristics and land management are major contributors to soil erosion (Grace 2000). Roadside shoulders create large areas that have exposed soil and steep slopes (Liu et al. 2014). Erosion and small landslides on destabilized slopes create economic and social disruption (Montgomery et al. 2019). The establishment of vegetation has been recognized as very useful for increasing shear resistance on an unstable slope and is commonly used for reducing roadside slope erosion (Liu et al. 2014; Stokes et al. 2007).

2.2 Previous Study

This study is a continuation of the work done by Niedzinski (2021). In the previous study, five plots were prepared in May 2021 based on existing designs (Grace 2002; Liu et al. 2014). These previous studies were based in rural China under conditions that were more extreme due to large population, tourism development and countryside migration than the area of concern in Alabama. This study was designed to replicate roadside slope conditions on the U.S. Highway 280 corridor between Auburn and Alexander City where shallow slope failures have been observed (Niedzinski 2021).

The previous study (Niedzinski 2021) focused entirely on vegetation condition aboveground and run-off. Runoff was measured using collection bins and HOBO U20L water loggers. Total Sediment Yield was determined using Total Suspended Solids (TSS) and accumulated volume. TSS analysis and collection bin water loggers proved to be high in error due to overflowing or overturning of bins during storm event, low precipitation, and the small plot size. To minimize the large error propagation of the TSS analysis, Niedzinski (2021) suggested *in situ* measurements such as soil-moisture probes and erosion pins for studying surface soil erosion which can provide a more direct measurement of how the soil is behaving near each vegetative cover. This study (Niedzinski 2021) also concluded that the plots containing the juniper shrubs and vetiver grass performed the best in terms of growing and adapting to surrounding conditions while the plots containing the fern and vetch were in the worst condition.

2.3 Species Used for Roadside Slope Stability

Vegetation plays an important role in soil stabilization. Above-ground vegetation and roots combine to physically protect soil against erosion (De Baets et al. 2008; Ford et al. 2016; Gyssels et al. 2005). Both native and exotic grass species were previously used in Alabama for erosion control (Grace et al. 1998). One of the most common species used in northern and central Alabama as a vegetative erosive control is tall fescue grass (Irland 2019; Pitt 2003). The species germinates in 6-8 days, tolerates full sun and poor soil conditions, is fairly drought resistant, and tolerates regular foot traffic (ASWCC 2018; USDA 2021). Fescue grass grows in bunches, so it can have an uneven distribution with bare patches of soil exposed that might require occasional maintenance for re-seeding (Cook, 2005; USDA, 2021). The grass also needs mowing. Large-scale mowing operations can create long, deep ruts in the slope which lead to larger slope failures (Montgomery et al. 2019).

Replacing fescue grass with a species that requires less maintenance but still develops a deep root system to improve slope stability would decrease the costs associated with maintenance and repair of roadside slopes. Several vegetation types present potential options based on previous literature. Vetiver (*Vetiveria zizaniodies)* is a common grass native to southeast Asia. It has been used for decades to improve slope stability and streambank establishment and decrease sediment runoff in agricultural areas (Dalton et al. 1996). Previous studies on vetiver have stated that the morphological properties of the root have ideal qualities for erosion control and slope stabilization (Grimshaw and Helfer 1995; Yoon 1995). They emphasize the early developing and deeply penetrating fibrous root system of vetiver and its capability of anchoring firmly into steep slope profiles.

Juniper shrubs, such as *Juniperus chinensis 'Parsoni'* and *Juniperus horizontalis "wiltonii,"* are also used for erosion control along slopes and embankments. (USDA, 2021). Juniper shrubs can have extensive lateral and deep roots which can anchor soil and stabilize slopes as well as dense fibrous roots at the soil surface which can have great root tensile strength (Comino and Marengo 2010; Lyons et al. 2009). The plots containing juniper plants were also very successful at establishment in the previous study (Niedzinski 2021).

Given the success of vetiver grass in the previous study, another deep-rooted grass was selected for testing that was native to the study region and could be established from seed. Switchgrass is climatically adapted throughout most of the United States and tolerates both clay and sandy soils (Prairie Nursery 2021; USDA, NRCS 2021a). Switchgrass roots can grow up to six feet deep. The root system can break through soil strata, improve the structure of the soil and is thus considered a superior soil stabilizer for erosion control (Earnst Seeds 2017; Simon and Collison 2002). Vetiver systems also appeared to have mainly beneficial effects for slopes around 26^{o} gradient (Jotisankasa 2015) which also supports our the case for our study area. When applying the vetiver grass on very steep slope (> 60^{o}), some caution should be exercised (Jotisankasa 2015).

It is important to consider if plants will be grown from seed or potted plants on roadside slopes. There are pros and cons to both methods. If cost is taken into consideration, seeds are much cheaper than plants. The cost of one potted plant is equivalent to almost 25 seeds for general garden plants and vegetables (Lynne 2013). On the other hand, raising plants from seed takes several weeks of daily care but buying already established plants saves the time and maintenance cost. Seeding is also a delicate process. There is a greater chance of losing plants than with established potted plants. Timing is a key factor for growing plants from seeds. Planting from seeds requires the right time and season that is suitable for planting. Potted plants are less sensitive to timing (Lynne 2013).

2.4 Erosion Measurement

To compare the erosion control potential of different vegetation species, a suitable and effective procedure is needed to measure surface erosion and sediment movement. Different methods and instruments have been used to measure surface erosion. These include erosion pins, total station, Xtion Pro, stereophotos, pinboard, laser scanner and roller chain (Thomsen et al. 2015). The Xtion Pro, stereo photos, and laser scanner are more expensive methods. Total station is an electronic surveying instrument that combines horizontal angle, vertical angle, and distance measurement. Although total station surveys can effectively measure erosion or deposition by accurately measuring the locations of specific points, the collected data can be coarse and lack the point density needed to accurately measure erosion on slopes. Data collection with a total station can also disturb the study area (Myers et al. 2019). A laser scanner uses lidar technology to create high-resolution point clouds of a surface showing three-dimensional topography by combining laser-based distance measurements with precise orientation. Though this technique provides superior measurement precision and accuracy, it faces issues with vegetated surfaces and vegetation must be removed for good results (Myers et al. 2019).

Erosion pins are a simple, inexpensive, easy to maintain, and highly effective method to estimate shallow soil erosion and deposition (Haigh 1977; Kearney et al. 2018). The head of an erosion pin is considered a fixed reference and changes in its elevation are interpreted as changes in the height of the surroundings. It is generally desirable that the value reported for any individual study area be the mean of several erosion pins. Pins should be hammered into the soil perpendicular to the slope (Haigh 1977).

It is common practice to calculate annual erosion or deposition rates from pin measurements as the mean net change in pin height over a given area. However, studies shows that net 'real number' change does not produce strong relationships with erosion rates. Instead, the absolute value of height change is strongly correlated with multiple erosion-related factors and better able to detect significant differences in erosion between plots. Absolute value can capture interactions between slope and cover management. Therefore, while using erosion pins for comparative analysis between land management practices or monitoring changes in erosion over time, the absolute value of pin height change is expected to be a better indicator than calculating the net real number change (Kearney et al. 2018).

2.5 Root Biomass

Slope stabilization is different from surface erosion control as the soil needs to be reinforced and soil shear strength needs to be increased (Duncan et al. 2014; Morgan and Rickson 1994). Erosion pins can only measure erosion and does not indicate the stability of a slope. Roots are important for slope stability as they have hydrologic and mechanical effects that increase soil strength and slow overall sediment mass movement (Morgan and Rickson 1994; Simon and Collison 2002). A well-developed root system with high biomass density (dry mass of roots per volume of soil) provides more soil stabilization (Hunolt, 2013). Root biomass helps bind the soil together by forming aggregates and granular structure which improves the tilth and erosion resistance of the soil (USDA, NRCS 2021b). *In situ* measurements of soil with tree roots indicates that soil strength increases linearly as root biomass increases. Root systems increase the stability of forested slopes by anchoring through the soil mass into fractures in bedrock, crossing zones of weakness to more stable soil, and by providing interlocking long fibrous binders within the weak soil mass (Ziemer 1981). The anchorage effect of coarse roots strongly depends on depth and spatial density. In many vegetation types, roots do not extend deep enough into the soil to prevent mass wasting processes or the spatial density is not high enough to stop soil movement around the roots, in which case there might not be any strengthening effect (Reubens et al. 2007). Mixes of vegetation types might also provide deeper and more completely developed structural roots than monocultures of the same species (Reubens et al. 2007).

Large improvements in slope stability is associated with high root length density (Hamidifar et al. 2018) and high fine-root content (Saifuddin and Osman 2014). When considering shallow slope failure, the uppermost soil layer has the most influence on slope stability and herbaceous roots are more likely to have an effect. Although most herbaceous root systems are assumed to be shallow, there are exceptions such as vetiver grass (*Chrysopogon zizanioides*) (Ali and Osman 2008; Kokutse et al. 2016). Previous studies could not assign slope stability to specific vegetation types or root types. Instead, it was proposed that stability depends on species and structural diversity (Löbmann et al. 2020). Generally, herbaceous vegetation performs better than woody species during the establishment phase, as plant density of herbaceous species is usually higher, and they need less time to build up significant fine-root systems. Some shrubs can also lead to satisfactory results (Burylo et al. 2011).

Sampling of rhizosphere soil by extracting and shaking the root system is a simple method for measuring root biomass (Luster and Finlay 2006). Whole tree root systems and adhering soil can be extracted, with the help of a mechanical digger (Turpault et al. 2005). The most suitable, efficient and economic method for separating and measuring the root biomass is hand sieving (Frasier et al. 2016; USDA, NRCS 2021b). Another method is using a mixer equipped with a speedometer to cut and separate the roots. However, this method is costlier and some root material is lost during the cutting and sieving processes (Blouin et al. 2007).

2.6 Root Effects on Soil Shear Strength

It is possible to determine the effect of root biomass by calculating the increased shear strength due to roots (Pollen and Simon 2005). Roots can increase soil shear strength by anchoring a soil layer and by forming a binding network within the layer (Sidle 1992; Waldron 1977; Waldron and Dakessian 1981). Shear strength of a soil indicates its resistance to shear failure. Specifically, it can be defined as the resistance to deformation by the action of tangential (shear) stress. Soil shear strength is commonly approximated by considering a frictional component and a cohesive component (Flerchinger et al. 2013). The presence of roots can increase the shear strength of the soil by acting as tensile reinforcement.

The average root tensile strength can be used to compute the shear strength increase in soil due to penetration of roots across a shear plane. The computation adapts a simple model of root-reinforced soil subjected to direct shear (Wu et al. 1979) . According to this model, when the soil shear zone is distorted, a tensile force develops in the roots which can be resolved into a tangential component which directly resists shear and a normal component which increases the confining stress on the shear plane. The root tensile strength is critical to determine how a specific plant species will contribute to slope stabilization (Nilaweera and Hengchaovanich 1996). The distribution of root diameters are also needed, as smaller roots are stronger per unit area than large roots resulting in decreasing root tensile strength with increasing root diameter. In addition to diameter, moisture content, root bark roughness, root tortuosity, elasticity, and thickness also have effects on root tensile strength (Pollen and Simon 2005).

3. Methodology

3.1 Previous Study

This study is a continuation of the work done by Niedzinski, 2021. In Niedzinski (2021), five plots were prepared in May 2020 based on the design of previous studies (Grace 2002; Liu et al. 2014). Each plot consisted of a 5 ft x 10 ft wooden frame built from pressure-treated 2x4s (Figure 1). A silt fence and straw wattle were installed above the plots to divert upslope sediment and runoff. Five different species were planted in May 2020: juniper shrubs (*Juniperus chinensis 'Parsoni'*), fescue grass (*Lolium arundinaceum*), maidenhair ferns (*Adiantum pedatum*), hairy vetch (*Vicia villosa* Roth) and vetiver grass (*Vetiveria zizaniodies)* (Niedzinski 2021). For the current study, the same experimental design was used with some modifications to the species of vegetation and the data collection methods.

3.2 Roadside Plots

The area of land used for the experiment is 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. The test plots are shown in Figure 1. This area has a humid subtropical climate with mean annual rainfall of 132 cm and mean annual temperature of 64.3°F. Particle size analysis of study area soil was performed with the Integral Suspension Pressure method (Durner and Iden 2021) using a Pario device (Meter Environment, Pullman, WA). The surface soil layer (0-25 cm) is clay loam (29% sand, 40% silt and 31% clay) and deeper layers (>25 cm) are silt loam (23% sand, 65% silt and 12% clay). Clay particles are smaller than 0.002

mm in diameter. Silt particles are from 0.002 to 0.05 mm in diameter. Sand ranges from 0.05 to 2.0 mm (USDA 1987).

Figure 1: Roadside plots with vegetation (juniper, vetiver, fescue grass control, mix and switchgrass), December 2021

Three plant species, juniper shrubs, fescue grass and vetiver grass that were planted in the previous study were kept as they were growing and stablishing well. The vetiver grass was over 6 feet tall and were trimmed to 3 ft on April 28, 2021. On April 12, 2021, maidenhair ferns (*Adiantum pedatum*) were cleared from the plots because of poor growth and establishment. It was replaced with a mixture of blue rug juniper (*Juniperus horizontalis 'wiltonii'*) and fescue grass (*Lolium arundinaceum*). This mixture was selected because the juniper plants grew and established well in this soil and weather condition, but bare soil and weeds were present between the plants as juniper requires a 4-foot spacing. Fescue grass, which is treated as the control in this study because it is currently used by ALDOT, was used to cover the empty spaces between each plant (Cherrylake, 2021). Six potted plants were planted, and the fescue grass seeds were spread between the juniper plants.

On the fifth plot the hairy vetch grew well but became very invasive and started to take over the surrounding area. Therefore, vetch was also cleared on July 13, 2021, and on July 22, 2021, Switchgrass (*Panicum virgatum*) seeds were planted on that plot. Switchgrass was chosen because its deep and fibrous root system makes it an ideal plant for slope stabilization and erosion control, and it is also climatically adapted throughout most of the United States. It tolerates both clay and sandy soils.

The silt fence at the top of the plot was cut to reduce its height by half on April 28, 2021. The shade from the fence was limiting the growth of the fescue grass control at the top of the plot. The site was treated with herbicide at the beginning of June, as weeds were surrounding the plots and the plots, were at the risk of being invaded by weeds. Spectracide (United Industries Corporation, USA), which can kill 470+ types of weeds but does not harm the species planted, was used as herbicide for the site. At the end of June and beginning of July, extensive weeds were pulled out or removed using weeding tools.

3.3 Erosion Measurement

Three erosion pins (Figure 2) were installed in each plot on April 12, 2021, to measure sediment loss due to overland flow. EasyFlex anchoring spikes (Dimex Corp., USA) were used as erosion pins (Figure 2). Each erosion pin has a length of 8 inches and is made of non-corrosive nylon. Erosion pins were installed one foot inside the left boundary of the plots and 2, 5 and 8 feet away from the upper boundary of the plot (Figure 3). Erosion pins were installed perpendicular to the ground in a line parallel to the slope as suggested in a previous study (Haigh 1977). After the first erosion pins produced reasonable data, four more erosion pins were installed in each plot on September 17, 2021, to increase statistical power. Three were installed similarly to the existing erosion pins but at the right side of the plot (Pin 5, 6 and 7). Another pin (pin 4) was placed in the middle of the plot one foot below the upper boundary (Figure 3). For ANOVA analysis, pins 1 & 5 were considered as upslope pin and pins 3 and 7 were considered as downslope pin (Figure 3).

Figure 2: Erosion pin

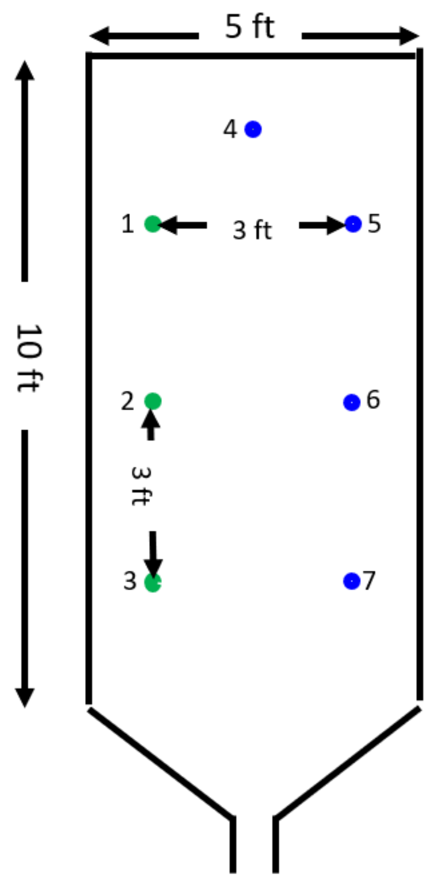

Figure 3 : Layout of the erosion pins in a single plot (Green points indicate older and blue points indicate newer pins)

After installing the pins, a ruler was used to measure the visible height of the erosion pins above the ground. Due to soil disturbance from installation of the erosion pins, data was not collected during a one-month stabilization period after installation. The first measurement after this period was used as the baseline height for the study. Values that are greater than the baseline value indicate erosion is occurring at the point while values less than baseline indicate that deposition is occurring. The erosion pins were monitored and measured biweekly or after any large rain event from April 12, 2021, to April 15, 2022 (Figure 4). To maintain the one month waiting period to let the pins stabilized, analysis was done on data collected from May 25, 2021 to April

15, 2022 for the pins that were installed early and from October 12, 2021 to April 15, 2022 for the pins installed later.

Figure 4: Measuring height of the erosion pins

3.4 Root Biomass

3.4.1 Sampling

Samples for root biomass testing were collected from the three plots containing the juniper shrub, vetiver grass and Control Plot - K-31 Fescue grass. These plots were selected because they were established at the same time and represent three contrasting erosion control strategies. Sampling, which should be carried out when soil is moist (Frasier et al. 2016), was conducted after a rain event. A fixed-volume soil core sampler (AMS, American Falls, ID) and plastic liners with plastic end caps were used to collect the samples (Figure 5a and 5b). The soil core sampler can collect a 15 cm core. The sampler was used three times in each sampling location so that samples were collected from the surface to a depth of 40 cm.

(a) (b)

Figure 5: a) Sampling of soil with soil core sampler; b) Sample in plastic liner

Juniper samples were collected on February 6, 2022 and the rest were collected on February 13,2022. Samples were collected from two places for each plot. One was collected from an upslope (Figure 5a), and another was collected from a downslope position. The exact position of the upslope sampling spot was two feet downward from the upper boundary and on the centerline of the plot and the downslope sampling position was six feet downward the upslope position and on the centerline of the plot. The positions of the sampling spots in each plot are shown in figure 6.

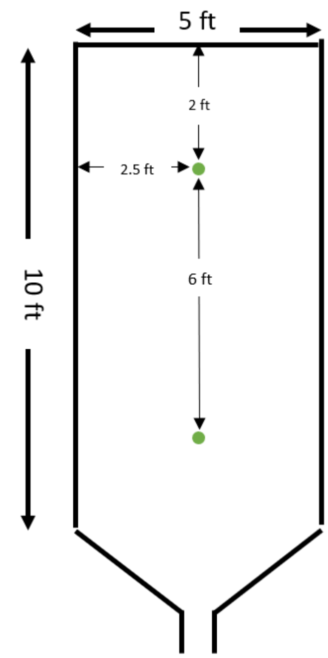

Figure 6: The position of the sampling points (green dots)

After removal from the core sampler, the plastic liners with soil samples were closed with plastic end caps and sealed using duct tape. Each sample was placed in a separate marked plastic bag and refrigerated until analysis.

3.4.2 Root Biomass Measurement

The soil samples were cut into 5 cm sections to determine the distribution of root biomass by depth. The samples were placed in pre weighed pans and then weighed. Then the samples were dried in the oven at 110ºC for 24 hours and weighed again. The moisture content was calculated using the following formula:

$$\text{Moisture Content }\% = \frac{(\text{weight of wet soil} - \text{weight of dry soil})}{\text{weight of wet soil}} \times 100 \qquad 3.1$$

Roots can be removed from the soil by hand rinsing through a sieve (USDA, NRCS 2021b). After measuring moisture content, individual samples were soaked in water for 30 minutes to break down soil aggregates (Jayasundara 2014).

Figure 7 : Collecting the floating roots

The floating roots were collected with tweezers (Figure 7). Soil must be dispersed for successful separation of the roots and plant residue from the soil sample. Tap water is used instead of distilled water, to avoid puddling and dispersion problems.

Figure 8 :Washing and separating the roots

Next, to separate the rest of the roots from the soil, the samples are washed through a 2mm (#10) sieve first and then through a 600 μm (#30) sieve under a running tap (Figure 8). The remaining roots retained on the sieves are collected with tweezers again. The roots collected on the sieves were placed into pre-weighed oven safe dishes (Figure 9) and dried at 60°C for 24 hours. After drying, the samples were reweighed using a precision balance and their mass was determined in grams.

Figure 9*:* Collected root samples

The root biomass data were expressed as g m^{-3}. The following calculation procedure was followed for each soil core section. The height of the plastic liners that were used to collect the soil sample is 15 cm and the diameter is 5 cm. The equation below was used to calculate the soil volume. The diameter for each soil sample is same as the diameter of the plastic liners and the height of the samples was the height of each section which was 5 cm from 0-30 cm depth and 10 cm for 30-40 cm depth.

$$V = \pi r^2 h \tag{3.2}$$

Here, V is the volume of the soil section (m^3), r is the radius of the soil corer (m) and h is depth of each soil section (m). 3.14159 is used as π in this equation.

The volume was measured in m^3. The measured root mass was divided by the volume of each soil section to give root biomass in g/m^3,

$$Root\ Biomass = \frac{\text{Mass of root in soil section (g)}}{V\ (\text{m}^3)} \quad 3.3$$

The diameter of each of the roots was measured using a digital slide caliper with precision 0.01 mm. For each soil layer, all the root sections with more than 0.1 mm diameters were measured, and the average root diameter of each soil layer was used for analysis and calculations. The root diameter was measured at the middle of each root section.

3.5 Erosion Pin Data Analysis

The erosion pin data were analyzed in Microsoft Excel Version 2205 (Build 16.0.15225.20278) using the data analysis package. Regression analysis and Single Factor ANOVA were used. Graphical comparison of erosion pin heights with daily total rainfall was also done.

3.5.1 Regression Analysis

Regression analysis was performed on the actual change in height of the erosion pins installed on the plots containing juniper shrub, vetiver grass, fescue grass control to compare surface erosion among the plots. Change in height of the erosion pins were calculated relative to October 12, 2022, as all the erosion pins were stabilized for data collection from that date. The analysis was performed on 17 measurements from May 25, 2021, to April 15, 2022. Time was used as the X variable and the change in the height of the erosion pins relative to October 12,2022 was used as the Y variable. The *P*-value of the slope and R^2 values were calculated to determine if the slope is significantly different from zero as that would indicate that there is a significant trend in erosion pin height over the course of the study. If slope was significant, the 90% confidence interval of the slopes were compared to determine if there were significant differences among the plots. Regression analysis was done separately considering upslope (Pins 1, 4 and 5), mid slope (Pins 2 and 6) and downslope (3 and 7) separately for all three plots.

3.5.2 ANOVA Analysis

Single Factor ANOVA was performed on two sets of data. First, ANOVA analysis was performed to determine the relationship between the actual change in the height of the erosion pins relative to the erosion pins height from October 12, 2022, and the species planted. Therefore, the groups were juniper, vetiver and grass control as these were the established species. Each plot has 7 erosion pins installed hence each group had 7 counts and the total count for 4 groups was 27 (4×7) for ANOVA analysis. Data from October 12, 2022 to April 15, 2022 were used for this analysis.

The second set of data included two groups – upslope and downslope. Four species – juniper, vetiver, grass control and the mix were used for this analysis. The upslope group contained total actual change in height of the two erosion pins installed two feet from the top boundary of the plots (pin 1 & 5) and the downslope group contained total actual change in height of the two erosion pins installed eight feet from the top boundary (Pin 1 & 7) of each of the four plots (Figure 3). The distance the upslope and downslope pins considered for this analysis is six feet. The alpha value used for both cases was 0.05, and the total change in erosion pins were recorded from May 25, 2021, to April 15, 2022.

3.5.3 Graphical Analysis of Erosion Pin Height and Rainfall

A graphical analysis was performed on rainfall data and the absolute erosion pin height. Daily rainfall data for the site are collected by NCAT. The plots were made using the data from August 4, 2021, to April 15, 2022. Qualitative relationships between large rain events and change in erosion pin height were noted. The First month of data after installing the erision pins were excluded while doing this analysis.

3.6 Root Biomass Data Analysis

Root biomass was measured for three species- Juniper, vetiver, and the grass control as they were planted at the same time. Data was divided into two parts- upslope and downslope. Then, root biomass data was plotted against depth in a bar chart to show root biomass distribution with depth for both upslope and downslope data. The X-axis represents soil depth, and the Y-axis represents root biomass in the bar charts. The root diameters data were also presented in box plots and bar charts separately for upslope and downslope.

3.7 Root Tensile Strength (Tr)

As stated in several studies (Bischetti et al. 2007; De Baets et al. 2008; Operstein and Frydman 2000; Pollen et al. 2004; Tosi 2007) root tensile strength (T_r) decreases with increasing root diameter (D), following the power regression relationship

$$T_r = aD^{-b} \tag{3.4}$$

Tr is average tensile strength of roots per average root cross-sectional area of soil (MN/m^2) and root diameter is in mm. The results were multiplied by 1000 to convert to kN/m^2. Here, a and b are parameters which are different for each species. The parameter values for each of the three species for calculating root tensile strength (T_r) in this study were collected from previous studies (Nilaweera and Hengchaovanich 1996; Pollen and Simon 2005) and are given in Table 1. Root tensile strength data were presented in box plots separately for upslope and downslope.

Table 1: Species-specific *a* and *b* parameter values used in equation 3.4 for root tensile strength.

Species	*a*	*b*
Juniper	22.9	0.54
Vetiver	59.8	0.58
Fescue	43.1	1.00

3.8 Increased Shear Strength Due to Roots (ΔS)

The following simplified equation was used to calculate increased soil shear strength due to roots (ΔS)

$$\Delta S = T_r\ (V_r/V) \times 1.2 \qquad 3.5$$

where ΔS is increased shear strength due to roots (kN m^{-2}), T_r is average tensile strength of roots per unit area of soil (kN m^{-2}) and Vr/V is root to soil volume ratio. The value 1.2 was selected by a previous study (Wu et al. 1979) to replace a more complex bracketed term. This equation was adapted from previous studies (Pollen et al. 2004; Pollen and Simon 2005) where root area ratio was used instead of root volume ratio. We used root volume ratio because it can be determined without destructive sampling of the research plots. Root volume (V_r) was calculated using total measured root diameter (D) and measured root length (L). The following equation was used to calculate root volume (Vr).

$$V_r = \pi(\frac{D}{2})^2 L \qquad 3.6$$

ΔS data was divided into two parts- upslope and downslope. Then the increased shear strength (kN m^{-2}) data was plotted against depth (cm) in a bar chart to show increased shear strength due to roots with depth for both upslope and downslope data. The Y-axis represents soil depth, and the X-axis represents increased Shear Stress due to roots (ΔS) in the bar charts.

4.Results and Discussion

4.1. Results

4.1.1. Vegetation Growth and Establishment

The three plant species that were planted in May 2020 – juniper shrubs (*Juniperus chinensis* 'Parsoni'), fescue grass (*Lolium arundinaceum*), and vetiver grass (*Vetiveria zizaniodies*) – were already established successfully. The vetiver grass grew quickly after being trimmed once in April, 2021.The mixture of blue rug juniper (*Juniperus horizontalis* "wiltonii") and fescue grass (*Lolium arundinaceum*) started growing well initially, but its performance deteriorated after being overgrown by invasive plants. Switchgrass seeds, which were sown in July 2021, did not grow as they were planted off season. Figure 10 shows the condition of the plots as of April 2022.

Figure 10: All test plots, April 2022

During the study period, the plots containing the juniper (Figure 11a) and vetiver plants (Figure 11b) had the best general establishment. The area surrounding the junipers was overgrown by similar weeds as the other plots and weeding was done only once. However, these surrounding plants did not impact the growth of the juniper, as the juniper shrubs showed visible growth and establishment.

The vetiver grass performed similarly. The grass was fully grown, and the almost impenetrable layer developed by the hedgerows made the plot strongly resistant to weeds and other invasive plants. The condition of the plot containing the fescue grass control (Figure 11c) remained consistent throughout the entire test period. It grew well but did not cover the whole area, leaving some bald patches where soil loss could occur. It also showed low weed resistance and was overgrown by some invasive plants. However, the grass control managed to co-exist in the plot with the invasive species and it remained as the dominant species. The growth of the fescue grass was denser at the downslope parts of the plot which might be due to the shading from the silt fence during the first part of the study.

The plot containing the mix (Figure 11d) started to show good establishment initially. However, it began to show low weed resistance. As a result, native weeds and plants in the surrounding area began to encroach and took over the plots. This hampered the growth of the mix, especially the fescue grass. The juniper plants in the mix are still in good condition but growing very slowly.

Overall, the plots containing the juniper shrubs and vetiver grass performed the best in terms of growth in the study site conditions. After all invasive plants were removed in July 2021, these plants were the most resistant to invasive species and grew most consistently. Although the juniper shrub grew well, it did not cover all of the surface of the plot. To resolve the problem of the remaining bare soil area, juniper is likely to perform better when it is planted in a mix with a grass

(a)

(b)

(c)

(d)

Figure 11: a) Juniper Shrub; b) Vetiver grass; c) Fescue grass; d) Mix of juniper shrub and grass control

species. The vetiver developed the most visible aboveground biomass. The grass control plot had moderate resistance to weed. The mix plot was overgrown by the weeds shortly after it was planted, and extensive weeding also disturbed its growth. That is why the mix has had very slow and sparse growth.

4.1.2. Erosion Pin Data Analysis

Erosion pin height was plotted with daily rainfall for comparison (figure 12). The erosion pins show some rise and fall in height after rainfall events which can mean sediment movement influenced rainfall. But the change is height is not always consistent with the rainfall events. Several large changes in erosion pin height were observed after rainfall in March 2022, though this event did not represent the largest daily rainfall in the dataset. This may mean that factors besides depth, such as rainfall intensity, must be considered.

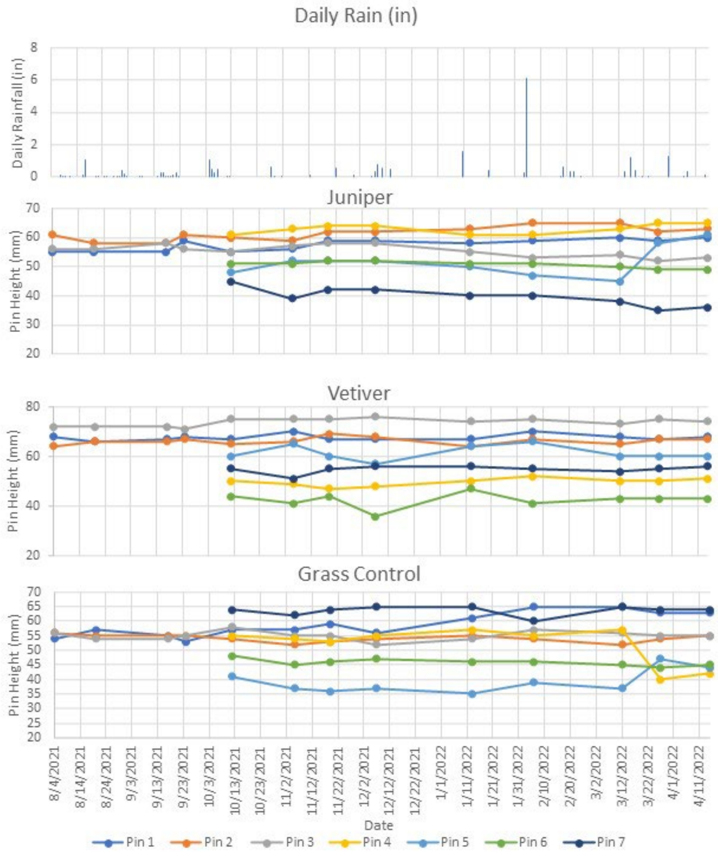

Figure 12: Comparison of pin height and daily rainfall

The erosion pin data were collected for four plots. The switchgrass and the mix plot were excluded due to its poor establishment. Statistical analysis was done on the actual change of the erosion pin height to determine differences in surface erosion and deposition among the plots. A linear regression model was fit to time (*X*) and erosion pin measurements (*Y*) for each plot to determine if there was a significant trend in erosion pin height. ANOVA analysis was used to determine if the difference in total surface erosion data among the plots was statistically significant. Regression analysis was done on the three species juniper, vetiver, and grass control in 3 different positions as these species established well.

Table 2: Slope of the regression line between time in days (X) and change in erosion pin height in mm (Y).

Species	Position	Slope (90% CI)	R^2	P-value
Juniper	Upslope	0.018 (0.009, 0.026)	0.28	<0.01
Juniper	Midslope	0.006 (-0.001, 0.013)	0.09	0.13
Juniper	Downslope	-0.020 (-0.031, -0.009)	0.29	<0.01
Vetiver	Upslope	0.001 (-0.005, 0.007)	0.00	0.76
Vetiver	Midslope	0.011 (0.000, 0.021)	0.11	0.09
Vetiver	Downslope	0.018 (0.010, 0.026)	0.36	<0.01
Grass Control	Upslope	0.011 (-0.004, 0.026)	0.05	0.22
Grass Control	Midslope	-0.007 (-0.013, -0.001)	0.16	0.04
Grass Control	Downslope	0.013 (0.006, 0.021)	0.30	<0.01

The regression analysis summary (Table 2) shows that R^2 values for every species is less than 0.5, indicating that the independent variable (time) is explaining only a small amount of the variation in the dependent variable (erosion pin data). If the P-Value is less than the significance level 0.05, then the model fits the data well. P-value is smaller than 0.05 in all the downslope cases and for juniper upslope which indicates that there is a statistically significant relationship between change in soil height and time in those cases. Different positions show different types of slopes for erosion pin height change.

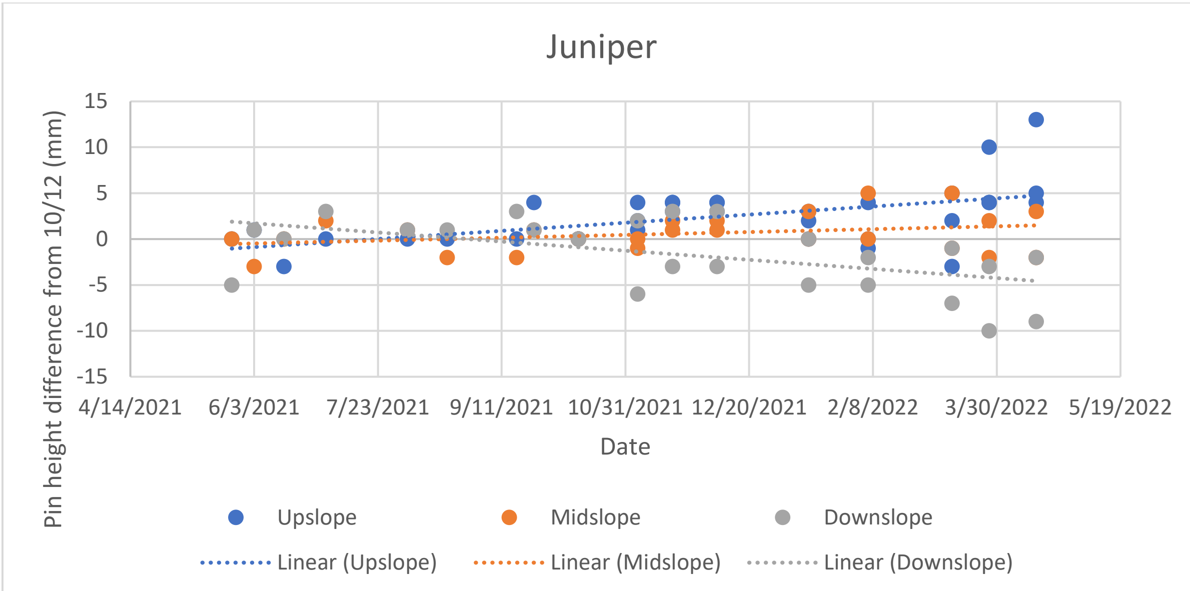

Figure 13 : Linear regression analysis plot (Juniper Shrub)

Figure 13 shows linear regression analysis plot for juniper shrub. For juniper the slopes for upslope, midslope and downslope positions are 0.018, 0.006 and -0.02 respectively. Which means the Juniper shows erosion from the top pins, almost no erosion at the middle pins, and deposition at the bottom pins. The juniper showed more growth at the base of the plot, which may have slowed the water flow leading to deposition.

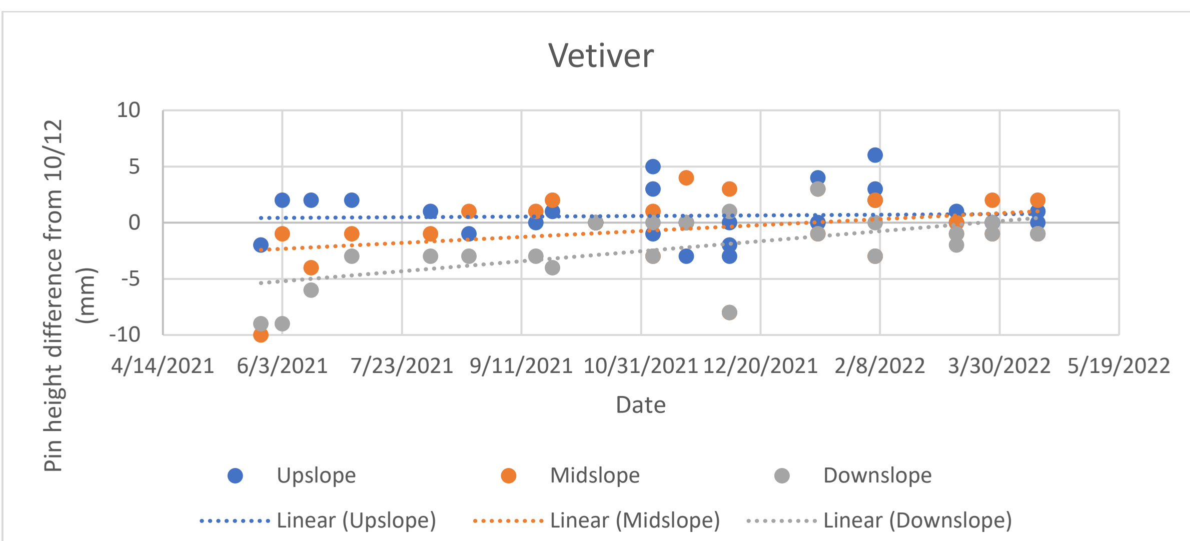

Figure 14:Linear regression analysis plot (Vetiver)

Figure 14 shows linear regression analysis plot for vetiver grass. For vetiver the slopes for upslope, midslope and downslope positions are 0.001, 0.011 and 0.018 respectively. The vetiver established uniformly across the plot. For a uniform surface, the flow velocity is expected to be highest at the bottom of the plot because of the accumulation of rainfall over the plot. This could be why the vetiver shows little to no erosion at the upslope and midslope and erosion at the downslope.

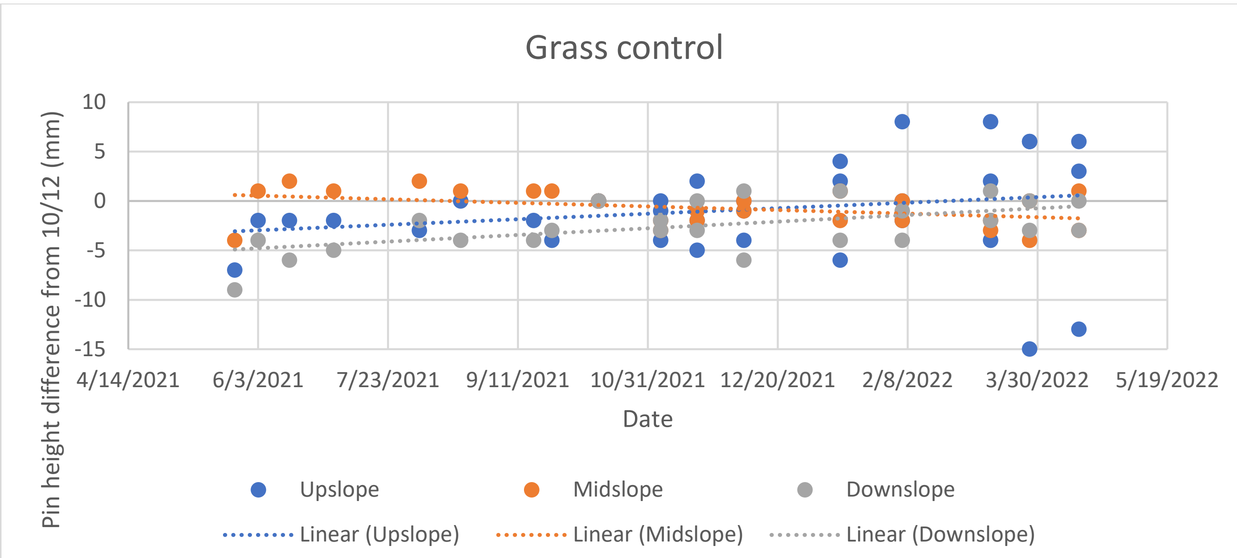

__Figure 15__: Linear regression analysis plot (Grass Control)

Figure 15 shows linear regression analysis plot for fescue grass control. The slopes for upslope, midslope and downslope positions are 0.011, -0.007 and 0.013 respectively. The control shows erosion at the top of the slope, deposition in the middle, and small erosion at the bottom.

The summary of the one-way ANOVA analysis for different species for actual height change is shown in Table 3. The F value (0.23) was smaller than the F critical value (3.55) with a P-value of 0.80. Thus, the null hypothesis of no significant difference in surface erosion between the plots is not rejected.

Table 3:Summary of ANOVA analysis for the species

ANOVA Analysis: Species					
Groups	**Mean (cm)**	**Variance (cm^2)**	***F***	***P*-value**	***F* critical**
Juniper	1.71	47.90	0.23	0.80	3.55
Vetiver	0.14	1.47			
Fescue Grass	0.71	7.90			

The summary of the one-way ANOVA analysis for upslope and downslope is shown in Table 4. The F value (4.31) and the F critical value (4.6) is very close, and the P-value is 0.05. Thus, there is a statistically significant difference in surface erosion between upslope and downslope erosion pins. The average shows positive values in upslope and negative values in downslope, which means that upslope had more erosion and downslope encountered more deposition.

Table 4:Summary of ANOVA analysis for upslope and downslope

ANOVA Analysis: Slope Position					
Groups	**Mean (cm)**	**Variance (cm^2)**	***F***	***P*-value**	***F* critical**
Upslope	0.56	0.17	4.31	0.05	4.6
Downslope	-0.09	0.61			

The results show that surface sediment movement had a weak but significant relationship with time in most cases. In other words, surface soil erosion and deposition occurred during the growth and establishment of vegetation, but other factors contribute to variability in erosion rate. The erosion pin results showed that the species showed different patterns in surface erosion and deposition during the study period. It also showed higher changes in erosion pin height among upslope than downslope locations.

4.1.3. Root Data Analysis

4.1.3.1 Root Biomass Distribution With Depth

The root biomass was determined for only the three species (juniper, vetiver, grass control) that were planted at the same time and established well. The root biomass data were plotted against depth to compare depth distribution of root biomass of the species (Figures 16 and 17). In the upper layers of the soil, the amount of root biomass is very similar among the species. However, the root biomass of vetiver increases with depth and shows higher amounts of root biomass than the other species in the deeper soil layers.

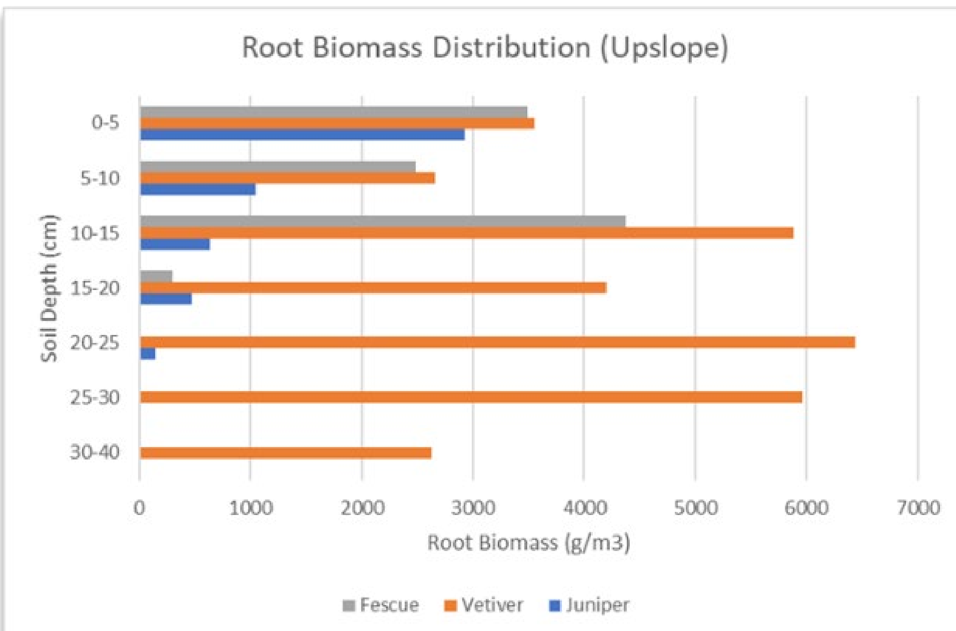

Figure 16: Root biomass distribution with depth (upslope)

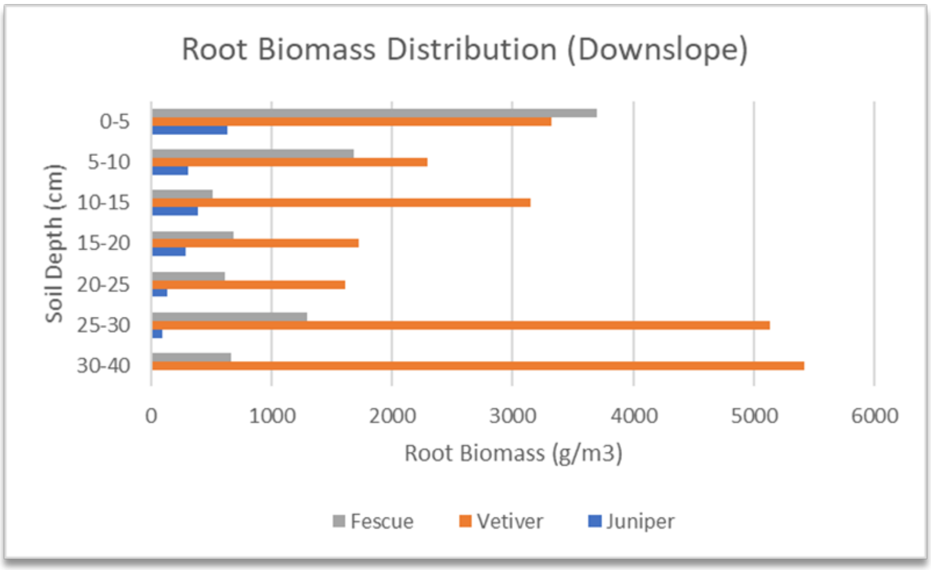

Figure 17: Root biomass distribution with depth (downslope)

The range for root biomass for juniper was 0-2930 g/m^3 for upslope and 16-637 g/m^3 at downslope. For vetiver it was 2634-6437 g/m^3 for upslope and 1612-5423 g/m^3 at downslope. Finally for the grass control the range was 0-4378 g/m^3 for upslope and 516-3695 g/m^3 at downslope. The juniper and grass control showed little to no root biomass in soil layers deeper than 20 cm. However, the grass control showed more deep-rooted biomass in the downslope than upslope as it grew more densely in the downslope. The vetiver plants had the highest root biomass amount in both upslope and downslope and was the most deep-rooted species in both cases. Moreover, vetiver has biomass in deeper layers that can stabilize roadside shallow slopes. This data suggests that vetiver is most suitable for slope stabilization by having the highest biomass and being the deepest-rooted species.

4.1.3.2 Root Diameter (*D*)

The diameter of roots was measured for every soil layer and box plots were created to compare the species (Figure 18 and 20) and Figure 19 and 21 shows the average diameter with depth for upslope and downslope respectively. The results show that vetiver root diameter is significantly high in all soil layers. Grass control and juniper show almost similar root diameter values.

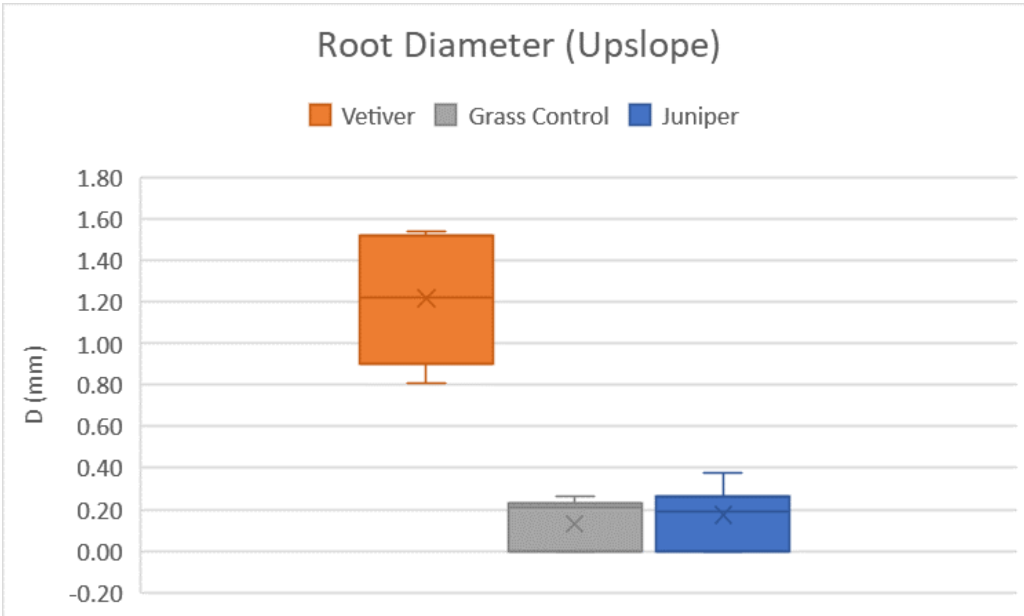

Figure 18: Comparison of root diameter by species (upslope)

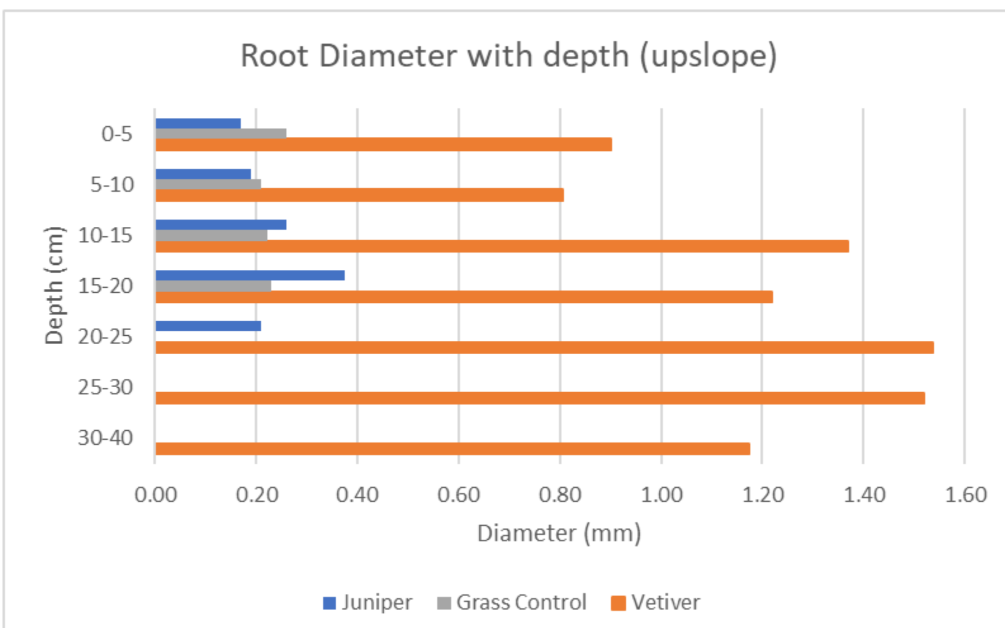

Figure 19: Depth distribution of root diameter (upslope)

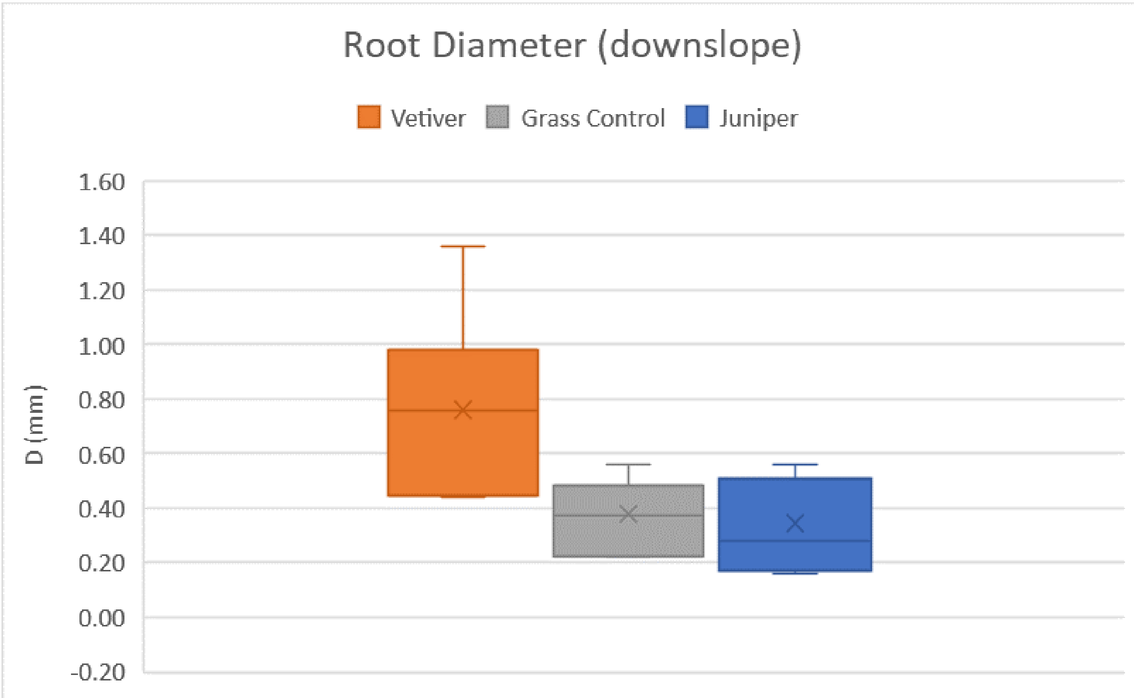

Figure 20: Comparing root Diameter for different species (downslope)

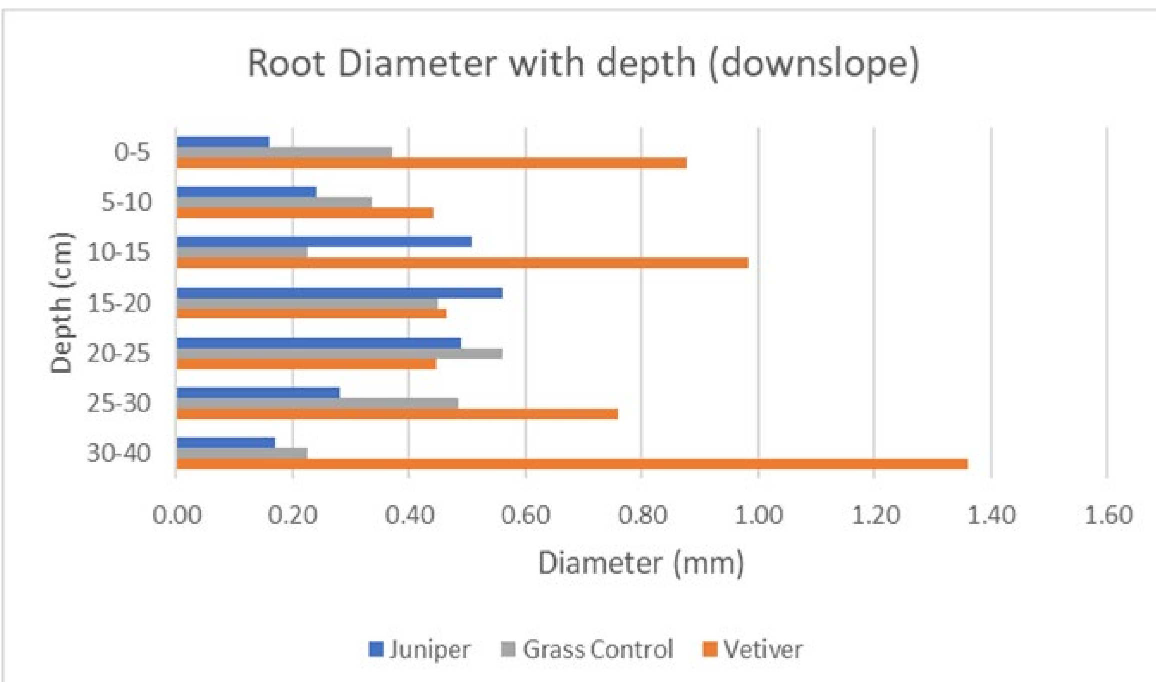

Figure 21: Depth distribution of root diameter (downslope)

4.1.3.3 Root Tensile Strength (T_r)

The root tensile strength (T_r) was calculated for every soil layer and box plots were created to compare the species (Figure 22 and 23) for upslope and downslope respectively. The results show that fescue grass roots had the highest tensile strength in the downslope because it had denser growth and more variation in root diameters. This is because root diameters were smaller in the downslope. In the upslope, grass control also showed higher values of tensile strength, but vetiver was deeper rooted. Root tensile strength (T_r) is inversely proportional to root diameter. Because having many very thin and fibrous, roots grass control has higher values than vetiver for root tensile strength.

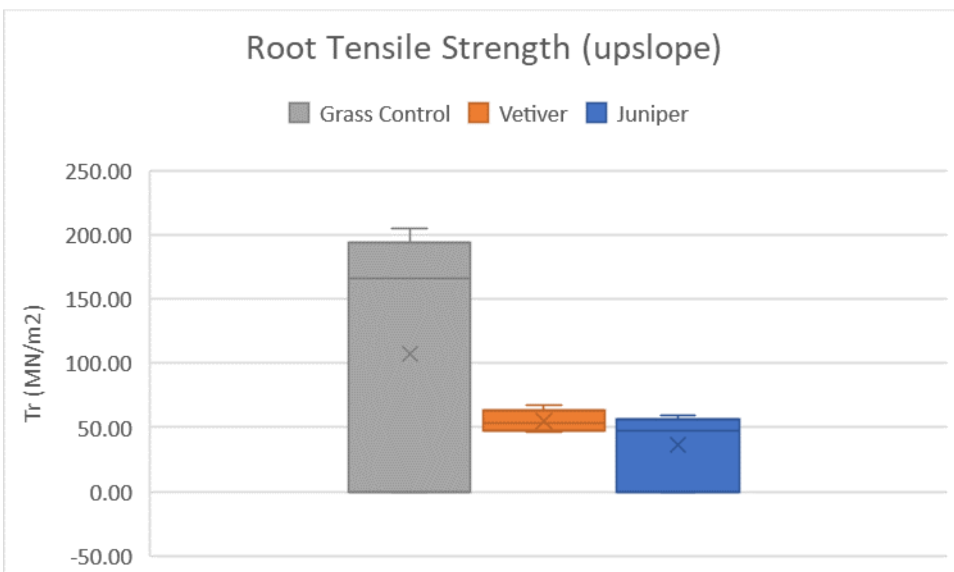

Figure 22: Comparing root tensile Strength (T_r) for different species (upslope)

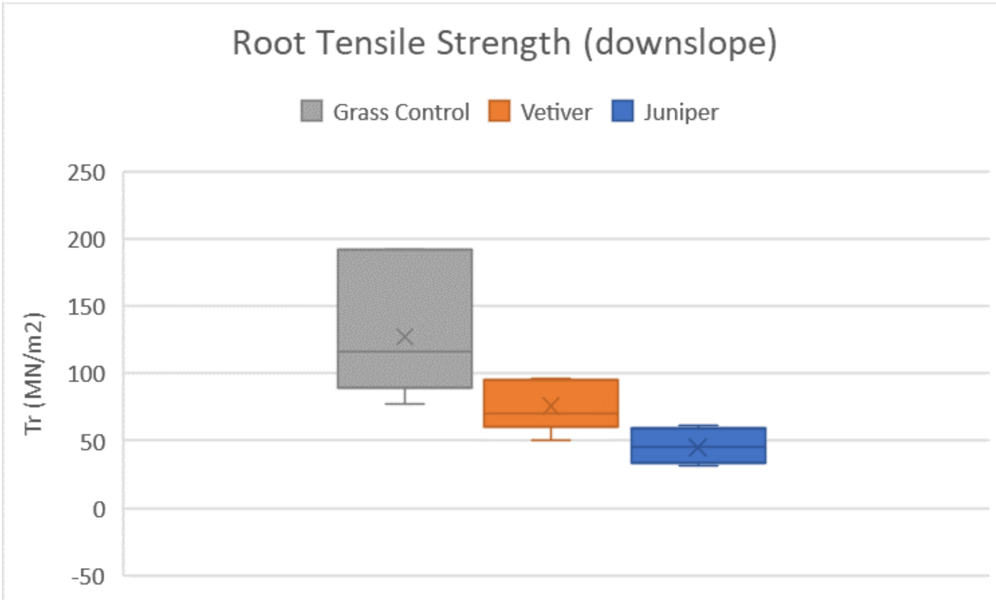

Figure 23: Comparing root tensile Strength (T_r) for different species (downslope)

4.1.3.4 Increased Shear strength Due to Roots (ΔS)

Figures 24 and 25 show that the vetiver roots are most consistent in increasing the shear strength in every layer, including a very large increase in the deeper layers. However, the grass control caused the highest increase in the shear strength of the soil in the downslope upper layer. As the deeper layers were considered, it is observed that ΔS decreased for juniper and grass whereas it increased for vetiver.

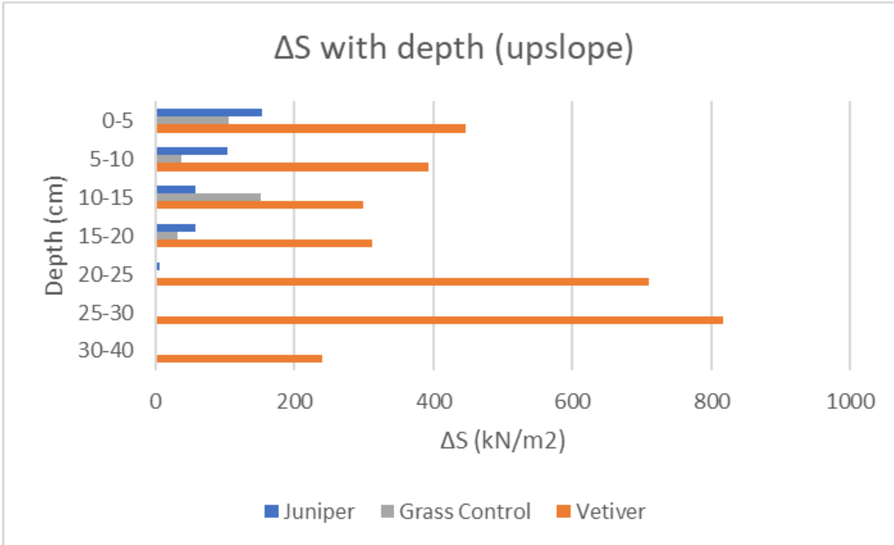

Figure 24: Depth distribution of increased shear strength due to roots (*ΔS*) (upslope)

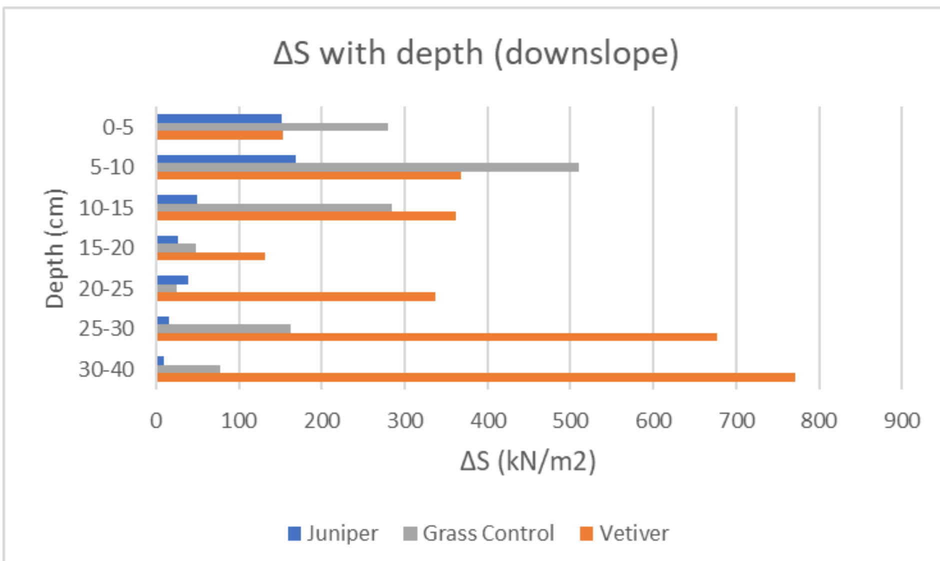

Figure 25: Depth distribution of increased shear strength due to roots (*ΔS*) (downslope)

The highest *ΔS* values for vetiver was 817 kN/m^2 (upslope) and 771 kN/m^2 (downslope). Compared to vetiver, juniper and grass control showed very low values. The highest values for juniper are 153 kN/m^2 (upslope) and 169 kN/m^2 (downslope). Finally, the highest values for fescue grass control are 151 kN/m^2 (upslope) and 510 kN/m^2 (downslope). In the deeper layers, vetiver roots had the highest values of increased shear strength due to roots (*ΔS*) while the other species show very low or nonexistent increase in shear stress. This happens as the total volume of root biomass for vetiver increases as it goes deeper in the soil. In the case of downslope upper layers, vetiver has more root volume than grass control. But the grass control's increased shear stress is higher because it has significantly finer roots than vetiver and increased soil shear stress due to root tensile strength being inversely proportional to root diameter. It should be noted that roots could not be identified by species, so some of the roots sampled from the grass control plot are likely from weeds. However, in terms of both biomass quantity and depth distribution, vetiver performed significantly better compared to other species. Thus, by increasing soil shear strength vetiver roots helped the soil becoming more resistant to shallow slope failures.

4.2. Discussion

According to the previous study at this site, the plots containing the juniper shrubs and vetiver grass performed best in terms of growing and establishing under the local conditions (Niedzinski 2021). They also performed best in the current study in terms of growth, and vetiver performed best when belowground growth for slope stabilization was considered. The grass control, on the other hand, leaves bare patches of soils while establishing. Previous studies found that this can lead to greater sediment and runoff yield as the lack of ground cover fails to protect the soil from raindrop impact and overland flow (Grace 2002). Similarly, in this study, different vegetation species provided different ground cover and showed different patterns of erosion. As the previous study by Niedzinski (2021) was focused on only aboveground behavior of the plants, soil loss and run-off, this study was expanded by considering belowground traits of the plants that can help slope stabilization.

The vegetative covers made the soil loss in all the plots within the limit of 0.8-1.8 mm/yr which is significantly lower than a previous study conducted on completely bare steep slope which were 20 mm/yr. However, the study was conducted over a 10-year period and it is advised to do long term studies to observe any significant difference in erosion pin height (Hart et al. 2017). According to another long-term study, the erosion rate difference between upslope and downslope erosion pins was significant, which supports our study where upslope and downslope pins are 6 ft apart. Although in the long term study the distance between the top and bottom pins were not constant and varied with the height of slope and ranged between 1 and 4 ft (Zaimes et al. 2021).

In general, fine roots (roots < 3 mm in diameter) are considered more important to soil stabilization than coarse roots (Reubens et al. 2007). Most of the biomass sampled from the plots, including vetiver, would be considered fine roots. Although some deeper vetiver root parts are greater than 3 mm in diameter, overall vetiver stabilizes the slope the most. In a previous study conducted on vetiver roots in Brazil for stabilizing slopes, it can be seen that the highest root biomass value was of 4840 g m^{-3} and the mean root tensile strength (T_r) was 83000 kN per m^2 of root area (Machado et al. 2015). In our study the highest root biomass value was of 6437 g m^{-3} and the mean T_r was 65000 kN/m^2. According to several studies, root tensile strength (T_r) decreases with increasing root diameter (D) (De Baets et al. 2008; Pollen and Simon 2005). Therefore, in our study, despite having higher root biomass due to larger diameter roots, tensile strength was lower for vetiver.

A previous study conducted on different types of vegetation shows that all of them can increase shear strength significantly. Herbaceous plants, grasses and shrubs increased shear stress (ΔS) by around 300, 250 and 160 kN/m^2 respectively, which the study deemed satisfactory (De Baets et al. 2008). Compared to this, in our study, vetiver also increased soil shear strength to a very large extent. The maximum and average ΔS that vetiver provided was 817 kN/m^2 and 430 kN/m^2. The average ΔS of grass control and juniper is 122 kN/m^2 and 60 kN/m^2 which is lower than vetiver grass. In the previous study by Niedzinski (2021), qualitatively both juniper and vetiver performed better than the grass control for overall sediment control and run-off movement. In this study vetiver performed better in all aspects of erosion control and slope stabilization.

5. Conclusion

5.1 Research Conclusion

This study aimed to compare the potential and qualities of different vegetation species for prevention of erosion and shallow slope failure. All the vegetation types were planted side by side in the same type of soil and experienced the same weather conditions and treatment.

This study had three major objectives. The first objective was to determine methods of analysis that can accurately quantify the effects of different vegetation on decreasing sediment movement and increasing slope stabilization on a roadside steep slope. Using erosion pins to determine sediment movement is one the most efficient and cost-effective methods. It is an easy and acceptable way to find sediment movement in the plots. Erosion pins were successful in determining sediment movement in the plots with respect to time. However, there were possible measurement errors, and long-term data are needed to show more accurate differences among the plots. Measuring root biomass is a feasible method to determine the improvements in slope stabilization. Root tensile strength and the increase in shear strength of soil due to roots were calculated also from root diameter and length calculated. These parameters clearly differentiated between the species and identified which species are better for slope stabilization.

The second objective was to evaluate and compare different vegetation species to identify those that are low maintenance but able to provide better or similar erosion control and slope stabilization to a grass mix. The results show that juniper and vetiver grew and stablished well under standard roadside slope conditions. Even though juniper grew well, it showed low weed resistance. On the other hand, vetiver grass showed excellent resistance to weeds compared to the other species. The change in erosion pin heights indicates sediment movement in each plot. From the data that was collected in the relatively short study time it can be concluded that, different vegetation covers showed different patterns of erosion in different positions of the slope. Also, upslope soil is subjected to more erosion and downslope soil showed more deposition. Comparison with rainfall shows that rain events can have different effects on different vegetation covers for surface erosion.

Another objective was to determine the depth distribution of root biomass density. The root biomass data shows that vetiver provides the most root biomass and is the deepest rooted of the species tested. Additionally, by penetrating long and strong roots in a soil profile, vetiver can increase the shear strength of soil significantly at shallow depths. These suggests that vetiver is most suitable for slope stabilization.

5.2 Limitations of This Study

In this study erosion pins were used for measuring surface soil loss. However, erosion pins are more prone to human error, and they can also cause disturbance to test plots. Erosion pins also take a long time to provide proper results. The short duration of this study limits the results deduced from the erosion pins. In this study, measures were taken to keep upslope runoff and sediment off the plots to minimize variability. Under real conditions, runoff and erosion could be more than this test site acquired. Moreover, resistance to roadway contaminants of the vegetation species were also not considered in this study.

5.3 Recommendation for future works

This study focused on both above and below ground traits of vegetation. Although differences between vegetation species were observed in deeper slope stabilization, a longer study period should be considered to compare aboveground sediment movement accurately. In future studies, soil moisture probes and measuring organic content of soil can also be beneficial as these factors affect soil erosion and can directly provide clear insight about any change in soil component due to any vegetation cover (Fitzjohn et al. 1998; Polyakov and Lal 2004, 2008; Stone and Hilborn).

Vetiver grass was identified as a promising option for erosion control and slope stabilization. However, it is a non-native species that must be planted from slips that have been sterilized so they will not produce seeds. This is more costly and labor intensive than planting from seed. Future work should consider other native grasses, such as switchgrass, that are deep-rooted and can be planted from seed. However, to grow vegetations from seed, seeds need to be planted during the season recommended and do require some care, such as watering and reseeding of bare patches.

Measuring the movement of water along the plots accurately can also provide important insights. In the previous study (Niedzinski, 2021), runoff analysis was done which proved to have large error. While costly, the construction of high-quality permanent weirs could provide more precise measurement of runoff. Finally, a limitation of this study was that only natural rain events were considered. Using a rainfall simulator is recommended to understand the effect of vegetative covers for minimizing deeper slope failures during extreme rain events.

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Appendices

Appendix A. Raw Data: Erosion Pin Height

Erosion Pin Height (cm)								
Erosion pin heights								
Juniper								
Days	Pin 1	Pin 2	Pin 3	Days	Pin 4	Pin 5	Pin 6	Pin 7
4/28/2021	5	5.5	4.9	9/17/2021	6	5.5	5.3	4.4
5/25/2021	5.5	6	5	9/24/2021	6	5.6	5.2	4.3
6/3/2021	5.6	5.7	5.6	10/12/2021	6.1	4.8	5.1	4.5
6/15/2021	5.2	6	5.5	11/5/2021	6.3	5.2	5.1	3.9
7/2/2021	5.5	6.2	5.8	11/19/2021	6.4	5.2	5.2	4.2
8/4/2021	5.5	6.1	5.6	12/7/2021	6.4	5.2	5.2	4.2
8/20/2021	5.5	5.8	5.6	1/13/2022	6.1	5	5.1	4
9/17/2021	5.5	5.8	5.8	2/6/2022	6.1	4.7	5.1	4
9/24/2021	5.9	6.1	5.6	3/12/2022	6.3	4.5	5	3.8
10/12/2021	5.5	6	5.5	3/27/2022	6.5	5.8	4.9	3.5
11/5/2021	5.6	5.9	5.7	4/15/2022	6.5	6.1	4.9	3.6
11/19/2021	5.9	6.2	5.8					
12/7/2021	5.9	6.2	5.8					
1/13/2022	5.8	6.3	5.5					
2/6/2022	5.9	6.5	5.3					
3/12/2022	6	6.5	5.4					
3/27/2022	5.9	6.2	5.2					
4/15/2022	6	6.3	5.3					
Vetiver								
Days	Pin 1	Pin 2	Pin 3	Days	Pin 4	Pin 5	Pin 6	Pin 7
4/28/2021	5.2	4.1	5.1	9/17/2021	4.8	5.2	4.3	6.4
5/25/2021	6.5	5.5	6.6	9/24/2021	4.8	6.3	4.5	5.4
6/3/2021	6.9	6.4	6.6	10/12/2021	5	6	4.4	5.5
6/15/2021	6.9	6.1	6.9	11/5/2021	4.9	6.5	4.1	5.1
7/2/2021	6.9	6.4	7.2	11/19/2021	4.7	6	4.4	5.5
8/4/2021	6.8	6.4	7.2	12/7/2021	4.8	5.7	3.6	5.6
8/20/2021	6.6	6.6	7.2	1/13/2022	5	6.4	4.7	5.6
9/17/2021	6.7	6.6	7.2	2/6/2022	5.2	6.6	4.1	5.5
9/24/2021	6.8	6.7	7.1	3/12/2022	5	6	4.3	5.4
10/12/2021	6.7	6.5	7.5	3/27/2022	5	6	4.3	5.5
11/5/2021	7	6.6	7.5	4/15/2022	5.1	6	4.3	5.6
11/19/2021	6.7	6.9	7.5					
12/7/2021	6.7	6.8	7.6					
1/13/2022	6.7	6.4	7.4					
2/6/2022	7	6.7	7.5					
3/12/2022	6.8	6.5	7.3					
3/27/2022	6.7	6.7	7.5					

4/15/2022	6.8	6.7	7.4					
Grass Control								
Days	Pin 1	Pin 2	Pin 3	Days	Pin 4	Pin 5	Pin 6	Pin 7
4/28/2021	5	4.5	4.9	9/17/2021	5.5	3.8	5.1	6.2
5/25/2021	5	5	4.9	9/24/2021	5.5	4.2	5	5.7
6/3/2021	5.5	5.5	5.4	10/12/2021	5.5	4.1	4.8	6.4
6/15/2021	5.5	5.6	5.2	11/5/2021	5.4	3.7	4.5	6.2
7/2/2021	5.5	5.5	5.3	11/19/2021	5.3	3.6	4.6	6.4
8/4/2021	5.4	5.6	5.6	12/7/2021	5.5	3.7	4.7	6.5
8/20/2021	5.7	5.5	5.4	1/13/2022	5.7	3.5	4.6	6.5
9/17/2021	5.5	5.5	5.4	2/6/2022	5.5	3.9	4.6	6
9/24/2021	5.3	5.5	5.5	3/12/2022	5.7	3.7	4.5	6.5
10/12/2021	5.7	5.4	5.8	3/27/2022	4	4.7	4.4	6.4
11/5/2021	5.7	5.2	5.5	4/15/2022	4.2	4.4	4.5	6.4
11/19/2021	5.9	5.3	5.5					
12/7/2021	5.6	5.4	5.2					
1/13/2022	6.1	5.5	5.4					
2/6/2022	6.5	5.4	5.7					
3/12/2022	6.5	5.2	5.6					
3/27/2022	6.3	5.4	5.5					
4/15/2022	6.3	5.5	5.5					
Mix								
Days	Pin 1	Pin 2	Pin 3	Days	Pin 4	Pin 5	Pin 6	Pin 7
4/28/2021	4.6	4.7	4.6	9/17/2021	5.5	6.6	6.7	6.6
5/25/2021	4.5	5	4.6	9/24/2021	5.3	6.9	7	6.6
6/3/2021	4.8	5.5	4.5	10/12/2021	4.6	7.1	6.7	6.5
6/15/2021	4.6	5.5	4.5	11/5/2021	4.5	6.7	7.7	7.7
7/2/2021	5.1	5.6	4.5	11/19/2021	4.5	6.6	7.4	6.5
8/4/2021	4.4	5.4	4.6	12/7/2021	4.2	6.5	7.2	7.5
8/20/2021	4.1	5.3	4.2	1/13/2022	4.5	6.7	7.6	6.6
9/17/2021	4.1	5.3	4.2	2/6/2022	4.3	6.5	7.3	6.7
9/24/2021	4.1	5.4	4	3/12/2022	4	6	7.2	6.3
10/12/2021	4.1	5.2	3.8	3/27/2022	4.2	6.1	7.2	6.4
11/5/2021	4.1	5.2	3.9	4/15/2022	4.4	6.4	7.4	6.5
11/19/2021	4.1	5.1	3.9					
12/7/2021	4.3	5.5	3.9					
1/13/2022	4.5	5.2	3.7					
2/6/2022	5.4	5.3	3.2					
3/12/2022	5	4.5	3					
3/27/2022	5.2	4.8	3					
4/15/2022	5.4	5.2	3					

Appendix B. Raw Data: Root Parameters

Vetiver								
	Depth (cm)	Moisture Content (%)	Root Biomass (g/m3)	V_{root} (mm3)	V_{soil} (mm3)	D_{avg} (mm)	T_{ravg} (MN/m2)	ΔS (kN/m2)
Upslope	0-5	16.16	3557.03	574.66	98200	0.90	63.52	446.04
	5-10	22.57	2658.86	474.87	98200	0.81	67.75	393.12
	10-15	17.27	5881.87	491.47	98200	1.37	49.89	299.60
	15-20	15.54	4203.67	478.48	98200	1.22	53.34	311.87
	20-25	8.65	6437.88	1246.64	98200	1.54	46.65	710.66
	25-30	12.34	5967.41	1424.04	98200	1.52	46.95	817.03
	30-40	17.47	1633.41	676.29	184400	1.18	54.47	239.74
Downslope	0-5	19.70	3320.77	194.24	98200	0.88	64.53	153.17
	5-10	24.14	2292.26	314.55	98200	0.44	95.90	368.63
	10-15	19.41	3153.77	489.52	98200	0.98	60.44	361.57
	15-20	6.23	1728.11	115.32	98200	0.47	93.13	131.24
	20-25	4.74	1612.02	289.41	98200	0.45	95.22	336.75
	25-30	6.02	5136.46	789.93	98200	0.76	70.12	676.91
	30-40	31.31	5422.45	2365.74	184400	1.36	50.07	770.78
Grass Control								
	Depth (cm)	Moisture Content (%)	Root Biomass (g/m3)	V_{root} (mm3)	V_{soil} (mm3)	D_{avg} (mm)	T_{ravg} (MN/m2)	ΔS (kN/m2)
Upslope	0-5	15.60	3487.78	51.85	98200	0.26	165.77	105.03
	5-10	18.91	2490.84	14.76	98200	0.21	205.24	37.03
	10-15	17.06	4377.80	63.71	98200	0.22	193.71	150.81
	15-20	15.53	302.44	14.04	98200	0.23	187.39	32.15
	20-25	17.00	2.04	0.00	98200	0.00	0.00	0.00
	25-30	14.43	0.00	0.00	98200	0.00	0.00	0.00
	30-40		0.00	0.00	184400	0.00	0.00	0.00
Downslope	0-5	27.43	3695.52	197.62	98200	0.37	115.79	279.62
	5-10	29.79	1681.26	324.23	98200	0.34	128.66	509.75
	10-15	24.37	516.29	121.55	98200	0.23	191.56	284.52
	15-20	18.73	687.37	41.02	98200	0.45	95.78	48.01
	20-25	22.45	611.00	25.77	98200	0.56	76.96	24.24

	25-30	21.52	1297.35	149.24	98200	0.49	88.87	162.07
	Depth (cm)	Moisture Content (%)	Root Biomass (g/m3)	V_{root} (mm3)	V_{soil} (mm3)	D_{avg} (mm)	T_{ravg} (MN/m2)	ΔS (kN/m2)
	30-40	21.09	667.03	61.69	184400	0.23	191.56	76.90
Juniper								
	Depth (cm)	Moisture Content (%)	Root Biomass (g/m3)	Vroot (mm3)	Vsoil(mm3)	Davg (mm)	Travg(MN/m2)	ΔS(kN/m2)
Upslope	0-5	23.30	2929.74	210.76	98200	0.17	59.62	153.55
	5-10	20.68	1044.81	150.45	98200	0.19	56.14	103.22
	10-15	20.09	638.49	100.32	98200	0.26	47.40	58.10
	15-20	23.87	474.54	121.25	98200	0.38	38.85	57.57
	20-25	20.07	142.57	7.62	98200	0.21	53.19	4.95
	25-30	21.04	0.00	0.00	98200	0.00	0.00	0.00
	30-40	22.00	1.08	0.00	184400	0.00	0.00	0.00
Downslope	0-5	26.89	636.46	200.87	98200	0.16	61.60	151.22
	5-10	22.71	304.48	280.77	98200	0.24	49.35	169.32
	10-15	23.33	391.04	123.06	98200	0.51	33.01	49.64
	15-20	17.19	287.17	68.95	98200	0.56	31.32	26.39
	20-25	15.81	139.51	98200.00	0.49	33.66	39.04	39.04
	25-30	16.25	97.76	98200.00	0.28	45.54	15.64	15.64
	30-40	16.88	16.81	184400.00	0.17	59.62	8.76	8.76