land

Article

Comparison of Vegetation Types for Prevention of Erosion and Shallow Slope Failure on Steep Slopes in the Southeastern USA

Homayra Asima †, Victoria Niedzinski †,‡, Frances C. O'Donnell * and Jack Montgomery

Department of Civil and Environmental Engineering, Auburn University, Auburn, AL 36849, USA
* Correspondence: fco0002@auburn.edu; Tel.: +1-334-844-7168
† These authors contributed equally to this work.
‡ Current Address: School of Earth and Climate Sciences, University of Maine, Orono, ME 04469, USA.

Abstract: Shallow slope failures due to erosion are common occurrences along roadways. The use of deep-rooted vegetative covers is a potential solution to stabilize newly constructed slopes or repair shallow landslides. This study compared species that may provide slope stabilization for sites in the Piedmont region of the southeastern USA. Six species were tested on experimental plots under natural rainfall conditions, and vegetation health and establishment were monitored. Two methods were used to measure surface erosion, measurement of total suspended solids in collected runoff and erosion pins. While measurement uncertainty was high for both methods, differences were evident between species in the spatial distribution of surface erosion that was related to the quality of vegetation establishment. For three species that established well, soil cores were collected to measure root biomass at depths up to 40 cm. Vetiver grass (*Vetiveria zizaniodies*) had substantially higher mean root biomass (3.75 kg/m^3) than juniper shrubs (*Juniperus chinensis*; 0.45 kg/m^3) and fescue grass (*Lolium arundinaceum*; 1.28 kg/m^3), with the most pronounced difference in the deepest soil layers. Seeding with turf grass such as fescue is a common practice for erosion control in the region but replacing this with vetiver on steep slopes may help prevent shallow landslides due to the additional root reinforcement. Additional work is needed to measure the magnitude of the strength gain.

Keywords: erosion; vegetative covers; root biomass; erosion pins; vetiver grass

Citation: Asima, H.; Niedzinski, V.; O'Donnell, F.C.; Montgomery, J. Comparison of Vegetation Types for Prevention of Erosion and Shallow Slope Failure on Steep Slopes in the Southeastern USA. *Land* **2022**, *11*, 1739. https://doi.org/10.3390/land11101739

Academic Editors: Chiara Piccini and Rosa Francaviglia

Received: 31 August 2022
Accepted: 6 October 2022
Published: 8 October 2022

1. Introduction

Shallow slope failures due to erosion are common occurrences along roadway slopes in regions where high intensity rainfall is prevalent [1,2]. These instabilities are usually relatively small in size, but the consequences can cause major economic and social disruption [3,4]. Sediment from erosion can also have significant environmental impacts [5]. Many factors can impact roadside erosion, such as rainfall characteristics, slope gradient, rutting caused by lawn maintenance equipment, roadside construction, soil type, and the presence and type of vegetation [6].

The establishment of vegetation on newly constructed slopes can prevent erosion and increase slope stability [2,7–10]. Well-developed aboveground vegetation prevents surface erosion by intercepting rainfall and wind, increasing surface roughness, binding loose soil particles, and creating a physical barrier to sediment movement [11–14]. There is a nonlinear relationship between precipitation and sediment yield, with precipitation driving erosion while also increasing vegetation growth up to the point where vegetation is no longer water-limited [15]. Plant root systems provide belowground support and can prevent shallow slope failures by increasing soil strength through reinforcement [16–19]. Roots are strong in resisting tension forces while soil is strong in resisting compression forces [20], so root-permeated soil creates a mixed material that can withstand both forces [21]. Roots perpendicular to the soil surface reinforce the soil mass on the sheared surface while roots growing parallel increase in-plane tensile strength [22,23]. Additionally, plants remove water from the soil through transpiration, which prevents slope failures by reducing the unit weight of the soil and increasing apparent cohesion from matric suction [3,24–26].

Plant species and functional types differ in the traits that determine their suitability for use in vegetative covers on steep slopes. Recent reviews of vegetation traits and their effects on slope stability have been published by [8] and [10]. Rapid growth after planting and abundant, evenly distributed aboveground biomass are key to preventing surface erosion [6,27]. Generally, herbaceous vegetation performs better than woody species during the establishment phase [28]. Some vegetation types have specific characteristics, such as grasses that can grow in hedgerows [29,30] and ferns that form rhizome mats [31], which make them particularly effective in binding soil and forming physical barriers to erosion. High root length density [32] and fine-root content [33] are important to soil strength, and these are typically associated with herbaceous vegetation. However, woody vegetation tends to have deeper roots to prevent slope failures [18], though deep rooted grass species do exist [34,35]. These traits must be weighed against practical concerns, such as suitability for local conditions, ease of planting, and maintenance requirements [6,27,36–38].

In the southeastern USA., turf grasses grown from seed are the most common vegetative erosion control [6]. These perform well on relatively flat terrain, where deep root structure is not needed for stabilization [39]. However, turf grasses require mowing. On steeper terrain, mowing can cause ruts that increase erosion (Figure 1) and may expand into shallow slope failures during rain events [4]. There is interest among transportation management agencies in finding alternatives to turf grass that would provide deeper soil stabilization while still establishing quickly and preventing surface erosion. The goal of this study is to evaluate the field performance of several candidate species in experimental plots in the Piedmont region of Alabama. This area is especially prone to shallow slope failures and erosion along slopes due to mowing activities [4,5] (Figure 1a).

(**a**) (**b**)

Figure 1. Eroded slopes along (**a**) US-280 near Waverly, Alabama (photo from Google StreetView) and (**b**) Alabama Highway 69 near Tuscaloosa, Alabama (photo provided by Jacob Hodnett, ALDOT).

Previous experimental plot studies of erosion and slope stability have found substantial differences between vegetation types. In a study of very steep (42.5°) slopes in central China, a mix of grass and shrubs reduced runoff and surface erosion, and had deeper roots than grass alone [2]. Plots with any type of planted vegetation performed better than those that were allowed to revegetate naturally. Studies in a semi-arid region of Spain found differences in erosion rate between species that were mainly driven by quality of establishment [40,41]. A previous study in the southeastern USA found a plot planted with a mix of native grass seed had a lower sediment yield than an exotic seed mix [42], though the difference was not statistically significant. A study by [43] examined combining biochemical surface treatments with vegetation and found that using seeded biochemical treatments on slopes was effective for both short- and long-term stabilization against erosion. Recent work by [44] highlighted the potential for vetiver grass to support resilient transportation systems by mitigating slope failures and improving stormwater quality, but this study also highlighted the relative lack of use of vetiver in the United States.

To determine the efficacy of a species for slope stabilization, both prevention of surface erosion and stabilization of deeper soil layers must be assessed. Previous studies have measured sediment yield by collecting runoff and measuring total suspended solids (TSS) in the collected runoff [2,42]. While this method is well-established, constructing runoff collection infrastructure is costly and adequate replication for statistical analysis is difficult to achieve. The method is also prone to missing data [42], especially during periods of high intensity rainfall when most erosion occurs. Methods that directly measure changes in the elevation of the vegetated surface are an alternative that have the advantage of characterizing spatial patterns in surface erosion. Some techniques that are common for bare soil surfaces, such as total station surveys and lidar scanning, do not work well on vegetated surfaces [45,46]. Erosion pins offer a simple, low-cost alternative that provides point-based measurements of erosion or deposition through a manual measurement of surface height relative to the fixed reference point of the pin head. In this study, both runoff collection and erosion pins are used to assess surface erosion. For deeper soil stabilization, the measurement of root biomass and morphological characteristics in soil core samples is an accepted and established method [2,47].

This study has the following objectives:

- Select vegetation types that may provide erosion control and slope stabilization for priority sites and compare them to the current management practice of planting turf grass from seed.
- Determine which species establish and grow well on moderately steep roadside slopes in the Piedmont region of the southeastern USA using experimental plots. This includes vetiver grass, which has not previously been used in this region.
- Compare surface erosion rates from the experimental plots based on whole-plot sediment yield determined from runoff collection and point-based erosion or deposition measured with erosion pins.
- Estimate the contribution of each species to increased slope stability by measuring root biomass and diameter distribution in soil cores collected from the experimental plots.

This study addresses processes on small (<50 m) constructed slopes in humid environments over short time scales (<2 years) post-construction. Recent research on vegetation-sediment interaction has emphasized the importance of orographic effects on precipitation that occur over large elevation gradients [48] and ecogeomorphic coevolution of landforms that occurs over centennial scales in arid and semi-arid environments [49], and these are outside the scope of the current research. Based on erosion control strategies that were successful in previous studies [40,41], we focus on planted vegetation rather than allowing for vegetation to establish naturally after disturbance. Therefore, the variation in species prevalence associated with slope, aspect, soil type, and other factors is not considered.

2. Materials and Methods

The materials and methods for this study are summarized in the flow chart shown in Figure 2.

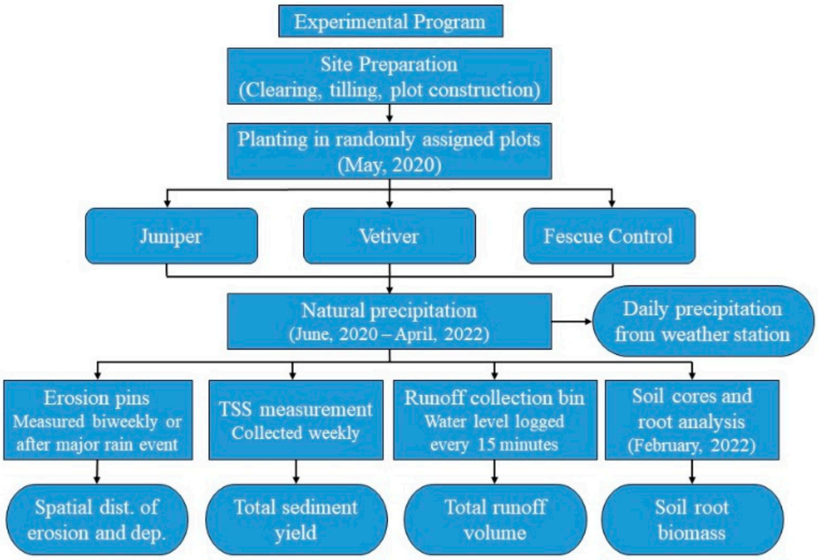


Figure 2. Flow chart illustrating the materials and methods for this study.

2.1. Study Site

This study focuses on the Piedmont region of the southeastern USA, and particularly the state of Alabama. Shallow slope failures and erosion on highway cut slopes are a common occurrence in this region due to the prevalence of high-intensity rainfall [50] and hilly terrain. The Piedmont region is one of the fastest growing areas of the United States in terms of population and land-use change [51] and there is a need to identify sustainable solutions to managing soil erosion in this region. This area has a humid subtropical climate with mean annual rainfall of 132 cm and mean annual temperature of 17.9 °C. Most rainfall occurs as localized convective thunderstorms occurring in the summer and as widespread frontal precipitation, including tropical storms that occur in the fall through spring. Class A annual pan evaporation is 122 cm [52]. While vegetation growth is generally not water-limited, droughts do occur, particularly in the fall.

The experimental plots were established on a roadside slope along the National Center for Asphalt Technology (NCAT) Test Track in Opelika, AL, USA (32.595390°, −85.296363°). The plots have a 25–30° slope. Particle size analysis of study area soil was performed with the Integral Suspension Pressure method [53] 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). The plots are on a north-facing slope, so conditions are slightly cooler with less radiation than the local average. Daily precipitation data were collected onsite by NCAT using an automated weather station.

2.2. Experimental Plot Design

The experimental plot design was based on [2] and [42]. The plots were prepared, built and planted in May 2020. Existing vegetation was treated with Round-Up herbicide (Bayer, Germany) and removed with a small excavator. Each plot consisted of a 1.5 m × 3 m wooden frame built from pressure-treated lumber (Figure 3). 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. A trench was dug 2 m above the frames, creating a berm directly above the plot to divert water coming from the slope above the plots. An erosion fence was erected at the top of the frames and below the berm to prevent sediment movement from the slope above the plots.

(**a**) (**b**)

Figure 3. Completed experimental plot after installation and planting with plots 1–5 shown left to right (**a**) and plot dimensions (**b**).

2.3. Vegetation Planting and Maintenance

Prior to planting, the area was tilled with a mechanical rototiller. Vegetation and seeds were planted according to the providers' instructions. Seeding straw was spread over plots where plants were grown from seed and in bare areas of plots with potted plants. Plots were watered regularly for three weeks after planting. Six vegetation types were selected for testing based on previous literature on vegetative covers for erosion control:

- Grass Control: One plot was planted with turf grass typical of what would be used for erosion control under current management practices in Alabama [6]. The Kentucky-31 cultivar of fescue grass (*Lolium arundinaceum*) was planted from seed. This plot was used to compare the other species with the status quo.
- Deep-rooted Grass: Vetiver grass (*Vetiveria zizaniodies)* is a deep-rooted grass native to southeast Asia that has been used for decades to improve slope stability, improve streambank establishment, and decrease sediment run-off in agricultural areas [44,54–56]. 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 [30]. Slips were planted in four hedgerows parallel to the slope.
- Woody Shrub*:* Juniper is a deep-rooted, drought tolerant woody shrub that grows well on steep slopes [56]. It was grown from potted plants. Either *Juniperus chinensis* or *Juniperus horizontalis* was planted based on availability. The two species have similar characteristics.
- Perennial Legume: Hairy vetch (*Vivica villosa*) is a winter-active legume species used for erosion control and as an agricultural cover crop due to its ability to fix atmospheric nitrogen. It has a fast above- and belowground growth rate and high transpiration rate [57]. Hairy vetch grows best when planted in the fall so it can be beneficial for fall/winter construction projects when other species are typically dormant [56]. It was planted from seed in this study.
- Fern: Ferns are 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 [58]. Maidenhair fern (*Adiantum pedatum*) is native to the southeast and is able to grow on near-vertical faces [31]. They were planted from potted plants.
- Native Prairie Grass*:* Native species are generally preferred in landscaping because they are adapted to local conditions and can enhance native biodiversity [59–61]. Unlike non-native deep-rooted grasses, they can be grown from seed. Switchgrass (*Panicum virgatum*), which has a deep and fibrous root system and is climatically adapted throughout the USA [27], was planted from seed.

Initially, each species, except switchgrass, was planted in one randomly assigned plot. There were problems with the establishment of maidenhair fern and hairy vetch. One was replaced with switchgrass and the other with a mix of juniper and fescue grass after the first year of the study. The species used and planting dates are summarized in Table 1. The vetiver grass was trimmed from a height of 2 m to a height of 1 m in April 2021. Weeds were a persistent problem. A broad-spectrum herbicide (Spectracide, United Industries, St. Louis, MO, USA) was applied and weeds were manually removed from all plots in July 2020 and late June and early July of 2021.

Table 1. Species planting dates in experimental plots. Plot numbers are described in Figure 3.

Species	Plot	Planting Date	Termination Date
Juniper [1]	1	May 2020	August 2022
Vetiver	2	May 2020	August 2022
Fescue	3	May 2020	August 2022
Maidenhair Fern	4	May 2020	July 2021
Hairy Vetch	5	May 2020	April 2021
Juniper [2] and Fescue	4	July 2021	August 2022
Switchgrass	5	April 2021	August 2022

[1] *Juniperus chinensi;* [2] *Juniperus horizontalis.*

2.4. *Runoff and Erosion*

Two methods were used to estimate erosion: runoff collection with TSS measurements and erosion pins. The runoff collection method was applied from June 2020 to March 2021, and erosion pins were applied from August 2021 to April 2022. Previous studies have traditionally only used one of these methods [2,16,62], but we found them to be complimentary to obtain both the spatial distribution of erosion and deposition and the total settlement yield.

2.4.1. Runoff Collection with TSS

A hole was dug at the base of each plot, and a 68-L plastic bin was placed in the hole. 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. In each bin, a U20L HOBO water level logger (Onset, Bourne, MA, USA) was suspended from the lid with wire and submerged in water. The loggers were deployed on October 7 2020 and were set to record pressure and temperature every 15 minutes. Prior to this date, water depths were measured manually once per week. An additional logger was placed outside of the bins to record atmospheric pressure. Measured pressures were converted to change in water level at 15-min intervals using software HOBOware V3.7 analysis software (Onset, Bourne, MA, USA). Change in water level was converted to change in volume using the dimensions of the bin.

Once per week, a well-mixed sample of water from each bin was collected. TSS in each sample was measured by filtration following US Environmental Protection Agency method 160.2 [63]. After sampling, the bins were emptied and cleaned and filled with a known volume of clean water such that the water was above the measurement threshold of the water level logger. Assuming TSS of the clean water is negligible, sediment yield (SY) in g for each one-week collection period was determined by multiplying the measured TSS (g/L) by the total volume in the bin (L) at the end of the week. The volume was divided by the surface area of the plot (5.23 m^2) to give runoff depth (mm, after unit conversion).

2.4.2. Erosion Pins

Erosion pins estimate erosion and deposition at point locations by indicating the change in height of the land surface relative to a fixed reference [64]. EasyFlex 8-inch (20 cm) nylon anchoring spikes (Dimex, Marietta, OH, USA) were used as erosion pins and were installed perpendicular to the ground. Three erosion pins were installed in each plot on 12 April 2021. Pins were installed 0.3 m inside the left boundary of the plots. This distance minimizes edge effects while making it possible to measure the pin height without requiring foot traffic in the plot. The pins were placed 0.6, 1.5, and 2.4 m away from the upper boundary of the plot. These pins are considered upslope, midslope, and downslope, respectively, for analysis. After the first erosion pins produced reasonable data, four additional pins were added to each plot to increase statistical power. Three were added inside the right boundary of the plot in the same configuration as the previous pins. One additional upslope pin was added in the middle of the plot 0.3 m from the top boundary.

A ruler with 1 mm gradations was used to measure the visible height of the erosion pins above the ground. 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 12 April 2021 to 15 April 2022. Due to soil disturbance from installation of the erosion pins, data were not collected during a one-month stabilization period after installation [65]. The first measurement after this period was used as the baseline height for the study. Thus, the first set of pins was analyzed from 25 May 2021 to 15 April 2022 and the second set of pins was analyzed from 12 October 2021 to 15 April 2022.

Some studies have suggested that the absolute value of change in erosion pin height is a better indicator of erosion when multiple pins are considered, because it differentiates plots with both erosion and deposition [65]. In this study, we are interested in overall sediment yield from the plots, so actual change in pin height is used for analysis. Linear regression analysis with either time in days or cumulative rainfall based on daily measurements is the independent (X) variable and change in erosion pin height is the dependent (Y) variable. Time and cumulative rainfall are strongly correlated, so they were considered in separate single-variable regression models rather than a multivariate model. The measurement on 12 October 2021 was used as the baseline because all pins were installed and stabilized by that date. A statistically significant positive slope indicates erosion is occurring at the pin location while a negative slope indicates deposition. One-way ANOVA was used to determine if change in erosion pin height from 12 October 2021 to 15 April 2022 was significantly different among plots. An unpaired t-test was used to determine if the mean change in erosion pin height over the same time period was different for upslope and downslope pins. A significance level of 10% was used for statistical analyses due to the inherently high variability in erosion data. All statistical analyses were performed in Microsoft Excel V16.

2.5. Root Biomass Analysis

Samples for root biomass testing were collected from the three plots that were planted at the beginning of the study and had established well: fescue, vetiver, and juniper. Samples were collected in February 2022 after nearly two years of growth. Sampling was carried out when the soil was moist, for best results [66]. A fixed-volume soil core sampler (AMS, American Falls, ID, USA) was used to collect the samples. Cores were collected with a slide hammer until the point of resistance, which was reached at 40 cm depth. One upslope and one downslope sample was collected 0.6 m and 1.8 m from the upper plot boundary.

The soil cores were cut into 5 cm sections to determine the distribution of root biomass with depth. Due to dry soil near the bottom of the soil profile, the core could not be sectioned below 30 cm depth, so 30–40 cm depth is analyzed together. Methods from [67] were used to determine root biomass. The samples were dried at 110 °C for 24 h and weighed before and after drying to determine moisture content. After drying, samples were soaked in tap water for 30 min to break down soil aggregates. Roots were collected by washing the samples through a 2 mm (#10) sieve followed by a 600 µm (#30) sieve under running tap water. The roots collected on the sieves were dried at 60°C for 24 h. Roots were weighed after drying to determine dry root biomass in each sample (g) and converted to a soil root biomass (g/m^3) by dividing by the volume of the core section.

3. Results

3.1. Vegetation Growth and Establishment

After the initial planting, all five of the plant species were able to grow and establish successfully. However, native weeds and plants in the surrounding area began to encroach and quickly took over the plots, and weeding was required. After weeding, the two plots containing the hairy vetch and maidenhair fern were overwhelmed by the disturbance and showed little new growth. The plots were overtaken by fescue grass from the adjacent plot, as well as white clover (*Trifolium repens*) and ground-ivy (*Glechoma hederacea*). Fescue grass grew well if it had direct sun. The small amount of shading caused by the silt fence resulted in poor establishment at the top of the plot. The height of the fence was reduced after the first year of the study.

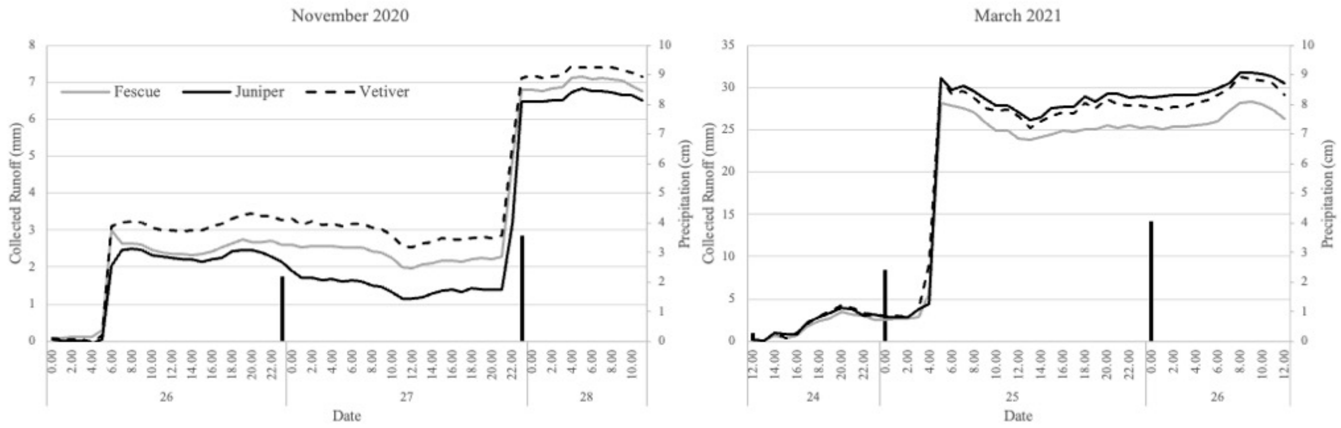
During the first year of the study, vetiver and juniper were the most successful at general establishment. The area surrounding the junipers was overgrown by similar weeds as the other plots, but this did not impact the growth of the juniper. A mix of juniper and fescue grass was planted at the start of the second year (Table 1) as a potential strategy to improve the weed resistance of the area surrounding the juniper. However, weeds were still an issue. By September 2020, the vetiver was nearly at its full height (2 m) and the hedgerows developed an almost impenetrable layer that was resistant to weeds. In November 2020, the vetiver reverted to a dormant stage but remained healthy and regrew the next year. The switchgrass that was planted in the second year of the study did not grow well as it was planted off season due to issues with obtaining seeds. Thus, switchgrass is excluded from further analysis. Juniper, vetiver, and fescue are compared in the subsequent analyses due to their good establishment and consistent growth throughout the study (Figure 4).

Figure 4. Final condition of the three plots where vegetation established well, photographed in April 2022. Shown from left to right are juniper, vetiver, and fescue.

3.2. Runoff and Erosion

3.2.1. Runoff Collection Method

The time series of runoff for the three plots is shown in Figure 5 for two representative rainy periods, one during the first year after planting and one almost one year after planting. The juniper had the lowest runoff volumes while vetiver and fescue had similar values during most of each rain event. While subtle differences between plots in slope or underlying soils cannot be ruled out, this difference was consistent across rain events.



(**a**) (**b**)

Figure 5. Daily precipitation and hourly change in runoff volume from three erosion plots during rainy periods: (**a**) six months after planting; and (**b**) ten months after planting.

Based on the runoff collection and TSS method, the plot with fescue grass had the highest sediment yield over the first nine months of the study while the plot with the juniper shrubs had the lowest (Figure 6). The initial spike in sediment yield in June was collected one month after planting and shows that the grass provided the least amount of initial surface-soil stabilization. All three species showed similar spikes in sediment during rain events at the end of November and the end of March.

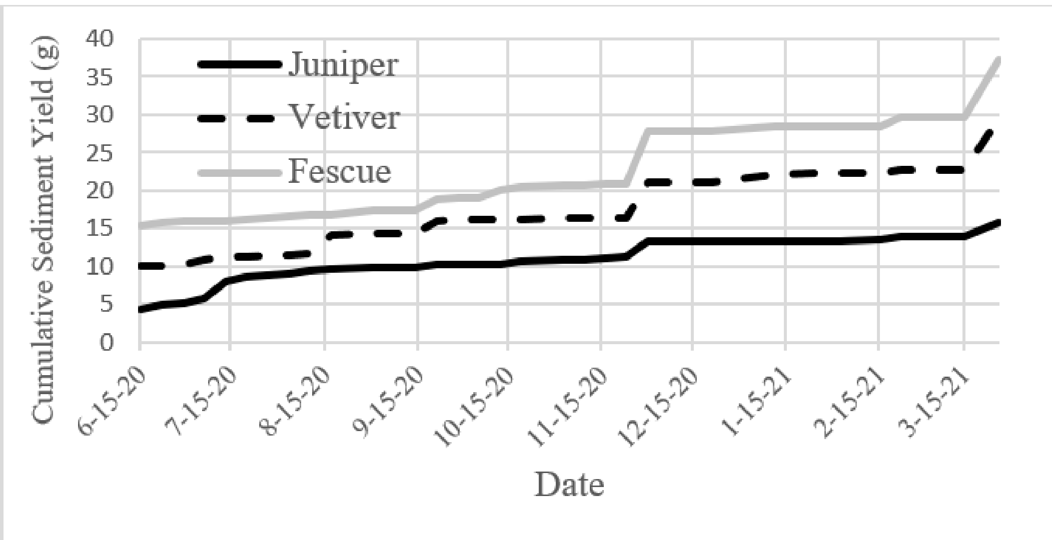


Figure 6. Cumulative sediment yield during the first year of the study measured using the runoff collection with TSS method.

3.2.2. Erosion Pins

As previously discussed, a single-variable regression model was used to assess changes in erosion pin height during the study period. The linear regression models with time and cumulative rainfall as the independent variables produced similar results in terms of which subsets of the data had the best model performance. However, R^2 values were consistently higher for models with time as the dependent variable, so this is considered for analysis. Linear regression between time and erosion pin height showed spatial variability in erosion and deposition among the species tested. For juniper (Figure 7) the slopes for upslope, midslope and downslope positions are 0.018, 0.006 and −0.02 respectively. This indicates 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 water flow leading to deposition. For fescue grass (Figure 8), the slopes for upslope, midslope and downslope positions are 0.011, −0.007 and 0.013, respectively. There is deposition and erosion evident at the midslope and downslope, respectively. While the slope was positive for the upslope pins, the high variability in the data for this area makes it difficult to draw conclusions about the dynamics. For vetiver (Figure 9), the slopes for upslope, midslope and downslope positions are 0.001, 0.011 and 0.018, respectively. The vetiver established uniformly across the plot but was not present near the plot outlet because it was not possible to plant slips in this small area. 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. The denser growth of the vetiver may also change the overland flow patterns and velocities [68], but these flow patterns were not measured in this study.

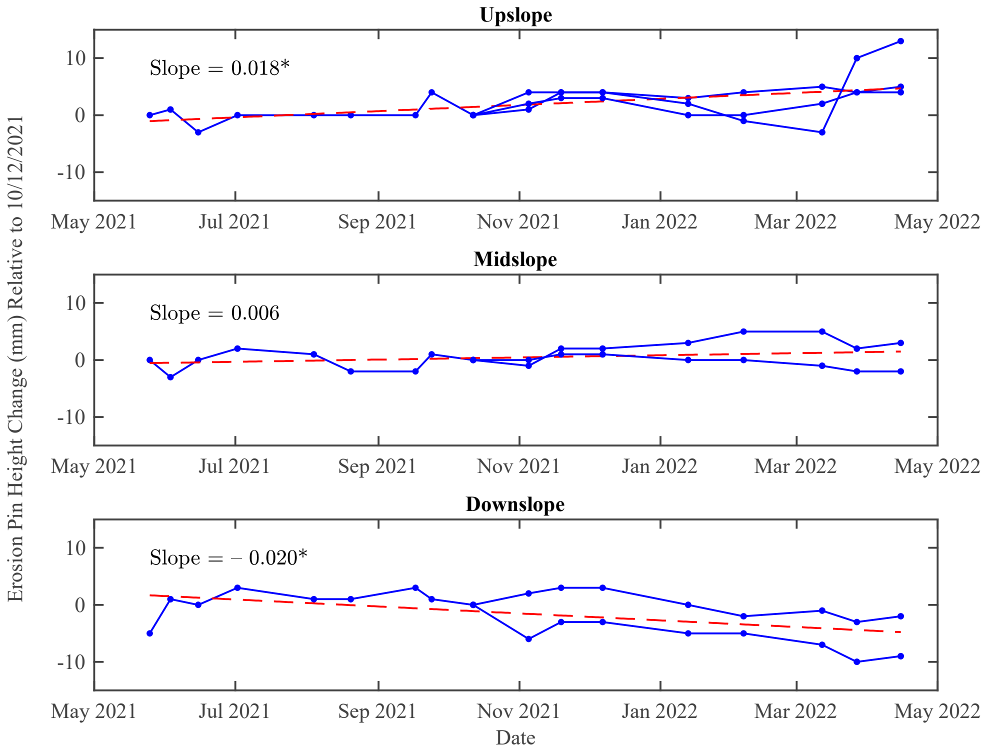


Figure 7. Linear regression for the plot with juniper between time in days and erosion pin height relative to the measurement on 12 October 2021, when all erosion pins were installed and stabilized. Solid blue lines and markers show the trajectory of measurements for each erosion pin and dashed red lines show the regression line. Regression slope is given in each plot with * indicating a regression p-value less than 0.1. Regression lines are calculated separately for upslope (**top**), midslope (**middle**), and downslope (**bottom**).

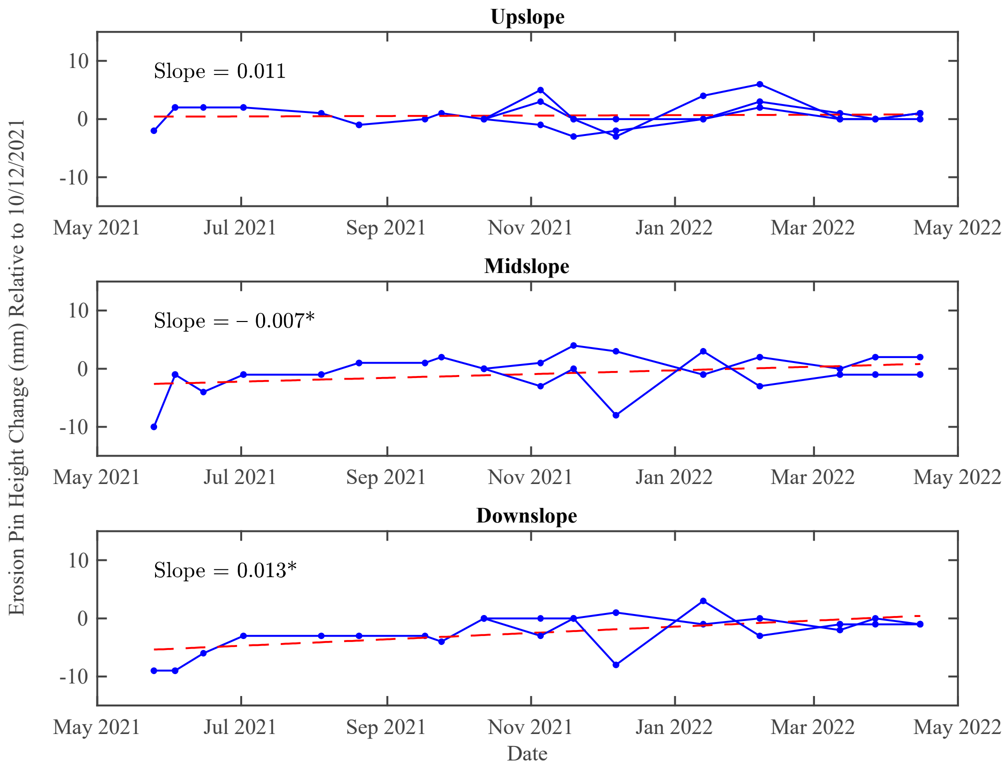


Figure 8. Linear regression for the plot with vetiver between time in days and erosion pin height relative to the measurement on 12 October 2021, when all erosion pins were installed and stabilized. Solid blue lines and markers show the trajectory of measurements for each erosion pin and dashed red lines show the regression line. Regression slope is given in each plot with * indicating a regression p-value less than 0.1. Regression lines are calculated separately for upslope (**top**), midslope (**middle**), and downslope (**bottom**).

The regression analysis summary (Table 2) shows that the R^2 value 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 height). Other potential sources of variation include spatial variability in erosion patterns and measurement errors. The species differed in which positions showed significant erosion or deposition. However, where erosion or deposition was occurring, the rates were similar, as indicated by overlapping 90% confidence intervals of the slope values. An exception to this is between the vetiver and juniper. These do not overlap at the upslope or downslope locations, though it should be noted that the R^2 and p values for vetiver upslope indicate that time was not a significant predictor of change in erosion pin height (Table 2).

One-way ANOVA analysis of the effect of species on change in erosion pin height did not show a significant effect ($F = 0.55$, $p = 0.58$), indicating similar mean change among plots (Figure 10a). Thus, the differences between plots were primarily in the spatial distribution of erosion and deposition due to differences in the uniformity of vegetation establishment. The influence of slope position indicated a clear pattern of positive change in pin height for upslope pins, indicating erosion negative values, and deposition in downslope pins (Figure 9b). A t-test demonstrated a significant difference between upslope and downslope pins ($t = 1.48$, $p = 0.08$).

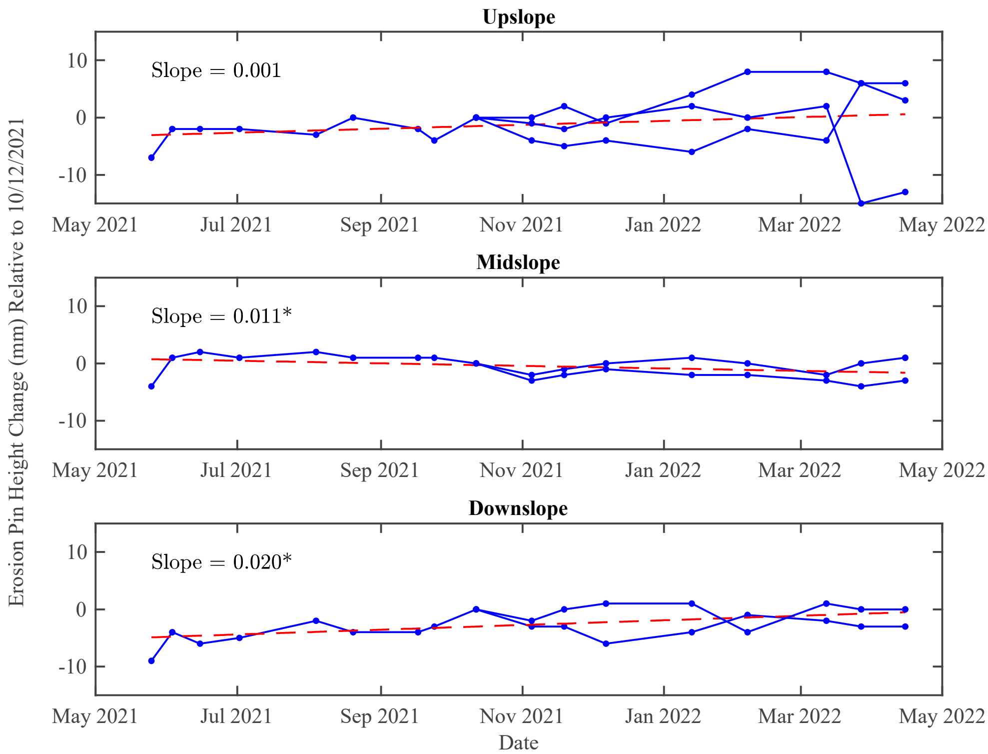


Figure 9. Linear regression for the plot with fescue grass between time in days and erosion pin height relative to the measurement on 12 October 2021, when all erosion pins were installed and stabilized. Solid blue lines and markers show the trajectory of measurements for each erosion pin and dashed red lines show the regression line. Regression slope is given in each plot with * indicating a regression *p*-value less than 0.1. Regression lines are calculated separately for upslope (top), midslope (**middle**), and downslope (**bottom**).

Table 2. Slope of the regression line with 90% confidence interval between time in days and change in erosion pin height in mm and regression statistics for each plot and slope position.

Species	Position	Slope (90% CI)	R^2	*p*-Value
Juniper	Upslope [1]	0.018 (0.009, 0.026)	0.28	<0.01
Juniper	Midslope	0.006 (−0.001, 0.013)	0.09	0.13
Juniper	Downslope [2]	−0.020 (−0.031, −0.009)	0.29	<0.01
Fescue	Upslope	0.011 (−0.004, 0.026)	0.05	0.22
Fescue	Midslope [2]	−0.007 (−0.013, −0.001)	0.16	0.04
Fescue	Downslope [1]	0.013 (0.006, 0.021)	0.30	<0.01
Vetiver	Upslope	0.001 (−0.005, 0.007)	0.00	0.76
Vetiver	Midslope [1]	0.011 (0.000, 0.021)	0.11	0.09
Vetiver	Downslope [1]	0.020 (0.014, 0.027)	0.36	<0.01

[1] Significant erosion ($p < 0.10$); [2] Significant deposition ($p < 0.10$).

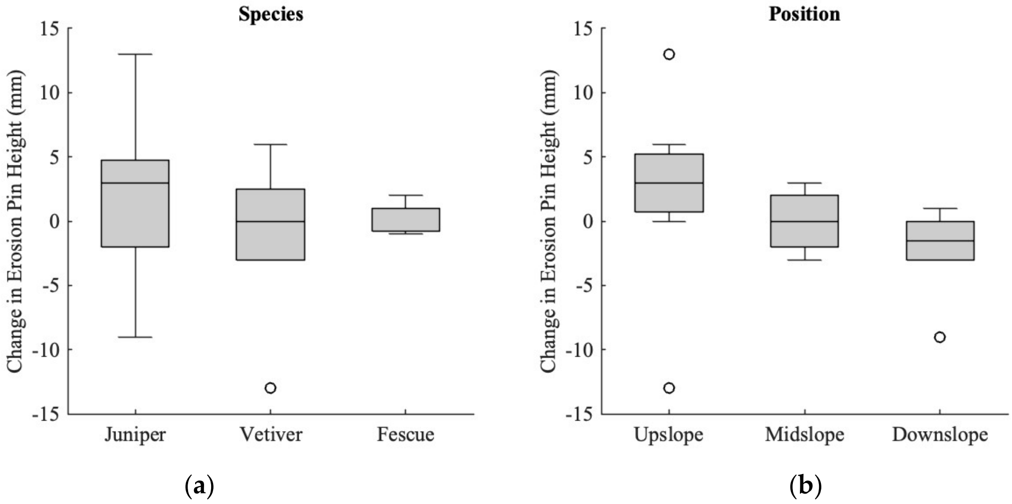


Figure 10. Boxplots showing the change in erosion pin height between 12 October 2021 and 15 April 2022, as grouped by (**a**) species planted on the experimental plot (data from all slope positions included); and (**b**) slope position of the erosion pin (data from all plots included).

3.3. Root Biomass

Vetiver had the highest overall root biomass in the top 40 cm of soil (3.75 kg/m^3), followed by fescue (1.28 kg/m^3) and juniper (0.45 kg/m^3). In the upper layers of the soil, the amount of root biomass is very similar among the species (Figure 11). 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. Total root biomass was substantially higher for vetiver while juniper was lower than the other species (Table 3). Root biomass was generally higher in the upslope core, though this was most pronounced for juniper. It should be noted that roots could not be identified by species, so some of the roots sampled from the juniper and fescue plots are likely from weeds. Very few weeds were present on the vetiver plots.

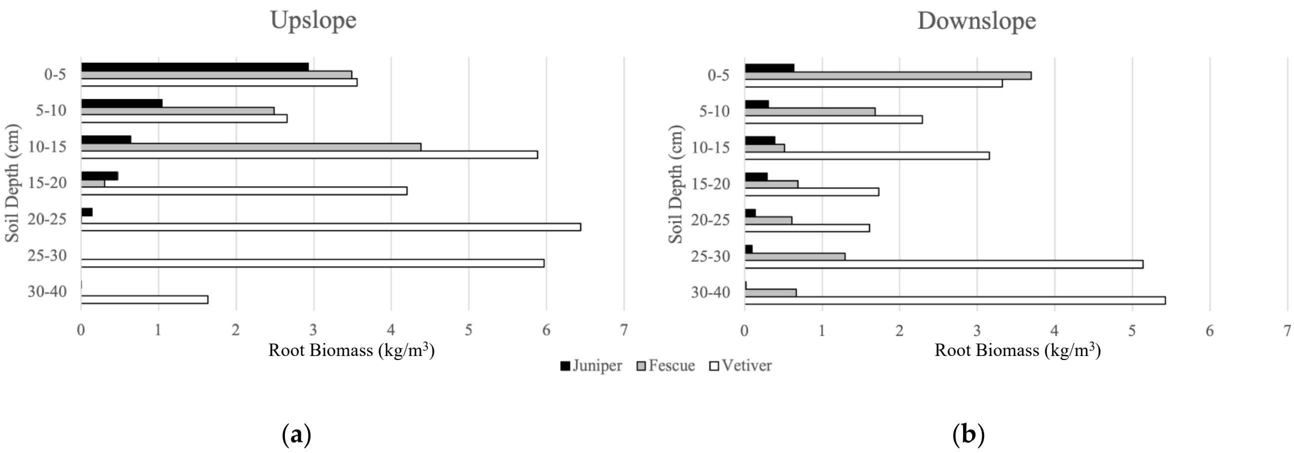


Figure 11. Root biomass by layer for three species in the (**a**) upslope core; and (**b**) downslope core.

Table 3. Root biomass by species in the top 40 cm of soil for the upslope core, the downslope core, and the mean of the two cores.

Species	Upslope (kg/m^3)	Downslope (kg/m^3)	Mean (kg/m^3)
Juniper	0.65	0.24	0.45
Fescue	1.33	1.23	1.28
Vetiver	4.00	3.51	3.75

Vetiver produced roots with a larger diameter than both the fescue and juniper (Figure 12). Root tensile strength, which is assessed per unit area, is inversely proportional to diameter [20,69], so a dense, fibrous root system with many small diameter roots is better for slope stability [18,70,71]. Given the similar biomass abundance in upper soil layers and prevalence of small diameter roots, fescue may be a better choice than juniper if only surface stabilization is needed. However, the root biomass analysis (Figure 11) demonstrated that vetiver is clearly better for deeper slope stabilization due to the greater abundance of deep root biomass. Additional work is needed to directly measure the impact of these roots on the strength of the slopes.

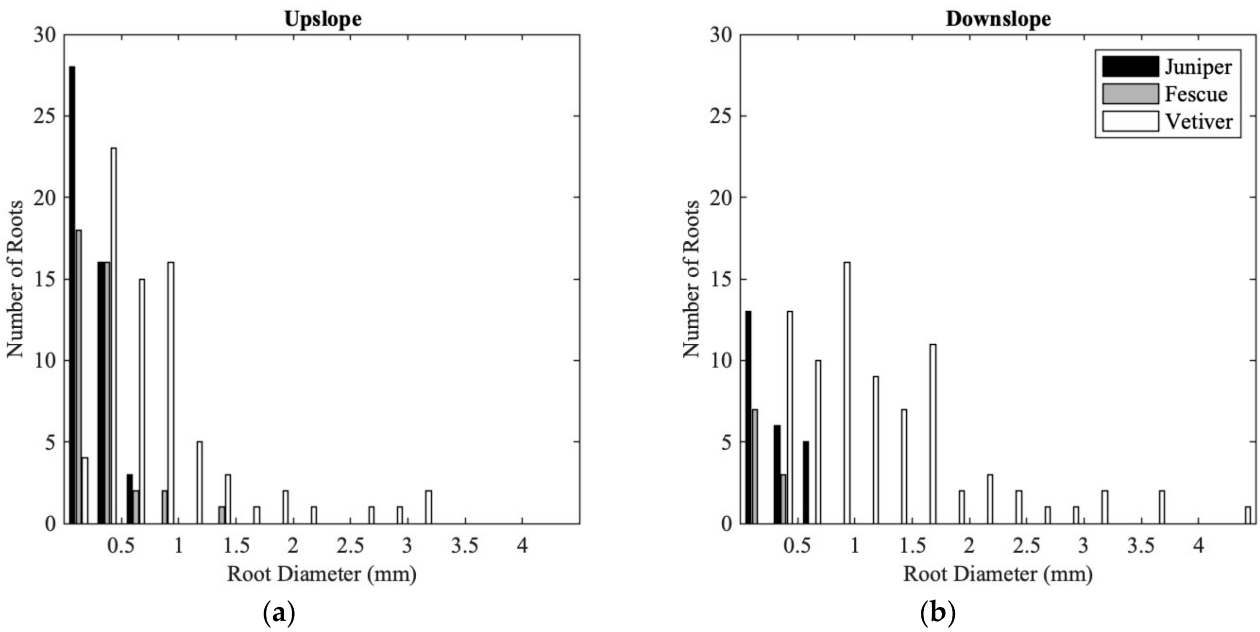


Figure 12. Histograms of root diameter measured at the midpoint of roots extracted from the (**a**) upslope core; and (**b**) downslope core.

3.4. Results Summary

This study addressed four research objectives. The first objective was to select vegetation types that may provide erosion control and slope stabilization for priority sites and compare them to the current management practice of planting turf grass from seed. Five vegetation types were tested—deep-rooted (vetiver) grass, woody shrubs, perennial legume, fern, and native prairie grass—and were compared to fescue grass grown from seed. The second objective was to determine which species establish and grow well on moderately steep roadside slopes in the Piedmont region of the southeast USA. Of the species tested, vetiver grass and juniper shrubs grew well (Figure 4). The third objective was to compare surface erosion rates from the experimental plots. Juniper and vetiver both had slightly lower sediment yield than fescue grass when sediment yield from the whole plot was considered (Figure 6). Erosion pins indicated that there was more spatial variability in erosion and deposition within the juniper and fescue plots due to uneven vegetation establishment (Figures 7–9). The final objective was to estimate the contribution of each species to increased slope stability by measuring root biomass and diameter in soil cores. Vetiver grass had substantially higher root biomass than the other species, particularly in deeper soil layers (Figure 11).

4. Discussion

Vetiver grass and juniper shrubs both established well on the experimental slopes and present possible alternatives to seeding with turf grasses such as fescue on high-priority sites. The failure of the perennial legume (hairy vetch) and maidenhair fern demonstrate the importance of weed resistance in species used for erosion control and slope stabilization in the study region. Vetiver showed the best weed resistance of the species tested while juniper may be suitable if a weed resistant species is planted in the interspace between plants.

The plot containing juniper had the lowest runoff amounts and sediment yield based on the runoff collection with TSS method (Figures 5 and 6). The erosion pin data suggest that this is because deposition is occurring at the base of the plot, as measured by the downslope pins (Figures 7–9), where aboveground vegetation establishment was strong (Figure 4). This suggests that the vegetation near the bottom of the plot was slowing runoff and allowing for deposition. If runoff was ponding as it slowed, it could increase infiltration [14], causing the lower runoff volumes observed. The highest rates of erosion were observed on the upslope pins in the juniper plot (Figure 10a), but the plot had the lowest total sediment yield (Figure 6). This demonstrates the high potential of juniper to create a barrier to sediment movement with good establishment.

In the other plots, with more even vegetation establishment, erosion and deposition rates were more consistent across the plot. This agrees with previous studies that emphasized the importance of good vegetation establishment in preventing erosion [41,42]. This study used two methods to compare surface erosion: runoff collection with TSS, which measures total sediment yield, and erosion pins, which measure the spatial distribution of erosion and deposition. The methods proved to be complimentary, as information on the spatial pattern of erosion was helpful in relating vegetation establishment to observed runoff and sediment yield. We did not directly quantify the effects of vegetation density on overland flow velocities or patterns and this remains an important topic for future research [68,72–75].

Despite the issues with establishment, the overall erosion rates observed in this study were within the limit of 2–7 mm/yr. This is much lower than a previous study conducted on a completely bare steep slope which had erosion rates of 20 mm/yr [62]. This study, which was conducted over a 10-year period, also recommended longer monitoring duration than was possible in the current study for erosion pins. Overall, the changes observed in the erosion pin heights were very small relative to the measurement precision ($\pm$ 1 mm) of a manual ruler. Longer monitoring until higher erosion or deposition values are observed may allow for more robust statistical analysis. Another difference with studies on bare slopes was in the pattern of erosion. On bare slopes, higher erosion rates are typically observed near the bottom of the slope, because that is where sheet flow velocities are highest [76]. The vetiver plot showed this same pattern. The pattern of higher erosion rates in the upslope pins observed for this study in the juniper and fescue (Figure 10b) was also found in a large study of vegetated streambanks slopes using erosion pins [77].

Slope stability also depends on root biomass, diameter distribution, and architecture [8]. Vetiver grass added substantially more belowground biomass than the other species tested (Figure 11). In general, fine roots (roots < 3 mm in diameter) are considered more important to soil stabilization than coarse roots [18]. Most of the biomass sampled from the plots, including vetiver, would be considered fine roots. While juniper and fescue had a slightly higher abundance of small diameter roots in upper soil layers, the deeper biomass of vetiver is key for increasing soil strength [20,24]. A previous study of vetiver grass in Brazil found similarly high levels of root biomass [78]. Based on the outcomes of this study, vetiver grass is a promising alternative to the current practice of seeding with turf grass that should be explored by managers. This study is one of the first to examine the use of vetiver grass in Alabama and the Piedmont region of the southern USA. and so this strong establishment and growth should be encouraging to those considering using vetiver. Future research should also measure additional factors that can influence slope failures, such as soil moisture and soil organic matter content [79–81]. Given the weak predictive power of daily rainfall as a predictor of change in erosion pin height, future studies should also measure sub-daily rainfall for the calculation of rainfall intensity as this is a better predictor of erosion than rainfall depth [82].

The performance of a vegetative cover must be weighed against practical concerns, such as ease and cost of planting and maintenance requirements. Vetiver 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. Future studies could also consider applying seeded biochemical solutions such as those used by [43] to combine temporary biochemical surface stabilization with the benefits of native grasses.

5. Conclusions

This study compared several vegetation types for erosion control and slope stabilization on roadside slopes in the Piedmont region of Alabama. The focus was on deep-rooted species that could be an alternative to planting turf grass from seed, the prevailing slope management practice in the region. The test plots were established on a relatively steep cut slope (25–30°) at the NCAT Test Track in Opelika, AL, USA. The response of the plots was monitored for over two years using erosion pins and TSS measurements.

Vetiver grass and juniper shrubs established well. Juniper and vetiver both had slightly lower sediment yield than fescue grass when sediment yield from the whole plot was considered. Erosion pins indicated that there was more spatial variability in erosion and deposition within the juniper and fescue plots, likely due to uneven vegetation establishment. Selecting a species with strong and even establishment is important to preventing surface erosion. Vetiver grass had more abundant and deeper root biomass than the other species in the study, suggesting it will be best for slope stabilization. This was the first study to test vetiver grass in the Piedmont region of the southeast and demonstrates that it is a promising option for slope stabilization. Future work is needed to directly measure the impact of vetiver roots on slope stability and to investigate effects of vegetation density and planting arrangement.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/land11101739/s1, Table S1: Water Level Logger Dataset; Table S2: Runoff Collection and TSS Dataset; Table S3: Erosion Pin Dataset; Table S4: Root Analysis Dataset.

Author Contributions: Conceptualization, F.C.O. and J.M.; methodology, H.A., V.N., F.C.O. and J.M.; formal analysis, H.A. and V.N.; investigation, H.A. and V.N.; resources, F.C.O. and J.M.; data curation, H.A. and V.N.; writing—original draft preparation, H.A., V.N. and F.C.O.; writing—review and editing, H.A., V.N. and J.M.; visualization, H.A. and V.N.; supervision, F.C.O.; project administration, F.C.O. and J.M.; funding acquisition, F.C.O. and J.M. All authors have read and agreed to the published version of the manuscript.

Funding: Financial support for this work was provided by the Auburn University Highway Research Center.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available in the Supplementary Materials as Tables S1–S4.

Acknowledgments: The authors thank M. Kiernan, J.R. Ellis, H. Xiao, Z. Hilliard-Shepherd, J. Anderson, C. Barrie, L. Rahimikhameneh and V. Aguilar for assistance with field and lab work. Michael Perez, Guy Savage, and the staff of the Auburn University Erosion and Sediment Control Test Facility assisted with site selection, preparation, and maintenance. Jason Nelson and the National Center for Asphalt Technology provided site access and coordination.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Knights, M.J.; Montgomery, J.; Carcamo, P.S. Development of a Slope Failure Database for Alabama Highways. *Bull. Eng. Geol. Environ.* **2020**, *79*, 423–438. [CrossRef]
2. Liu, Y.J.; Wang, T.W.; Cai, C.F.; Li, Z.X.; Cheng, D.B. 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. *Sci. Total Environ.* **2014**, *485*, 93–102. [CrossRef] [PubMed]
3. Morgan, R.P.; Rickson, R.J. *Slope Stabilization and Erosion Control: A Bioengineering Approach*; Taylor & Francis: Oxfordshire, UK, 2003.
4. Montgomery, J.; Knights, M.; Xuan, M.; Carcamo, P. *Evaluation of Landslides along Alabama Highways*; Report to the Alabama Department of Transportation, Highway Research Center: Auburn, AL, USA, 2019.
5. National Research Council. *Assessing and Managing the Ecological Impacts of Paved Roads*; National Academies Press: Washington, DC, USA, 2005.
6. Alabama Soil and Water Conservation Committee Alabama Handbook for Erosion Control, Sediment Control and Stormwater Management on Construction Sites and Urban Areas, Alabama Soil and Water Conservation Committee, Montgomery, AL, USA. 2018. Available online: https://alabamasoilandwater.gov/wp-content/uploads/2021/03/2018-Handbook-Vol-1.pdf (accessed on 21 September 2022).
7. Stokes, A.; Spanos, I.; Norris, J.E.; Cammeraat, E. *Eco- and Ground Bio-Engineering: The Use of Vegetation to Improve Slope Stability: Proceedings of the First International Conference on Eco-Engineering 13–17 September 2004*; Springer Science & Business Media: Berlin/Heidelberg, Germany, 2007; ISBN 978-1-4020-5593-5.
8. Bordoloi, S.; Ng, C.W.W. The Effects of Vegetation Traits and Their Stability Functions in Bio-Engineered Slopes: A Perspective Review. *Eng. Geol.* **2020**, *275*, 105742. [CrossRef]
9. Liu, X.; Lan, H.; Li, L.; Cui, P. An Ecological Indicator System for Shallow Landslide Analysis. *CATENA* **2022**, *214*, 106211. [CrossRef]
10. Löbmann, M.T.; Geitner, C.; Wellstein, C.; Zerbe, S. The Influence of Herbaceous Vegetation on Slope Stability–A Review. *Earth-Sci. Rev.* **2020**, *209*, 103328. [CrossRef]
11. He, J.J.; Cai, Q.G.; Tang, Z.J. Wind Tunnel Experimental Study on the Effect of PAM on Soil Wind Erosion Control. *Environ. Monit. Assess.* **2008**, *145*, 185–193. [CrossRef]
12. Roundy, D. How Do Plants Help Prevent Erosion Control? Granite Seed: Lehi, Utah, 2019.
13. Rousseva, S.; Torri, D.; Pagliai, M. Effect of Rain on the Macroporosity at the Soil Surface. *Eur. J. Soil Sci.* **2002**, *53*, 83–93. [CrossRef]
14. Greenway, D.R. Vegetation and Slope Stability. In *Slope Stability: Geotechnical Engineering and Geomorphology*; Chichester: West Sussex, UK, 1987; pp. 187–230.
15. Langbein, W.B.; Schumm, S.A. Yield of Sediment in Relation to Mean Annual Precipitation. *Eos Trans. Am. Geophys. Union* **1958**, *39*, 1076–1084. [CrossRef]
16. Chen, H.; Zhang, X.; Abla, M.; Lü, D.; Yan, R.; Ren, Q.; Ren, Z.; Yang, Y.; Zhao, W.; Lin, P. Effects of Vegetation and Rainfall Types on Surface Runoff and Soil Erosion on Steep Slopes on the Loess Plateau, China. *Catena* **2018**, *170*, 141–149. [CrossRef]
17. Ranjan, V.; Sen, P.; Kumar, D.; Sarsawat, A. A Review on Dump Slope Stabilization by Revegetation with Reference to Indigenous Plant. *Ecol. Process.* **2015**, *14*, 1–11. [CrossRef]
18. Reubens, B.; Poesen, J.; Danjon, F.; Geudens, G.; Muys, B. The Role of Fine and Coarse Roots in Shallow Slope Stability and Soil Erosion Control with a Focus on Root System Architecture: A Review. *Trees* **2007**, *21*, 385–402. [CrossRef]
19. Masi, E.B.; Segoni, S.; Tofani, V. Root Reinforcement in Slope Stability Models: A Review. *Geosciences* **2021**, *11*, 212. [CrossRef]
20. De Baets, S.; Poesen, J.; Reubens, B.; Wemans, K.; Baerdemaeker, J.D.; Muys, B. Root Tensile Strength and Root Distribution of Typical Mediterranean Plant Species and Their Contribution to Soil Shear Strength. *Plant Soil* **2008**, *305*, 207–226. [CrossRef]
21. Bennett, S.J.; Simon, A. *Riparian Vegetation and Fluvial Geomorphology*; American Geophysical Union: Washington, DC, USA, 2004; Volume 8.
22. Zhou, Y.; Watts, D.; Li, Y.; Cheng, X. A Case Study of Effect of Lateral Roots of Pinus Yunnanensis on Shallow Soil Reinforcement. *For. Ecol. Manag.* **1998**, *103*, 107–120. [CrossRef]
23. Stokes, A.; Atger, C.; Bengough, A.G.; Fourcaud, T.; Sidle, R.C. Desirable Plant Root Traits for Protecting Natural and Engineered Slopes against Landslides. *Plant Soil* **2009**, *324*, 1–30. [CrossRef]
24. Simon, A.; Collison, A.J.C. Quantifying the Mechanical and Hydrologic Effects of Riparian Vegetation on Streambank Stability. *Earth Surf. Process. Landf.* **2002**, *27*, 527–546. [CrossRef]

25. Nelson, S.A. Slope Stability, Triggering Events, Mass Movement Hazards. *Nat. Disasters* **2013**. Tulane University, New Orleans, LA, USA. Available online: https://www2.tulane.edu/~{}sanelson/Natural_Disasters/slopestability.pdf (accessed on 21 September 2022).
26. Patil, U.D.; Shelton III, A.J.; Aquino, E. Bioengineering Solution to Prevent Rainfall-Induced Slope Failures in Tropical Soil. *Land* **2021**, *10*, 299. [CrossRef]
27. Cook, T. Tall Fescue Lolium Arundinaceum (Schreb.) Darbysh. Oregon State University, Corvallis, OR, USA. 2005. Available online: https://agsci.oregonstate.edu/sites/agscid7/files/horticulture/beaverturf/TallFescue-1-5-05V.pdf (accessed on 21 September 2022).
28. Burylo, M.; Hudek, C.; Rey, F. Soil Reinforcement by the Roots of Six Dominant Species on Eroded Mountainous Marly Slopes (Southern Alps, France). *Catena* **2011**, *84*, 70–78. [CrossRef]
29. Sharif, M. US Army Experience: Cold Tolerance and Seed Viability Characteristics of Vetiver. In Proceedings of the Second International Vetiver Conference, Thailand, 18–22 January 2000.
30. Truong, P. Vetiver Grass System: Potential Applications for Soil and Water Conservation in Northern California. In Proceedings of the Application of the Vetiver System for Phytoremediation of Mercury Pollution in the Lake and Yolo Counties, Northern California, 10 May 2000; Volume 9.
31. Knouse, J.A. Ferns as Conservation Agents. Available online: https://www.jaknouse.athens.oh.us/ferns/ferncons.html (accessed on 30 March 2021).
32. Hamidifar, H.; Keshavarzi, A.; Truong, P. Enhancement of River Bank Shear Strength Parameters Using Vetiver Grass Root System. *Arab. J. Geosci.* **2018**, *11*, 611. [CrossRef]
33. Saifuddin, M.; Osman, N. Evaluation of Hydro-Mechanical Properties and Root Architecture of Plants for Soil Reinforcement. *Curr. Sci.* **2014**, *107*, 845–852.
34. Ali, F.H.; Osman, N. Shear Strength of a Soil Containing Vegetation Roots. *Soils Found.* **2008**, *48*, 587–596. [CrossRef]
35. Kokutse, N.K.; Temgoua, A.G.T.; Kavazović, Z. Slope Stability and Vegetation: Conceptual and Numerical Investigation of Mechanical Effects. *Ecol. Eng.* **2016**, *86*, 146–153. [CrossRef]
36. Levine, E.R.; Knox, R.G.; Lawrence, W.T. Relationships between Soil Properties and Vegetation at the Northern Experimental Forest, Howland, Maine. *Remote Sens. Environ.* **1994**, *47*, 231–241. [CrossRef]
37. Raich, J.W.; Tufekciogul, A. Vegetation and Soil Respiration: Correlations and Controls. *Biogeochemistry* **2000**, *48*, 71–90. [CrossRef]
38. Lynne, K. Starting Seeds vs. Buying Plants: Which Is Better? New Life on A Homestead. *New Life Homestd.* **2013**. Available online: https://www.newlifeonahomestead.com/starting-seeds-vs-buying-plants/ (accessed on 21 September 2022).
39. Messer, R.C. Evaluating Maintenance Techniques for Long-Term Vegetation Establishment on Disturbed Slopes in Alabama. M.S. Thesis, Auburn University, Auburn, AL, USA, 2011.
40. Bochet, E.; García-Fayos, P.; Tormo, J. How Can We Control Erosion of Roadslopes in Semiarid Mediterranean Areas? Soil Improvement and Native Plant Establishment. *Land Degrad. Dev.* **2010**, *21*, 110–121. [CrossRef]
41. Bochet, E.; García-Fayos, P.; Poesen, J. Topographic Thresholds for Plant Colonization on Semi-Arid Eroded Slopes. *Earth Surf. Process. Landf. J. Br. Geomorphol. Res. Group* **2009**, *34*, 1758–1771. [CrossRef]
42. Grace, J.M. Effectiveness of Vegetation in Erosion Control from Forest Road Sideslopes. *Trans. ASAE* **2002**, *45*, 681.
43. Hodges, T.M.; Lingwall, B.N. Effects of Microbial Biomineralization Surface Erosion Control Treatments on Vegetation and Revegetation along Highways. *Transp. Res. Rec.* **2020**, *2674*, 1030–1040. [CrossRef]
44. Kim, K.; Riley, S.; Fischer, E.; Khan, S. Greening Roadway Infrastructure with Vetiver Grass to Support Transportation Resilience. *CivilEng* **2022**, *3*, 147–164. [CrossRef]
45. Myers, D.T.; Rediske, R.R.; McNair, J.N. Measuring Streambank Erosion: A Comparison of Erosion Pins, Total Station, and Terrestrial Laser Scanner. *Water* **2019**, *11*, 1846. [CrossRef]
46. Thomsen, L.M.; Baartman, J.E.M.; Barneveld, R.J.; Starkloff, T.; Stolte, J. Soil Surface Roughness: Comparing Old and New Measuring Methods and Application in a Soil Erosion Model. *Soil* **2015**, *1*, 399–410. [CrossRef]
47. Hunolt, A.E.; Brantley, E.F.; Howe, J.A.; Wright, A.N.; Wood, C.W. Comparison of Native Woody Species for Use as Live Stakes in Streambank Stabilization in the Southeastern United States. *J. Soil Water Conserv.* **2013**, *68*, 384–391. [CrossRef]
48. Srivastava, A.; Yetemen, O.; Saco, P.M.; Rodriguez, J.F.; Kumari, N.; Chun, K.P. Influence of Orographic Precipitation on Coevolving Landforms and Vegetation in Semi-Arid Ecosystems. *Earth Surf. Process. Landf.* **2022**, *47*, 2846–2862. [CrossRef]
49. Saco, P.M.; Moreno-de las Heras, M. Ecogeomorphic Coevolution of Semiarid Hillslopes: Emergence of Banded and Striped Vegetation Patterns through Interaction of Biotic and Abiotic Processes. *Water Resour. Res.* **2013**, *49*, 115–126. [CrossRef]
50. NRCS Information on Rainfall, Frequency, & Distributions NRCS NEH Part 630 Ch.4. Available online: https://www.nrcs.usda.gov/wps/portal/nrcs/detailfull/national/water/?cid=stelprdb1044959 (accessed on 27 May 2020).
51. Terando, A.J.; Costanza, J.; Belyea, C.; Dunn, R.R.; McKerrow, A.; Collazo, J.A. The Southern Megalopolis: Using the Past to Predict the Future of Urban Sprawl in the Southeast US. *PLoS ONE* **2014**, *9*, e102261. [CrossRef]
52. US Department of Agriculture. National Weather and Climate Service Interactive Map. Available online: https://www.nrcs.usda.gov/wps/portal/ (accessed on 21 September 2022).
53. Durner, W.; Iden, S.C. The Improved Integral Suspension Pressure Method (ISP+) for Precise Particle Size Analysis of Soil and Sedimentary Materials. *Soil Tillage Res.* **2021**, *213*, 105086. [CrossRef]

54. Dalton, P.A.; Smith, R.J.; Truong, P.N.V. Vetiver Grass Hedges for Erosion Control on a Cropped Flood Plain: Hedge Hydraulics. *Agric. Water Manag.* **1996**, *31*, 91–104. [CrossRef]
55. Kemper, W.D. Vetiver Grass: A Thin Green Line against Erosion. *J. Soil Water Conserv.* **1993**, *48*, 426–427.
56. US Department of Agriculture, The PLANTS Database: Plant List of Attributes, Names, Taxonomy, and Symbols. US Department of Agriculture, Natural Resource Conservation Service, National Plant Data Team, Baton Rouge, LA, USA. 2015. Available online: http://Plants.Usda.Gov (accessed on 21 September 2022).
57. Wiesmeier, M.; Lungu, M.; Hübner, R.; Cerbari, V. Remediation of Degraded Arable Steppe Soils in Moldova Using Vetch as Green Manure. *Solid Earth* **2015**, *6*, 609–620. [CrossRef]
58. Chau, N.L.; Chu, L.M. Fern Cover and the Importance of Plant Traits in Reducing Erosion on Steep Soil Slopes. *Catena* **2017**, *151*, 98–106. [CrossRef]
59. DuBois, L.; Latimer, J.G.; Appleton, B.L.; Close, D. America's Anniversary Garden. Native Plants. Publication 426-223. Virginia Cooperative Extension, Blacksburg, VA, USA. 2009. Available online: https://vtechworks.lib.vt.edu/bitstream/handle/10919/48226/426-223_pdf.pdf?sequence=1 (accessed on 21 September 2022).
60. Correll, D.L. Principles of Planning and Establishment of Buffer Zones. *Ecol. Eng.* **2005**, *24*, 433–439. [CrossRef]
61. Hoag, C.J. Vertical Bundles: A Streambank Bioengineering Treatment to Establish Willows and Dogwoods on Streambanks. In *Technical Note USDA-NRCS. Boise, Idaho-Salt Lake City, Utah. Plant Material*; USDA-NRCS (US Department of Agriculture Natural Resource Conservation Service): Boise, Idaho; Idaho-Salt Lake City, Utah, 2009; Volume 53, pp. 1–6.
62. Hart, E.A.; Mills, H.H.; Li, P. Measuring Erosion Rates on Exposed Limestone Residuum Using Erosion Pins: A 10-Year Record. *Phys. Geogr.* **2017**, *38*, 541–555. [CrossRef]
63. USEPA Method 160.2: Total Suspended Solids (TSS) (Gravimetric, Dried at 103–105° C) US Environmental Protection Agency, Washington, DC, USA. 1999. Available online: https://www.nemi.gov/methods/method_summary/5213/ (accessed on 21 September 2022).
64. Haigh, M.J. The Use of Erosion Pins in the Study of Slope Evolution. *Br. Geomorphol. Res. Group Tech. Bull.* **1977**, *18*, 31–49.
65. Kearney, S.P.; Fonte, S.J.; García, E.; Smukler, S.M. Improving the Utility of Erosion Pins: Absolute Value of Pin Height Change as an Indicator of Relative Erosion. *CATENA* **2018**, *163*, 427–432. [CrossRef]
66. Frasier, I.; Noellemeyer, E.; Fernández, R.; Quiroga, A. Direct Field Method for Root Biomass Quantification in Agroecosystems. *MethodsX* **2016**, *3*, 513–519. [CrossRef] [PubMed]
67. Franks, C.D.; Goings, K.A. Separating Roots from the Soil by Hand Sieving. Available online: https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs142p2_050967.pdf (accessed on 21 September 2022).
68. Wang, L.; Zhang, Y.; Jia, J.; Zhen, Q.; Zhang, X. Effect of Vegetation on the Flow Pathways of Steep Hillslopes: Overland Flow Plot-Scale Experiments and Their Implications. *CATENA* **2021**, *204*, 105438. [CrossRef]
69. Pollen, N.; Simon, A. Estimating the Mechanical Effects of Riparian Vegetation on Stream Bank Stability Using a Fiber Bundle Model. *Water Resour. Res.* **2005**, *41*, W07025. [CrossRef]
70. Grimshaw, R.G.; Helfer, L. *Vetiver Grass for Soil and Water Conservation, Land Rehabilitation, and Embankment Stabilization: A Collection of Papers and Newsletters Compiled by the Vetiver Network*; The World Bank: Washington, DC, USA, 1995.
71. Yoon, P.K. Important Biological Considerations in Use of Vetiver Grass Hedgerows (VGHR) for Slope Protection and Stabilisation. In *Vegetation and Slopes*; Institution of Civil Engineers: London, UK, 1995; pp. 212–221.
72. Zhang, S.; Zhang, J.; Liu, Y.; Liu, Y.; Wang, Z. The Effects of Vegetation Distribution Pattern on Overland Flow. *Water Environ. J.* **2018**, *32*, 392–403. [CrossRef]
73. Tinoco, R.O.; San Juan, J.E.; Mullarney, J.C. Simplification Bias: Lessons from Laboratory and Field Experiments on Flow through Aquatic Vegetation. *Earth Surf. Process. Landf.* **2020**, *45*, 121–143. [CrossRef]
74. Nicosia, A.; Di Stefano, C.; Pampalone, V.; Palmeri, V.; Ferro, V.; Polyakov, V.; Nearing, M.A. Testing a Theoretical Resistance Law for Overland Flow under Simulated Rainfall with Different Types of Vegetation. *CATENA* **2020**, *189*, 104482. [CrossRef]
75. Li, C.; Pan, C. Overland Runoff Erosion Dynamics on Steep Slopes with Forages under Field Simulated Rainfall and Inflow. *Hydrol. Process.* **2020**, *34*, 1794–1809. [CrossRef]
76. Zhuang, X.; Wang, W.; Ma, Y.; Huang, X.; Lei, T. Spatial Distribution of Sheet Flow Velocity along Slope under Simulated Rainfall Conditions. *Geoderma* **2018**, *321*, 1–7. [CrossRef]
77. Zaimes, G.N.; Tamparopoulos, A.E.; Tufekcioglu, M.; Schultz, R.C. Understanding Stream Bank Erosion and Deposition in Iowa, USA: A Seven Year Study along Streams in Different Regions with Different Riparian Land-Uses. *J. Environ. Manag.* **2021**, *287*, 112352. [CrossRef] [PubMed]
78. Machado, L.; Holanda, F.S.R.; da Silva, V.S.; Maranduba, A.I.A.; Lino, J.B. Contribution of the Root System of Vetiver Grass towards Slope Stabilization of the São Francisco River. *Semin. Cienc. Agrar.* **2015**, *36*, 2453–2463. [CrossRef]
79. Fitzjohn, C.; Ternan, J.L.; Williams, A.G. Soil Moisture Variability in a Semi-Arid Gully Catchment: Implications for Runoff and Erosion Control. *Catena* **1998**, *32*, 55–70. [CrossRef]
80. Polyakov, V.; Lal, R. Modeling Soil Organic Matter Dynamics as Affected by Soil Water Erosion. *Environ. Int.* **2004**, *30*, 547–556. [CrossRef]

81. Polyakov, V.O.; Lal, R. Soil Organic Matter and CO_2 Emission as Affected by Water Erosion on Field Runoff Plots. *Geoderma* **2008**, *143*, 216–222. [CrossRef]
82. Williams, J.R. Sediment-Yield Prediction with Universal Equation Using Runoff Energy Factor. In *Present Prospect. Technol. Predict. Sediment Yield Sources 1975*; US Department of Agriculture, Agriculture Research Service: Washington DC, USA, 1975; pp. 244–252.