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Research Article

Comparison Between Vetiver and Brachiaria Grass in Erosion Control in Tropical Climate

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Received: 15 May 2024; **Revised:** 31 July 2024; **Accepted:** 5 August 2024

Abstract: The use of conservation practices, such as level planting and the use of cover crops, can reduce the magnitude of erosion processes, reducing losses of soil, water, nutrients, and organic carbon. The aim of this study was to compare erosion control using vetiver, bare soil, and brachiaria grass. The experiment was carried out over a period of ten months, representing the rainy season in the humid tropical climate of Rio de Janeiro. Erosion was monitored on three Gerlach-type runoff erosion plots with different types of soil cover. Erosion was quantified by analyzing the sediment in runoff samples using the following methods: 1) the evaporation method described in APHA-Standard Methods 2540 B (2005) when the sediment concentration was greater than 200 $mg \cdot L^{-1}$, and 2) the filtration method described in APHA-Standard Methods 2540 D (2005) when the sediment concentration was less than 200 $mg \cdot L^{-1}$. During an extreme heavy rainfall event (precipitation of 38.8 mm and rainfall intensity of 13.6 $mm \cdot h^{-1}$), the vetiver system showed erosion of 1.04 $kg \cdot ha^{-1}$, while the brachiaria grass had erosion values of 41.66 $kg \cdot ha^{-1}$. Thus, it is clear that vetiver was more efficient at controlling erosion due to its deep fasciculated roots, which enhance infiltration, and its vegetative character, which forms a physical barrier and slows down runoff, reducing erosive energy and retaining sediment. On the other hand, the bare soil showed erosion of 2,531.61 $kg \cdot ha^{-1}$, highlighting the efficiency of using grasses to control erosion.

***Keywords*:** runoff-erosion plot, vetiver system, sediment yield, runoff, Brachiaria grass

1. Introduction

Erosion constitutes the process of disaggregation, transport and deposition of soil particles that can be differentiated in geological or natural erosion and anthropogenic or accelerated erosion. Geological erosion occurs in natural conditions over long periods of time (millions of years) by modifying the geomorphology of the earth's surface. Moreover, anthropogenic or accelerated erosion is caused by human activities that cause an increase in the speed of erosive processes, causing the degradation of soil and water resources in short periods of time (months or years).[1]

Raindrop impact on soil due to inadequate vegetation cover leads to soil particle detachment causing clogging up of

DOI: https://doi.org/10.37256/sce.5220244925

soil pores and formation of crust. Disruption in soil structure alters porosity and decreases the rate of rainfall infiltration causing an increase in surface runoff, and in consequence, promoting floods and sedimentation processes within rural and urban river systems.[1] Runoff reduction can be achieved either through physical barriers such as terraces and ditches, or with live barriers, such as grass hedges.[1]

Live barriers consist of vegetation cultivated in contour buffer strips in order to control the volume and speed of runoff and increase infiltration. These barriers form a natural terrace that restrains sediments, organic matter, fertilizers and pesticides avoiding contamination and siltation of water resources.[2] Vetiver grass (*Chrysopogon zizanioides*) presents a prominent role in relation to other plants used as live barriers mainly due to its high rusticity and adaptability to different soil and climate conditions, rapid growth and deep rooting. *Chrysopogon zizanioides* is a perennial bunchgrass of the Poaceae family, native to India with approximately 2 m of height and a dense root system reaching 5 m of depth. Stems are fine, erect and resistant, which function as sediment and waste retainers and lead to runoff diffusion. The deep root system has a tensile strength equivalent to 1/6 of steel resistance. This feature assists in soil fixation and the formation of a subsurface downstream barrier, ensuring greater water infiltration and also an increase of organic matter in the soil through the degradation of dead roots. The root system lies beneath the surface which enables resistance to fire, frost and animal trampling.[3]

Brachiaria decumbens (Urochloa decumbens) is a grass of African origin, native to tropical regions where annual rainfall exceeds 800 mm and high temperatures prevail. Its growth is reduced with decreasing temperatures, and it does not tolerate frost. Brachiaria can be cultivated in most soils in Brazil, including those with low fertility. This species is notable for its high dry mass production capacity, tolerance to water deficiency, nutrient absorption from deeper soil layers, and nutrient recycling, allowing it to thrive in diverse environmental conditions. Brachiaria produces large quantities of stolons and branches vigorously, making it recommended for areas with rough topography, contributing to the recovery of areas undergoing initial erosion. It is also tolerant to shading and moderate drought. The grass is commonly propagated by seeds and flowers throughout its growth stage. Its root system is moderately deep, voluminous, branched, and aggressive, capable of penetrating compacted soil layers. As the roots die and decompose, they form channels (biopores), thereby increasing the absorption of water and nutrients.[4]

The use of plant species to stabilize and control erosion processes is more efficient and economical than other erosion control techniques.[5,6] Vegetation provides soil cover through its roots and residues. In addition, the anatomical and physiological differences and different growth patterns of plants act differently on erosion processes. In view of the above, the aim of this study was to quantify the rates of erosion and surface runoff on a slope in a humid tropical climate, assessing the efficiency of Vetiver and Brachiaria grasses in containing erosion and surface runoff.

2. Materials and methods

The experiment was realized during a period of ten months, beginning in May 2011 and ending in February 2012, in which the period from September to February represents the rainy season in the humid tropical climate of Rio de Janeiro. A digital rain gauge and thermometer that recorded data every 15 minutes were installed in the study area. The rainfall intensity was quantified using the I30, which represents the maximum 30-minute rainfall intensity. Runoff and sediment yield were measured in three Gerlach-type runoff-erosion plots and also by using a Coshocton wheel runoff sampler. The total runoff volume was also collected. Six compost-deformed topsoil samples were collected from each of the three erosion plots at a depth of 0-10 cm to determine granulometric curves. Soil textural analysis was conducted via sieving and sedimentation according to the reference.[7] A compost topsoil sample from the three erosion plots at a depth of 0-10 cm was collected for chemical analysis following the method described by reference.[8,9] Statistica 7® software was used for statistical studies since it presents a wide selection of basic and advanced analytical processes for the most diverse areas of study. Hydraulic conductivity was measured in situ using a Guelph permeameter.

2.1 *Location, site description and climate*

The study was conducted in Fundão Island situated in Rio de Janeiro, between the meridians of 43° 12' 25" and 43° 14' 45" west longitude of Greenwich and the parallels of 22° 49' 55" and 22° 53' 10" south latitude. The area has approximately 501.26 ha.

Fundão Island was formed by an embankment in an original archipelago composed of eight islands of varying dimensions: Cabras Island, Baiacu Island, Catalão Island, Fundão Island, Pindaí do Ferreira Island, Pindaí Island of France, Bom Jesus Island and Sapucaia Island (Figure 1).

The climate type is humid mesothermal with a low water deficit, and the site has a well-defined dry season from June to August and a rainy season from September to March. The mean temperature in summer (i.e., from December to March) is 28 °C, and the mean temperature in winter (i.e., from June to September) is a mild 20 °C.

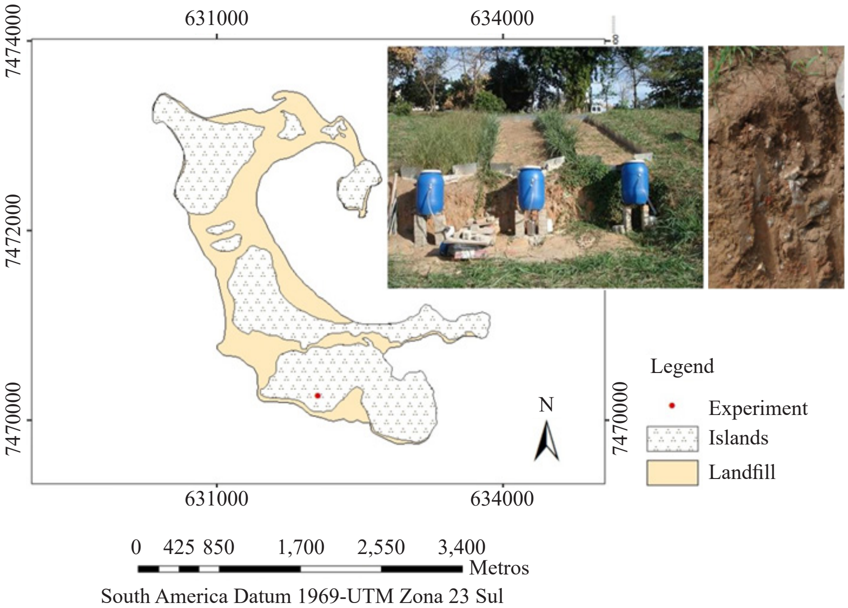


Figure 1. Map of Federal University of Rio de Janeiro and the location of the experiment. Erosion plots: Vetiver grass (left), bare soil (middle) and Brachiaria grass (right). The soil profile is presented on the top right side of the figure

2.2 *Chemical properties*

The chemical properties of this soil were characterized according to the methodology recommended by Empresa Brasileira de Pesquisa Agropecuária[10] and described below.

Hydrogen potential (pH): pH measurement using a combined electrode immersed in a solid aqueous suspension: liquid (H_2O) ratio 1:2.5. An Orion potentiometer model 710A (Orion Research Inc., Boston, MA, USA) was used for this purpose.

The extraction of exchangeable calcium (Ca^{2+}) and magnesium (Mg^{2+}) was determined using a KCl (1 mol/L) solution, while sodium (Na^+) and potassium (K^+) were analyzed using a solution known as Mehlich-1, and then Ca^{2+} and Mg^{2+} ions were measured by Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES), model ULTIMA 2 (Horiba Inc, Japan) and Na^+ and K^+ were measured by Flame Photometer model DM-6 (Digimed). The exchangeable aluminum content (Al^{3+}) was obtained by extraction with KCl solution (1 mol/L) and determined by the volumetric method with diluted NaOH solution.

2.3 *Erosion plots*

To collect runoff and sediment yield measurements, three Gerlach-type runoff-erosion plots with the following covers were installed: (1) vetiver grass (*Chrysopogon zizanioides* (L.) Roberty), (2) bare soil and (3) Brachiaria grass (*Brachiaria decumbens*). Vetiver and Brachiaria grass was planted in May 2011. The initial growth stage corresponded to the period from May 2011 through August 2011. The plots were located in an area with a slope of 21% that was composed of an embankment that enabled construction on the campus of the university (Figure 1). Vetiver grass was planted along contours across the slope, with 20 cm between culms and 100 cm between rows. The Brachiaria grass was sown in furrows spaced 20 cm apart, with the seeds thrown in. The sowing depth should be between 2.0 and 3.0 cm, as the seeds are small.

Vetiver grass is a pioneer agent for land rehabilitation and forestry establishment on steeply sloping lands due to extreme climate and soil adaptability. Vetiver has tolerance to high alkalinity, salinity, acidity and presence of heavy metals. Vetiver survives prolonged drought and flood, and grows in a wide range of temperatures from -20 °C to 55 °C. Nevertheless, Vetiver grass is not potentially invasive and does not outcompete native species mainly because most cultivars do not produce viable seeds and are intolerant to heavy shade.[11,12] A cultivar registered as Monto Vetiver did not produce caryopses in a glasshouse, dryland, irrigated and wetland environments. In the case of forestation, Vetiver grass will improve soil physical conditions creating favorable micro-climates that promote soil conservation by reducing erosion and enhancing infiltration. When the forest becomes fully established with a closed canopy, the resulting shade will reduce vetiver growth.[13] Crops can be cultivated with vetiver without invasive problems. Babalola cites[14] that vetiver grass hedges are used to contain erosion in crops maize. The mean grain yield of maize over the five seasons was 49.1% higher on the vetiver plots than on the no-vetiver plots. The gain in production was attributed to the reduction of runoff flow velocity, increased infiltration and soil nutrient quality and soil moisture storage by vetiver strips.

Vetiver grass plays a fundamental role in the revegetation of degraded soils, as it improves the physical properties of the soil by offering mechanical support to the system, therefore, it is highly recommended for use in slope stabilization. One of the most important features is the presence of an extremely fasciculated and deep root system, which contributes to soil stabilization, preventing landslides whose instability planes are less than two meters.[2]

Signal grass or Brachiaria grass (*Brachiaria decumbens*) is native to Africa and was introduced in Brazil in the 1960s. It is in essence a plant of tropical climate with great adaptability to acidic and low fertility soils. Another factor that must be considered is the great resistance to water stress, requiring an average of 800 mm of water annually. Brachiaria grass has an average height between 50 cm and 100 cm with great ground cover being widely used for erosion control.[15] Brachiaria root system is fasciculated and has an effective depth of 47 cm and a root density of 0.52 $g \cdot m^{-3}$.[16]

The plots were 7 m long by 2.5 m wide, with an area of 15 m^2. The plot was delimited using a 40 cm wide tinplate that was placed into the soil to a depth of 20 cm. The tinplate retained the rain water within the plot and prevented raindrops from spattering outside in and vice versa. A funnel-shaped trough was installed at the end of the plot to collect runoff water in the spillway of the Coshocton wheel, which was inserted into a 250 L container. Runoff water was collected and measured after rainfall events in all erosion plots. Erosion was quantified by analyzing the sediments in runoff samples using the following methods: 1) the evaporation method described in APHA-Standard Methods 2540 B[17] when the sediment concentration was greater than 200 $mg \cdot L^{-1}$, and 2) the filtration method described in APHA-Standard Methods 2540 D[18] when the sediment concentration was less than 200 $mg \cdot L^{-1}$. After a rainfall event, 250 mL samples were collected after homogenization of the total runoff that was collected from each of the 250 L containers in the three plots. The 250 mL samples were oven-dried to measure sediment yield. After drying, the containers with the sediments were weighed and the quantity of sediments was obtained. These values were multiplied by the total runoff in L to obtain the total sediment yield in g for each erosion plot after every rainfall. Furthermore, because the area of the plot was 15 m^2 the results were multiplied by 1.5 to obtain a measurement equivalent to $kg \cdot ha^{-1}$. The sediment yield and runoff measurements enabled comparisons between treatments and established the soil conservation potential.

2.4 *Statistical assessment*

Considering the complexity and high variability that are typically observed in erosion studies, this type of study frequently uses multivariate statistical methods. Cluster analyses were performed using Statistica 7® software[19] to identify differences among the three types of soil cover.

One of the first steps in environmental statistical analysis should be the careful study of the distribution of variables. In the present study, the Lilliefors test (LF) was performed, considering a level of 2% significance. The LF test is based on verifying whether the maximum distance between the empirical distribution and the theoretical cumulative distribution (Z distribution) is statistically significant or not.

The existence of outliers that could affect the final results of the statistical analysis was investigated before applying any multivariate method. In multidimensional data, an observation is considered an outlier if it presents extreme values in the multivariate distribution and not only in one variable or another. In order to detect discrepant data, a multivariate comparison was made between the Mahalanobis distance and the robust distance.[20] After the identification of the atypical observations, those that showed a true discrepancy would be excluded in comparison with the rest of the data studied. In this study, outliers were not observed.

Principal component analysis (PCA) is the most widely used multivariate technique to explore, interpret, and reduce data without loss of information. It was one of the first developed with robust methods. In this case, eigenvalues, eigenvectors and correlation and covariance matrices are determined by robust calculus not subject to the influence of outliers. The main components (MC) obtained constitute the new response variables and are used in the subsequent analyzes of the study. The interpretation of each MC is based on the variables that most contribute to the MC.

In the principal component analysis, all correlated variables were used, aiming to increase the number of degrees of freedom. Thus, only one of the correlated variables was chosen to represent the set. The previous techniques were used to evaluate the behavior of this set of samples, so they will not be presented in the work.

Cluster analysis were performed in this study. Cluster analysis is a term used to describe several numerical techniques whose fundamental purpose is to classify the values of a data matrix under study in discrete groups.

This multivariate classificatory technique explores the similarities between cases, individuals or objects or between variables defining them in groups, considering simultaneously, in the first case, all variables measured in each individual and in the second, all individuals in which the same measurements were taken. The Ward clustering method is optimal because it minimizes intra-group variation and maximizes variation between groups.

2.5 *Guelph permeameter hydraulic conductivity test*

Hydraulic conductivity was estimated in the three erosive plots with a Guelph permeameter. Nine infiltration tests were realized in the top, middle and bottom portion of each plot at a depth of 20 cm. A soil auger was used to drill a borehole at the desired depth. The Guelph permeameter consisted basically of a water container composed of an acrylic tube mounted on a level tripod with a Mariotte bottle positioned in the borehole. A constant rate of flow was achieved using the Mariotte bottle device. A steady-state rate of water into the saturated soil was measured at successive reading periods of 10 min. Each conductivity test was conducted for a period of 60 min, in which infiltration rates reached stabilization.

3. Results and discussion

3.1 *Erosion and runoff analysis*

The granulometric curves for the soil in the erosion plots are presented in Figure 2. Brachiaria is considered an invasive plant, also referred to below as weed cover. The textural class is coarse sandy loam, with 11% clay, 15% silt, 18% fine sand, 19% medium sand, 19% coarse sand and 18% gravel. Initially, soil aggregation does not differ significantly in the three erosion plots which is indicated by the small difference between the granulometric curves in the presence and absence of dispersant (Figure 2). This textural class presents moderate resistance to erosion. Topsoil sample chemical analysis (Table 1) presents high levels of Ca, Mg, K and P which contributed to good vegetate growth. The presence of high values of pH and Ca, which is a flocculating agent that enhances soil aggregation contributed slightly to the prevention of the erosive process.

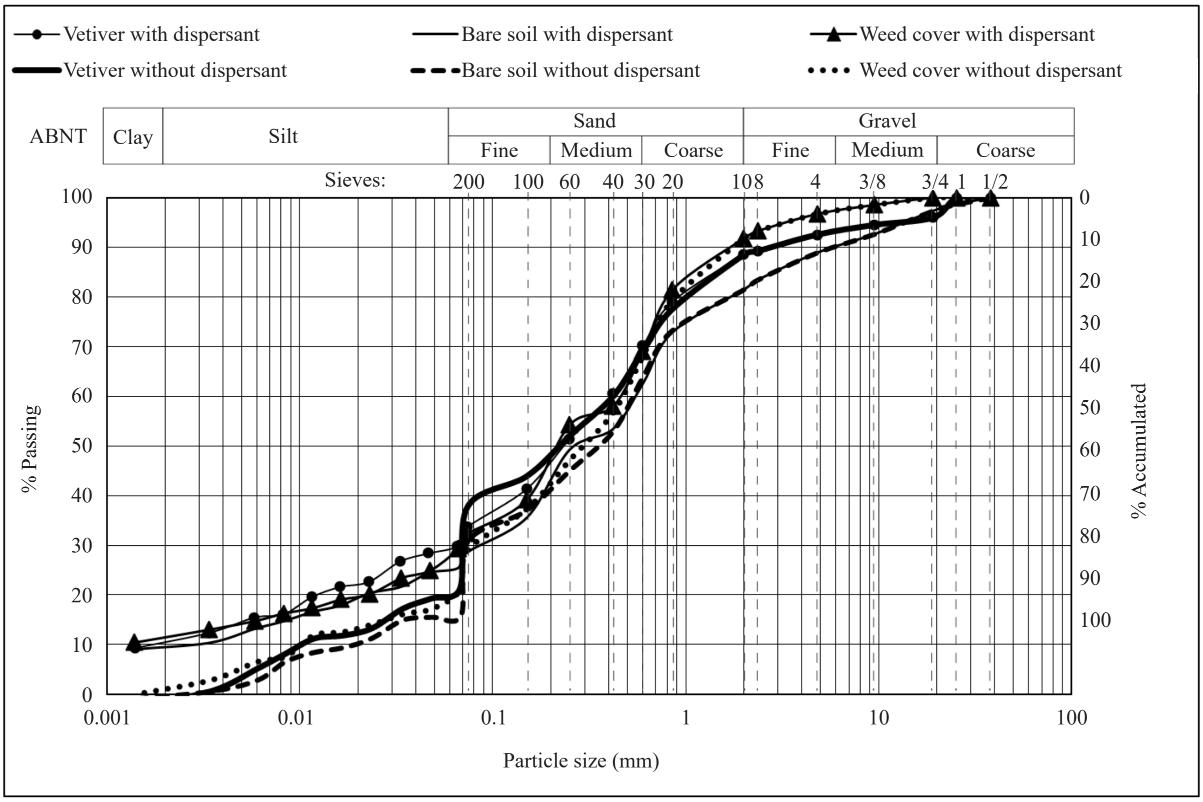


Figure 2. Granulometric curves in the presence and absence of dispersant for soil samples from a depth of 0 to 10 cm in the inferior portions of the three experimental plots

Table 1. Chemical analysis of the compost topsoil sample from the three erosion plots at a depth of 0-10 cm

Ca^{2+}	Mg^{2+}	Na^{+}	Al^{3+}	K^{+}	P	pH (H_2O)
	($cmol_c \cdot kg^{-1}$)				($mg \cdot kg^{-1}$)	
6.4	0.7	0.08	0	28	37	8.1

In the vetiver grass plot, more than three months were required for the cluster of culms to join together and form a tightly closed hedge. Prior to this event (i.e., between May and June), erosion and runoff were greater in this plot than in the other two plots (Figures 3 and 4), this is due to disturbances in the soil structure caused by the soil preparation techniques used to plant this grass. Vetiver grass grows by tillering, with shoots sprouting on the sides to form clusters that spread sideways. In early-stage growth, the clusters are spread apart and form preferential runoff flow paths that originate from spaces in the successive hedgerows. Cluster analyses relative to different types of soil cover during the initial growth stage of vetiver revealed differences between treatments. It is clear that, in this case, precipitation influenced more intensely runoff in the vetiver plot than in the other plots (Table 2 and Figure 5b).

After the establishment and development of the grasses, as expected, most of the runoff and sediment yield occurred in the bare soil plot, indicating that the erosive processes were more intense in this treatment than in the other two plots (Tables 2 and 3) (Figures 6 and 7). The vetiver grass and Brachiaria grass plots exhibited runoff and sediment yield measurements that were lower than those of the bare soil plot (Table 2) (Figures 6 and 7). Cluster analysis confirms significant differences between erosion and runoff in the between plots (Figure 5c).

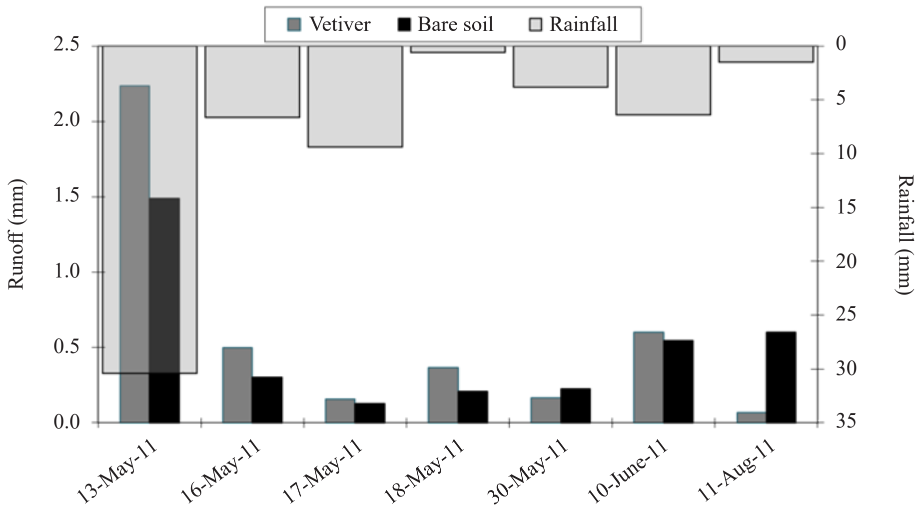


Figure 3. Rainfall and runoff events in the vetiver plot during the initial growth stage

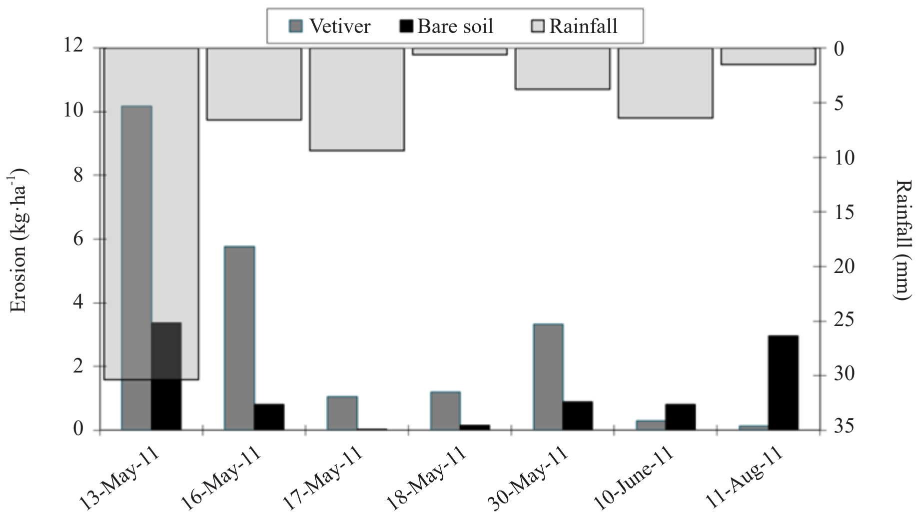


Figure 4. Rainfall and erosion events in the vetiver plot during the initial growth stage

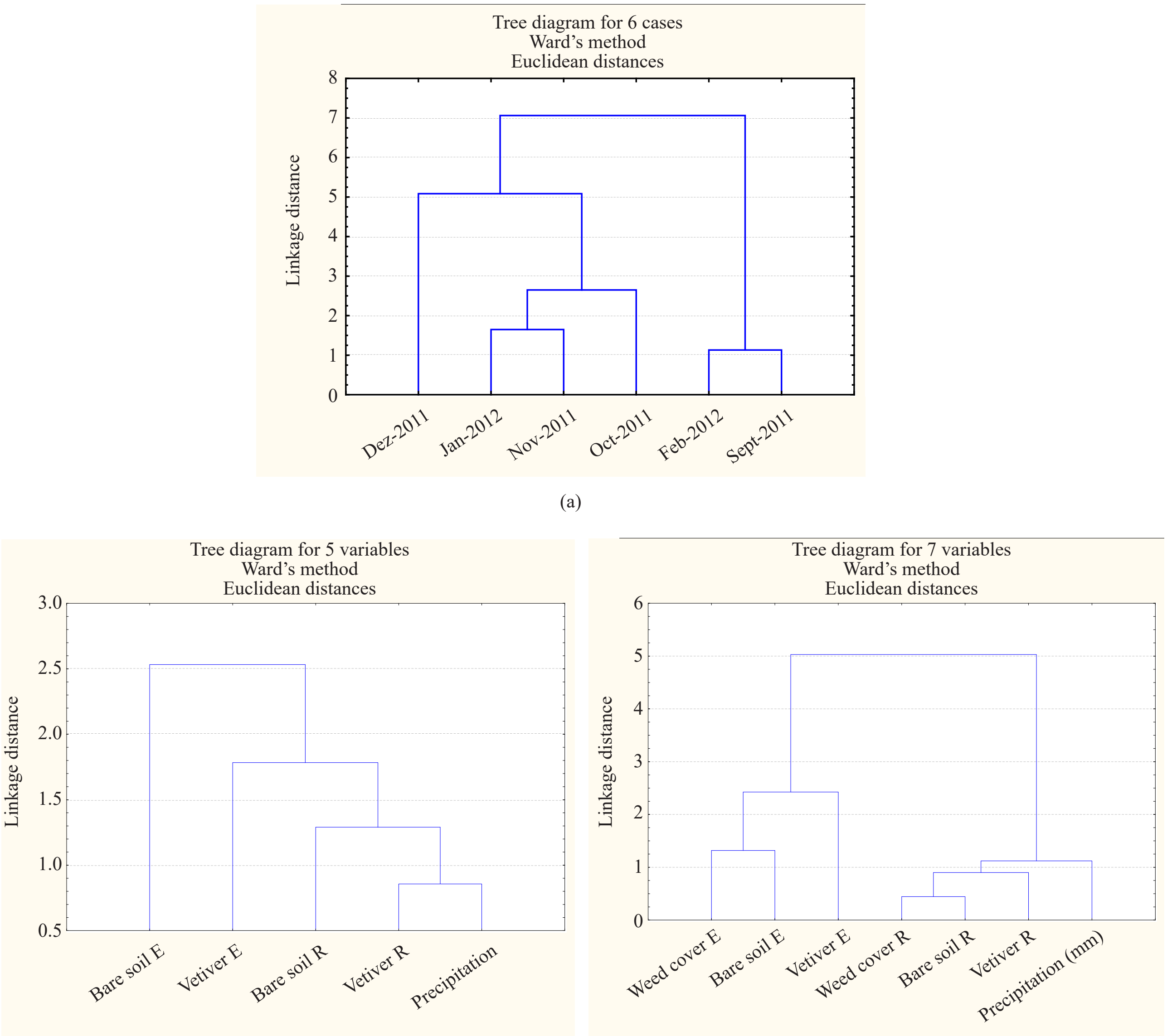
Probably, the increased presence of roots in the topsoil of the vetiver grass and Brachiaria grass plots makes the soil more porous and permeable, improving infiltration capacity and consequently reducing runoff compared to the bare soil plot (Table 2). Sang-Arun[21] noted that rills and gullies are rarely found in weed-covered soils. On the other hand, splashing occurs in bare soils can lead to rill and gully formation. The weed cover provided interception and protection from rain drop impact, as well as dispersion of rain water. In addition, the root system of the weeds contributed to surface roughness and reduced runoff. The physical barrier of the grass hedge made the largest contribution to the prevention of erosion and runoff in the vetiver and brachiaria plots. The profound roots of the vetiver grass are important for sustaining erect grass and enhancing filtration through the stems.[22] Devitt and Smith[23] and Mapa[24] reported that plant roots form macropores that increase infiltration rates and thus preferential flow. Root density in the subsoil is increased by some species which impels preferential infiltration into deeper soil horizons.[25] Infiltration rates in the vetiver plot were higher than the Brachiaria grass and bare soil plots (Table 4) corroborating with the above citations. Vetiver grass is used as a buffer, reducing the speed of runoff and reducing the dragging and transportation of soil particles. The extensive and profound roots of the vetiver grass support higher rates of infiltration and reduce runoff, generating less erosion.

Table 2. Major precipitation (P), rainfall intensity (RI), runoff (R), runoff-precipitation ration (R/P) and erosion (E) events in the erosion plots

Date	P	RI	Vetiver			Bare soil			Brachiaria		
			R	R/P	E	R	R/P	E	R	R/P	E
	mm	$mm \cdot h^{-1}$	mm	%	$kg \cdot ha^{-1}$	mm	%	$kg \cdot ha^{-1}$	mm	%	$kg \cdot ha^{-1}$
14-Sep-11	26.3	6.4	0.05	0.19	2.08	1.00	3.80	18.08	0.86	3.30	16.76
4-Oct-11	15.6	7.6	0.40	2.56	1.12	0.60	3.85	0.98	0.60	3.85	2.04
16-Nov-11	47.4	8.6	1.41	2.98	0.13	1.73	3.66	1.90	1.86	3.94	9.70
23-Nov-11	24.2	15.0	0.87	3.60	0.27	1.52	6.31	33.86	1.03	4.27	13.51
12-Dec-11	38.8	13.6	1.68	4.33	1.04	2.13	5.50	2,531.61	1.86	4.81	41.66
20-Dec-11	19.4	0.8	1.20	6.19	1.63	1.81	9.35	45.82	1.06	5.50	7.09
29-Dec-11	46.6	3.2	1.28	2.75	0.42	1.88	4.03	37.46	1.39	2.99	0.68
04-Jan-12	52.8	7.2	2.41	4.57	0.59	4.74	8.98	122.48	2.88	5.47	5.10
09-Jan-12	13.6	3.2	0.19	1.42	0.16	0.38	2.79	9.60	0.26	1.91	0.25
30-Jan-12	47.8	22.8	1.20	2.51	1.42	1.93	4.04	7.64	1.66	3.49	6.64
14-Feb-12	33.0	5.6	1.17	3.56	1.51	0.91	2.77	2.86	1.08	3.29	8.49

Table 3. Sediment entrainment potentials in the erosion plots

Month	Vetiver	Bare soil	Brachiaria
	$kg \cdot ha^{-1} \cdot mm^{-1}$		
Sep-2011	21.0	14.5	18.4
Oct-2011	1.2	1.7	1.2
Nov-2011	0.3	12.7	8.4
Dec-2011	0.8	440.7	11.6
Jan-2012	0.3	25.9	1.7
Feb-2012	1.3	3.2	7.7



(a)

(b) (c)

Legend: Weed cover E-weed cover erosion, bare soil E-bare soil erosion, vetiver E-vetiver erosion, weed cover R-weed cover runoff, bare soil R-bare soil runoff, vetiver R-vetiver runoff

Figure 5. a) Cluster analysis of precipitation. b) Cluster analysis of erosion, runoff and precipitation during the initial growth stage of vetiver grass (left) and c) the full development of vetiver grass (right)

A cluster analysis of precipitation identified the following two similarity groups: 1) September 2011 and February 2012 and 2) October 2011, November 2011, December 2011 and January 2012. The first group showed similar minor precipitation and rainfall intensity measurements, and, so presented less interference in runoff (Figure 5a). The second group showed a greater similarity between November and January. Even though October presented less precipitation, the rainfall intensity was higher leading to a greater runoff to precipitation ratio, thus, making part of the second similarity group. Moreover, the highest rates of runoff and erosion were related to high rainfall intensity in December 2011 (Figures 5a, 6 and 7) even though it was not the highest precipitation. The largest erosion event occurred on December 12, 2011, with the effects occurring mainly in the bare soil plot with a high value of 2,531.61 $kg \cdot ha^{-1}$ and in the brachiaria plot with 41.66 $kg \cdot ha^{-1}$, while the vetiver plot showed erosion of only 1.04 $kg \cdot ha^{-1}$.

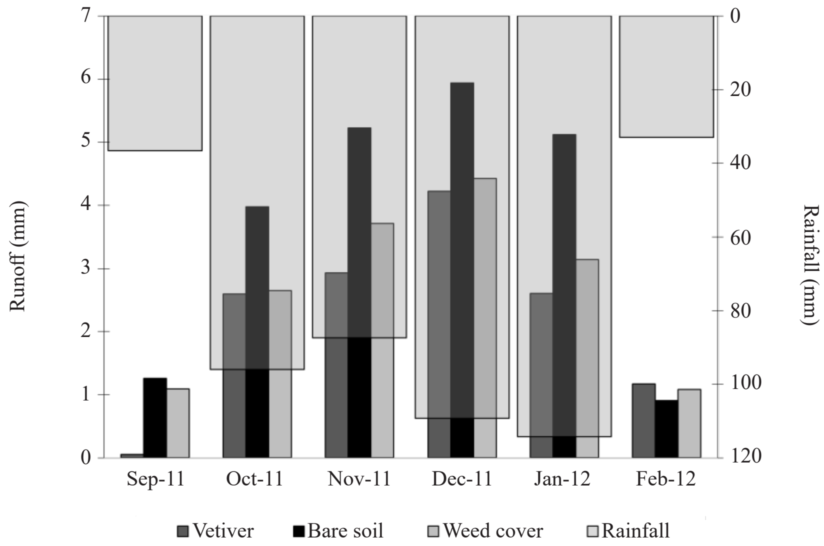


Figure 6. Total rainfall and runoff in the months between September 2011 and February 2012

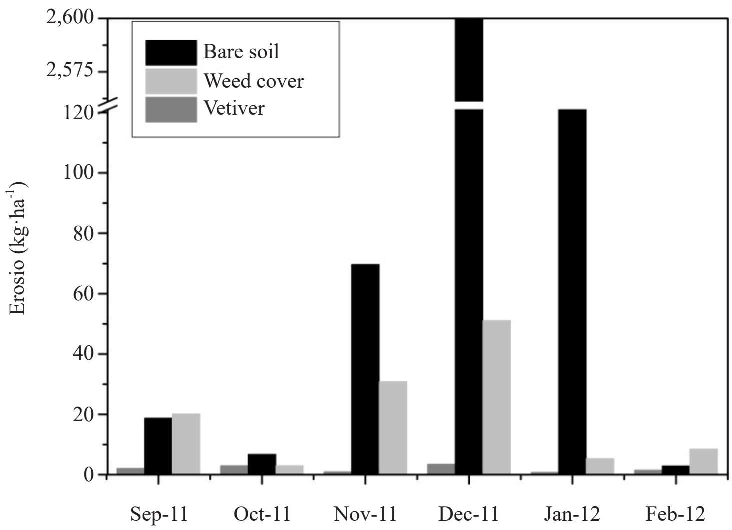


Figure 7. Total erosion in the months between September 2011 and February 2012

Table 4. Infiltration rates in the erosion plots with Guelph permeameter

Erosion plot	Infiltration rates (cm·h^{-1})			
	Top	Middle	Bottom	Average
Bare soil	0.8	0.6	1.9	1.1
Brachiaria	2.9	20.4*	4.7	3.8
Vetiver	7.8	12.5	9.5	9.9

Note: *The infiltration rate of 20.4 was not considered in the average

Despite Brachiaria grass having a denser plant cover than vetiver, its root system is much less deep. This is because Brachiaria grass has a different root anatomy to vetiver, where around 60% of its adventitious roots are in the first 10 cm of the soil and around 90% of its roots are in the first 20 cm.[26] Furthermore, the infiltration rate of 20.4 $cm \cdot h^{-1}$ in the middle portion of the Brachiaria grass erosion plot was outstanding possibly because the borehole made contact with an ant burrow, and, so forth, was not considered in the average (Table 4).

Some studies suggest the use of Brachiaria grass as soil conditioner, improving the soil's physical and chemical properties and biological activity, which can recover degraded or nutritionally unbalanced soils. Brachiaria grass is recommended for slopes, contributing to the recovery of areas with erosion processes, due to good vegetation cover derived from the large emission of stolons and dense ramification. Furthermore, *Brachiaria decumbens* contributes to the improvement of the following characteristics: increment of macro porosity resulting in better soil aeration, increased water infiltration enhancing surface runoff reduction, and better soil aggregation reducing susceptibility to erosion.[14]

The vetiver plot with a great development of the root system allowed the maintenance of soil structure. Roots increase surface roughness and create soil macropores that provide greater capacity for infiltration.[27] Disturbed soil structure reduces infiltration capacity and increases erodibility.[28] The process of erosion causes degradation of the soil structure. Roots reduce soil erosion by binding the soil particles at the ground surface.[27] The bare soil plot probably rapidly reached field capacity during the extremely heavy rainfall on 12 December 2011. These extreme events are typical of tropical climate being recurrent in the state of Rio de Janeiro. Saturated hydraulic conductivity is related to macroporosity which is correlated to soil texture, porosity, soil structure and bulk density.[29] Fonseca[30] found low values of macroporosity and microporosity in subsurface soil layers that indicated low structural continuity of the soil in erodible areas. Pagliai[31] cites that conventional plowing decreases total macroporosity results in lower values of hydraulic conductivity that lead to greater runoff and erosion. The soil in the vetiver plot was probably not saturated in this extreme event due to enhanced water infiltration. Preferential flow paths are assembled through the vetiver grass roots. Water infiltration and storage capacity influence the possibility of the occurrence of landslides.[32] Plant roots are essential in shallow slope stabilization and erosion control.[33-35]

At the stage of full development of the vetiver and Brachiaria grasses, two groups of similarity were formed by the different treatments with regard to: 1) erosion and 2) surface runoff (Figure 5c). In the first group, erosion from vetiver was separated from erosion in the Brachiaria grass and bare soil plots, demonstrating that erosion in the vetiver plot was different from other plots. The second similarity group indicates that rainfall directly influenced runoff, so vetiver runoff was separated from Brachiaria grass runoff and bare soil runoff, indicating that the treatment with vetiver ground cover is significantly different from the treatment with bare soil or Brachiaria grass. The experimental results and statistical analysis showed that vetiver reduced surface runoff and prevented erosion compared to Brachiaria grass and bare soil.

The vetiver system has been used in tropical countries mainly due to its low-cost, tolerance and feasibility.[36] Rahardjo[37] emphasizes the aesthetic, environmental value and sustainability of the vetiver system. Truong and Loch[12] commented that the vetiver conservation system is more practical and requires less maintenance than conventional engineering structured systems. Oshunsanya[38] reported a substantial reduction of soil loss using vetiver hedgerows in an intercropping system. Vetiver grass hedges are more effective for erosion control than contour banks and strip cropping.[39] Coppin and Richards[40] cited various effects of vegetation on slopes: protection against splashing (raindrop impact), interception of rainfall, reduction of runoff, reinforcement of soil by roots, increased water infiltration and uptake by roots, and intensification of evapotranspiration.

3.2 *Changes to the soil's chemical properties*

The implantation of permanent soil cover (living = aerial part + roots) promotes three fundamental actions for the reorganization of the new structure:[41-43] a) cushions the impact of raindrops that cause the dispersion of particles, microstructures, micro- and macro-aggregates; b) keeps macro-aggregates protected, reducing the rate of intra-aggregate C oxidation; c) the roots of the cover crop create a drying and moistening process around them, providing approximation, compression and reorganization of dispersed particles and microstructures, as well as promoting the interlacing of aggregates.

The use of grasses in erosion control also contributes to an increase in the organic matter content in the soil organic matter (SOM), which conditions various physical, chemical and physical-water properties of the soil, buffers acidity and serves as a substrate for biota.

Organic matter has 4 main properties due to its structure:[44]

-Polyfunctionality: a large number of functional groups providing a broad spectrum of reactivity;

-Negative macromolecular charge: allows greater reactivity with other soil molecules;

-Hydrophilicity: tendency to form strong hydrogen bridges with water;

-Structural malleability: capacity for intermolecular intermolecular association and change in molecular conformation depending on changes in pH, redox values, electrolyte concentration and bonding with functional groups.

Soil organic matter (SOM) acts directly on soil structure, giving greater stability to aggregates. Aggregates are conglomerates formed by soil minerals (clay particles, fine sand and silt), plant and microbial residues and organic matter strongly bound to clay. The main functions of aggregates are: to maintain porosity which provides aeration and water infiltration rates that are favorable to microbial and plant growth; to increase structural stability in relation to wind and water erosion; and to store carbon by protecting organic matter from microbial decomposition.[45]

The increase in organic matter influences the physical structure of the soil through greater water retention, better aeration and, consequently, greater resistance to erosion due to its colloidal particles, which are capable of forming an emulsion in contact with water.[46] Chemical improvements in the soil also occur through the action of complexing agents, which prevent the soil from decomposing. In addition, they increase the buffering power of soils, reducing pH variations in the environment.

Soil organic matter (SOM) is also fundamental in retaining cations in the soil, especially in tropical environments, since it contributes to the largest proportion of the cation exchange capacity (CEC), given that the Fe and Al oxides, oxyhydroxides and hydroxides, and kaolinite that predominate in the clay fraction of highly weathered soils have a low CEC and reduced specific surface area.[45]

Root exudates are defined as organic compounds secreted or released by the surface of younger roots. They are important in the formation of mucigel, which serves to improve root-soil contact (especially in conditions where the soil is dry) and serves as a lubricant for good root movement in the soil. At this root-soil interface (rhizosphere) there is a greater release of exudates, nutrients and energy for microorganisms. Therefore, the concentration of nutrients and salts, electrical conductivity and pH, among other attributes, are found in the rhizospheric soil in conditions that at least partially ensure the nutritional demands and other needs for plant growth and protection.[45]

At the same time, the roots exude organic compounds-glomalins, polysaccharides and interstratified amino acids -which act as a cementing agent, promoting greater stability and longevity of the new soil structure. Over time, the frequent addition of straw and roots creates a continuous flow of C and N, lodging in the granulometric fractions of the soil at different stages of oxidation of the organic compounds.[47]

4. Conclusions

Vetiver grass hedges are efficient for erosion and runoff control, reducing the speed of runoff and diminishing the dragging and transportation of soil particles. Vetiver grass roots are extensive and profound supporting higher rates of infiltration which reduce runoff, and, thus, provide less erosion. Moreover, the great density of vetiver grass roots in the topsoil makes the soil more porous and permeable forming macropores that increase infiltration rates and thus preferential flow. Root density in the subsoil is increased impelling preferential infiltration into deeper soil horizons. However, the soil conservation potential of this treatment is reached only after three months of implementation of the vetiver system, when the hedge closes and effectively traps sediments.

Brachiaria decumbens is the most widespread grass in Brazil. This species emits large quantities of stolons and branches vigorously and can be recommended for areas with hilly topography, contributing to the recovery of areas with an initial erosion process. The main morphological characteristics of these plants that promote erosion control are good soil cover, dense and resistant roots and the formation of a mesh in the soil. In this way, the soil structure is favored, which allows for greater water infiltration and mechanical reinforcement in the soil. In addition, there is greater moisture conservation for the development of microorganisms and an increase in organic matter. This variety of brachiaria is also adapted to a wide range of temperatures, soil pH, humidity conditions, low fertility and compaction problems.

On the other hand, bare soil showed greater erosion. This is because the impact of raindrops on this type of soil is greater, thus promoting the detachment of small and light soil particles, such as clay and organic matter, which favors the increased disintegration of this soil.

Erosion and runoff can be controlled using vegetation cover, which became clear from this study. In general, the vegetation reduced the speed and volume of surface runoff, preventing the formation of torrents.

Acknowledgements

The authors would like to thank the government agency CNPq (National Council for Scientific and Technological Development), CAPES and Faperj for financial support.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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