The impact of vegetation cover on soil erosion in the drainage network of banana crop

El impacto de la cobertura vegetal en la erosión del suelo en la red de drenaje del cultivo de banano

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ABSTRACT

In Urabá (Colombia), precipitation generates high rates of soil erosion in banana drainage systems due to its intensity and frequency, as well as soil susceptibility resulting from exposure. One approach to mitigate this erosion is the use of a vegetation cover. The aim of this study was to determine the impact of vegetation cover on soil erosion rates in the drainage systems of a banana plantation. For this purpose, a comparison was made during the last quarter of 2022 between experimentally measured erosion rates (simulated in a greenhouse), observed erosion rates (using sedimentation boxes in field drainage channels), and potential estimation (using the USLE equation). In the greenhouse, bare soils presented higher losses at 38.16 t ha^{-1} year^{-1}, statistically differing from conventional management (CMT) and vegetation cover (VCT) treatments, which recorded values of 24.70 and 18.97 t ha^{-1} year^{-1}, respectively. A similar trend was observed in the field. Based on estimated erosion potential (USLE), no differences between treatments were identified, with CMT exhibiting the highest erosion potential at 96.47 t ha^{-1} year^{-1}. Additionally, other soil variables, such as slope and type of soil, influenced erosion susceptibility regardless of the kind of existing cover.

Key words: soil conservation, erosion estimation, *Musaceae*, soil loss.

RESUMEN

En Urabá (Colombia), la precipitación genera tasas de erosión del suelo altas en los sistemas de drenaje de banano debido a la intensidad, frecuencia y susceptibilidad del suelo resultante de la exposición. Una alternativa para mitigar esto es el uso de cobertura vegetal. El objetivo de este estudio fue determinar el impacto de dicha cobertura en las tasas de erosión del suelo en los sistemas de drenaje de una plantación de banano. Para ello, se realizó una comparación durante el último trimestre de 2022 entre las tasas de erosión medidas experimentalmente, simuladas en un invernadero, y las tasas de erosión observadas utilizando cajas de sedimentación en los canales de drenaje en campo, junto con una estimación potencial utilizando la ecuación USLE. En el invernadero, los suelos sin cobertura presentaron mayores pérdidas con 38,16 t ha^{-1} año^{-1}, diferenciándose estadísticamente de los tratamientos de manejo convencional (TMC) y cobertura vegetal (TCV), que tuvieron valores de 24,70 y 18,97 t ha^{-1} año^{-1}, respectivamente. Esta tendencia se observó de manera similar en el campo. Con el potencial erosivo estimado (USLE), no se identificaron diferencias entre los tratamientos, siendo el TMC el que mostró el mayor potencial erosivo con 96,47 t ha^{-1} año^{-1}. Notablemente, otras variables del suelo como la pendiente del terreno y el tipo de suelo influyen en la susceptibilidad a la erosión, independientemente del tipo de cobertura existente.

Palabras clave: conservación de suelo, estimativa de erosión, *Musaceae,* pérdida de suelo.

Introduction

Banana is a crop that exhibits high sensitivity to excess water (Mohd *et al*., 2021; Teoh *et al*., 2022). It is estimated that the optimal depth of the water table in soils where bananas are planted should be 1 m or deeper (Durango *et al*., 2020; Gutiérrez & Romero, 2010). The fluctuation of the water table levels near the surface or depths less than 1 m generates hypoxia or anoxia in the roots, producing root rot, which adversely affects crop yields and productivity (Moreno *et al*., 2020). In that sense, it is necessary to have efficient drainage systems which allow water tables to be maintained at appropriate depths and functioning correctly. Poorly designed and constructed drainage networks favor sedimentation or generate damages to its structure, destabilizing slopes, which causes soil movements, clogging of drainage areas, and susceptibility to erosion (Bai & Cui, 2021; Durango *et al*., 2020; Salazar, 2010).

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Water-driven erosion is one of the most critical soil degradation factors due to the displacement of particles, leaching of nutrients and organic matter, leading to a loss of soil fertility (Delgado-Bejarano *et al*., 2023; Tessema *et al*., 2020). For this reason, models have been developed to estimate water erosion, such as the universal soil loss equation (USLE) proposed by Wischmeier and Smith (1978). This equation has been used for decades and has been revised in the RUSLE version (Renard *et al*., 1991), which predicts the average annual erosivity rates of an area based on precipitation (R), soil type (K), topography (LS), vegetation cover (C), and management activities (P). Among these factors, vegetation cover shows the most variability, probably due to human activity and climate variations (Zhao *et al*., 2020).

In the case of Urabá, Antioquia department (Colombia), precipitation causes the highest erosion rates in the drainage system because of its intensity and frequency (Amellah & el Morabiti, 2021; Bai & Cui, 2021). An alternative to mitigate this adverse condition involves the use of vegetation covers on the slopes. These covers decrease the erosive process by creating a barrier effect between water droplets and the soil slope. Additionally, they promote soil particle aggregation and improve some physical properties such as porosity, structure, infiltration, and cohesion (Bai & Cui, 2021; Durango *et al*., 2020; Salazar, 2010). Cunha *et al*. (2022) mention that the implementation of conservation practices, such as well-covered grasslands, allowed for a reduction in eroded soil from 10.2 million t to 4 million t between 1986 and 2016, highlighting the importance of ground cover in reducing erosion in drainage areas such as watersheds.

This study aimed to assess the impact of vegetation covers on erosion rates in the drainage systems of banana plantation with simulations in greenhouse, field channels, and USLE.

Materials and methods

Description of study area

The research was conducted in both greenhouse and field settings. The greenhouse is located in the residential complex "Los Almendros" at km 4 on the Carepa – Apartadó road, in the municipality of Carepa, Antioquia (Colombia) (Fig. 1). The fieldwork was conducted at the Ramiro Jaramillo Sossa experimental farm located 2 km northwest of the urban center of the municipality of Carepa. Both locations belong to the Banana Research Center (Cenibanano), which is associated with the Colombian Banana Growers Association (Augura). The two experiments (field and greenhouse conditions) were carried out simultaneously and lasted three months from September to December 2022. The agroclimatic conditions of the experimental farm include average annual precipitation of 2961 mm, average temperature 27°C, altitude of 20 m a.s.l., and typical conditions of the tropical rainforest (bh-T) (Instituto de Hidrología Meteorología y Estudios Ambientales, 2022; Jaramillo, 2014).

Stage I. Greenhouse conditions

Nine sedimentation boxes were prepared using plastic containers measuring 34, 28, and 20 cm in length (l_{cs}), width (w_{cs}) and depth (h_{cs}), respectively. Each box was filled with 17 kg of soil obtained from the experimental field area, clay loam in texture, classified as Fluvaquentic Eutrudepts. The weed species *Peperomia pellucida, Selaginella* sp. and *Digitaria horizontalis*, commonly found in banana crops, were established in a mixture from rooted cuttings in three trays (three replicates). These were watered weekly until complete coverage of the trays was achieved (VCT). In three other trays, the same weed species were established, but conventional pruning was carried out (CMT). The remaining trays were left with bare soil without plants (BST).

A wooden structure was designed to support and arrange each of the trays at a 45° angle to the surface, simulating the average slope of the tertiary channels under field conditions (Fig. 2). They were randomly distributed in the section set up for the greenhouse experiment. A 3 L plastic container was attached to the underside of each box, which acted as a collector. The most frequently occurring precipitation event recorded in the banana region from 2019 to 2021 was 10 mm. This value was used in the experiment, with 10 mm of water applied to each tray weekly for eight consecutive weeks. The excess of water from each tray was recovered and stored (runoff and leachate) to determine the total volume (V_T) for the evaluation period. A subsample of 100 ml (V_s) was then taken and dried in an oven at 60°C until reaching constant weight. Once this condition was reached, the accumulated soil in the subsample (m_s) was weighed and the total soil removed from the tray during the evaluation period (m_T) was determined using Equation 1:

$$m_T=\frac{V_T{*}m_s}{V_s} \tag{1}$$

Stage II. Field conditions

The drainage system structure in the experimental field consisted of tertiary level drains designed to facilitate water exit from the soil profile; secondary drains removed water from the plots, while primary drains water removed from

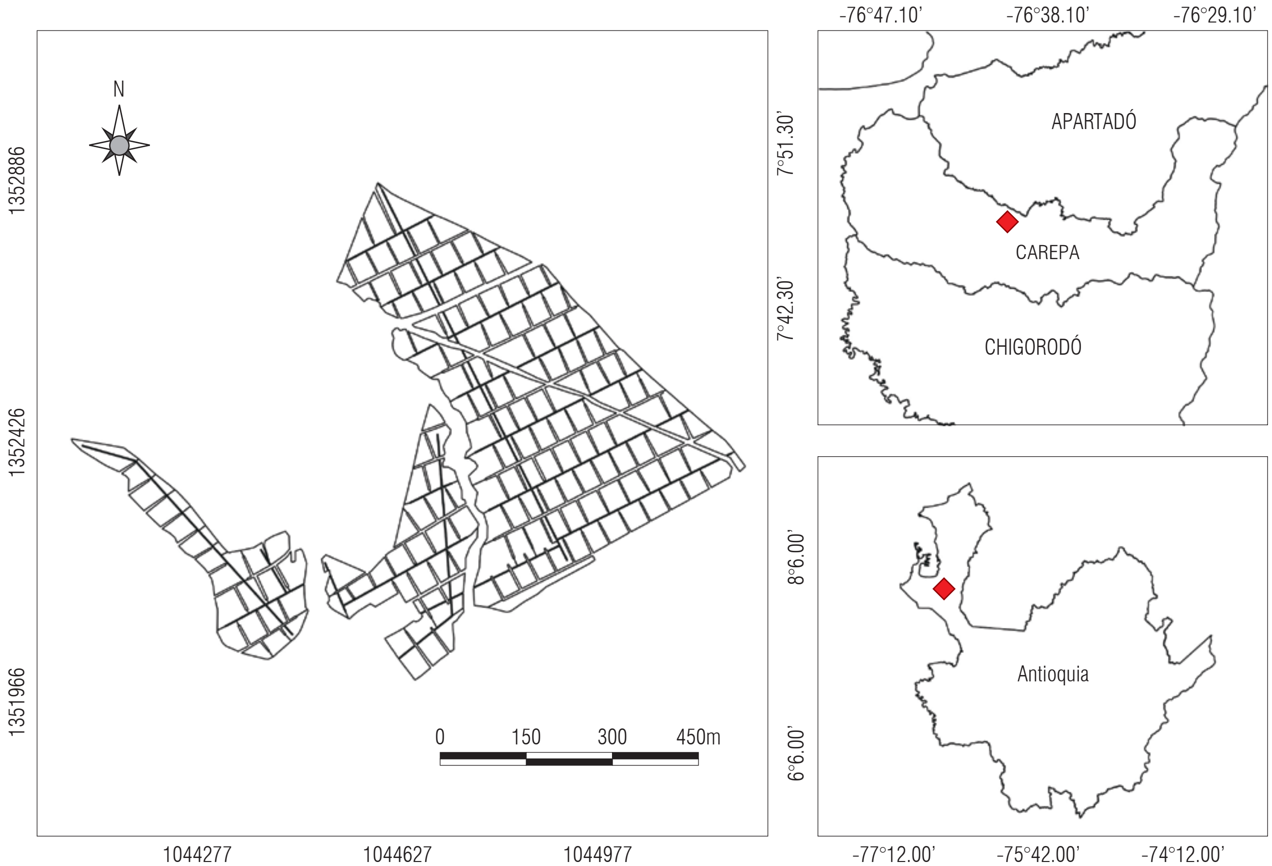

FIGURE 1. Location of the study zone in the Antioquia department (Colombia), WGS 84 Magna Sirgas Colombia West Zone (CRS:3115).

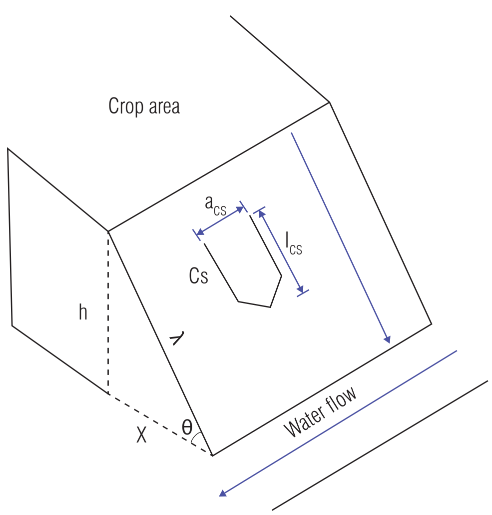

FIGURE 2. Sketch of a tertiary drainage, where y: drainage depth; x: horizontal distance relative to height; h: drainage slope; Cs: sediment collection and delimitation box; l_{cs}: box length; a_{cs}: box width; λ: slope length.

the farm. In plots 4, 9, and 10, a tertiary drain was selected and three sedimentation boxes of 50 cm by 30 cm long (l_{cs}) and width (a_{cs}) respectively were installed in the central part of these plots. The top of the box was left open to allow runoff water collected along the length of slope (λ) to enter (Fig. 2). In each box, one of the treatments described above (VCT, CMT, BST) was randomly installed.

At the beginning of the measurements, a 20 L capacity plastic container was attached to the bottom of each sedimentation box. Each week, percolated water was collected, its volume (V_T) determined, and a 50 ml subsample (V_s) extracted. Using the same methodology as in Stage I, the eroded soil was determined.

Variables

Precipitation. The precipitation data were obtained by a pluviometer located in the experimental field, which had daily records. For the study, data for the period from 2019 to 2021 were analyzed.

Modified photochemical reflectance index (MPRI). An image with a RGB (Red, Green, Blue) camera was captured over the slope of each of the treatments (Pacheco & Montilla, 2021). The sedimentation plots in the image were manually delineated, and the degree of vegetation cover was determined using the MPRI, which relates the green

(G) and red (R) bands as shown in Equation 2 (Delgado-Bejarano *et al*., 2023; Pacheco & Montilla, 2021):

$$MPRI=\frac{G-R}{G+R} \tag{2}$$

Slope (m_{se}) and *length* (λ). The inclination angle of the slope was estimated by measuring the channel depth (h) and the slope length (λ) using tape measures. The slope angle (θ) was obtained by Equation 3:

$$\theta= \sin^{-1}(\frac{h}{\lambda}) \tag{3}$$

The length (L_{se}) of the catchment area along the slope was determined as the distance between the top of the channel and the lower boundary of the sedimentation box.

Soil organic matter content. At the beginning of the experiment, soil sampling was carried out at the point adjacent to each sedimentation box, and the organic matter content of the soil was determined in the laboratory using the method of Walkley and Black (1934).

Soil permeability. The permeability was determined in each sedimentation box in the area adjacent to the soil slope by evaluating the hydraulic conductivity of the soil using Zhang's (1997) method with a mini disc infiltrometer.

Soil texture. This parameter was determined in the laboratory by the hydrometer method (Bouyoucos), finding the values of each soil fraction (clay, silt, and sand) (Jaramillo, 2014). For the greenhouse samples, soil used in the traps was analyzed, while in the field, a soil sample was taken from each trap in the area adjacent to the study channel.

Analysis by the Universal soil loss equation (A)

The Universal soil loss equation (USLE) was used to estimate soil erosion for each treatment (A, t ha^{-1} $year^{-1}$) (Eq. 4). The USLE incorporates parameters including vegetation cover (C, dimensionless), slope gradient (S, dimensionless), slope length (L, dimensionless), rainfall erosivity (R, MJ mm ha^{-1} h^{-1} $year^{-1}$), soil erodibility (K, t h MJ^{-1} mm^{-1}) and management practices (P, dimensionless):

$$A = C*LS*R*K*P \tag{4}$$

The vegetation cover factor was calculated using the vegetation index (MPRI). The parameters α and β of the equation were assigned values of 2 and 1, respectively (Eq. 5) (Almagro *et al*., 2019; Amellah & el Morabiti, 2021; Bai & Cui, 2021; Delgado- Bejarano *et al*., 2023):

$$C = e^{\left(-\alpha*\frac{MPRI}{(\beta-MPRI)}\right)} \tag{5}$$

The topographic factor was represented by the length (L) and the slope gradient (S) estimated by using equations 6, 7, and 8, which are based on the parameters m_{se} and λ, which correspond to the slope exponent and the horizontal projection of the slope, respectively. In equation 6, the parameter m_{se} takes values of 0.2, 0.3, 0.4, and 0.5 when the slope is less than 1%, between 1 and 3%, between 3 and 4.5%, or greater than 4.5%, respectively. The slope gradient (S) is a function of the slope angle in degrees (θ), which varies depending on whether this value in % (θ) is less than or greater than 9% (Wijesundara *et al*., 2018; Wischmeier & Smith, 1978).

$$L=\left(\frac{\lambda}{22.13}\right)^{m_{se}} \tag{6}$$

$$S=10.8 \sin\theta +0.03 \text{ ; } \theta<9\% \tag{7}$$

$$S=16.8 \sin\theta -0.05 \text{ ; } \theta\geq 9\% \tag{8}$$

The erosion caused by rain (R) was calculated as illustrated in equation 9, where P_{Pi} refers to the precipitation of the i-th month (mm), P_j to the annual precipitation of the j-th year (mm), based on the number of years in the time series n_j (Bai & Cui, 2021; Han *et al*., 2021).

$$R=\frac{\sum_1^{n_j}\left(\sum_1^{12} 1.735*10^{\left(1.5*\left(\frac{Pp_i^2}{Pj}\right)-0.8188\right)}\right)}{n_j} \tag{9}$$

The soil erodibility factor (K) refers to the effect of soil properties on its susceptibility to being eroded or transported due to the impact of raindrops. Equation 10 was used to calculate this parameter (Efthimiou *et al.,* 2020; Mahapatra *et al*., 2018; Wischmeier & Smith, 1978), considering soil properties of organic matter content (OM), permeability (p), structure (s), and particle size ratio (M) using Equation 11:

$$K=\left[\frac{2.1*10^{-4}(12-OM)*M^{1.14}+3.25(s-2)+2.5(p-3)}{100}\right]*0.1317 \tag{10}$$

$$M=(Silt(\%)+Sand(\%))*\left(100-Clay(\%)\right) \tag{11}$$

The p parameter was determined on a scale of 1 to 6 based on the classification of the United States Department of Agriculture (1999). For the variable s, the classification given by Wischmeier and Smith (1978) was used.

Finally, the P factor indicates the management practices that can be implemented to reduce the amount of soil transported or eroded, ranging from 0 to 1, where 0 indicates that the activity completely reduces erosion, and 1 indicates that no conservation practice is done. Wischmeier and Smith (1978) highlighted key conservation practices, such as contour plowing, terracing, and no tillage systems. In the case of drainage networks, no conservation practices are applied, so the factor P is equal to 1.

Statistical analysis

The erosion rates directly measured through sedimentation tanks under both greenhouse and field conditions, as well as those estimated through the EEP, were considered as response variables in each case. These were analyzed based on the treatments (types of coverage) using an analysis of variance test (ANOVA). The normality of the residuals of the model and the homoscedasticity between treatments were evaluated. If the assumptions were not met, the Kruskal-Wallis non-parametric test was applied, followed by a post-hoc LSD test or Tukey test. The correlation between the parameters of the EEP with the erosive potential was determined using a Spearman correlation coefficient.

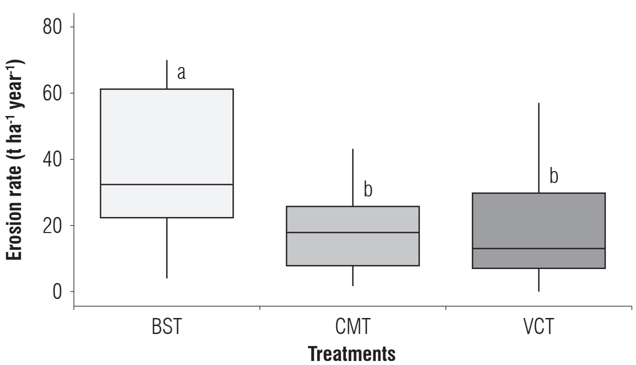

FIGURE 3. Distribution of soil erosion under greenhouse conditions. BST: Bare soil; CMT: Conventional management; VCT: vegetation cover. Different letters denote significant differences according to the LSD test ($P \leq 0.05$).

Results and discussion

Greenhouse conditions

The greenhouse evaluations revealed significant differences in soil erosion rates among the different types of vegetation cover (*P*=0.00533, Fig. 3).

As shown in Figure 3, BST exhibited the highest erosion rate compared to the other treatments, with a mean of 38.16 t ha^{-1} year^{-1}. This value is qualified as intermediate erosion according to the classification given by Han *et al.* (2021). This higher erosion rate is expected because the soil is completely exposed to the impact of irrigation drops and the particle transport by runoff. CMT recorded an average erosion rate of 24.70 t ha^{-1} year^{-1}. The VCT recorded the lowest average erosion values (18.97 t ha^{-1} year^{-1}). However, there were no significant differences between these two. These results show that there is a significant decrease in soil erosion with the presence of vegetation cover. However, there was no effect due to the cover management (*e.g.*, pruning). These results are consistent with those found by Bai and Cui (2021) in China, where bare soil had higher erosion rates compared to soils covered with corn and soybean crops, the latter presenting lower erosion values. These results show the importance of the barrier effect provided by soil vegetation covers and are in accordance with the coverage factor of the greenhouse experiment. In Figure 4, the BST presents a value of one (1) in the C factor, indicating that the soil is completely exposed to erosive processes. For the CMT, the C factor ranged between 0.88 and 1, showing a low level of soil protection, while the VCT presents the lowest values of C factor (0.55-0.63), indicating a greater potential of protection against erosion, although no significant differences between the latter two treatments were observed.

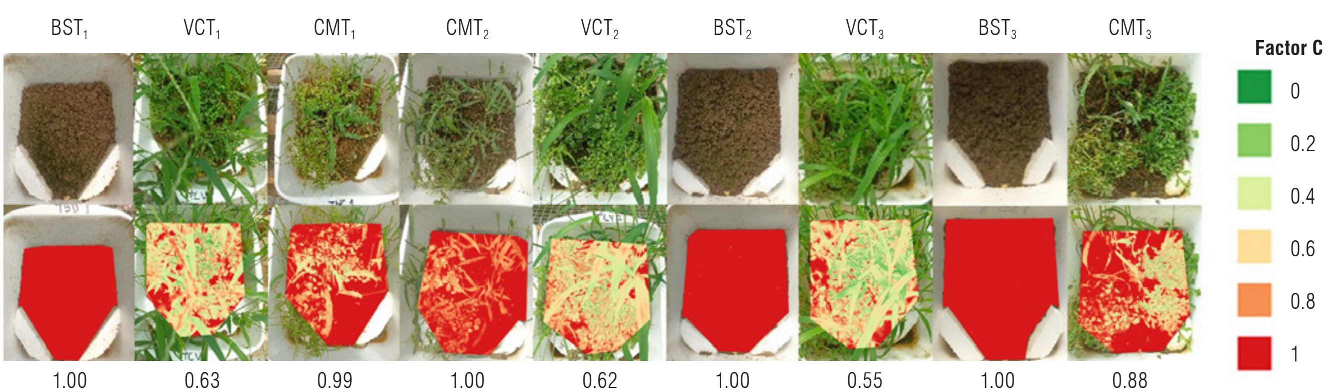

FIGURE 4. Protective effect of soil covers. BST: Bare soil; CMT: conventional management; VCT: vegetation cover. Factor C represents the effect of vegetation cover on soil erosion, where 0 indicates complete protection, and 1 indicates no protection.

Field evaluations

The accumulated weekly precipitation is shown for the evaluation period (weeks 38 to 50 of 2022). This period coincided with the rainy season that occurs in the region at the end of the year. Consequently, precipitation events were observed every week during the field experiment (Fig. 5).

Sedimentation boxes. During the field evaluations, statistical differences were found among the treatments (P=0.02126). The treatments exhibited the following order of erosion rates: BST > CMT > VCT. The mean erosion rate of BST was classified as high (50-80 t ha^{-1} $year^{-1}$), while those measured in VCT and CMT did not present significant differences and were classified as medium rates (25-50 t ha^{-1} $year^{-1}$) based on the classification by Han *et al.* (2021).

The field evaluations showed the same behavior seen in the greenhouse experiment (Stage I); there was a significant decrease in soil erosion rates with vegetation cover, but no statistical difference was found in the type of management given to the covers. These findings are in accordance with those of Chen *et al.* (2019) in China, who reported an exponential decrease in erosive rates with increasing cover crop percentages, explaining the lower average values of VCT during the evaluations. Without active management, cover crops exhibit higher leaf density which provides greater barrier effects. Huerta-Olague *et al.* (2018) also mention that the covers generally tend to decrease the runoff and erosion rates. In Mexico with four cover crops, these authors found an exponential decrease in soil erosion with all of them. Additionally, they mention that the plant structure plays a crucial role in soil protection, with denser crops demonstrating greater abilities to protect the soil against erosive agents. The effect of covers in reducing erosion rates has been reported by various authors (Beniaich *et al.*, 2023; Hou *et al.*, 2020; Koirala *et al.*, 2019; Xu *et al.*, 2019; Zhao *et al.*, 2020). Although there are no significant differences between VCT and CMT, channels with VCT management may present negative issues in operation, as these can obstruct water flow and decrease the speed at which water moves through the channel (Bond *et al.*, 2020; Salazar, 2010; Tang *et al.*, 2023; Zhao *et al.*, 2019). This situation can lead to adverse effects, especially during periods of heavy rainfall when the channels must function properly to prevent flooding and damage to plantations. Therefore, proper maintenance is recommended, including pruning and weed removal, to reduce soil erosion and preserve channel functionality.

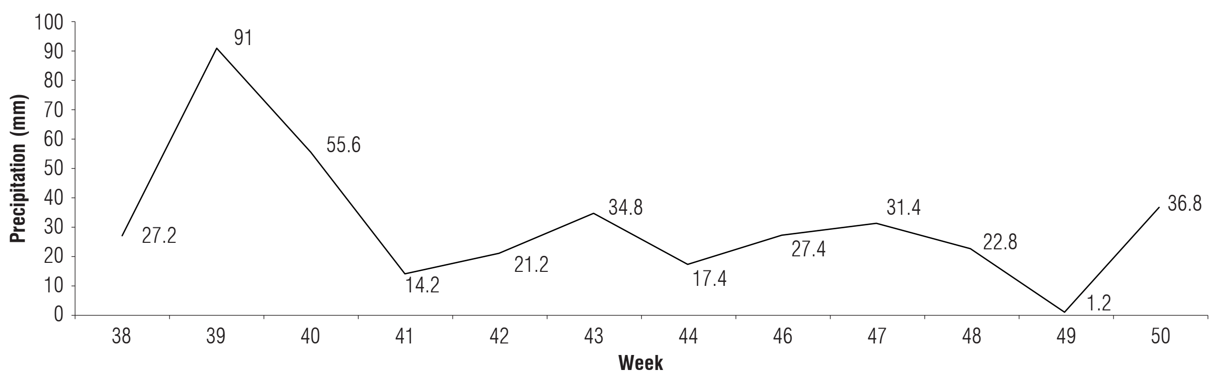

FIGURE 5. Accumulated weekly precipitation during the weeks 38 to 50 of 2022 (September-December) corresponding to the field evaluation period.

TABLE 1. Soil texture and organic matter content in the evaluated channels.

Treatments	Replicate	Sand (%)	Silt (%)	Clay (%)	Texture	OM (%)
BST	1	18.56	39.49	41.95	C	2.47
CMT	1	27.91	36.04	36.05	CL	2.24
VCT	1	23.13	38.98	37.89	CL	3.07
BST	2	20.69	36.4	42.91	C	2.60
CMT	2	24.00	39.13	36.87	CL	2.19
VCT	2	28.62	41.74	29.64	CL	2.05
BST	3	17.84	37.63	44.53	C	2.63
CMT	3	23.24	44.39	32.37	CL	2.10
VCT	3	22.49	39.71	37.8	CL	2.13

OM (%): soil organic matter content; BST: Bare soil; CMT: conventional management; VCT: vegetation cover; C: clay; CL: clay loam.

Erosive potential with USLE

The soils in the study area had an A horizon between 0 and 7 cm; based on the classification of USDA (2018), the soils were categorized as degradation class 2, which indicates a loss between 25 to 75% of the thickness of the upper horizon of 20 cm, suggesting erosive processes in the area. Additionally, the soils exhibited a structure of fine to moderate sub-angular blocky aggregates, with the characteristics of texture and organic matter presented in Table 1.

Statistical differences in potential erosion values were found between the treatments (*P*=0.0317, Tab. 2). Based on the classification presented by Han *et al*. (2021), all treatments fell within the very high erosion risk (80-150 t ha^{-1} $year^{-1}$).

TABLE 2. Erosive potential of the evaluated soil.

Treatment	Erosion (t ha^{-1} $year^{-1}$)
BST	93.11 ab
CMT	96.47 a
VCT	87.87 b

BST: Bare soil; CMT: conventional management; VCT: vegetation cover. Different letters denote significant differences according to the Tukey HSD ($P \leq 0.05$).

These results indicated that the CMT treatment had the highest erosion potential, followed by BST and, finally, VCT. This suggests that external conditions besides the presence of covers make the soil susceptible to erosion. A Spearman correlation revealed that the LS factor had a correlation value of 0.66 and K factor of 0.46, which indicates that these two factors cause higher susceptibility to soil erosion, regardless of the coverage management. Belayneh *et al*. (2019) mentioned that the erosion rates in the Gumara watershed have a high relationship with its slopes, where steeper slopes result in higher erosion values. Additionally, Han *et al*. (2021) found that higher erosion rates are attributed to heavy precipitation (R), erodibility (K), and soil slopes (LS). Koirala *et al*. (2019) also refer to the increase in erosion with increasing land slopes.

These findings highlight that any erosion control strategies should use a comprehensive approach, considering the implementation of vegetation covers and the soil and landscape factors that contribute to the erosive potential. Therefore, a successful conservation solution must be adapted to the specific conditions of the area, incorporating practices that enhance soil properties such as soil structure and infiltration rates.

Conclusions

The presence of vegetation covers on the slopes of the channels significantly reduces the soil erosion rates compared to bare soil. This shows the protective effect of vegetation covers and emphasizes the importance of the plant cover implementation to minimize soil particle transport and control erosion in drainage systems for banana crops. However, it is crucial to properly maintain these vegetation covers to preserve the functionality of the channels without obstructing the water flow, allowing the lowering of water table levels in banana crops, especially during heavy rainfall seasons.

In addition to the influence of vegetation covers on erosive rates, other soil parameters such as texture, organic matter content, permeability, and land slopes, in this case, channel slopes, determine the erosive potential of the area. Therefore, any erosion control strategy should incorporate these factors to develop sustainable conservation solutions, including beneficial plant coverages. Such strategies should not only reduce erosion but also improve soil properties.

Conflict of interest statement

The authors declare that there are no conflicts of interests regarding the publication of this article.

Author´s contributions

LDB and LMVA designed and conducted the experiments; LMVA collected the data; LDB and DCS analyzed the data; JJPZ, MAB, SZH, and RAVV supervised the project. LDB prepared the draft of the manuscript. All authors reviewed and approved the final version of the manuscript.

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