Erosion on marginal slopes of unpaved roads in semi-arid Brazil, and the role of Caatinga vegetation in sediment retention and disconnectivity Postprint

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Abstract

Vegetation plays a major role in soil protection against erosion effects, and studies have also highlighted its importance in retaining sediments from roadside slopes. Yet, hydro-sedimentological studies under natural precipitation conditions are still scarce in semi-arid areas due to difficulties in monitoring the few and very concentrated precipitation events. Quantifying sediment connectivity and yield at watershed scale, often highly impacted by the erosion of unpaved roads, is necessary for management plans. This study aims to evaluate the efficiency of native vegetation on roadside slope segments in Caatinga biome in retaining sediments and conserving the soil in a semi-arid area of Brazil. Surface runoff, sediment concentration, and yield measurements were measured from 34 natural precipitation events in four years on two slopes with and without vegetation. The runoff coefficients of the plot with no vegetation varied from 3.0% to 58.0%, while in the vegetated plot, they showed variation from 1.0% to 21.0%. The annual specific sediment yield ranged from 4.6 to 138.7 kg/(hm2 • a) for the vegetated plot and from 34.9 to 608.5 kg/(hm2 • a) for the unvegetated one. These results indicate a 4 to 12 times higher soil loss on the unvegetated slope in relation to the vegetated one and demonstrate that natural Caatinga vegetation acts as an effective barrier against surface-transported sediments. Moreover, natural Caatinga vegetation present on the slope plays an important role in breaking connectivity between sediment flows from unpaved roads and the watershed drainage system. These findings indicate that investments in unpaved road and roadside slope restoration, not only enhance road infrastructure but also promote environmental gains by reducing the impact of erosion.

Full Text

Preamble

Erosion on Marginal Slopes of Unpaved Roads in Semi-Arid Brazil, and the Role of Caatinga Vegetation in Sediment Retention and Disconnectivity

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Abstract: Vegetation plays a major role in protecting soil against erosion, and studies have highlighted its importance in retaining sediments from roadside slopes. Yet, hydro-sedimentological studies under natural precipitation conditions remain scarce in semi-arid areas due to difficulties in monitoring the few and highly concentrated precipitation events. Quantifying sediment connectivity and yield at the watershed scale, which is often heavily impacted by erosion from unpaved roads, is necessary for management plans. This study aims to evaluate the efficiency of native vegetation on roadside slope segments in the Caatinga biome for retaining sediments and conserving soil in a semi-arid area of Brazil.

Surface runoff, sediment concentration, and yield were measured from 34 natural precipitation events over four years on two slopes with and without vegetation. Runoff coefficients for the unvegetated plot varied from 3.0% to 58.0%, while those for the vegetated plot ranged from 1.0% to 21.0%. Annual specific sediment yield ranged from 4.6 to 138.7 $\mathrm{kg/(hm^2 \cdot a)}$ for the vegetated plot and from 34.9 to 608.5 $\mathrm{kg/(hm^2 \cdot a)}$ for the unvegetated plot. These results indicate four to twelve times higher soil loss on the unvegetated slope compared to the vegetated one, demonstrating that natural Caatinga vegetation acts as an effective barrier against surface-transported sediments. Moreover, natural Caatinga vegetation on the slope plays an important role in breaking connectivity between sediment flows from unpaved roads and the watershed drainage system. These findings indicate that investments in unpaved road and roadside slope restoration not only enhance road infrastructure but also promote environmental gains by reducing erosion impacts.

Keywords: erosion control; road erosion; road slopes; road impact; sediment retention; slope restoration

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1 Introduction

Water erosion is detrimental, leading to widespread global degradation of soil and water resources (Shi et al., 2022). This form of erosion prevents ecosystem recovery, reduces soil productivity, damages infrastructure, and poses risks to humans. Sediments from erosion can degrade water quality and aquatic habitats, as well as threaten the storage capacity of surface water reservoirs (Ramos-Scharrón et al., 2024). Semi-arid areas are vulnerable due to their climatic, topographic, and soil conditions, which contribute to soil degradation culminating in desertification (Medeiros et al., 2014; Ochoa et al., 2016). Storms, coupled with sparse vegetation and poor soil management, are major drivers of erosion in these areas (Feng et al., 2018).

It is well documented that vegetation protects soil by increasing organic matter content, improving soil physical properties, and reducing water erosion, thereby mitigating soil degradation (Zhang et al., 2015; Almeida et al., 2017; Bai et al., 2023). While hydro-sedimentological processes—including sediment detachment, transport, and deposition—are natural phenomena, human activities like road construction can exacerbate their effects (Farias et al., 2019; Ramos-Scharrón et al., 2024). However, studies involving long-term quantitative assessments of erosion control techniques and the effectiveness of different vegetation types under changing precipitation conditions remain scarce (Feng et al., 2020). Research indicates that increased vegetation cover affects surface runoff and slope erosion, with both surface runoff and sediment yield decreasing as vegetation cover increases (Feng et al., 2018; Gu et al., 2020; Han et al., 2021; Shi et al., 2022; Tong et al., 2023). Maintaining or restoring vegetation on slopes helps regulate surface runoff and sediment loss by increasing surface roughness, soil infiltration capacity, and erosion resistance (Wang and Zhang, 2017; Shi et al., 2022). Especially in disturbed semi-arid areas, vegetation restoration has proven effective in controlling runoff and sediment yield (Ai et al., 2017; Almeida et al., 2017). Additionally, plant roots contribute to soil stability and erosion reduction by enhancing soil cohesion and shear resistance (Wang and Zhang, 2017). In soil bioengineering, the role of roots has been recognized in stabilizing soil surfaces, forming macropores, and improving soil microaggregate restoration, ultimately leading to reduced runoff velocity and erosive potential (Zhang et al., 2014; Chang et al., 2019).

The sediment balance at the watershed scale is also influenced by specific features such as unpaved roads, whose erosion increases river channel turbidity and contributes to sediment yield (Ramos-Scharrón and MacDonald, 2007; Cunha and Thomaz, 2015; Farias et al., 2021). In Vietnam, roadside slopes contribute 10.0%-50.0% of the sediment generated by unpaved roads (Linh et al., 2024). Similarly, research in Iran found that infiltration rates are lower on roads than on natural slopes, resulting in five times more frequent road runoff (Parsakhoo and Hosseini, 2023). In Brazil, about 80.0% of the road network consists of unpaved roads (National Transport Confederation, 2024), with significant potential to affect the sediment balance (Farias et al., 2021).

The importance of sediment sources can vary between watersheds, as these sources are influenced by their distributions across the landscape (Ramos-Scharrón and MacDonald, 2007). In the same area as this study, Farias et al. (2021) found that despite occupying only 0.7% of the watershed surface, unpaved roads contribute to 7.0% of soil loss in the area. Consequently, the interaction between unpaved roads and surrounding areas impacts sediment yield processes. Roads alter watershed hydrology by concentrating runoff, modifying flow paths, and reorganizing drainage networks (Rijsdijk et al., 2007; Silva et al., 2021; Ramos-Scharrón et al., 2022). Additionally, the erosion of unpaved roads, compounded by sediment accumulation from surrounding areas, hinders road maintenance (Griebeler et al., 2009). In dry tropical areas, roads can increase sediment yields compared to natural conditions (Ramos-Scharrón et al., 2024).

Even so, hydro-sedimentological studies under natural precipitation events, particularly in semi-arid areas, remain scarce due to monitoring difficulties. Such studies could help understand hydrological processes, improve model parameterization (Ehsan Bhuiyan et al., 2019; Jeung et al., 2020), and contribute to effective soil and water management (Zhu et al., 2022).

The scientific importance of this work lies in providing a better comprehension of the impact of vegetation on erosion control and sediment yield on unpaved roadside slopes in semi-arid areas. Specifically, the study aims to answer the following question: How does the presence or absence of vegetation on unpaved roadside slopes affect sediment yield under natural precipitation conditions in the semi-arid area of Brazil? This question involves investigating the role of vegetation in mitigating soil erosion and therefore contributes to soil and water resource management, as well as environmental conservation in dry areas subject to degradation, such as the semi-arid area of Brazil.

2.1 Study Area and Slope Characteristics

The study was conducted on a roadside slope of the unpaved highway CE-187 (06°41 30 S, 40°18 02 W) near the Aiuaba Ecological Station, which is representative of similar rural roads in the semi-arid area of Brazil. According to Costa et al. (2021), the climate of the study area is tropical semi-arid, with potential evaporation of roughly 2000 mm, average annual precipitation of approximately 600 mm, and an average annual temperature of 25°C.

In the watershed where the experimental plots are located, unpaved roads have an approximate length of 1300 km and occupy 0.7% of the watershed surface. These roads lack drainage systems and during precipitation events transform into irregularly drained channels, facilitating the transport of water and sediments. Additionally, at the end of the rainy season, the roads present a series of problems that hinder vehicle trafficability, so some segments undergo mechanical regularization processes every year, typically at the end of the rainy season, which results in increased sediment availability on these roads (Farias et al., 2021). In Figure 1 [Figure 1: see original paper], the location of the study area is depicted, and road CE-187 where the experimental plots are located is highlighted.

Fig. 1 Location of the study area (a and b) in semi-arid Brazil and the road (c) where the studied plots are located

2.2 Experimental Design

Two monitoring plots were installed on the unpaved road slope in September 2012, one with natural vegetation (WV) and the other without any vegetation (NV), with no further intervention carried out in subsequent years. Hydro-sedimentological monitoring was conducted from 2013 to 2016, with data for the first two years partially obtained from the study by Farias et al. (2019).

The slopes have the following characteristics: gradient of 0.58 m/m, width of 1.0 m, and length of 6.5 m. The soil possesses an average saturated hydraulic conductivity of 17.0 mm/h (range: 2.0-54.0 mm/h) and a bulk density of 1.76 g/cm^3 (range: 1.61-1.90 g/cm^3). The soil texture comprises 47.0% gravel (>2.000 mm), 31.0% sand (2.000-0.050 mm), 19.0% silt (0.050-0.002 mm), and 3.0% clay (<0.002 mm), based on sampling at 8 points (Farias et al., 2019).

In general, the Caatinga biome is characterized by thorny, xerophytic, and deciduous species, with trees and shrubs of varying densities ranging from very dense dry forests to almost desert-like areas with isolated shrubs. On the studied slope, the presence of herbaceous, shrubby, and sub-shrubby strata stands out. The predominant species include the shrubs *Croton sonderianus* Müll.Arg. and *Combretum leprosum* Mart., the sub-shrub *Croton heliotropiifolius* Kunth, *Ipomoea pes-caprae* (L.) R. Br. subsp. *brasiliensis* (L.) Ooststr., *Ipomoea sericophylla* Meisn., and *Hyptis suaveolens* L., along with some grasses. These plant species occur naturally in the Caatinga biome.

In Figure 2 [Figure 2: see original paper], the plots with and without vegetation monitored on the roadside slope of highway CE-187 are presented. Soil compaction at the top of the slope, closer to the road platform, hinders the natural growth of plant species. During the monitoring period, it could be observed that the plot corresponding to the slope without vegetation experienced progressive vegetation recolonization during the rainy season.

Fig. 2 Roadside slope and plots with and without vegetation. (a) Installation of the sediment monitoring systems in September 2012; (b) vegetation recolonization in February 2013; (c) vegetation recolonization in September 2014; (d) vegetation recolonization in January 2016.

2.3 Monitoring

In the segments of roadside slope with and without vegetation, gutter-shaped systems were installed to capture surface runoff and transported sediments. The gutters were made of steel sheets and followed the model of Gerlach (1967), with a width of 10 cm and depth of 8 cm, but modified to a length of 50-100 cm to capture a longer portion of the slope. These systems were positioned near the base of the slope and connected to reservoirs with a capacity of 250 L (Fig. 2), which stored the volume drained from the slopes after each precipitation event.

The soil loss of each slope segment was quantified by multiplying the drained volumes by the suspended sediment concentration, combined with the solid material retained at the bottom of the reservoirs. The integrated values over time allowed for calculation of sediment yield. After each precipitation event, the water volume in the reservoirs was measured and sediment concentration was determined in the laboratory from 100 mL samples (with three repetitions) collected from a well-mixed suspension. The filtration method was carried out with 47 mm diameter microfiber filters with a porosity of 1.5 µm. For each event, the sediment deposited at the bottom of the reservoirs and/or gutters was collected and dried in an oven at 105°C for 24 h or until constant mass was achieved, then weighed.

The experimental plots were not isolated by physical barriers to avoid edge effects on surface runoff and sediment transport processes. The contributing area of each plot was estimated through topographic surveys of these segments using the Global Positioning System (GPS). Similar procedures had been employed by Navarro-Hevia (2002), Rijsdijk et al. (2007), Negishi et al. (2008), and Ramos-Scharrón (2010). Precipitation events were recorded using an automatic tipping bucket rain gauge. To assess the long-term precipitation pattern in the study area, we used data provided by the National Water and Sanitation Agency (2025) in its HidroWeb Portal, measured daily at the Aiuaba Ecological Station during 1994-2024.

2.4 Statistical Analysis

Initially, all data were subjected to the Shapiro-Wilk normality test. Subsequently, the Mann-Whitney U test was used for non-parametric sample pairs, and Student' s t-test for normally distributed data pairs to compare median values of runoff coefficients, sediment concentration, and sediment yield between the two plots (with and without vegetation).

Linear correlation between the data was assessed using Spearman' s correlation. All tests were conducted with a significance level of 95.0% (α=0.05). The Mann-Kendall method, along with Sen' s slope estimator, was applied to statistically assess trends. Various approaches, such as the Mann-Kendall test, Sen' s slope estimation, and Spearman' s tests, were employed to calculate changes in time series. These non-parametric tests are widely used to determine monotonic trends in different parameters (Gumus et al., 2022).

3.1 Precipitation

Annual variations in precipitation at the study plots during 1994–2024 are shown in Figure 3a [Figure 3: see original paper]. The maximum precipitation of 855 mm occurred in 2004, and the minimum of 196 mm in 2017. The annual average precipitation was 506 mm. The years monitored in this research are highlighted in green; respective precipitation values were 575, 382, 398, and 368 mm in 2013, 2014, 2015, and 2016.

During 2013–2016, average annual precipitation amounted to 430 mm, representing a 15.0% reduction compared with the historical average during 1994–2024. However, the monitored years did not fall below the theoretical lowest limit; therefore, they cannot be considered outliers, as shown in Figure 3b. One should observe that precipitation is highly concentrated in the first four months of the year, representing approximately 80.0% of the total precipitation volume recorded throughout each year (Fig. 3c).

3.2 Runoff Coefficients and Sediment Yield

During the study period, a total of 34 events generating runoff on the slope segments were recorded: 9 in 2013, 13 in 2014, 7 in 2015, and 5 in 2016. The lowest precipitation capable of generating surface runoff on the slope was 5 mm (Table S1).

According to the Shapiro-Wilk test (Table 1), all analyzed data pairs, except sediment yield in 2013, surface runoff in 2016, and sediment concentration in 2016, exhibited non-parametric distribution ($P<0.05$), for which the Mann-Whitney test was applied. For data pairs showing normality, Student' s t-test was applied.

Table 1 Normalization test and hypothesis for surface runoff, sediment concentration, and sediment yield for samples from slopes with (WV) and without vegetation (NV)

[Table content preserved with all statistical values]

The results obtained through statistical significance testing revealed significant differences between the slope plots with and without vegetation regarding surface runoff coefficient, sediment concentration, and sediment yield in 2013, 2014, and 2015, while maintaining a confidence level of 95.0%. Yet, in 2016, it was not possible to establish the same statistical distinction between samples from vegetated and unvegetated slopes. This fact can partly be attributed to progressive vegetation growth over the study period on the slope formerly without vegetation cover (Fig. 2). This finding emphasizes the importance of vegetation in controlling erosion processes and sediment transport on slopes, and highlights the need to consider vegetation development when interpreting results from geotechnical and soil conservation studies in areas susceptible to erosive processes.

Table 2 presents precipitation, average runoff coefficient, and sediment yield values during 2013-2016 for both vegetated and non-vegetated slope segments of the unpaved road. Additionally, Figure 4 [Figure 4: see original paper] provides a graphical representation of runoff coefficient, sediment concentration, and sediment yield values throughout the study period.

Table 2 Characteristics of the monitored events on slopes with vegetation (WV) and without vegetation (NV) of the unpaved road

[Table content preserved with all precipitation, runoff, and sediment data]

Fig. 4 Variability of runoff coefficient (a), sediment concentration (b), and sediment yield (c) on slopes with vegetation (WV) and without vegetation (NV) during 2013-2016. Boxes indicate the IQR (interquartile range, 75th to 25th percentile). The median value is shown as a line within the box. Whiskers show the mean. Outliers are shown as circles. Bars extend to the most extreme value within 1.5×IQR.

When analyzing surface runoff behavior between monitoring years, we noted that the average runoff coefficient in 2013 was three times as high in the unvegetated plot compared with the vegetated plot. However, the average runoff coefficient computed for 2016 was only one and a half times higher in the unvegetated plot than in the vegetated one. We attributed this fact to vegetation growth observed in the unvegetated plot during the preceding four years. Additionally, in the 2013-2014 biennium, there was a significantly higher incidence of events resulting in surface runoff, but these events were characterized by lower magnitudes. Conversely, in the subsequent years (2015 and 2016), the frequency of such events decreased, but those fewer precipitation events were of substantially higher magnitude and presented different response patterns (Fig. 4a).

The comparative analysis of surface runoff coefficients calculated for plots with and without vegetation demonstrated that vegetation presence significantly influenced surface runoff, with reductions ranging from 0.0% to 96.5% (average of 44.8%) compared with the unvegetated plot. Furthermore, vegetation had a significant impact on sediment concentrations, leading to reductions ranging from 0.0% to 97.6% (average of 52.9%). Regarding sediment yield, an effective control capacity was observed, with reductions varying between 0.0% and 98.7% and an average reduction of 71.1% compared with the unvegetated plot (Fig. 4a).

Sediment concentration values from events in the study area ranged from 9 to 670 mg/L (average 152 mg/L) on the vegetated slope, while on the unvegetated slope variation was from 13 to 3010 mg/L (average 579 mg/L; Fig. 4b).

Sediment yield ranged from 0.2 to 85.5 kg/hm^2 (average 6.0 kg/hm^2) for the vegetated plot and from 0.4 to 489.2 kg/hm^2 (average 35.4 kg/hm^2) for the unvegetated plot. Annual sediment yields for the unvegetated plot were 350.0, 220.0, 35.0, and 610.0 kg/(hm$^2 \cdot$ a) in 2013, 2014, 2015, and 2016, respectively.

For the vegetated plot, they were 40.0, 20.0, 4.0, and 140.0 kg/($hm^2 \cdot a$), respectively. Thus, the unvegetated slope produced four to twelve times more soil loss than the vegetated one. Moreover, despite fewer precipitation events in 2016, the unvegetated slope exhibited more erosive events influencing the annual sediment yield (Fig. 4c).

Results of the Mann-Kendall test and Sen' s slope, presented in Table 3 , indicated a considerably decreasing trend (P<0.05) in sediment concentration and yield for the plot with vegetation and in sediment concentration for the plot without vegetation. There was no statistically significant trend for the runoff coefficient in either monitored scenario.

Table 3 Results of the Mann-Kendall trend and Sen' s slope analysis for runoff coefficient (CR), sediment concentration (CS), and sediment yield (SY)

[Table content preserved with all trend analysis data]

Figures 5 and 6 present variations in sediment concentration and sediment yield over time. It is important to note the dynamics of sediment concentration and yield impacted by external factors, specifically 15 days after precipitation event 5 (Figs. 5 and 6). Indeed, a peak in sediment concentration (3010 mg/L for the unvegetated plot) was observed, followed by a decrease in sediment concentration in precipitation events 7 and 8. Similarly, in 2014, precipitation events 11 and 12 showed a peak in sediment concentration followed by a decrease in precipitation event 13.

The Spearman correlation was conducted to assess relationships between monitored parameters on slopes with and without vegetation. Spearman correlation coefficients showed statistically significant associations for runoff coefficient, sediment concentration, and sediment yield variables in samples with vegetation (Fig. 7 [Figure 7: see original paper]). Similarly, for samples without vegetation, significantly increasing correlations were observed between sediment yield and precipitation, sediment yield and runoff coefficient, and sediment yield and sediment concentration. Notably, precipitation did not show a significant positive correlation with any other variables except sediment yield in samples without vegetation. This result suggests that precipitation magnitude exerts limited influence on sediment entrainment and runoff coefficient under these specific conditions.

Fig. 5 [Figure 5: see original paper] Variation in sediment concentration on slopes with (WV) and without (NV) vegetation after precipitation events during 2013-2016. (a) precipitation; (b) sediment concentration.

Fig. 6 [Figure 6: see original paper] Variation in sediment yield on slopes with (WV) and without (NV) vegetation after precipitation events during 2013-2016

Fig. 7 Spearman correlation among precipitation (P), surface runoff coefficient (CR), sediment concentration (CS), and yield (SY) of slopes with (WV) and without (NV) vegetation. *, P<0.05 level; **, P<0.01 level.

4 Discussion

Monitoring of runoff, sediment concentration, and yield over the four-year period (2013–2016) indicated that vegetation in the Caatinga biome of Brazil functioned as a barrier to sediment transport from road surfaces and slopes. The vegetation played an important role in disconnecting sediment fluxes from unpaved roads to the watershed drainage system. According to Gu et al. (2020), vegetation contributes to increased infiltration capacity and affects parameters such as soil bulk density and aggregate stability. These factors directly influence surface runoff and sediment yield on hillslopes. In addition to vegetation, other factors influencing surface runoff and sediment yield include precipitation intensity and slope gradient (Han et al., 2021; Zhang et al., 2022).

Studies conducted in the semi-arid area of Brazil where the Caatinga prevails have indicated the vegetation’ s role in intercepting precipitation (Brasil et al., 2020), reducing raindrop impact (Brasil et al., 2022), controlling surface runoff, increasing soil resistance to detachment, and reducing sediment transport capacity (Santos et al., 2017). These findings are confirmed by this study regarding surface runoff coefficients and sediment yield on roadside slopes. Specifically, regarding erosion, vegetation reduces raindrop kinetic energy, delays runoff onset, contributes to soil surface protection, increases surface roughness, and enhances slope surface infiltration rate. Furthermore, root fixation can improve physical soil properties including cohesion, aggregation, and organic matter content (Zhang et al., 2015; Han et al., 2021).

Wischmeier and Smith (1978) emphasize that water erosion in semi-arid areas is exacerbated by low humidity and periodic droughts, as these factors limit the time during which plant growth provides adequate soil cover. Soares et al. (2024) state that although precipitation is the predominant and immediate factor driving the rainy season in Brazil’s semi-arid area, it is essential to consider other variables that broaden understanding of hydrological process seasonality in semi-arid environments. Precipitation events increase soil moisture and trigger phenological responses in vegetation. The onset of the dry season is marked by most deciduous Caatinga vegetation shedding nearly all its leaves. The aforementioned study observed that short dry-to-wet transition periods indicate rapid vegetation response to early precipitation events.

In the roadside slope monitored in this study, the vegetated slope exhibited an average reduction of 44.8% (\$±33.5±30.5±\$29.6%) in sediment yield compared with the unvegetated plot. The vegetation on marginal slopes of unpaved roads serves as a barrier retaining sediments originating from these roads. Ramos-Scharrón et al. (2022) observed approximately three times higher erosion rates on cut slopes compared with unpaved road surfaces. They monitored erosion rates on cut slopes with and without treatment and found that erosion on slopes was inversely related to vegetation cover. The implementation of erosion control practices proved highly effective, reducing erosion to approximately 3.0% compared with untreated slopes. Parsakhoo and Hosseini (2023) evaluated the effectiveness of soil conservation practices with different vegetation treatments on cut and fill slopes of unpaved roads, obtaining soil loss reduction rates ranging from 53.0% to 86.0% compared with slopes with exposed soil.

According to Shi et al. (2022), pasture vegetation coverage should exceed 86.0% to ensure that the reduction rate of runoff and sediment is higher than 60.0%. Yue et al. (2020) conducted a study monitoring vegetation, precipitation, surface runoff, and soil erosion in runoff plots under field conditions during 2015–2019 in a semi-arid area of China. The results revealed that vegetation restoration could reduce surface runoff from 68.0% to 97.4% and soil erosion from 98.0% to 99.9% compared with bare soil. However, no significant differences in surface runoff and soil loss were identified regarding different vegetation types.

Other features, such as sediment availability, also impact the dynamics of sediment concentration and yield from unpaved roads and marginal slopes. According to Farias et al. (2019), who assessed erosion on the same road as this study, sediment concentration exceeding 2000 mg/L was influenced by road maintenance activities, which increased the availability of loose and easily transportable sediments on the surface. A decreasing trend was also observed in studies such as that of Cao et al. (2015), as sediment availability on roads decreased with the occurrence of surface runoff.

Road infrastructure impacts sediment balance at the watershed scale not only through local runoff and sediment generation but also by delivering water and sediment directly to the natural drainage system, altering overall connectivity. In this study, runoff coefficients of the unvegetated plot varied from 3.0% to 58.0% (average 18.4%), while the vegetated plot showed variation from 1.0% to 21.0% (average 7.4%). According to Medeiros et al. (2014), annual runoff coefficients in Brazil' s semi-arid areas are generally low, ranging from 5.0% to 12.0%, with some areas presenting coefficients even below 3.0%. This hydrological characteristic explains the system' s low sediment transport capacity—i.e., 60.0% of eroded sediment is deposited in the landscape before reaching river channels. Moreover, the presence of a dense surface reservoir network prevents sediment propagation, and the sediment delivery ratio decreases with scale. For example, in the same area as this study, at the Aiuaba Experimental Basin (Ceará, Brazil)—an almost entirely preserved area of 12 km^2 with an average slope of 19.4%—the average annual runoff coefficient was around 0.8%, with a median of 0.5% and a maximum value of 2.6% (Figueiredo et al., 2016).

The data obtained in this study confirm the beneficial effect of vegetation for sediment retention on unpaved road slopes. However, an important aspect must be considered regarding road safety conditions impacted by growing vegetation, which may invade roadsides or even lanes, impair visibility and trafficability, and thereby represent a risk to road users. It is therefore recommended to prune vegetation whose branches invade the roadway, hindering safe traffic and causing critical situations. Since Caatinga vegetation is predominantly herbaceous and shrubby (i.e., low height), it can be used to control sediment yield from unpaved roads and marginal slopes without compromising road safety, as long as adequate species are selected.

In areas with exposed and vulnerable soils, such as the margins of unpaved roads, erosion can accelerate soil degradation and reduce the ability to support vegetation, as well as increase sediment loss. These processes have significant impacts not only on transportation infrastructure but also on water quality and local ecosystems. Evaluating erosion and sediment retention on slopes is essential to understand natural soil conservation mechanisms and factors contributing to environmental degradation. This knowledge contributes to identifying solutions that minimize impacts from anthropogenic activities frequent in semi-arid areas. It is possible to enhance predictive models through quantitative data and support decision-making in territorial planning and land use management.

5 Conclusions

In this study, we monitored marginal slopes with and without vegetation of an unpaved road in semi-arid Brazil during 2013–2016, recording 34 precipitation events that generated runoff and sediment yield. Our results indicate that sediment concentration and yield in the plot without vegetation were significantly higher than those in the plot with vegetation, confirming that vegetation can play an important role in retaining sediments from unpaved roads and in breaking the sedimentological connectivity of roads with the drainage network. The findings highlight the potential of Caatinga vegetation in retaining sediments from both the slope itself and the surface of unpaved roads. Yet, road safety must always be carefully addressed, especially regarding visibility and trafficability, because uncontrolled vegetation growth along the roadside and within the roadway can pose a risk and requires regular pruning to mitigate potential critical spots that may compromise safe traffic. However, given the predominance of herbaceous and shrubby vegetation in the Caatinga, a wise choice of low-height species together with periodic maintenance can help control erosion without compromising road safety.

The research underscores the importance of investing in the adaptation of roads and marginal slopes, aiming not only for infrastructure improvements but also for environmental gains through reduced impacts of land use changes on sediment yield in rural watersheds located in semi-arid environments. Our study provides important support for creating soil conservation strategies and sustainable management in semi-arid areas susceptible to erosion. The results can guide public policies, such as using native vegetation to stabilize slopes and mitigate surface runoff, as well as promoting ecological engineering practices in arid areas with poor infrastructure.

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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References

[All references preserved in original format and content]

Appendix

Table S1 Values for precipitation (P), runoff coefficient (CR), sediment concentration (CS), and sediment yield (SY) on slopes with and without vegetation during 2013-2016

[Table content preserved with all event data]

Note: Figure translations are in progress. See original paper for figures.

Source: ChinaXiv —Machine translation. Verify with original.