



An assessment of the shade and ground cover influence on the mitigation of water-driven soil erosion in a coffee agroforestry system

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Abstract Coffee cultivation under agroforestry systems is one of the main agricultural activities in Central America, but climate change is putting its sustainability at risk. Rainfall erosivity has worsened, thus driving soil losses. Although the vegetal covers in coffee agroforestry systems play a crucial role in controlling erosion, the specific influence of each cover layer remains unclear. In this study, we assessed the influence of the canopy (tree and banana cover and coffee cover) and ground cover (weed and litter) on water driven soil erosion, to determine which type of cover has the most influence on soil erosion control. The study site is situated in the core and buffer zones of the Macizo de Peñas Blancas National Park (Nicaragua), where seventeen coffee sampling plots with an agroforestry system composed of an *Inga spp* and *Musa spp* canopy cover were analysed. The results showed that the $19.2 \pm 3.4\%$ of the soil surface was affected by erosion and it was mainly related to the litter ground cover ($r = -0.95$, $P < 0.001$). Also, this cover presented the best partial correlation

($r_{yl,tcw} = -0.93$, $P < 0.001$) when the effects of the other vegetal covers were eliminated. Specifically, the litter cover accounted for 90% of the erosion variability, while the impact of the other types of cover was negligible, accounting for just 1% of the erosion. We conclude that litter layer is more important than canopy cover for effective erosion control, and the main function of shade trees is as a source of litter biomass.

Keywords Shaded coffee · Water erosion · Erosion control · Canopy cover · Litter cover

Introduction

In Central America, coffee production is one of the main income-generating agricultural activities for small producers, since the expansion of commodity crops promoted by the agricultural revolution during the second half of the twentieth century (Patel 2013), when farming systems in developing countries evolved from subsistence models to commercial farming (Harwood 2019). According to the FAO (2022), the area dedicated to coffee production in Central America between 1961 and 2020 increased at an average annual rate of 1.04%. Currently coffee farming occupies an area of 1.69 million ha., the 15.32% of the world's surface area dedicated to this crop. In Nicaragua, the growth rate was 0.98% in the same period, reaching a total area of 149,418 ha. Moreover, this increase in cultivated area was accompanied

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by a rise in crop yield, which increased at an average annual rate of 0.35% regionwide, from 502.7 to 616.6 kg ha⁻¹ between 1961 and 2020. In Nicaragua, coffee yield was higher still, at an average annual rate of 2.31%, from 276.1 to 1062.5 kg ha⁻¹ during the same period.

The current scenario of global climate change is putting the future of this crop in Central America at risk. The erosivity of the rains has worsened in the last years by the growing number of extreme weather events (tropical storms and hurricanes), a trend that will only continue in the coming decades, according to IPCC (2019). In consequence, there will be increased soil losses, which is one of the acute problems facing mountain agriculture at tropical latitudes.

The works that have analyzed water erosion in coffee cultivation under different management systems, showed that shaded coffee recorded significantly lower erosion rates than unshaded coffee. Ataroff and Monasterio (1997) found in coffee farms in Venezuela that the soil loss in the sun plantations (1.57 and 0.73 Mg ha⁻¹ year⁻¹) were twice that of shade (0.79 and 0.43 Mg ha⁻¹ year⁻¹), during the two years of experimentation, respectively. De Carvalho et al. (2021) showed in a study carried out in Brazilian coffee plantations that the soil loss in unshaded coffee (13.8 kg ha⁻¹) almost tripled that recorded in shaded system (3.6 kg ha⁻¹). Verbist et al. (2010) found in Indonesian farms under unshade coffee an average soil loss of 7–11 Mg ha⁻¹ year⁻¹, which decreased to 4–6 ha⁻¹ year⁻¹ under shade coffee. The runoff coefficient was also very different: 10–15% under unshade coffee and 4–7% under shade coffee system.

In coffee cultivation, the combination of shade and ground cover means that this agroforestry system presents a water cycle with very particular characteristics. The microclimate generated by the shade cover reduces water losses due to transpiration from the coffee plants and evaporation from the soil. Lin (2010) observed a 32% reduction in evapotranspiration with shade cover of 30% or more. In addition to this function of the upper layers, the litter layer helps reduce runoff, thereby increasing the infiltration of water into the soil (Marín-Castro et al. 2017). In this respect, Cannavo et al. (2011) reported that coffee crops grown beneath shade trees presented more effective water infiltration into the soil (to a depth of 100–200 cm), than those with no such shade cover, due to the greater content of the litter

layer. This circumstance increased water availability and enhanced complementarity between coffee and shade trees for access to this resource. The microclimatic conditions of the agroforestry system make it a valuable strategy for mitigating the impact of climate change on coffee production (Lasco et al. 2014). Litter biomass also plays a fundamental role because provides organic matter to the soil and improves the aggregate stability. This aspect turns these cultivation systems into important carbon sinks (Macedo et al. 2023), also contributing to erosion control (Pan et al. 2022).

Although the cover of agroforestry systems is believed to play an important role in erosion control, the specific influence of canopy cover and soil cover remain to be clarified. According to some researchers, shade cover is the most important factor (McDonald et al. 2002; Hartemink 2006); for others, however, it may be ground cover (Jassogne et al. 2013; Blanco and Aguilar 2015) or both aspects, in combination (Ataroff and Monasterio 1997). These discrepancies have arisen because, to date, no specific comparative analysis has been made of the influence of vegetal layers on water-driven erosion in shaded coffee plantations.

Current climate change is causing negative impacts on small coffee producers in Central America and to mitigate its effects, different soil conservation measures are being implemented, including agroforestry techniques (Harvey et al. 2018). Generally, strategies to adapt coffee crops to climate change seek to make use of canopy and soil cover; however, the effectiveness of each type of cover has not yet been established. This question is of some importance, as knowledge of how cover layers protect against erosion would allow farmers to design and implement appropriate management plans, and thus develop crops resilient to climate change.

Given the importance of these considerations, the objective of our study was to assess the influence of canopy cover (trees, bananas and coffee plants) and ground cover (weeds and litter) on water-driven soil erosion in coffee agroforestry, in order to determine the influence of each layer in this respect and to draw key technical recommendations for mitigation soil erosion. This is in line with the goals that promotes the concept “*transformative adaptation*” (TA) of Leal et al. (2022), as the action pathway more efficient to climate change adaptation. For the purposes of this

study, achieving the indicated objectives would allow us to establish the good TA practices that farmers should use in the intervention areas.

Materials and methods

Site characteristics

This study was conducted in 2016, in 17 of 1 ha sampling plots located in 8 coffee farms. They are all situated in the core or buffer zones of the Macizo de Peñas Blancas National Park, in the Departments of Jinotega and Matagalpa (Nicaragua), occupying the former forested parts of this mountainous area (Fig. 1). All farms used the same cultivation and cover management system. The agroforestry system was based on a coffee crop (*Coffea arabica*) under a shade canopy composed of different species of *Inga* spp and *Musa* spp, mainly *Inga oersterdiana* Benth. and *Inga punctata* Willd., *Musa acuminata* Colla and *Musa balbisiana* Colla. Other species sporadically present include *Ceiba pentandra* (L.) Gaertn., *Cedrela Odorata* L. and *Erythrina fusca* Loureiro. All the plantations were in full production, with

coffee plants mainly of 4 to 8 years old. The density of coffee plants was 3,700 to 5,600 plants ha⁻¹, with a distance of 0.7 to 1.0 m between plants, and 1.5 to 2.0 m between rows. Shade cover management was carried out by pruning the trees, which occur on the average once or twice each year. The aims are to control their growth and avoid excessive shading. Weed control was carried manually (machete), coupled with the application of herbicide. First, the weeds are removed using a machete. Smaller weeds may escape this mechanical action and therefore the control process is continued with the application of herbicide, normally paraquat or glyphosate. Paraquat applications are usually 2.75 to 4.25 L ha⁻¹; and those of glyphosate of 2.25 – 3.5 L ha⁻¹. This management is repeated an average of 3 times per year.

The climate is humid tropical, with an average annual rainfall ranging from 2414 mm in Matagalpa to 2770 mm in Jinotega. The mean annual temperature ranges from 20 to 25 °C. The study area is considered highly suitable for coffee production, thanks to its favourable climatic conditions (Lara et al. 2017). The study plots presented slopes of 20–77% (average slope 43 ± 4.3%). The soils in the study plots are mainly chromic cambisols (IUSS-WRB 2022) and

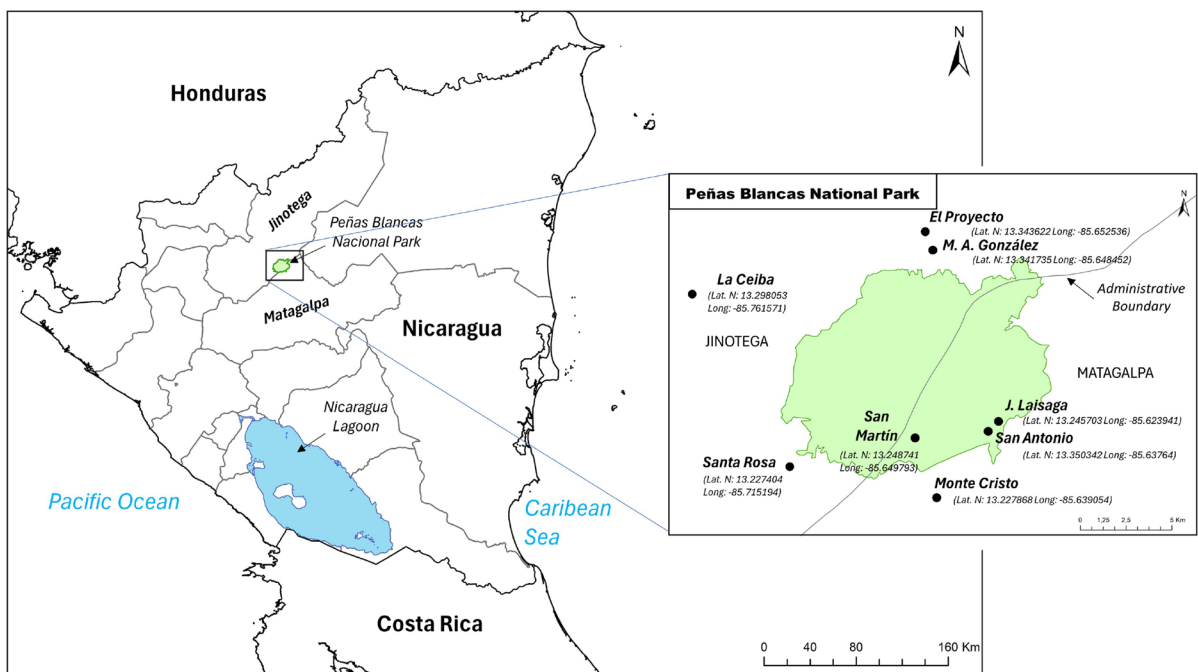


Fig. 1 Location of the study agroforestry coffee farms

present in the first 10 cm of soil these characteristics (mean \pm standar error) ($n=17$): clay loam texture ($28.8 \pm 1.9\%$ clay, $31.1 \pm 1.6\%$ fine silt, $12.5 \pm 0.8\%$ coarse silt and $27.6 \pm 1.6\%$ sand), with 5.81 ± 0.1 pH, 45.5 ± 3.2 g kg^{-1} organic carbon, $0.5 \pm 0.07\%$ equivalent calcic carbonate, 47.1 ± 3.4 meq 100 gr^{-1} cationic exchange capacity and $24.5 \pm 2.7\%$ base saturation rate.

Analytical methods applied to determine soil erosion and vegetal cover

Soil erosion was analysed using the method described by Blanco (2018), which determines the percentage of surface affected by erosion. The method measures erosion using visual indicators. It is an adapted version of the presence/absence test of visual indicators and their number and size of Stocking and Murnaghan (2001). Visual indicators differentiated the surface processes and types of erosion shown in Table 1. These observations are coded by means of an index (capital letter) and a subscript. The first indicates the process type: erosion directly affecting unaltered soil (E), erosion affecting soil previously disturbed by agricultural practices with implements (machete) (M), no-erosion (N) and others (O). M is of particular interest for this work because this tool, used for weeding, breaks up the original structure of the topsoil and makes it easier for surface runoff to carry away soil particles. The suscript indicates the type of erosion (splash, sheet, rill and gully erosion) or the vegetal cover that protect the soil.

Sampling to calculate the eroded surface and the vegetal cover was conducted using transects. Three transects were carried out per sampling plot. These plots were placed in 8 agroforestry coffee farms representative of the study area. As 17 sampling plots were analyzed, a total of 51 transects were carried out. The quadrants and transects were drawn from the centre of the plot (point 0, Fig. 2). The plots, with an area of 1 ha, were divided into four quadrants. Three of them are randomly selected for sampling, through a blind draw of numbered balls. The distances of the x/y axes of the transects were randomly determined using the same process. The transects were 10 m long and were sampled at 25 cm intervals. For each observation point, the surface process that affects the soil was determined, as well as the soil cover (distinguishing between bare soil, weeds, litter layer, stones and others) (see examples of observation points in Fig. 2). In total, 40 observation points of erosion and vegetation cover indicators were taken per transect, and therefore 120 observations per plot. The sampling was carried out only once per plot, in the middle of the rainy season (July and August) and before pruning the shade trees. Taking into account that the pruning periods of the farms are variable, the sampling schedule was agreed with the farmers to be able to do it before pruning.

Soil sample collection and analysis

A sample of surface soil (first 10 cm of soil) was taken at point 0 of each sampling plot (Fig. 2). Particle-size distribution was determined by the pipette method (Loveland and Whalley 1991). The pH was

Table 1 Processes and types of erosion that affect the soil in coffee crops (adapted from Blanco 2018)

E. Soil erosion by water

(Ei/Es/Er/Eg) Soil erosion by splash erosion (raindrop impact)/by sheet erosion/by erosion in rills/by erosion in gullies

M. Mechanical soil disturbance by tool (machete), affected by erosion, or erosion-susceptible

1. (Mes) Soil disturbed by tool use and susceptible to erosion (but not visible at present)

2. (Mi/Ms/Mr/Mg) Soil disturbed by tool use and affected by splash erosion (raindrop impact)/by sheet erosion/by erosion in rills/by erosion in gullies

N. No erosion

1. (Nw) No evidence of erosion beneath cover of weeds

2. (NI) No evidence of erosion beneath litter layer

O. Others

1. (Or) Stones

2. (Oa) Animals: tracks, faeces, carcasses, others

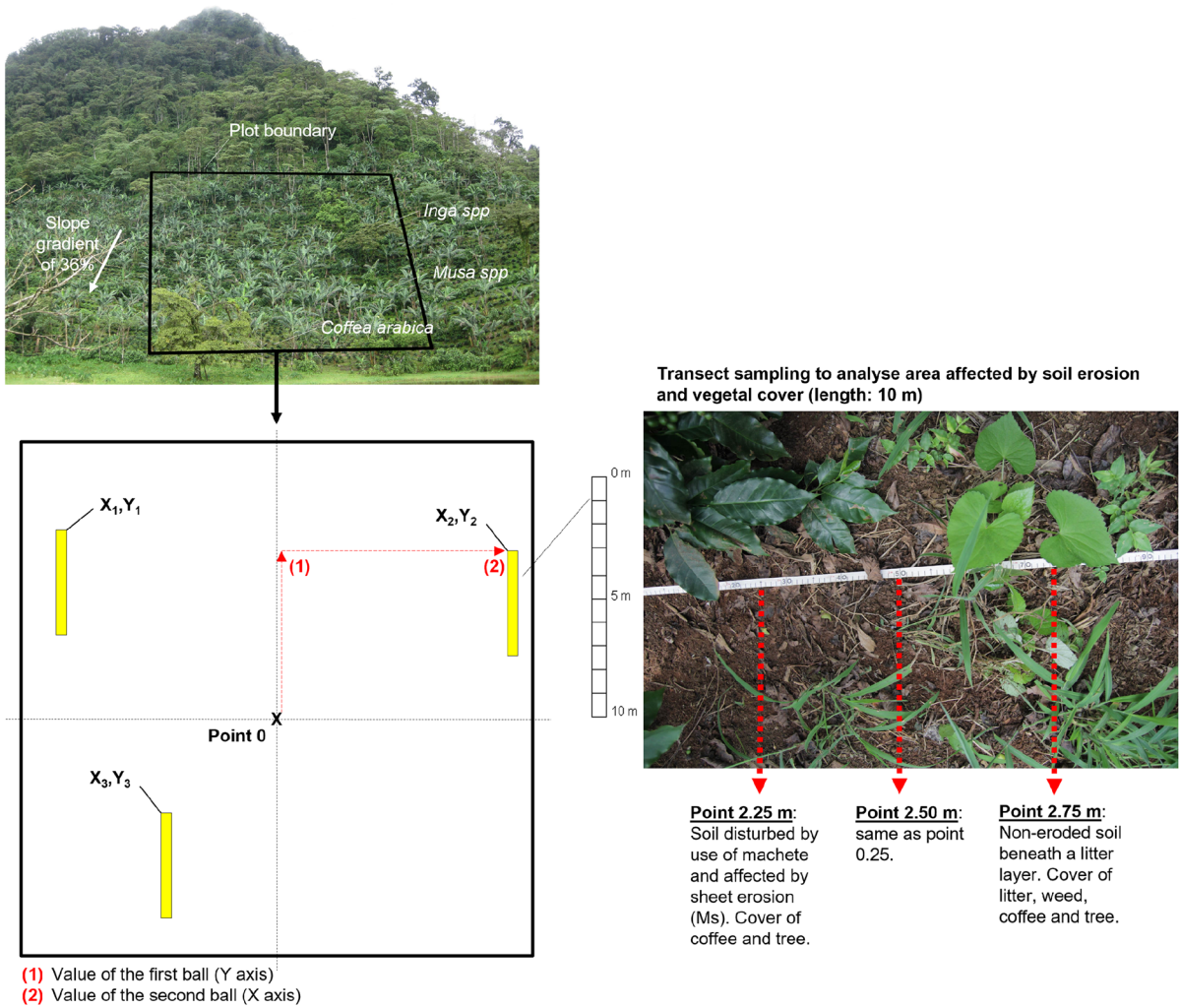


Fig. 2 Diagram of the sampling procedure used to estimate soil erosion and vegetal cover (adapted from Blanco 2018)

measured in a soil:water suspension 1:2.5 with a Crison pH-Meter Basic 20. The calcium carbonate content was determined by acid treatment with 1:1HCl and manometric reading of the pressure of CO₂ released. Total carbon was analyzed by dry combustion in an automatic LECO TruSpec-CN instrument, and organic carbon was estimated by the differences between total carbon (from LECO analysis) and inorganic carbon (from calcium carbonate analysis). The cation exchange capacity was measured in a VARIAN 220FS SpectrAA atomic absorption spectrometer (USDA 1972). The exchangeable bases were determined after saturation with ammonium acetate 1 N pH 7 and measurement of the elements in a VARIAN 220FS SpectrAA atomic absorption

spectrometer (USDA 1972). From the last two measurements the saturation rate has been determined. All atomic absorption spectroscopy measurements were performed in triplicate and standard solutions (Merck quality) were used for calibration.

Study method and analysis

The general-to-simple (GETS) modelling procedure of Clarke (2014) was used to establish the most efficient regression model that determines the area affected by erosion. The method, based on the theory of reduction, consists of simplifying an initial general model, which has all the analysis variables, into simpler models, successively eliminating the variables

with less explanatory power. By this procedure, the relative weight of the analysis variables in each of the generated models can be determined. Linear regression analysis (enter method) was used to obtain the models in each of the reduction stages. Bivariate correlation (Pearson's r) and partial correlation analysis were used to determine in each model the capacity of ground cover and canopy cover to explain the eroded surface. I.e., these were the statistics used to determine the specific weight of each variable to explain erosion. Finally, the coefficient of determination (r^2) was the statistics used to determine the explanatory capacity of the model. These analyses were conducted using IBM SPSS Statistics 25.0.

Results

Soil erosion and vegetal layers

In the sampled plots, the mean area affected by erosion (Et) was $19.2 \pm 3.4\%$ (minimum: 5.0%, maximum: 50.0%) (Table 2). Sheet erosion was the most frequent and important type, affecting both the soils that had been superficially disturbed using machete for weeding (Ms) (average: $11.2 \pm 3.8\%$, minimum: 0%, maximum: 43.3%) (Fig. 3), and the soils unaffected by the use of the tool (Es) ($5.7 \pm 1.9\%$, minimum: 0%, maximum: 26.7%). On average $77.3 \pm 3.5\%$ (minimum: 45.8%, maximum: 93.3%) of the surface area was unaffected by erosion, mainly

due to the protection of the litter layer (NI) (average: $73.1 \pm 4.5\%$, minimum: 35.8%, maximum: 93.3%) (Fig. 3).

The proportion of soil surface with ground cover (GC_{ALL}) was very high (average: $86.2 \pm 2.9\%$, minimum: 57.5%, maximum: 97.5%), of which a large proportion was litter (GC_L) (average: $82.4 \pm 3.3\%$, minimum: 51.7%, maximum: 97.5%) (Table 3). The litter layer was composed of leaves of trees and coffee, branches and herbaceous residues. Canopy cover, made up of coffee and shade of tree and banana layers (CC_{ALL}), was also very high (average: $89.2 \pm 6.2\%$, minimum: 56.7%, maximum: 143.3%). Of this, $59.6 \pm 2.2\%$ (mean value) was provided by the coffee plants (CC_C), and the remaining $29.6 \pm 5.4\%$ (mean value) by shade trees (CC_T).

Correlation analysis of the vegetal layers showed that the tree and banana canopy cover were directly related to the litter cover ($r=0.51$, $P<0.05$), i.e., the amount of litter layer increased with that of canopy cover. The coffee cover, however, presented no significant relationship with that of leaf litter (Table 4). There was no other significant correlation between variables.

Soil erosion in relation to vegetal layers

The first model, between the eroded surface (%) (as dependent variable) and all vegetal layers (%) (as independent variables), explained 91% of the variability of soil erosion ($r^2=0.91$, $P<0.001$) (Fig. 4). The correlation between the plant litter cover and

Table 2 Surface processes that affected the soil in the agroforestry system of coffee with *Inga spp* and *Musa spp* shade canopy (n=17)

Surface processes and actions	Abbreviation	Mean \pm std error	Min	Max
Splash erosion (%)	Ei	0.2 ± 0.1	0	1.7
Sheet erosion (%)	Es	5.7 ± 1.9	0	26.7
Soil disturbed by tool (machete) and susceptible to erosion (%)	Mes	2.2 ± 0.9	0	12.5
Soil disturbed by tool (machete) and affected by splash erosion (%)	Mi	2.1 ± 1.4	0	23.3
Soil disturbed by tool (machete) and affected by sheet erosion (%)	Ms	11.2 ± 3.8	0	43.3
No evidence of erosion beneath cover of weeds (%)	Nw	2.0 ± 0.5	0	6.7
No evidence of erosion beneath litter layer (%)	NI	73.1 ± 4.5	35.8	93.3
Other topsoil characteristics (stones) (%)	Or	3.5 ± 0.5	0.8	9.2
Total area affected by soil erosion (%)	Et	19.2 ± 3.4	5.0	50.0
No evidence of erosion (%)	Ene	77.3 ± 3.5	45.8	93.3

Std error: Standard error, Min: minimum value, Max: maximum value

Fig. 3 Visual indicators of the main processes that affected the soil in coffee agroforestry crops: (Ms) Soil disturbed by machete and affected by sheet erosion. Erosion pedestals can be seen (detail photo); (NI) No evidence of erosion beneath a cover of litter layer. Under this cover, decomposing plant remains are visible, showing that the soil surface is stable and unaffected by erosion (detail photo)



Table 3 Vegetal cover in an agroforestry system of coffee with *Inga spp* and *Musa spp* shade canopy (n=17)

Vegetal cover	Abbreviation	Mean ± std error	Min	Max
Tree and banana canopy cover (%)	CC _T	29.6 ± 5.4	13.3	86.7
Coffee canopy cover (%)	CC _C	59.6 ± 2.2	45.0	80.8
Total canopy cover (sum of tree, banana and coffee covers) (%)	CC _{ALL}	89.2 ± 6.2	56.7	143.3
Ground cover by weeds (%)	GC _W	3.8 ± 1.5	0	25.8
Ground cover by litter (%)	GC _L	82.4 ± 3.3	51.7	97.5
Total ground cover (sum of weeds and litter) (%)	GC _{ALL}	86.2 ± 2.9	57.5	97.5
Overlapping cover (sum of ground and canopy covers) (%)	OVC	175.4 ± 7.6	131.3	240.8

Std error: Standard error, Min: minimum value, Max: maximum value

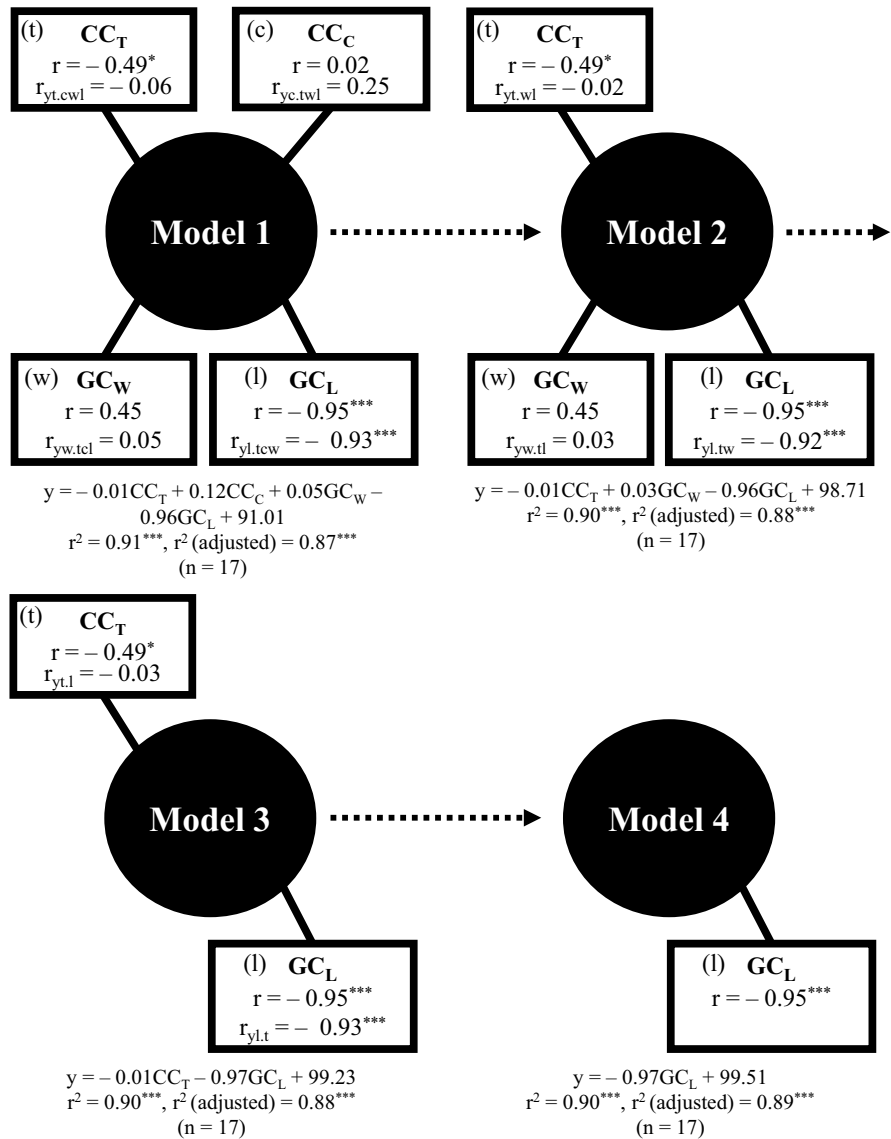
Table 4 Correlation between the vegetal layers of this agroforestry system of coffee with *Inga spp* and *Musa spp* shade canopy (n=17)

	CC _T	CC _C	GC _W	GC _L
CC _T	1	0,19	-0,47	0,51*
CC _C		1	-0,15	0,06
GC _W			1	-0,46
GC _L				1

CC_T: Tree and banana canopy cover; CC_C: Coffee canopy cover; GC_W: Ground cover by weeds; GC_L: Ground cover by litter. *Significant correlations at $P < 0.05$

the eroded surface ($r = -0.95$, $P < 0.001$) presented the best partial correlation ($r_{yl,tcw} = -0.93$, $P < 0.001$), when the effects of the other vegetal covers were eliminated. The small difference between these coefficients shows that the relationship between litter cover and erosion is not influenced by the other vegetal layers. The correlation between tree and banana canopy cover and eroded surface ranged from $r = -0.49$ ($P < 0.05$) to $r_{yt,cwl} = -0.06$ ($P > 0.05$) when the effects of the other vegetal layers were removed, showing that the effect on erosion is not attributable

Fig. 4 General-to-simple modelling applied to determine the influence of vegetal cover layers (t, c, l, w) on the surface affected by erosion (y) in an agroforestry system of coffee with *Inga spp* and *Musa spp* shade canopy. CC_T: tree and banana canopy cover; CC_C: Coffee canopy cover; GC_w: Ground cover by weeds; GC_L: Ground cover by litter. *Significant correlations at $P < 0.05$; **Significant correlations at $P < 0.01$; ***Significant correlations at $P < 0.001$. Non-significant differences are not marked. Note: Partial correlation is represented as follows: for example, $r_{yt,cwl}$ represents the correlation of the variable t (tree and banana canopy cover) with the water erosion, after removing the effect of the variables c (coffee canopy cover), l (ground cover by litter) and w (ground cover by weeds)



to the tree and banana covers, but rather to the other covers included in the analysis. The same conclusion is drawn regarding the ground cover by weeds ($r_{yw,tcl} = 0.05, P > 0.05$). Finally, the coffee cover ($r = 0.02$) showed a different pattern of behaviour, with a higher coefficient ($r_{yc,twl} = 0.25$), although it still bore no significant relationship with erosion.

Model 2, which includes all the independent variables except the coffee canopy, presents a similar trend (Fig. 4). This model explains 90% of the soil erosion variability ($r^2 = 0.90, P < 0.001$), only 1% less than the previous model. Again, the relationship between the ground cover of plant litter and the area

affected by erosion presented the best partial correlation ($r_{yl,tw} = -0.92, P < 0.001$) when the effects of the other vegetal layers were eliminated. Tree and banana canopy cover ($r_{yt,lw} = -0.02, P > 0.05$) and ground cover by weeds ($r_{yw,tl} = 0.03, P > 0.05$) were not significantly related to erosion when the effects of the other covers were removed, which reaffirms the conclusions drawn above. Model 3, which includes the litter cover and the tree and banana canopy, presents the same explanatory power of water erosion (Fig. 4). Soil erosion was only correlated with the litter layer ($r = -0.95, P < 0.001$) and showed a very similar partial correlation coefficient ($r_{yl,t} = -0.93, P < 0.001$)

organic carbon enrichment of the soil surface, caused by the decomposition of plant residues. This action improves the stability of the soil structure (Macedo et al. 2023) and makes it more resistant to dispersion from the impact of rain (Hu et al. 2018). It also promotes the formation of biological macropores, from the activity of earthworms, because the increase in plant litter on the ground surface favours the activity of soil biota (Zhang et al. 2018). Structural improvements and macroporosity both have benefits for soil hydrology, because macropores favour infiltration and structural stability is crucial to the long-term durability of these hydrological properties (Zhang et al. 2020). Accordingly, runoff is reduced and water erosion is controlled.

Results from our study also indicated that shade trees play an indirect role in controlling erosion. Correlation analysis between the litter layer and the tree and banana canopy cover, showed that the amount of waste cover increased with that of canopy cover ($r=0.51$, $P<0.05$). Results of Hairiah et al. (2006) are in line with the findings reported in this work. That paper estimated that the annual plant litter production in a tropical forest is approximately $14 \text{ Mg ha}^{-1} \text{ yr}^{-1}$. This figure decreases to $9.8 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ in coffee crops with an agroforestry system composed of different shade species, and to $4 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ in unshaded coffee crops. In view of these differences, the authors highlighted the importance of choosing and managing shade trees in coffee agroforestry systems for the provision of plant litter, with respect to controlling erosion and improving soil structure and biota. In this regard, Meylan et al. (2013, 2017) compared litter biomass contents and soil hydrological properties in a coffee agroforestry system shaded by *Erythrina spp* and *Musa spp* with an unshaded coffee cultivation. Results showed that the amount of litter biomass was significantly higher in the shade coffee, but the difference between *Erythrina spp* and *Musa spp* was not significant. Likewise, the soil infiltration rate under coffee shade was significantly higher than in soils under full sun coffee, and again there were no differences between both canopy covers.

These results are of special practical interest for farmers, because: (i) it showed that for effective erosion control, coffee farm management must be aimed at maintaining the litter layer, and (ii) it indicated that the shade trees role in soil erosion control is as a source of litter biomass.

Conclusions

This study showed that ground cover is more important than canopy cover in controlling soil erosion in coffee cultivation based on an agroforestry system. Specifically, the cover of plant litter is the layer with greatest influence on erosion. This relationship accounted for 90% of erosion variability. Therefore, the most effective erosion control measure in coffee crops should be based on the provision of a plant litter cover. However, the influence of tree canopy cover should not be underestimated, as it is an important source of supply of the vegetable litter that makes up the ground cover layer, and thus has a strong indirect influence on erosion control.

For practical purposes, it is of special interest for farmers to complete these findings with two new objectives: (i) to determine the minimum litter density to effectively control soil water erosion, adapted to each case, and (ii) to determine the litter biomass production of the main shade trees in coffee agroforestry systems. Both should be addressed in future research.

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Declarations

Competing interests The authors declare no competing interests.

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