

Cover crops in between-rows of *Coffea canephora* for reduction of soil erosion

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ABSTRACT: Soil erosion in tropical environments causes environmental, social and economic damage. Canephora coffee crops are impacted by soil erosion and testing alternatives to mitigate this damage is a current need. This study aimed to evaluate the losses of sediment, organic carbon, nutrients and surface runoff caused by water erosion in between-rows spacing of *Coffea canephora* Pierre ex A. Froehner plants in management with and without cover crops, and the effect of the intensity of rains on sediment loss and the surface runoff. The management practices tested in between-rows spacing of coffee plants were: ES - exposed soil after manual weeding with a hoe; CC1- soil covered by palisadegrass [*Urochloa brizantha* (Hochst. ex A.Rich.) R.D.Webster] and nutsedge grass (*Cyperus rotundus* L.); and CC2- soil covered with purslane plant (*Portulaca oleracea* L.). Nine experimental plots were installed to measure losses of sediment, organic carbon, nutrients and surface runoff in the periods from September/2021 to March/2022 and from September to December/2022. The CC1 and CC2 reduced losses of sediment, organic carbon, nutrients and the volume of surface runoff from 37 to 86 % compared to ES. The increase in volume and rainfall intensities increased sediment loss and the surface runoff linearly, being more intense in ES management. The maintenance of the cover crops in between-rows spacing of coffee plants proved to be advantageous for mitigating losses of sediment, organic carbon, nutrients and surface runoff caused by water erosion, contributing to soil conservation and the sustainability of canephora coffee production.

Keywords: soil loss, runoff, coffee, weeds, ground cover.

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Received: March 25, 2024

Approved: August 07, 2024

How to cite: Souza GS, Domiciano ML, Sarnaglia GR, Pretti IR, Gonçalves PT, Kaulz M, Oliveira EC, Moreira RMG. Cover crops in between-rows of *Coffea canephora* for reduction of soil erosion. Rev Bras Cienc Solo. 2025;49:e0240061.
<https://doi.org/10.36783/18069657rbcs20240061>

Editors: José Miguel Reichert  and Jean Paolo Gomes Minella .

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INTRODUCTION

The canephora coffee tree is produced in tropical regions and in places with altitudes below 1,000 m and accounts for 36 % of global production (Campuzano-Duque et al., 2021). Brazil is the largest coffee producer in the world, with the state of Espírito Santo being the largest producer of canephora coffee, responsible for approximately 64 % of national production (Conab, 2023). The majority of Brazilian coffee is produced in monoculture crops with no vegetation cover in between-rows spacing of plants (Carvalho et al., 2007; Ragassi et al., 2013). Most farmers plow or apply herbicides to control weeds, leaving the soil exposed to rain (Franco et al., 2002; Ragassi et al., 2013; Wang et al., 2015). Furthermore, most of these crops are in areas with high slopes (Bernardes et al., 2012), which intensifies soil erosion (Ramos-Scharrón and Figueroa-Sánchez, 2017; Tu et al., 2021). Areas with steep slopes and without conservation practices present a high soil loss potential and are a priority for adopting measures to mitigate erosive effects (Ziadat and Taimeh, 2013; Mendes Júnior et al., 2018).

Water erosion is one of the main causes of soil degradation in tropical environments (Carvalho et al., 2007; Ramos-Scharrón and Thomaz, 2016; Mendes Júnior et al., 2018). Also, water erosion causes losses of sediment, carbon, nutrients and water in surface runoff, which are essential for maintaining agricultural production and the ecological balance of the soil (Wang et al., 2021). This problem has induced losses of arable land, enhancing risks to global food security and the sustainability of terrestrial ecosystems (Lugato et al., 2018; Lal, 2019). In steep regions, the erosion process results in a sediment enrichment rate greater than 1.0 (Hernani et al., 1999; Bashagaluque et al., 2018). This accelerates soil degradation as soil nutrients and carbon in the highest areas are transported by surface runoff to lower deposit areas (Bertol et al., 2017; Lal, 2019).

It is important to point out that water erosion may be measured using experimental plots of sediment loss and surface runoff of different dimensions and with high variation in values (Hernani et al., 1999; Franco et al., 2002; Römkens et al., 2002; Tu et al., 2021). Sediment loss due to water erosion in coffee areas around the world are variable mainly due to changes in relief, soil, climate and management (Ziadat and Taimeh, 2013; Wang et al., 2015; Nguyen and Pham, 2018). Mendes Júnior et al. (2018) found sediment losses from 0.01 to 18.77 Mg ha⁻¹ yr⁻¹ in southeastern Brazil. Ramos-Scharrón and Thomaz (2016) observed sediment loss of 11.00 Mg ha⁻¹ yr⁻¹ in Puerto Rico. Tu et al. (2021) found sediment loss ranging from 8.52 to 12.29 Mg ha⁻¹ yr⁻¹ in a coffee crop in Vietnam. However, measurements of losses of sediment, carbon, nutrients and surface runoff in canephora coffee crops are still scarce in international literature.

Rain is the natural erosive agent in tropical regions, being one of the factors that determines the magnitude of damage caused, as well as the topography of the terrain (Franco et al., 2002; Römkens et al., 2002; Ziadat and Taimeh, 2013). The concentration of large volumes of rain in short periods, as in southeastern Brazil, provides greater surface runoff, with greater transport of sediment, carbon and nutrients, contributing to soil degradation (Römkens et al., 2002; Carvalho et al., 2007; Mendes Júnior et al., 2018). The damage intensifies even more when the affected areas are located in steep regions (Römkens et al., 2002; Ziadat and Taimeh, 2013), or in intensely anthropized soils, with reduced water infiltration capacity, resulting in greater surface runoff (Ramos-Scharrón and Figueroa-Sánchez, 2017).

The use of cover crops or weeds in between-rows of canephora coffee plants can be a solution to minimize losses of sediment, carbon, nutrients and surface runoff (Carvalho et al., 2007; Cardoso et al., 2012). Weeds management in between-rows of coffee plants does not require financial investment compared to planting cover crops, reducing the implementation cost of the crop (Ragassi et al., 2013; Silva et al., 2021). But there is a lack of information on the efficiency of cover crops or weeds in controlling erosion in between-rows spacing of canephora coffee plants. Depending on the growth, morphology, adaptation, decomposition of the plant residue and the management applied, weeds may help more or

less in controlling water erosion (Silva et al., 2021). This is because they act by intercepting raindrops, reducing the direct impact on the soil surface and the soil aggregates detachment and increasing surface roughness, reducing the speed of surface runoff (Carvalho et al., 2007; Lal, 2019). The cultivation of coffee intercropped with peanuts and crotalaria reduced soil loss by 28 % and increased the vegetative development of coffee plants by 15 % (Tu et al., 2021). Studies on losses of sediment, carbon and nutrients are essential to define adequate soil conservation practices in tropical environments (Lal, 2019). These studies are important to minimize erosion processes and to allow the sustainable development of agricultural crops (Villatoro-Sánchez et al., 2015; Mendes Júnior et al., 2018).

The testable hypotheses of this study were: (i) cover crops in between-rows spacing of canephora coffee plants reduce the losses of sediment, carbon, nutrients and surface runoff in relation to the management with exposed soil; (ii) different cover plants modify the erosion process and amount of sediment loss; and (iii) the impact of rainfall volume and intensity on sediment loss and surface runoff are minimized in managements with cover crops in between-rows spacing of canephora coffee plants. This research aimed at (i) evaluating the losses of sediments, organic carbon, nutrients and surface runoff caused by water erosion in between-rows spacing of *Coffea canephora* plants in management with and without cover crops; and (ii) evaluating the effect of the intensity of rains on the production of sediments and in volume of surface runoff.

MATERIALS AND METHODS

The study was carried out in an agricultural field of *Coffea canephora* Pierre x Froehner with hybrid clones of Conilon x Robusta (Espíndula et al., 2019), installed at the Federal Institute of Espírito Santo – Campus Itapina (latitude 29° 19' 58" S, longitude 40° 45' 56" W, and altitude of 71 m), in Colatina - Espírito Santo State, Brazil. The soil in the area is a *Latossolo Vermelho Amarelo* (Santos et al., 2018) or Oxisol (Soil Survey Staff, 2014), with 631, 94 and 275 of sand, silt, and clay, respectively, and a slope of 22 % (Table 1). The climate in the region is Aw (tropical wet and dry climate), according to the Köppen classification system (Alvares et al., 2013), characterized by hot and rainy summers, and cold and dry winters, with annual precipitation of 1,218 mm and an average temperature of 24.2 °C (Figure 1).

Canephora coffee seedlings were transplanted in August 2020 in a spacing of 3.0 × 0.9 m (3,703 plants ha⁻¹). The soil was subsoiled in the planting lines to a depth of 0.40 m and then the furrows were opened with an agricultural implement. Before planting, the soil was fertilized with 4 L of manure, 2 L of chicken litter and 0.20 kg of simple superphosphate per linear meter of furrow, adapted from Prezotti et al. (2019). Annually, the soil was fertilized with one application of 0.030 kg plant⁻¹ of monoammonium phosphate and six applications of 0.045 and 0.020 kg plant⁻¹ of urea and potassium chloride, respectively. Each canephora coffee plant was cultivated with three orthotropic branches. The experiment began in December 2021, when the plants were 16 months old after transplanting the coffee seedlings. Between-rows space of the coffee plants there were weeds that germinated from the soil's natural seed bank and were mowed close to the ground whenever they reached 0.30 m in height. In the period before the experiment, the herbicide glyphosate was applied three times in the area. A strip of 0.75 m on each side of the center of the line of the coffee plants (tree crown projection) was weeded.

Table 1. Chemical and physical characterization of soil at the layer of 0.00-0.20 m in the experimental area in August/2021 and August/2022

Year	pH	Prem	OC	P	K	Ca ²⁺	Mg ²⁺	Al ³⁺	H+Al	SB	CEC	BS	Sand	Silt	Clay
		mg L ⁻¹	g dm ⁻³	—	mg dm ⁻³	—	—	cmol _c dm ⁻³	—	—	—	—	g kg ⁻¹	—	—
2021	5.3	40	9.6	152	255	5.7	1.2	0.1	2.9	7.6	10.5	72	631	94	275
2022	6.6	40	9.9	126	361	5.0	1.2	0.0	2.1	7.3	9.3	78	-	-	-

Analysis method: Teixeira et al. (2017). pH: hydrogenionic potential in water (ratio 2.5:1); Prem: remaining phosphorus; OC: organic carbon; P: phosphorus; K: potassium; Ca: calcium; Mg: magnesium; Al: aluminum; H+Al: potential acidity; SB: sum of bases; CEC: cation exchange capacity; and BS: base saturation.

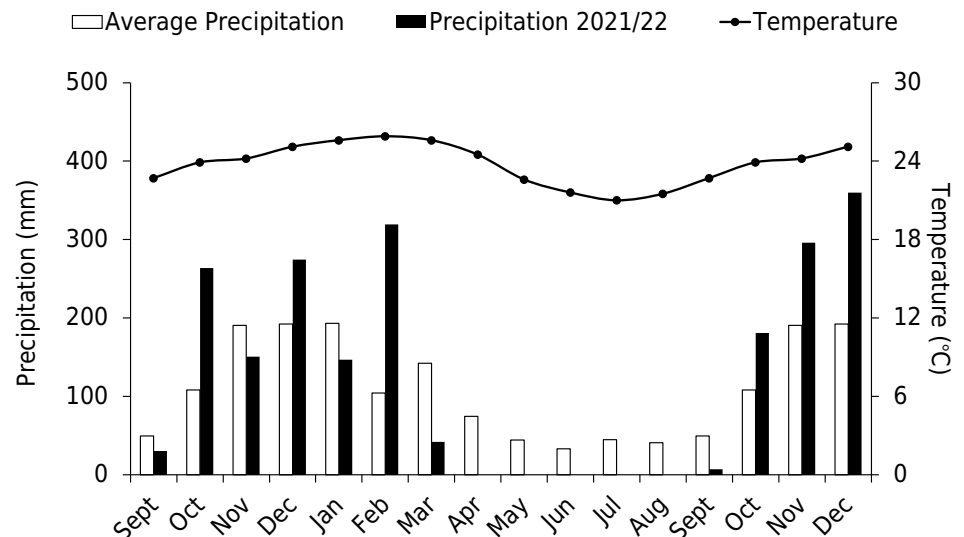


Figure 1. Average monthly precipitation, precipitation in the months of September/2021 to March/2022 and from September to December/2022 and average monthly temperature in the experiment area in Colatina-ES, Brazil. Source: adapted from National Water and Sanitation Agency (2022).

The management practices tested in between-rows spacing of coffee plants were: ES - soil exposed after manual weeding with a hoe; CC1 - soil covered by palisadegrass [*Urochloa brizantha* (Hochst. ex A.Rich.) R.D.Webster] and nutsedge (*Cyperus rotundus* L.); and CC2 - soil covered with purslane (*Portulaca oleracea* L.) (Figure 2). Weeds located in between-rows spacing of coffee plants grew freely in the area and were managed by mowing when they reached 0.30 m in height, producing an average biomass per cycle of 4.40 and 7.33 Mg ha⁻¹ for CC1 and CC2, respectively.

Three experimental plots measuring 0.08 m² (0.2 × 0.4 m) were installed in each treatment to collect sediment and volume of surface runoff, adapted from Franco et al. (2002), Römken et al. (2002) and Ziadat and Taimeh (2013). The plots were installed in the same topossequence (lower third). The plots boundaries were constructed of thermoplastic material plates, 0.20 m high, with 0.05 m buried in the ground. The collectors of sediment and the volume of surface runoff had the capacity to store 2 L. Surface runoff was collected from September/2021 to March/2022 and from September to December/2022, after each erosive rain to quantify sediment loss and volume of surface runoff (Hernani et al., 1999; Bertol et al., 2017). After the end of the evaluation of the first period, the collection plots of sediment and surface runoff were dismantled and randomly relocated in the area according to the presence of weeds in the following period.

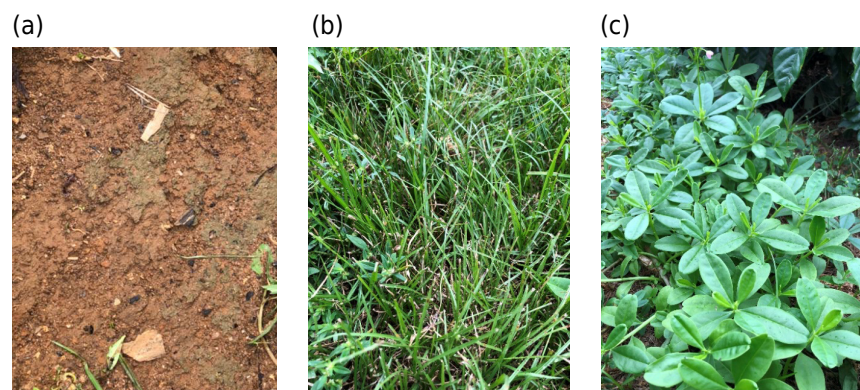


Figure 2. Illustration of managements with exposed soil (a) and cover crops with palisadegrass and nutsedge (b) and purslane (c), evaluated in the periods from September/2021 to March/2022 and from September to December/2022.

Rain volume and intensity data were collected by an automatic meteorological station (Sigma Sensores, EMM-RX 300, São José dos Campos, Brazil), 140 m away from the experiment area. After each erosive rain event, the collection containers were changed to avoid overflow and the collected material was taken to the laboratory for analysis. On days with erosion events, the volume of rainfall during the evaluation interval and the maximum and average intensities of erosive rain were quantified by the meteorological station, with a collection frequency of every 5 mins.

Surface runoff collectors remained at rest for 24 h in the laboratory after each erosion event to decant the solid fraction, adapted from Hernani et al. (1999). A sample of sediment (solid fraction) from each experimental unit was transferred to porcelain containers and taken to a forced circulation oven at 105 °C until constant mass. Wet and dry sediments masses were used in calculating sediment loss and volume of surface runoff, adapted from Hernani et al. (1999) and Bertol et al. (2017). The remainder of the samples were air-dried and stored, integrating a composite sample of erosion events (Bertol et al., 2017) used in chemical analyzes of the sediment (Tedesco et al., 1995). The properties evaluated in the sediment were: (i) phosphorus and potassium, with Mehlich-1 extractor; (ii) exchangeable calcium and magnesium, with KCl extractor (1 mol L⁻¹); and (iii) organic carbon, with sulfuric acid and heating, followed by titration with ammonium ferrous sulfate (Teixeira et al., 2017). The volume of the surface runoff (liquid fraction) was transferred and measured with a beaker. The liquid fraction was then stored in Falcon-type tubes and stored in a freezer at 4 °C (Bertol et al., 2017). The liquid fraction samples from the erosion events were part of a composite sample used to determine the contents of soluble nitrogen, phosphorus and potassium, according to Tedesco et al. (1995).

The enrichment rate was determined by dividing the nutrient contents contained in the sediment and surface runoff by the contents determined in the soil (Table 1), collected in August/2021 and August/2022 (Cardoso et al., 2012; Bashagaluke et al., 2018). Soil sediment entrainment potential was determined by the relationship between sediment loss and volume of surface runoff (Hernani et al., 1999; Cardoso et al., 2012).

The experimental design used was completely randomized with three treatments and three replications, in a total of nine experimental units. Each period was analyzed independently, containing 11 and 9 erosive events from September/2021 to March/2022 and from September to December/2022, respectively. Data were subjected to analysis of variance using the F-test ($p > 0.05$) and comparison of means using the Tukey test ($p > 0.05$) for losses of sediment, organic carbon, nutrients and surface runoff. Linear regressions ($p > 0.05$) were adjusted between sediment loss and surface runoff with rainfall volume and maximum and average intensities.

RESULTS

Higher values of sediment loss occurred in ES ($p < 0.001$ to 0.048) in all erosion events in relation to the managements with weeds in the two analyzed periods (Figure 3). In the period from September/2021 to March/2022 with eleven erosion events, the accumulated soil loss in the ES was 67.79 Mg ha⁻¹, while in CC1 and CC2 they were 11.11 and 13.57 Mg ha⁻¹, respectively (Figure 3a). These represents reduction of 84 and 80 %. In the period from September to December/2022, with nine erosion events, the accumulated sediment loss in ES management was 23.92 Mg ha⁻¹, while in CC1 and CC2 managements they were 8.63 and 7.19 Mg ha⁻¹, respectively (Figure 3b), i.e., reduction of 64 and 70 %.

Higher volumes of surface runoff occurred in the management with ES ($p < 0.001$ to 0.024) in relation to the managements with weeds in the period from September/2021 to March/2022 (Figure 3c). During this period, the accumulated surface runoff in ES was 1,792 m³ ha⁻¹, while in CC1 and CC2 they were 1,125 and 1,021 m³ ha⁻¹, respectively, that is, a reduction of 37 and 43 %. In the period from September to December/2022, volume of surface runoff did not differ statistically between managements ($p = 0.421$ to 0.913). In this period, the accumulated surface runoff in ES was 879 m³ ha⁻¹, while in CC1 and CC2 they were 962 and 671 m³ ha⁻¹, respectively (Figure 3d).

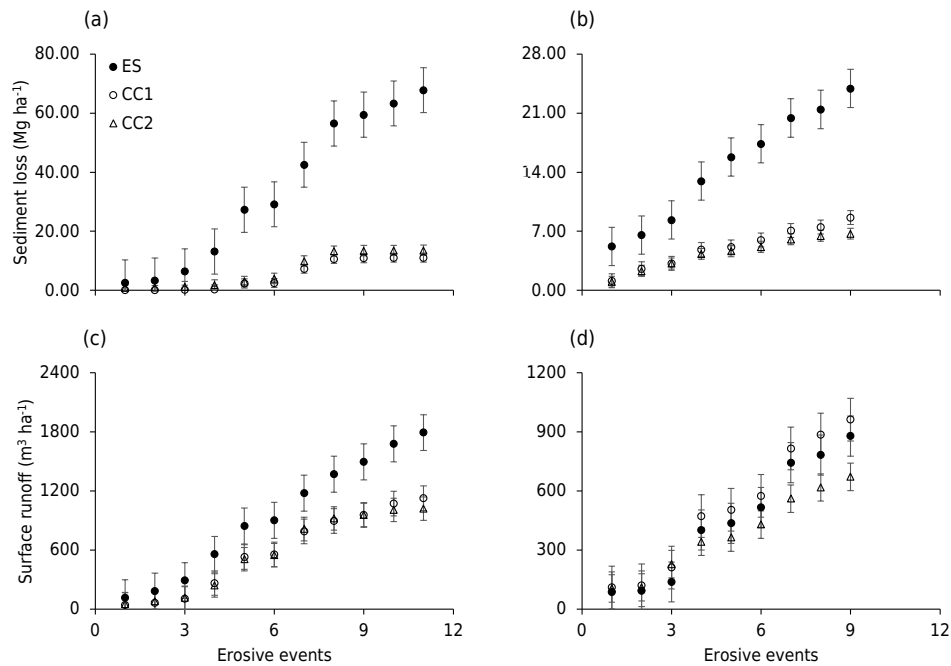


Figure 3. Accumulated sediment loss (a, b) and accumulated surface runoff (c, d) in erosive events in between-rows spacing of coffee plants with exposed soil (ES) and with cover crops (CC1 and CC2) evaluated in the periods from September/2021 to March/2022 (a, c) and from September to December/2022 (b, d). Bars represent standard error.

The highest values of volume and maximum and average rainfall intensities were 122 mm and 66 and 22 mm h⁻¹ in the period from September/2021 to March/2022, and 89 mm and 40 and 20 mm h⁻¹ in the period from September to December/2022, respectively (Figure 4). The increase in volume and maximum and average rainfall intensities increased sediment loss ($p < 0.001$ to 0.047) and surface runoff ($p < 0.001$ to 0.014) in the three managements in both periods, with the exception of sediment loss in CC1 from September/2021 to March/2022 for the volume of rainfall (Figure 4a) and in CC2 from September to December/2022 for the maximum and average intensities (Figures 4h and 4i). In both periods, ES showed a greater increase in sediment loss with higher values of angular coefficients with rainfall volume (0.102** and 0.058**) and maximum intensities (0.169** and 0.103**) and average (0.437* and 0.220**) than in managements with cover crops (0.016* to 0.021*; 0.027^{ns} to 0.034* and 0.059^{ns} to 0.093*) (Figures 4a, 4b, 4c, 4g, 4h and 4i). In both periods, CC1 and CC2 showed similar behavior for sediment loss related to rainfall volume and maximum and average intensities.

The same observed behavior for sediment loss happened for surface runoff in the period from September/2021 to March/2022 (Figures 4d, 4e and 4f), with higher values of the angular coefficient in the ES (2.432**, 3.992**, 10.562**) in relation to CC1 and CC2 (1.637** and 1.677**, 2.588** and 2.700**, 6.873** and 6.280**) for rainfall volume and maximum and average intensities, respectively. In the period from September to December/2022, CC2 showed the smallest increases in surface runoff with the increase in volume and maximum and average rainfall intensities (1.718**, 3.172**, 6.772*), while ES and CC1 showed similar behavior (2.962** and 3.101**, 5.192** and 5.492**, 10.935* and 11.645**) for rainfall volume and maximum and average intensities, respectively (Figures 4j, 4k and 4l). In all cases, the linear coefficient of the models was equal to zero, indicating the absence of sediment loss and surface runoff without the occurrence of rain.

The ES (0.38 Mg ha⁻¹ mm⁻¹) presented greater sediment entrainment potential ($p = 0.015$) in relation to CC1 and CC2 (0.11 and 0.14 Mg ha⁻¹ mm⁻¹) in the period from September/2021 to March/2022, with a reduction of 71 and 64 %, respectively (Figure 5). In the period from September to December/2022, ES (0.28 Mg ha⁻¹ mm⁻¹) again presented greater sediment entrainment potential ($p = 0.049$) in relation to CC1 (0.09 Mg ha⁻¹ mm⁻¹), with a reduction of 67 %, not statistically different from CC2 (0.14 Mg ha⁻¹ mm⁻¹).

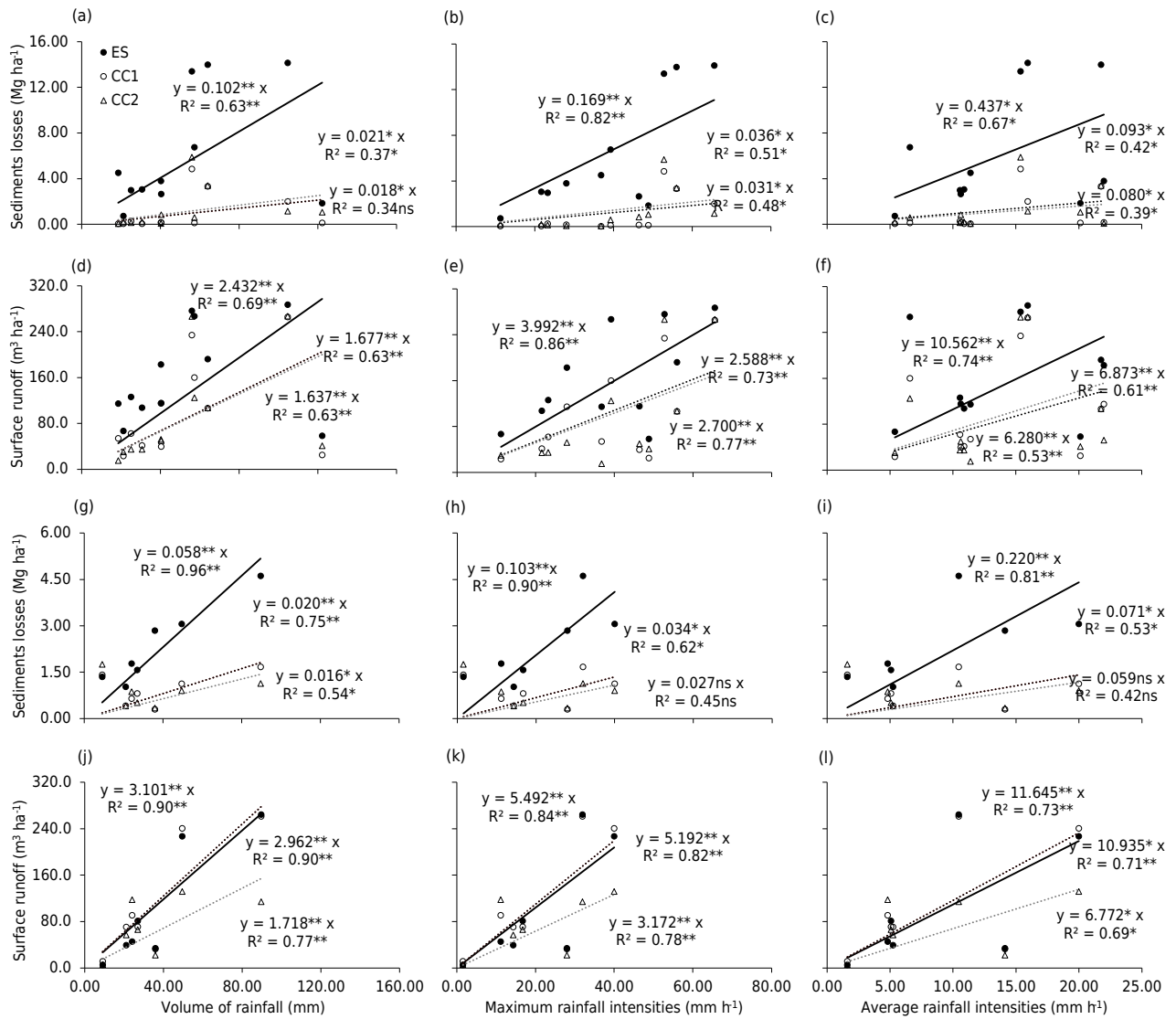


Figure 4. Linear regression between sediment loss (a, b, c, g, h and i) and surface runoff (d, e, f, j, k and l) with the volume and maximum and average rainfall intensities in between-rows spacing of coffee plants with exposed soil (ES) and cover crops (CC1 and CC2) evaluated from September/2021 to March/2022 (a to f) and from September to December/2022 (g to l). ^{ns} not significant (F test, $p > 0.05$); * and ** significant at 0.05 and 0.01, respectively.

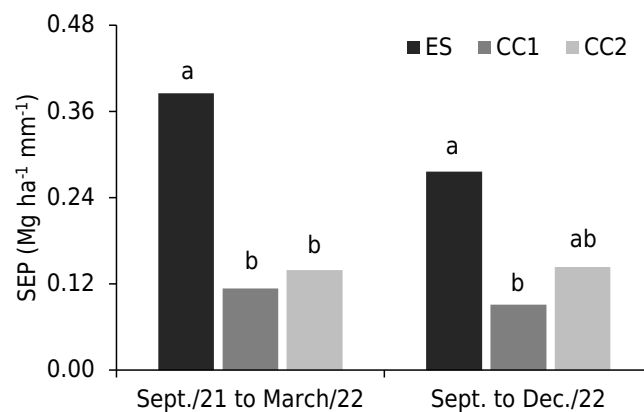


Figure 5. Sediment entrainment potential (SEP) in between-rows spacing of coffee plants with exposed soil (ES) and with cover crops with brachiaria and nutsedge (CC1) and purslane (CC2) evaluated in the periods from September/2021 to March/2022 and from September to December/2022. Averages followed by the same letter do not vary statistically (Tukey's test, $p < 0.05$).

In the period from September to December/2022, CC2 (136.26 mg dm⁻³) presented a lower potassium content ($p = 0.003$) in the sediment compared to ES (220 mg dm⁻³) and CC1 (210 mg dm⁻³), with a reduction of 38 and 35 %, respectively (Table 2). In the same period, CC1 (11.5 mg dm⁻³) and CC2 (12.1 mg dm⁻³) presented lower nitrogen content in surface runoff ($p = 0.043$) than ES (18.9 mg dm⁻³), with a reduction of 39 and 36 %, respectively. The managements did not differ statistically from each other for the contents of other nutrients and for organic carbon in the sediment or for the nutrients in surface runoff in the two periods evaluated ($p = 0.051$ to 0.939).

The CC2 (0.38) presented a lower sediment enrichment rate with potassium ($p = 0.003$) compared to ES (0.61) and CC1 (0.58) in the period from September to December/2022 (Table 3), with a reduction of 38 and 34%. The managements did not differ from each other ($p = 0.129$ to 0.937) for the enrichment rate of organic carbon and other nutrients in the two periods evaluated. The three managements presented enrichment rates greater than 1.00 for organic carbon (1.13 to 1.46) and magnesium (1.11 to 1.86) in both periods and for calcium (1.07 to 1.21) in the period from September to December/2022 and for ES and CC2 for potassium in the period from September/2021 to March/2022 (1.16 and 1.26). The other nutrients showed enrichment rates lower than 1.00 in the evaluated periods.

Table 2. Content of organic carbon (OC), nitrogen (N), phosphorus (P), potassium (K⁺), calcium (Ca²⁺) and magnesium (Mg²⁺) in sediment and/or surface runoff in the between-rows spacing of coffee plants with exposed soil (ES) and with cover crops (CC1 and CC2) sampled in the periods from September/2021 to March/2022 and from September to December/2022

Management ⁽¹⁾	Sediment					Surface runoff		
	OC	P	K	Ca ²⁺	Mg ²⁺	N	P	K ⁺
	g dm ⁻³	mg dm ⁻³		cmol _c dm ⁻³			mg dm ⁻³	
September/2021 to March/2022								
ES	13.2 a	58.0 a	297 a	5.63 a	2.23 a	14.8 a	0.33 a	60.4 a
CC1	12.9 a	44.1 a	234 a	4.40 a	1.90 a	31.0 a	0.41 a	54.9 a
CC2	10.8 a	39.7 a	321 a	4.27 a	2.03 a	20.9 a	0.31 a	56.4 a
September to December/2022								
ES	14.5 a	43.5 a	220 a	5.34 a	1.80 a	18.9 a	0.59 a	59.5 a
CC1	14.1 a	50.6 a	210 a	5.40 a	1.60 a	11.5 b	0.49 a	55.4 a
CC2	14.2 a	64.8 a	136 b	6.07 a	1.33 a	12.1 b	0.71 a	53.9 a

⁽¹⁾ Averages followed by the same letter do not differ statistically (Tukey's test, $p < 0.05$).

Table 3. Enrichment rate of sediment and surface runoff for organic carbon (OC), phosphorus (P), potassium (K), calcium (Ca) and magnesium (Mg) in the between-rows spacing of coffee plants with exposed soil (ES) and with cover crops with palisadegrass and nutsedge (CC1) and purslane (CC2) sampled in the periods from September/2021 to March/2022 and from September to December/2022

Management ⁽¹⁾	Sediment					Surface runoff	
	OC	P	K	Ca	Mg	P	K
September/2021 to March/2022							
ES	1.38 a	0.38 a	1.16 a	0.99 a	1.86 a	0.002 a	0.24 a
CC1	1.35 a	0.29 a	0.92 a	0.77 a	1.58 a	0.003 a	0.22 a
CC2	1.13 a	0.26 a	1.26 a	0.75 a	1.69 a	0.002 a	0.22 a
September to December/2022							
ES	1.46 a	0.35 a	0.61 a	1.07 a	1.50 a	0.005 a	0.16 a
CC1	1.42 a	0.40 a	0.58 a	1.08 a	1.33 a	0.004 a	0.15 a
CC2	1.43 a	0.52 a	0.38 b	1.21 a	1.11 a	0.006 a	0.15 a

⁽¹⁾ Averages followed by the same letter do not differ statistically (Tukey's test, $p < 0.05$).

The ES presented the greatest losses in the amount of organic carbon (890 and 347 kg ha⁻¹), phosphorus (3.90 and 1.03 kg ha⁻¹), potassium (20.48 and 5.29 kg ha⁻¹), calcium (76.2 and 25.5 kg ha⁻¹), magnesium (18.03 and 5.30 kg ha⁻¹) in the eroded sediment in the two periods under study (Table 4). The CC1 and CC2 showed reductions of 65 to 84 % for total organic carbon, 54 to 87 % for phosphorus, 65 to 88 % for potassium, 63 to 87 % for calcium and 68 to 86 % for magnesium in the sediment. The managements did not differ statistically from each other for nitrogen ($p = 0.421$ and 0.079), phosphorus ($p = 0.096$ and 0.711) and potassium ($p = 0.129$ and 0.353) in surface runoff in the two periods under study. CC1 and CC2 did not differ statistically from each other for nutrients in the sediment and surface runoff in the two periods under study.

DISCUSSION

The lower sediment loss and surface runoff in CC1 and CC2 in relation to ES occurred because of the presence of biomass on the soil surface (Figure 3), which intercepts raindrops (Nzeyimana et al., 2017) and acts as physical obstacle against surface runoff, creating tortuosity in the path of the erosive flow (Ramos-Scharrón and Thomaz, 2016; Wang et al., 2021). Even though grasses have thinner leaves and lower biomass production in the area compared to CC2 (Silva et al., 2021), these morphological differences did not result in differences in sediment loss and surface runoff between managements. Furthermore, weeds in between-rows spacing of coffee plants contributed to an increase in soil porosity and a reduction in density that favor water infiltration into the soil, which can reduce runoff volume and sediment transport (Ramos-Scharrón and Thomaz, 2016; Nzeyimana et al., 2017). Nguyen and Pham (2018) found a reduction of 63 to 76 % in soil loss in places with coffee cultivation using terraces and planting strips of grass and legumes compared to cultivation only on a contour line. For Tu et al. (2021), the cultivation of coffee with peanuts and sunn hemp (*Crotalaria juncea* L.) in between-rows spacing provided greater growth of coffee plants and reduced soil loss by 3.39 Mg ha⁻¹ yr⁻¹, corresponding to 28 %.

In areas with exposed soil, raindrops fall directly on the soil surface, which causes the closure of superficial soil pores by the impact of raindrops or the sealing by fine sediment, resulting from the disaggregation of particles (Ramos-Scharrón and Thomaz, 2016; Bashagaluke et al., 2018). These characteristics make water infiltration into the soil difficult and increase surface flow (Ramos-Scharrón and Figueroa-Sánchez, 2017), partly diverging from this research due to the lack of statistical difference between managements for the volume of surface runoff from September to December/2022 (Figure 3). This might be explained by the presence of cover crops that increase the water content in the soil, which resulted in a lower volume of rain to saturate the soil and consequently increase surface runoff (Ziadat and Taimeh, 2013; Ramos-Scharrón and Thomaz, 2016).

Table 4. Amount of organic carbon (OC), nitrogen (N), phosphorus (P), potassium (K), calcium (Ca) and magnesium (Mg) in sediment and/or surface runoff in the between-rows spacing of coffee plants with exposed soil (ES) and with cover crops (CC1 and CC2) sampled in the periods from September/2021 to March/2022 and from September to December/2022

Management ⁽¹⁾	Sediment					Surface runoff		
	OC	P	K	Ca	Mg	N	P	K
kg ha ⁻¹								
September/2021 to March/2022								
ES	890 a	3.90 a	20.48 a	76.2 a	18.03 a	27.5 a	0.58 a	107.3 a
CC1	140 b	0.50 b	2.50 b	10.1 b	2.61 b	33.0 a	0.45 a	61.6 a
CC2	141 b	0.50 b	4.07 b	11.0 b	3.20 b	21.7 a	0.32 a	60.2 a
September to December/2022								
ES	347 a	1.03 a	5.29 a	25.5 a	5.30 a	16.5 a	0.52 a	52.2 a
CC1	122 b	0.43 b	1.82 b	9.3 b	1.69 b	11.1 a	0.46 a	53.4 a
CC2	102 b	0.47 b	0.98 b	8.8 b	1.18 b	7.5 a	0.40 a	35.2 a

⁽¹⁾ Averages followed by the same letter do not differ statistically (Tukey's test, $p < 0.05$).

Sediment loss values of the three managements were consistent with those found by Nguyen and Pham (2018), ranging from 14.53 to 62.37 Mg ha⁻¹ yr⁻¹ in coffee plantations in Vietnam, and by Carvalho et al. (2007) in coffee plantations with cover crops and bare soil, ranging from 0.11 to 67.24 Mg ha⁻¹ yr⁻¹ in southeastern Brazil. However, sediment loss was greater than those found by Ramos-Scharrón and Thomaz (2016), ranging from 0.31 to 1.70 Mg ha⁻¹ yr⁻¹ for coffee plantations with cover crops and bare soil in Puerto Rico, and by Mendes Júnior et al. (2018) with a value of 1.58 Mg ha⁻¹ yr⁻¹ in southeastern Brazil. Volumes of surface runoff were lower than those found by Carvalho et al. (2007), ranging from 112.26 to 2,986.80 m³ ha⁻¹, and larger than Villatoro-Sánchez et al. (2015), on steep coffee slopes in Costa Rica, ranging from 330 to 1,030 m³ ha⁻¹.

The increase in volume and maximum and average rainfall intensities increased sediment loss and surface runoff linearly in the management with and without soil cover (Figure 4). This occurs due to soil saturation (Ziadat and Taimeh, 2013; Nzeyimana et al., 2017) or due to the rainfall intensity being greater than the rate of soil infiltration (Ramos-Scharrón and Figueroa-Sánchez, 2017). In both cases, the increase in rainfall volume and intensity resulted in greater surface flow and greater sediment entrainment potential (Römkens et al., 2002; Ziadat and Taimeh, 2013). In this study, CC1 and CC2 were efficient in reducing sediment and the volume of surface runoff, which agrees with Wang et al. (2021).

Rainfall in the first period was more erosive than in the second period, generating the greatest sediment loss and surface runoff, which agrees with Römkens et al. (2002). Furthermore, in the period from September/2021 to March/2022, coffee plants were smaller and consequently covered a smaller area. These two factors resulted in the highest values of sediment loss and surface runoff in the first period. High sediment loss resulting from a small increase in rainfall intensities indicates more soil susceptibility to erosion (Ziadat and Taimeh, 2013), as observed in this research. These results are further confirmed by the highest values of the angular coefficient of the linear equations of sediment loss in the two periods and surface runoff in the period from September/2021 to March/2022. A study carried out by Ziadat and Taimeh (2013) in soils cultivated with pasture and barley in Jordan did not show surface runoff at a rainfall intensity lower than 3 mm h⁻¹ and non-linear behavior for higher intensities, differing from the results of this research.

Reductions for the sediment entrainment potential in CC1 and CC2 in relation to ES were a result of the lower amount of produced sediments because of the cover crops that increase surface roughness and act as a physical barrier, decreasing the speed of surface flow (Römkens et al., 2002; Ziadat and Taimeh, 2013). These results agree with Cardoso et al. (2012), for soil cultivated with sunn hemp, jack beans, and millet, although the values are in a smaller range of values (0.040 to 0.061 Mg ha⁻¹ mm⁻¹). Carvalho et al. (2007) also found values ranging from 0.007 to 0.225 Mg ha⁻¹ mm⁻¹ in organic coffee crops with weeds in between-rows spacing and bare soil, respectively.

Reduction in CC2 in the potassium content in the sediment and of nitrogen content in the surface runoff, and in CC1 in the nitrogen content in the surface runoff may be the result of greater absorption by cover crops of these nutrients that have high mobility in the soil (Bramorski et al., 2015; Bertol et al., 2017), added to the beginning of the process of improving soil quality (Nzeyimana et al., 2017; Silva et al., 2021). In a long-term experiment with 15 years, Bertol et al. (2017) also found a reduction in the contents of organic carbon, phosphorus, potassium, calcium, and magnesium in sediment and surface runoff in management with plant residues on the soil surface in relation to management with periodic soil preparation, resulting in differences in soil nutrients contents. Therefore, the experiment period of less than two years was insufficient to modify the contents of organic carbon and soil nutrients between the evaluated management methods.

Reduction in the sediment enrichment rate with potassium in CC2 in relation to ES, in the period from September to December/2022, was presumably due to the presence of purslane plants on the soil surface (Table 4), with a value lower than 1,00, indicating the

conservationist nature of the use of purslane in between-row spacing of coffee plants, which agrees with Bashagaluque et al. (2018) and Silva et al. (2021). Canephora coffee crops in Brazil are generally well fertilized, reaching doses of 620, 140, and 600 kg ha⁻¹ of nitrogen, phosphorus, and potassium, respectively (Prezotti et al., 2019), and have high contents of soil nutrients (Prezotti et al., 2019), as presented in table 1. Thus, sediment enrichment rates greater than 1.00 demonstrate the ability of soil erosion to transport soil fertility outside the cultivation area (Cardoso et al., 2012; Bertol et al., 2017), promoting soil degradation, reducing coffee development (Wang et al., 2015; Tu et al., 2021) and increased production costs (Bashagaluque et al., 2018). Magnesium and organic carbon are the most vulnerable attributes in sediments, followed by calcium and potassium, which agrees with Cardoso et al. (2012). In the surface runoff, the enrichment rates were less than 1.00, agreeing with Hernani et al. (1999). These results also indicate that just the use of cover crops in between-rows spacing of canephora coffee plants is not enough to solve the problem of water erosion and the loss of carbon and nutrients, contributing to greenhouse gas emissions (Lugato et al., 2018; Lal, 2019).

The highest phosphorus and potassium contents occurred in the sediments compared to the surface runoff, contributing more significantly to soil impoverishment and degradation (Cardoso et al., 2012; Bramorski et al., 2015). Hernani et al. (1999) and Bertol et al. (2017) also found lower levels of phosphorus and potassium in the surface runoff than in sediments. The higher phosphorus content in the sediments reflects its specific adsorption and low solubility in the soil, while potassium is related to soil organic matter that is aggregated in the sediments (Hernani et al., 1999). Phosphorus was the nutrient lost in the smallest amount in the sediments and in the surface runoff, which agrees with Cardoso et al. (2012), while calcium and potassium were the nutrients that presented the highest quantities in the sediments and surface runoff, respectively, indicating the need for supplementation of these nutrients for the nutritional balance of canephora coffee crops (Wang et al., 2015; Prezotti et al., 2019).

Reductions in the amount of organic carbon and nutrients in sediments in CC1 and CC2 showed a lower amount of soil particles transported when using cover crops, which agrees with Hernani et al. (1999) and Bramorski et al. (2015). Plots without vegetation cover suffer physical degradation on the soil surface, increasing soil erodibility (Nzeyimana et al., 2017), which results in greater sediment production and surface runoff, increasing nutrient losses (Franco et al., 2002; Cardoso et al., 2012; Bertol et al., 2017). The CC1 and CC2 showed similar loss in the amount of nutrients, indicating that different weeds may efficiently control soil erosion in coffee plantations (Silva et al., 2021). Bashagaluque et al. (2018) found lower nutrient losses in cowpea compared to other systems with grasses and mixtures of legumes and grasses. Therefore, reducing nutrient losses is essential for the sustainable cultivation of canephora coffee plants and for protecting natural resources (Carvalho et al., 2007; Ziadat and Taimeh, 2013).

CONCLUSION

Weeds management in between-rows spacing of canephora coffee plants reduced sediment losses, organic carbon, nutrients and water (surface runoff), reducing soil degradation under canephora coffee plantations. Increase in rainfall volume and intensity significantly increased sediment loss and surface runoff, creating a greater sediment entrainment potential, which was reduced with weeds management in between-row spacing of canephora coffee plants. Management showed enrichment rates greater than 1.0 for organic carbon, potassium, calcium, and magnesium in the sediment, indicating that the erosion process reduced fertility and the amount of soil organic carbon. Maintenance of purslane in between-rows spacing of coffee plants proved to be advantageous for mitigating losses caused by water erosion, contributing to soil conservation and the sustainability of canephora coffee production.

DATA AVAILABILITY

The data will be provided upon request.

FUNDING

To the “Fundação de Amparo à Pesquisa e Inovação do Espírito Santo (Fapes)” for the financial resources designated to carry out part of the activities of this research (Process: 2022-XV00Z) and to Ifes for scientific initiation scholarships (10871/22) and financial support for publication.

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