Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Divergent rainfall delivery, runoff response, and retained-material composition across contrasting Andean coffee systems

Santiago Vásquez-Sogamoso[1]

santiago.vazquez@colmayor.edu.co

Institución Universitaria Colegio Mayor de Antioquia

Valeria Arias-Valencia[1]

Institución Universitaria Colegio Mayor de Antioquia

Víctor Manuel Serna[1]

Institución Universitaria Colegio Mayor de Antioquia

Andrea Anchila-Arteaga[1]

Institución Universitaria Colegio Mayor de Antioquia

Aura Cristina Restrepo[2]

Institución Universitaria Colegio Mayor de Antioquia

Research Article

Keywords: agroforestry hydrology, canopy redistribution, hydrological connectivity, mountain agriculture, soil-surface processes, tropical Andes

Posted Date: August 25th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-10694962/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: No competing interests reported.

Abstract

Hydrological regulation is frequently attributed to coffee agroforestry, but lower runoff beneath associated vegetation may partly reflect lower rainfall delivery to the soil rather than stronger surface regulation. We evaluated whether differences in rainfall delivery among contrasting coffee arrangements propagated to runoff and to the composition of transported material on steep Andean hillslopes. Six pre-existing 3 × 3 m runoff plots (two per arrangement) representing open-sun coffee, coffee associated with plantain (*Musa paradisiaca L.*), and coffee shaded by avocado trees (*Persea americana Mill.*) were monitored weekly for 21 weeks in southwestern Colombia. Open rainfall, within-plot rainfall, surface runoff, and the organic and mineral fractions of material retained on 1-mm and 100-µm meshes were quantified. Of 1187.96 mm of open rainfall, cumulative within-plot rainfall represented 88.27% in open-sun coffee, 46.64% in coffee-Musa, and 39.65% under tree shade. Absolute runoff was low (16.08, 12.74, and 11.72 mm, respectively), but runoff relative to within-plot rainfall was lowest in open-sun coffee (1.53% versus 2.30–2.49%). Mesh-retained material from tree-shaded coffee had the highest organic fraction (59.79%), whereas coffee-Musa showed the strongest mineral signal (49.96%). Weekly rainfall delivery and runoff covaried only moderately, and hydrological variables explained little variation in retained-material composition. Thus, canopy-mediated rainfall redistribution, runoff generation, and transported-material composition provided non-equivalent diagnoses. Agroforestry hydrological assessments should distinguish rainfall delivery from soil-surface regulation and source-material connectivity before attributing lower absolute runoff to improved water regulation.

Introduction

Tree-based coffee agroforestry is promoted as a means to diversify production while improving microclimate, soil condition, biodiversity, and water-related ecosystem services. Yet hydrological performance cannot be inferred from canopy presence alone. Recent work in coffee systems shows that agroforestry can substantially alter crop water use and drought response, while also creating spatially heterogeneous conditions and management trade-offs (Rigal et al. 2026). On steep humid hillslopes, runoff and surface disturbance are additionally controlled by rainfall, slope, ground cover, antecedent conditions, soil hydraulic properties, and hydrological connectivity (Ramos-Scharrón and Figueroa-Sánchez 2017; Ramos-Scharrón 2023; Blanco-Sepúlveda et al. 2024). In the Colombian Andes, these controls operate under strong hydroclimatic variability and complex topography (Galindo et al. 2022; Bedoya-Soto et al. 2025). Evaluating hydrological regulation in diversified coffee therefore requires separating processes that occur above the soil surface from those that govern overland flow after water reaches the ground.

Vegetation mediates the first transformation of rainfall through interception, throughfall, and stemflow. Leaves, branches, stems, and canopy gaps can either disperse rainfall or concentrate it at drip points and plant bases, generating strong heterogeneity in local soil wetting. The magnitude and spatial pattern of rainfall redistribution depend on storm characteristics, leaf area, canopy architecture, species composition, collector position, and monitoring duration (Cano-Arboleda et al. 2022; Rodrigues et al.

2022; de Mello et al. 2024). Plantain and shade trees create contrasting canopy architectures within coffee farms; banana canopies, for example, may funnel water toward specific locations (Yang et al. 2020). Consequently, less rainfall recorded beneath associated vegetation can reflect interception and lateral redistribution away from fixed collectors, not necessarily a lower capacity of the soil surface to generate runoff.

Once rainfall reaches the ground, the conversion of water to surface runoff depends on a second set of controls, including litter continuity, exposed soil, infiltration, antecedent wetness, microtopography, and connected flow paths. Ground cover can be more closely related to water-driven soil disturbance than shade itself in coffee agroforestry (Cerretelli et al. 2023; Blanco-Sepúlveda et al. 2024). Absolute runoff may therefore decline simply because less water is delivered to a plot, whereas runoff normalized by local rainfall delivery provides a complementary measure of surface response. The composition of transported material adds a third dimension. Organic-rich material can include litter fragments and organic-rich aggregates, whereas mineral-rich material can reflect detached aggregates or exposed mineral soil. Their relative abundance depends on source availability and connectivity as well as on runoff magnitude (Kirkels et al. 2014; Santana et al. 2024; Shi et al. 2025). Thus, rainfall delivery, runoff response, and particulate composition need not vary in parallel.

Few field studies have connected these three stages within the same coffee landscape, particularly under on-farm conditions in the tropical Andes. Such comparisons are also methodologically challenging because agroforestry systems are inherently spatially heterogeneous and reference plots may differ in local site properties (Minarsch et al. 2025). We therefore conducted a comparative observational study using six pre-existing runoff plots representing open-sun coffee, coffee associated with *Musa paradisiaca L.*, and coffee shaded by *Persea americana Mill.* The coffee-Persea arrangement constituted the tree-crop agroforestry system, whereas the other arrangements provided non-tree reference configurations within the same landscape. We asked whether the arrangements differed in (1) within-plot rainfall, absolute runoff, and runoff relative to rainfall received; (2) the organic-mineral composition of mesh-retained transported material; and (3) the temporal association between hydrological variables and retained-material composition. We expected associated vegetation to coincide with lower local rainfall delivery and lower absolute runoff, but not necessarily with lower runoff per unit of water received. We further expected tree-shaded plots to retain a more organic-rich fraction, coffee-Musa plots to show a stronger mineral signal, and composition to be only weakly coupled with weekly hydrological variation. These expectations were evaluated as plot-scale observational patterns rather than causal treatment effects.

Materials and methods

Study area

The study was conducted in the Santa Rita rural district of Andes municipality, southwestern Antioquia, Colombia, on the eastern-facing mountain landscape of the Western Cordillera. The monitored area was

located at approximately 1714–1734 m a.s.l. under humid tropical mountain conditions, with annual rainfall commonly ranging from 2000 to 2500 mm. The coffee landscape included open-sun stands and plots associated with plantain or shade trees. Monitored hillslopes had an approximate slope of 52%, representative of the steep terrain used for coffee production in the region.

Soils were influenced by volcanic-ash materials and locally classified at the Soil Order level as Andisols. Plot-specific texture, bulk density, hydraulic conductivity, aggregate stability, antecedent soil moisture, and infiltration were not measured. Canopy cover, litter cover, bare-soil percentage, crop density, and shade-tree density were also unavailable. Vegetation systems were therefore defined operationally by their dominant arrangement, and unmeasured soil or canopy properties were treated as candidate controls rather than demonstrated mechanisms.

Comparative field design and inferential scope

Six bounded runoff plots were distributed between two zones (A and B) within the same coffee-growing landscape. Each zone contained one plot representing each arrangement, yielding two plots per arrangement. Plots A1 and B1 represented open-sun coffee; A2 and B2 represented coffee associated with *Musa paradisiaca L.* AAB subgroup cv. Hartón; and A3 and B3 represented coffee under tree shade associated with *Persea americana Mill.* cv. Edranol. The main crop was *Coffea arabica L.*, approximately 5 years old. Each plot measured 3 × 3 m (9 m²).

Zones were selected for comparable crop age, hillslope setting, and local management. Arrangements were pre-existing and were not randomly assigned. No fertilization, litter removal, tillage, or other intervention was conducted inside plots during monitoring. The plot was the independent spatial unit, and weekly observations were repeated measurements within plots. With two plots per arrangement, vegetation arrangement and local plot identity could not be separated fully. Analyses therefore emphasize magnitudes, normalized responses, temporal co-variation, and consistency among indicators rather than replicated causal effects.

Runoff collection and rainfall monitoring

Each plot drained toward a collector channel connected by PVC pipe to an 85-L storage tank. A 1-mm mesh in the collector retained coarse plant fragments and aggregates, and a 100-µm nylon mesh at the pipe-tank connection retained smaller particles before water entered the tank. Material recovered from both stages was combined and operationally termed mesh-retained material transported by surface runoff. Collectors, meshes, pipes, and tanks were inspected and cleaned after each weekly interval. No tank overflow or persistent filter clogging was recorded during valid observations.

Open rainfall (P) was measured with four custom-fabricated manual rain gauges consisting of 20.3-cm-diameter funnels fitted to plastic bottles and mounted on wooden supports 1.3 m above ground in nearby open positions. Rainfall delivered within each plot (TF) was measured with two fixed manual

gauges, and the plot-level weekly value was their arithmetic mean. These gauges sampled local rainfall delivery but did not resolve the full spatial variability of canopy drip points. TF was used operationally as within-plot rainfall; because stemflow and interception loss were not measured, it was not interpreted as a complete canopy water balance. Gauge collection area and runoff depth were calculated as follows:

$A_c = \pi r^2$ (1)

$RO = V_r / A_p$ (2)

where A_c is gauge collection area (m^2), r is internal gauge radius (m), RO is runoff depth (mm), V_r is collected runoff volume (L), and A_p is plot area (9 m^2). Rainfall volume was converted to depth because 1 L m^{-2} is equivalent to 1 mm.

Field monitoring and data quality

Monitoring was conducted weekly for 21 consecutive weeks between July and December 2024. Collected water volumes were quantified volumetrically. Material retained on both meshes was recovered, combined by plot and date, labelled, and transported to the laboratory of the Institución Universitaria Colegio Mayor de Antioquia.

Observations affected by sampling failure, obstruction, sample loss, or missing paired data were coded as missing and were not replaced by zero. The week of 18 August 2024 was excluded because no valid rainfall, runoff, or retained-material data were available. Twenty valid weeks contributed to system-level hydrological totals; sample sizes in composition and correlation summaries varied according to paired field and laboratory records. Complete field-sample dry mass was not used to estimate plot-level export, so total soil loss or particulate mass per unit area was not calculated.

Loss-on-ignition characterization

Field samples were transferred to labelled kraft paper and oven-dried at 105°C for 24 h or until constant mass in a universal drying oven (UN30, Memmert GmbH + Co. KG, Schwabach, Germany). Material from both meshes was homogenized without removing plant fragments because the objective was to characterize the retained mixture. A representative quartered subsample was placed in a previously dried and weighed 50-mL crucible and weighed with a precision balance (Explorer EX223/E, OHAUS Corporation, Parsippany, New Jersey, USA; 220-g capacity, 0.001-g readability).

Subsamples were combusted at 500°C for 4 h in a laboratory muffle furnace (M104, Thermo Scientific, Langenselbold, Germany), cooled in a desiccator, and reweighed. Loss on ignition estimated the combustible fraction of the retained mixture while leaving an ash residue operationally interpreted as mineral material; it was not treated as a direct measurement of soil organic carbon. Calculations were:

$SDM = W_i - W_c$ (3)

MM = W_f - W_c (4)

OM = SDM - MM (5)

OM (%) = 100 × OM / SDM (6)

MM (%) = 100 × MM / SDM (7)

where SDM is dry subsample mass (g), W_i is crucible plus dry subsample mass, W_c is empty-crucible mass, W_f is crucible plus ash-residue mass, MM is mineral residue, and OM is mass lost during ignition. Organic and mineral percentages were complementary for each valid subsample. Because complete field-sample dry mass was not used to estimate export and particles smaller than 100 µm passed through the collection system, the analysis characterized retained-material composition rather than total sediment yield, particulate export, or soil loss per unit area.

Data analysis

The database contained plot-week observations indexed by date, zone, plot, and arrangement. The plot remained the independent spatial unit; weekly records described temporal behavior within plots. Weekly arrangement means for TF and RO were calculated from the two plots when both values were available, and cumulative values were obtained by summing weekly means. Two ratios separated rainfall delivery from runoff response: TF/P × 100, the proportion of open rainfall recorded inside plots, and RO/TF × 100, runoff relative to rainfall received inside plots.

Loss-on-ignition-derived organic and mineral fractions were summarized by arrangement using valid plot-week count, mean, standard deviation, median, and range. Counts represent repeated observations within two plots and were not treated as independent treatment replicates. Spearman coefficients for TF-RO, TF-organic fraction, and RO-organic fraction were calculated across pooled records and within arrangements to describe temporal co-variation. Trend lines were used as visual summaries rather than mechanistic models. Because the arrangements were represented by only two spatial plots, inferential P-values from pooled plot-week observations were not used to establish vegetation effects.

Cumulative magnitudes and normalized ratios provided the primary comparison. Analyses were conducted in R version 4.2.1 using RStudio version 2023. Interpretation focused on the direction and consistency of observed contrasts and on whether hydrological and compositional indicators converged or diverged.

Results

Rainfall delivery and runoff response

Open rainfall varied markedly and totaled 1187.96 mm across 20 valid weeks, with a weekly mean of 59.40 ± 45.92 mm. Within-plot rainfall differed more strongly among systems than runoff. Open-sun coffee received 52.43 ± 41.81 mm week⁻¹ and accumulated 1048.58 mm, equivalent to 88.27% of open rainfall. Coffee-Musa received 27.70 ± 15.53 mm week⁻¹ and accumulated 554.01 mm (46.64%), whereas tree-shaded coffee received 23.55 ± 13.89 mm week⁻¹ and accumulated 470.99 mm (39.65%; Table 1; Fig. 2).

Absolute runoff remained low. Cumulative RO was 16.08 mm in open-sun coffee, 12.74 mm in coffee-Musa, and 11.72 mm under tree shade, with weekly means of 0.80 ± 0.56, 0.64 ± 0.54, and 0.59 ± 0.39 mm, respectively. The ranking of absolute runoff followed within-plot rainfall, but differences were proportionally smaller. Runoff represented 1.53%, 2.30%, and 2.49% of TF, respectively. Thus, the two associated systems showed lower absolute runoff but not lower runoff relative to water recorded inside the plots.

Table 1
Rainfall delivery and surface runoff in three monitored coffee arrangements. Values are means ± standard deviation of valid weekly means; cumulative values are sums of weekly means

Variable	Open-sun coffee	Coffee-Musa	Coffee-tree shade
P, mean (mm week⁻¹)	59.40 ± 45.92	59.40 ± 45.92	59.40 ± 45.92
P, cumulative (mm)	1187.96	1187.96	1187.96
TF, mean (mm week⁻¹)	52.43 ± 41.81	27.70 ± 15.53	23.55 ± 13.89
TF, cumulative (mm)	1048.58	554.01	470.99
TF/P (%)	88.27	46.64	39.65
RO, mean (mm week⁻¹)	0.80 ± 0.56	0.64 ± 0.54	0.59 ± 0.39
RO, cumulative (mm)	16.08	12.74	11.72
RO/TF (%)	1.53	2.30	2.49

P: open rainfall; TF: within-plot rainfall; RO: surface runoff. Ratios were calculated from cumulative values. Two spatial plots represented each coffee system.

Organic-mineral composition of retained material

Pooled plot-week composition followed a different ranking from absolute runoff. Tree-shaded coffee had the highest mean loss-on-ignition-derived organic fraction (59.79 ± 10.17%; 40 repeated observations), open-sun coffee was intermediate (55.75 ± 10.31%; 34 observations), and coffee-Musa had the lowest mean organic fraction (50.04 ± 17.66%; 37 observations). Complementary mineral fractions were 40.21 ± 10.17%, 44.25 ± 10.31%, and 49.96 ± 17.66%, respectively (Table 2; Fig. 3).

The coffee-Musa arrangement also showed the broadest temporal dispersion in both fractions. Because these observations were repeated measurements within two spatial plots per system, the distributions describe temporal and within-system variation rather than replicated treatment effects.

Table 2
Loss-on-ignition-derived organic and mineral fractions of mesh-retained material

Coffee system	n	Organic fraction (%)	Mineral fraction (%)
Open-sun coffee	34	55.75 ± 10.31	44.25 ± 10.31
Coffee-*Musa paradisiaca*	37	50.04 ± 17.66	49.96 ± 17.66
Coffee-tree shade	40	59.79 ± 10.17	40.21 ± 10.17

Values are pooled means ± standard deviation of repeated plot-week subsamples from two spatial plots per system. The fractions are complementary and describe composition, not mass export.

Hydrological-compositional coupling

Across pooled weekly records, TF and RO covaried positively but only moderately (Spearman ρ = 0.30; n = 105; Fig. 4a). Arrangement-specific coefficients were 0.48 in coffee-Musa (n = 35), 0.34 in open-sun coffee (n = 32), and 0.12 under tree shade (n = 38). These coefficients describe temporal co-variation within a clustered dataset rather than independent replication of vegetation effects.

The organic fraction was only weakly associated with TF across pooled records (ρ = 0.10) and with RO (ρ = 0.13). Arrangement-specific TF-organic fraction coefficients ranged from approximately zero under tree shade to 0.34 in coffee-Musa, while RO-organic fraction coefficients ranged from 0.11 to 0.21. Weekly water inputs therefore explained little of the observed variation in the relative organic-mineral character of retained material.

Discussion

Rainfall redistribution was the dominant hydrological contrast

The clearest difference among the monitored coffee systems occurred before runoff generation: rainfall recorded inside the plots declined from 88.27% of open rainfall in open-sun coffee to 46.64% in coffee-Musa and 39.65% under tree shade. This pattern is consistent with associated vegetation intercepting and spatially redistributing rainfall before it reached the fixed collectors. Canopy rainfall delivery is strongly affected by architecture, species identity, storm properties, and collector position (Cano-Arboleda et al. 2022; Rodrigues et al. 2022; de Mello et al. 2024). In coffee agroforestry, hydrological effects of trees also extend beyond rainfall partitioning; recent coffee-avocado work has shown substantial differences in crop transpiration between agroforestry and monoculture, while emphasizing

spatial heterogeneity within shaded systems (Rigal et al. 2026). Together, these findings reinforce that tree-associated coffee alters the spatial architecture of water delivery rather than simply reducing a single water-balance component.

The large contrast in within-plot rainfall was not matched by an equivalent contrast in surface runoff. Open-sun coffee generated the highest cumulative runoff, but the difference among systems was small relative to the difference in water recorded at the surface. When runoff was normalized by TF, the associated arrangements showed higher RO/TF ratios than open-sun coffee. Because two fixed gauges cannot characterize the full spatial distribution of canopy drip points, these ratios should not be interpreted as whole-system hydrological efficiencies. Even so, the contrast is informative: lower absolute runoff under associated vegetation did not, by itself, demonstrate stronger runoff regulation per unit of locally delivered rainfall.

Soil-surface controls can decouple rainfall delivery from runoff

The nonparallel responses of TF and RO indicate that processes at the soil surface and along connected flow paths likely moderated the conversion of rainfall into overland flow. Ground-cover continuity, litter, soil hydraulic condition, antecedent wetness, microtopography, and hydrological connectivity can strongly influence runoff and sediment production on steep agricultural hillslopes (Ramos-Scharrón and Figueroa-Sánchez 2017; Ramos-Scharrón 2023; Davari et al. 2024; Perron et al. 2024). In coffee agroforestry, ground cover has been more consistently associated with erosion mitigation than shade alone, and management scenarios can substantially alter erosion risk (Cerretelli et al. 2023; Blanco-Sepúlveda et al. 2024). Volcanic-ash-influenced soils may also sustain high porosity and infiltration under favorable structural conditions (Suprayogo et al. 2020), although tropical Andean runoff responses remain sensitive to topography and land cover (Mosquera et al. 2023; Crespo et al. 2026). Because these properties were not quantified at the plot level, they remain plausible controls rather than demonstrated mechanisms.

This distinction matters for agroforestry ecosystem-service claims. A shaded system may receive less locally measured rainfall and consequently produce less absolute runoff even if the soil surface converts a similar or larger proportion of the received water to overland flow. Conversely, a system with greater rainfall delivery can still have a low runoff coefficient if infiltration and ground cover limit surface connectivity. Recent conceptual work on hydrology in diversified agroecosystems similarly emphasizes that water should be understood through spatial and biological heterogeneity rather than as a uniform input (Ameur 2026). Our plot-scale results provide an empirical counterpart to that idea for rain-fed mountain coffee.

Retained-material composition provided an independent signal

The composition of mesh-retained material followed a different pattern from the hydrological variables. Tree-shaded coffee had the highest organic fraction, coffee-Musa had the strongest mineral signal, and open-sun coffee was intermediate despite receiving the most rainfall and generating the highest cumulative runoff. The arrangement with the greatest runoff therefore did not contain the most mineral-rich retained material. This divergence is consistent with particulate transfer being governed by source-material availability and connectivity in addition to water volume (Kirkels et al. 2014; Ramos-Scharrón 2023; Santana et al. 2024; Shi et al. 2025).

The higher organic fraction under tree shade is compatible with a larger relative contribution of litter fragments, partially decomposed residues, and organic-rich aggregates. Agroforestry can increase organic inputs and alter soil properties, but those benefits vary with system structure and management (Ngaba et al. 2024). The stronger mineral signal in coffee-Musa could reflect greater availability of exposed mineral material, aggregate mobilization, or stronger connectivity between mineral source areas and runoff pathways. Plantain architecture can also concentrate water at drip points and stem zones (Yang et al. 2020). However, litter mass, bare-soil exposure, stemflow, drip-point intensity, and source-area connectivity were not measured, so these interpretations remain hypotheses for subsequent work rather than demonstrated mechanisms.

The analytical meaning of this gradient also requires caution. Loss on ignition quantified the relative combustible fraction of material larger than 100 µm retained by the collection system. It did not quantify soil organic carbon directly, particles smaller than 100 µm were not captured, and complete field-sample dry mass was unavailable. The reported fractions therefore cannot be converted to organic or mineral export, carbon fluxes, erosion rates, or total soil loss. Their value is complementary: composition revealed differences in the nature of transported material that runoff magnitude alone did not capture.

Implications for agroforestry assessment and study scope

Hydrological regulation in coffee agroforestry should therefore be assessed as a sequence of linked but non-equivalent processes: rainfall redistribution by the vegetation layer, conversion of delivered water to runoff at the soil surface, and mobilization of available source material. Measuring only absolute runoff can confound the first two processes; measuring runoff without composition can miss changes in the type of material transported. A stronger monitoring design would combine open rainfall, spatially replicated throughfall or rainfall-delivery collectors, stemflow, litter and bare-soil cover, infiltration or hydraulic conductivity, antecedent moisture, and complete sediment mass. Spatially explicit sampling around tree-crop interfaces would be particularly valuable because heterogeneity is intrinsic to agroforestry systems (Minarsch et al. 2025).

Repeated weekly measurements increased temporal resolution but did not increase the number of independent spatial units. Because each pre-existing arrangement was represented by two plots, system identity could not be separated fully from local plot differences. The results should therefore not be used to rank open-sun, coffee-Musa, and coffee-Persea systems as universally superior or inferior. Their broader contribution is methodological and conceptual: canopy-mediated water delivery, proportional

runoff response, and transported-material composition can diverge within the same steep coffee landscape, so multiple indicators are needed before hydrological ecosystem services are attributed to vegetation diversification.

Conclusions

Across this observational comparison, coffee with associated vegetation received substantially less rainfall at fixed surface collectors than open-sun coffee, whereas differences in absolute runoff were comparatively small and runoff relative to recorded within-plot rainfall was not lower. Tree-shaded coffee retained a more organic-rich fraction, coffee-Musa a more mineral-rich fraction, and retained-material composition was only weakly related to weekly water delivery or runoff. These patterns show that canopy-mediated rainfall redistribution, runoff generation, and source-material composition should be treated as distinct dimensions of hydrological ecosystem-service assessment. For coffee agroforestry, claims of improved runoff regulation should therefore be supported by measurements of both rainfall reaching the soil and soil-surface controls, ideally using spatially explicit sampling around tree-crop interfaces. Because the study used two pre-existing plots per arrangement and did not quantify stemflow, ground cover, infiltration, or total sediment export, the findings identify transferable monitoring principles rather than causal rankings among coffee systems.

Declarations

Competing interests

The authors have no relevant financial or non-financial interests to disclose.

Ethics approval

Not applicable. The study did not involve human participants or vertebrate animals.

Funding

This study was funded by the Institución Universitaria Colegio Mayor de Antioquia through its Internal Research Call.

Author Contribution

Conceptualization: S.V, A. R; Methodology: S.V, A.A, A. R; Validation: S.V, V.S, A.A, A. R; Formal analysis: S.V;Data curation: S.V, V.A-Valencia; Writing - original draft: S.V; Writing - review and editing: all authors;

Visualization: S.V; Supervision: S.V, A.A, A.R; Project administration and funding acquisition: S.V. All authors read and approved the final manuscript.

Acknowledgments

The authors acknowledge the Institución Universitaria Colegio Mayor de Antioquia for logistical support through its Internal Research Call.

Data availability

The datasets generated and analyzed during the current study are available from the corresponding author on reasonable request.

References

1. Ameur F (2026) From water dose to niche architecture: the 5D-Hydro framework for diversified agroecosystems. Agroforestry Systems 100:242. https://doi.org/10.1007/s10457-026-01625-1
2. Bedoya-Soto JM, Acevedo E, Sauchyn D, Poveda G, Urán A (2025) El Niño-Southern Oscillation impacts in a coffee growing region of Colombia and adaptation mechanisms among coffee producers. Journal of Environmental Studies and Sciences 16:298–318. https://doi.org/10.1007/s13412-025-01038-z
3. Blanco-Sepúlveda R, Lima F, Aguilar-Carrillo A (2024) An assessment of the shade and ground cover influence on the mitigation of water-driven soil erosion in a coffee agroforestry system. Agroforestry Systems 98:1771–1782. https://doi.org/10.1007/s10457-024-00989-6
4. Cano-Arboleda LV, Villegas JC, Restrepo AC, Quintero-Vallejo E (2022) Complementary effects of tree species on canopy rainfall partitioning: new insights for ecological restoration in Andean ecosystems. Forest Ecology and Management 507:119969. https://doi.org/10.1016/j.foreco.2021.119969
5. Cerretelli S, Castellanos E, González-Mollinedo S, Lopez E, Ospina A, Haggar J (2023) A scenario modelling approach to assess management impacts on soil erosion in coffee systems in Central America. Catena 228:107182. https://doi.org/10.1016/j.catena.2023.107182
6. Crespo CMG, Piscoya VC, de Melo RCP et al (2026) Topographic modulation of soil functional indicators in shaded coffee agroforestry systems: a multivariate and network-based approach. Scientific Reports 16:11455. https://doi.org/10.1038/s41598-026-37724-3
7. Davari M, Saeidpoor B, Khaleghpanah N, Moradi S (2024) Impacts of land use/cover change on soil hydrological properties, runoff, and erosion: results from micro-plots in Western Iran. Environmental Earth Sciences 83:508. https://doi.org/10.1007/s12665-024-11813-w

8. de Mello CR, Guo L, Yuan C, Rodrigues AF, Lima RR, Terra MCNS (2024) Deciphering global patterns of forest canopy rainfall interception: a synthesis of geographical, forest species, and methodological influences. Journal of Environmental Management 358:120879. https://doi.org/10.1016/j.jenvman.2024.120879
9. Galindo V, Giraldo C, Lavelle P, Armbrecht I, Fonte SJ (2022) Land use conversion to agriculture impacts biodiversity, erosion control, and key soil properties in an Andean watershed. Ecosphere 13:e3979. https://doi.org/10.1002/ecs2.3979
10. Kirkels FMSA, Cammeraat LH, Kuhn NJ (2014) The fate of soil organic carbon upon erosion, transport and deposition in agricultural landscapes: a review of different concepts. Geomorphology 226:94–105. https://doi.org/10.1016/j.geomorph.2014.07.023
11. Minarsch EML, Thoss VM, Beule L (2025) Guidance on spatial sampling designs and data reusability in agroforestry research. Agroforestry Systems 99:127. https://doi.org/10.1007/s10457-025-01225-5
12. Mosquera GM, Célleri R, Crespo P (2023) Effects of land cover on storm runoff generation in tropical Andean headwaters. Journal of Hydrology 624:129800. https://doi.org/10.1016/j.jhydrol.2023.129800
13. Ngaba MJY, Mgelwa AS, Gurmesa GA et al (2024) Meta-analysis unveils differential effects of agroforestry on soil properties in different zonobiomes. Plant and Soil 496:589–607. https://doi.org/10.1007/s11104-023-06385-w
14. Perron T, Legrand M, Janeau J-L et al (2024) Runoff and soil loss are drastically decreased in a rubber plantation combining the spreading of logging residues with a legume cover. Science of the Total Environment 913:169335. https://doi.org/10.1016/j.scitotenv.2023.169335
15. Ramos-Scharrón CE (2023) On the hydro-geomorphology of steepland coffee farming: runoff and surface erosion. Agricultural Water Management 289:108568. https://doi.org/10.1016/j.agwat.2023.108568
16. Ramos-Scharrón CE, Figueroa-Sánchez Y (2017) Plot-, farm-, and watershed-scale effects of coffee cultivation in runoff and sediment production in western Puerto Rico. Journal of Environmental Management 202:126–136. https://doi.org/10.1016/j.jenvman.2017.07.020
17. Rigal C, Hoang QT, Duong B et al (2026) Transpiration dynamics of Robusta coffee in response to irrigation regime, agroforestry system, and dry season severity. Agroforestry Systems 100:167. https://doi.org/10.1007/s10457-026-01540-5
18. Rodrigues AF, Terra MCNS, Mantovani VA et al (2022) Throughfall spatial variability in a neotropical forest: have we correctly accounted for time stability? Journal of Hydrology 608:127632. https://doi.org/10.1016/j.jhydrol.2022.127632
19. Santana DB, Rios GS, Lense GHE et al (2024) Soil and organic carbon losses by water erosion in coffee production areas in southern Minas Gerais, Brazil. Turkish Journal of Agriculture and Forestry 48:317–331. https://doi.org/10.55730/1300-011X.3184

20. Shi C, Liang Y, Qin W, Ding L, Cao W, Zhang M, Zhang Q (2025) Review of sediment connectivity: conceptual connotations, characterization indicators, and their relationships with soil erosion and sediment yield. Earth-Science Reviews 264:105091. https://doi.org/10.1016/j.earscirev.2025.105091
21. Suprayogo D, van Noordwijk M, Hairiah K et al (2020) Infiltration-friendly agroforestry land uses on volcanic slopes in the Rejoso Watershed, East Java, Indonesia. Land 9:240. https://doi.org/10.3390/land9080240
22. Yang B, Zhang W, Meng X et al (2020) Effects of a funnel-shaped canopy on rainfall redistribution and plant water acquisition in a banana (Musa spp.) plantation. Soil and Tillage Research 203:104686. https://doi.org/10.1016/j.still.2020.104686

Figures

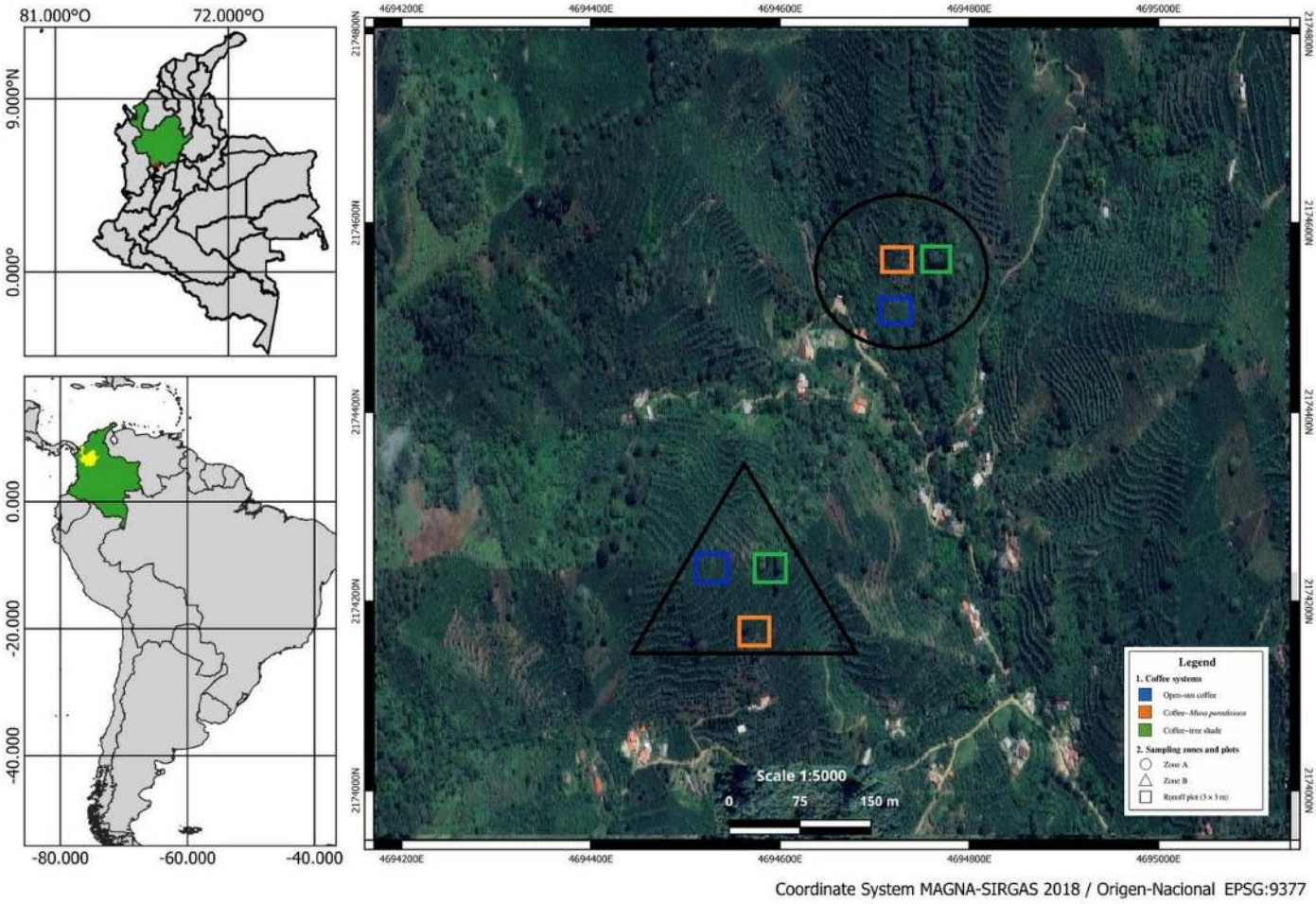


Figure 1

Study area and six pre-existing runoff plots in Santa Rita, southwestern Antioquia, Colombia. Zones A and B each contained one plot per coffee arrangement. Coordinate system: MAGNA-SIRGAS

2018/Origen-Nacional (EPSG:9377)

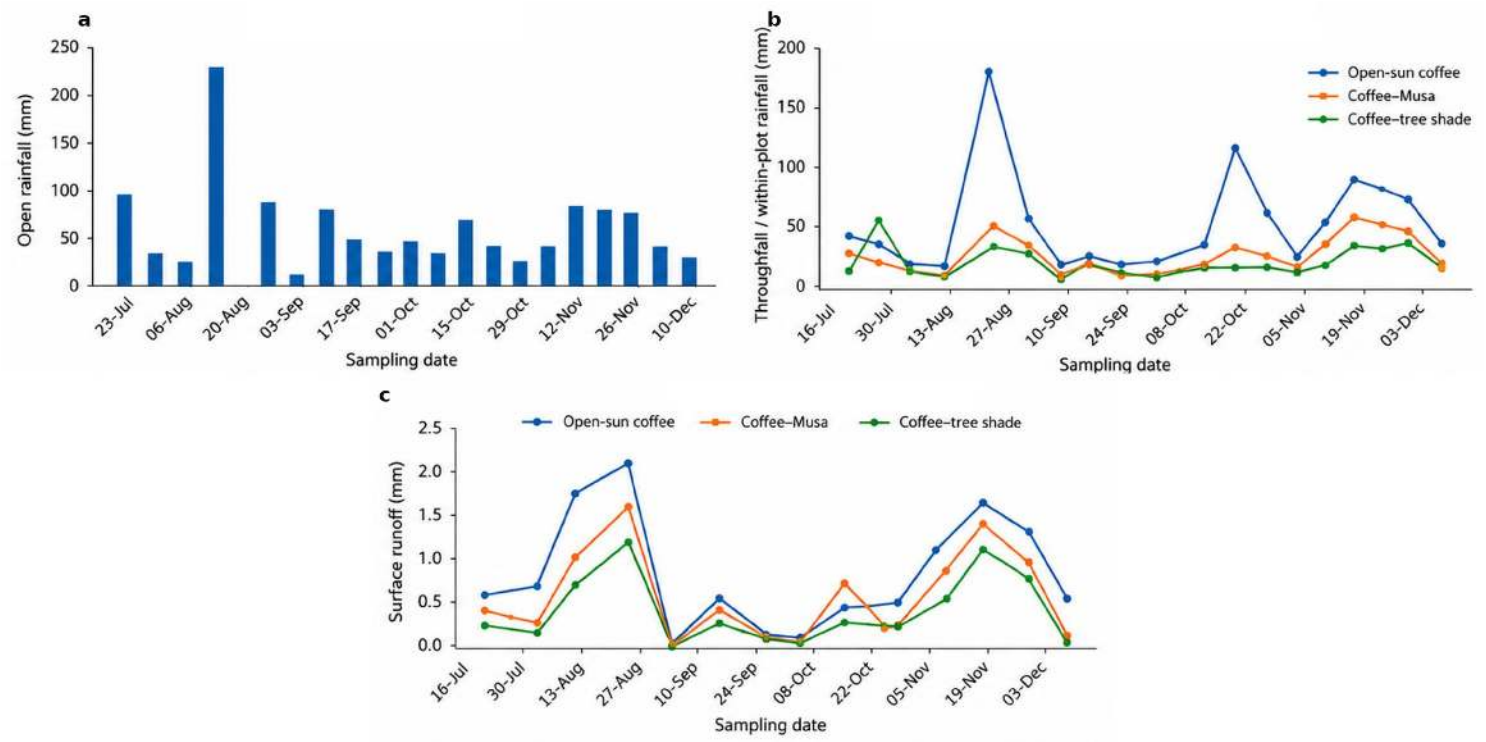


Figure 2

Weekly open rainfall, within-plot rainfall (TF), and surface runoff (RO) in three coffee arrangements. Values are means of two plots; 18 August 2024 was excluded

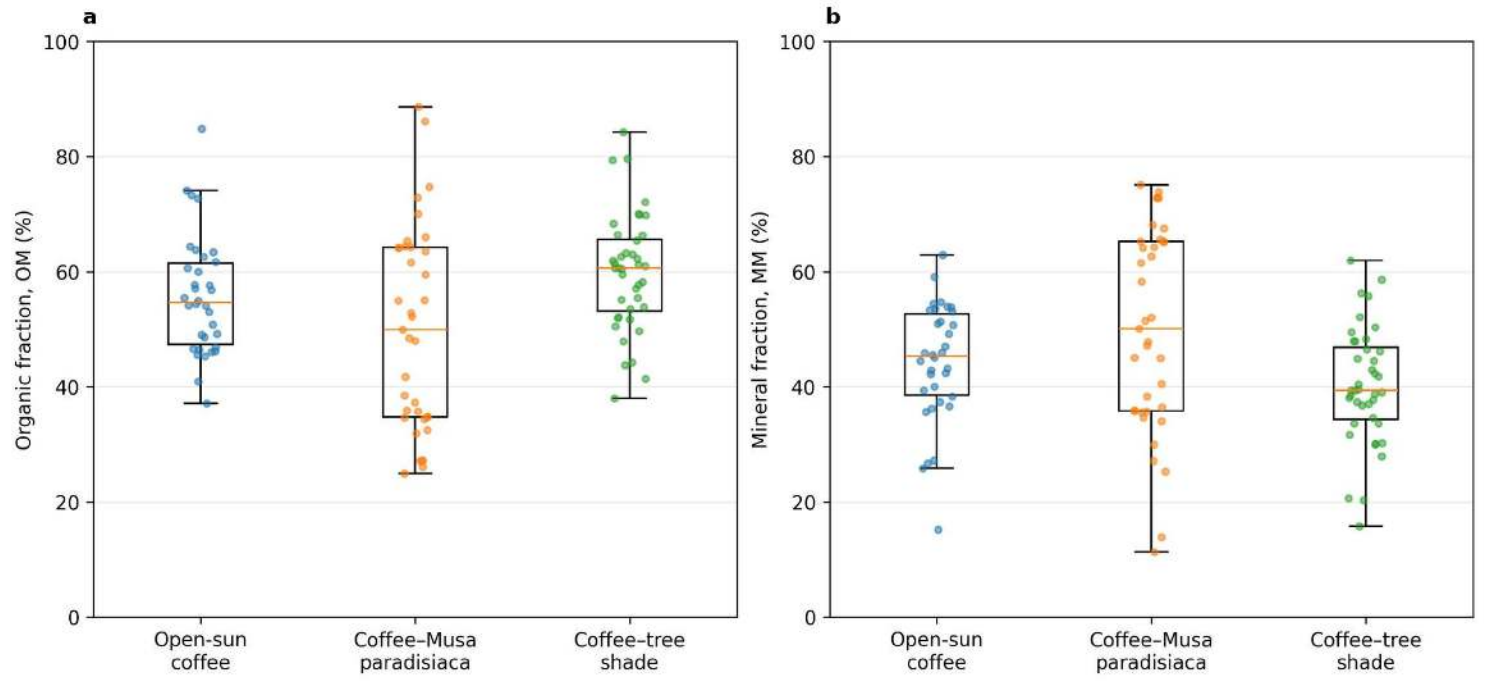


Figure 3

Loss-on-ignition-derived organic (a) and mineral (b) fractions of mesh-retained runoff material. Points are repeated plot-week subsamples from two plots per arrangement; fractions are complementary and do not represent total particulate export or soil loss

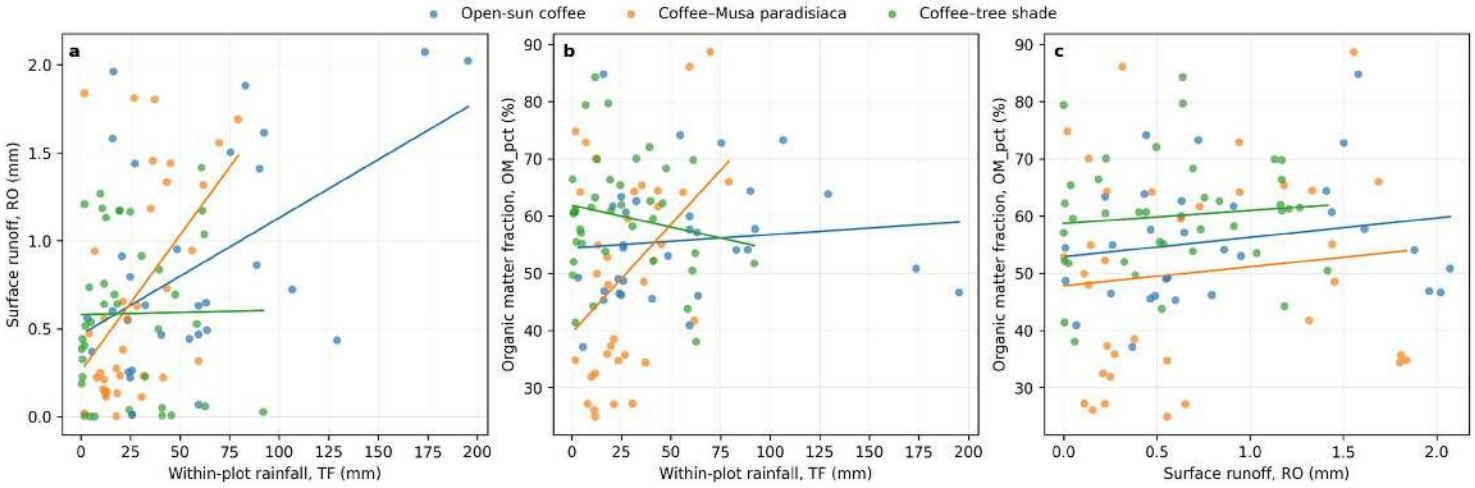


Figure 4

Exploratory relationships between within-plot rainfall, surface runoff, and organic fraction. Points are repeated plot-week observations; lines are arrangement-specific descriptive trends, not confirmatory treatment effects, because observations were repeated within two non-randomly assigned plots per arrangement