Malaysian Journal of Soil Science 2026 Vol. 30: 90-99

Integrated Agricultural Land–Use Patterns for Soil and Water Conservation in a Tropical Highland Watershed

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ABSTRACT

Land degradation caused by unsustainable cultivation practices remains a critical constraint to agricultural productivity in tropical highland regions. This study investigates the effects of various integrated agricultural land–use patterns on soil erosion, runoff, and land productivity in a tropical highland watershed of Southeast Asia. A field experiment and socio–economic survey was conducted from October 2024 to April 2025 using a Randomized Block Design comprising five treatments: (T1) cabbage–chili–tobacco, (T2) maize–upland rice, (T3) maize–kidney bean, (T4) coffee–elephant grass, and (T5) pine forest. Erosion and surface runoff were measured to assess soil loss and water regulation performance under different land–use types. The results showed that the T1 produced the highest erosion rate (25.15 t ha^{-1} yr^{-1}), while T5 recorded the lowest (3.89 t ha^{-1} yr^{-1}). All systems, however, exceeded the tolerable erosion threshold for Ultisols (11.21 t ha^{-1} yr^{-1}), indicating the need for improved soil conservation measures. Land allocation modeling revealed that an optimal land–use configuration, comprising 37% mixed agroforestry, 20.8% annual crops, and 5.7% grasslands, maximized income while minimizing soil loss. The findings underscore the importance of diversified and conservation–oriented land–use planning for achieving sustainable agricultural production and watershed resilience in tropical highland environments.

Keywords: Soil erosion, integrated farming systems, land–use optimization, watershed management, tropical highlands

INTRODUCTION

Land degradation remains a global environmental challenge that directly threatens food security, ecosystem stability, and rural livelihoods, particularly in tropical highland regions (Hakim *et al*., 2024). The degradation of land and water resources through soil erosion and surface runoff has accelerated under intensive agricultural practices and unplanned land–use change. Globally, more than 24 billion tons of fertile soil are lost annually due to erosion, and this rate is particularly severe in tropical regions where high rainfall intensity interacts with fragile soils and steep topography (Borrelli *et al*., 2020; Panagos *et al*., 2022). In such landscapes, soil erosion is not only a biophysical phenomenon but also a socio–economic concern because it reduces agricultural productivity, impairs hydrological balance, and increases sedimentation and flooding risks downstream (Wang *et al*., 2023; Shiferaw *et al*., 2021).

The watershed catchment serves as an ecological and hydrologically meaningful unit for planning and managing land and water resources. Integrated watershed management seeks to optimize agricultural productivity while maintaining ecological sustainability by balancing land–use intensity, hydrological regulation, and soil conservation (Xie *et al*., 2022). In tropical highlands, particularly in Southeast Asia, the upper watershed plays a crucial role in regulating downstream water supply and sediment loads. Unsustainable cultivation on steep slopes, such as continuous planting of annual crops without proper soil cover or contour management, often leads to severe soil erosion and nutrient loss (Sonneveld *et al*., 2019; Liu *et al*., 2020). This pattern mirrors the situation in many developing regions where population growth and land scarcity compel farmers to expand cultivation into marginal, erosion–prone uplands (Rahmawati *et al*., 2021).

Integrated Agricultural Land Management (IALM) or *integrated farming systems* have emerged as a viable solution for improving the resilience and productivity of such fragile environments. This approach combines multiple agricultural components: annual crops, perennials, livestock, and forestry within the same land unit to optimize resource use efficiency and ecological functions (Altieri *et al*., 2020). The system emphasizes nutrient recycling, biodiversity enhancement, and erosion control, thus offering an alternative to conventional monocropping (Pimentel & Burgess, 2019). Empirical evidence indicates that integrated land–use systems, such as agroforestry or mixed cropping, significantly reduce surface runoff, increase infiltration, and improve soil structure compared to monoculture farming (Wei *et al*., 2021; Gao *et al*., 2023).

In Indonesia, where approximately 21 million hectares of land are classified as degraded (Ministry of Environment and Forestry, 2023), integrated land management has become a national priority for achieving sustainable agricultural productivity. Many highland watersheds in Java and Sumatra experience accelerated degradation due to steep slopes, fragile Ultisols and Inceptisols soils, and the dominance of annual vegetable cropping (Agus *et al*., 2022). These soils, characterized by low cation exchange capacity and organic matter, are highly vulnerable to erosion when surface cover is removed (Rahman *et al*., 2020). Consequently, land productivity declines rapidly without adequate soil conservation measures. Previous research has shown that continuous cultivation of shallow–rooted crops, such as maize and cabbage, can cause erosion rates exceeding 20 t ha^{-1} yr^{-1} well above the tolerable limit for tropical soils (Arsyad *et al*., 2021). In contrast, multi–strata agroforestry systems or perennial–based farming reduce erosion by improving canopy interception and soil organic matter dynamics (Gupta *et al*., 2020). Integrated management of crops, livestock, and trees also enhances nutrient cycling, organic carbon sequestration, and resilience to climate variability (Lin *et al*., 2021; Fan *et al*., 2024; Hakim *et al*., 2025). However, adoption remains limited among smallholders due to socio–economic constraints, insecure land tenure, and insufficient institutional support (Suhardjo *et al*., 2022).

To address these challenges, this study focuses on assessing the performance of several integrated agricultural land–use patterns in a representative tropical highland watershed of Southeast Asia (Hakim *et al*., 2025). The research combines experimental and survey approaches to (1) evaluate the impact of different cultivation systems on soil erosion and runoff, and (2) determine optimal land–use allocation for both economic and environmental objectives.

The findings contribute to ongoing international discussions on sustainable land–use transitions under the United Nations Sustainable Development Goals (SDGs), particularly SDG 2 (Zero Hunger), SDG 13 (Climate Action), and SDG 15 (Life on Land). By examining the trade–offs between agricultural productivity and soil–water conservation, this study provides practical insights for designing land–use strategies that enhance ecosystem services while supporting rural livelihoods in tropical highland regions.

MATERIALS AND METHODS

Study area

The study was conducted in a representative tropical highland watershed located in Southeast Asia, situated between 1,100–1,250 m above sea level with slopes ranging from 30% to 40%. The area is characterized by a humid tropical climate with an average annual rainfall of approximately 2,000–2,500 mm, distributed over more than 100 rainy days per year. Soils are dominated by Ultisols and Inceptisols, known for their low organic matter, moderate permeability, and high susceptibility to erosion. Land use in the watershed is dominated by mixed vegetable farming, perennial crops, and small patches of forest and grasslands. The region faces rapid land–use change driven by agricultural intensification and population pressure, leading to declining soil fertility and increasing sediment yield in downstream reservoirs, a pattern consistent with other tropical upland catchments in Asia (Rahmawati *et al*., 2021; Gao *et al*., 2023).

Experimental design

A field experiment was conducted to evaluate the influence of various land–use patterns on soil erosion, runoff, and land productivity. The study adopted a Randomized Block Design (RBD) with five treatments and five replications. Each plot measured 2 x 22 m, consistent with the Universal Soil Loss Equation (USLE) experimental standard. Plots were established perpendicular to contour lines, with collection tanks installed at the downslope ends to capture runoff and sediment yield.

Five land–use patterns, reflecting existing local agricultural practices, were tested as treatments:

T1: Cabbage–chili–tobacco rotation (annual cropping)
T2: Maize–upland rice rotation
T3: Maize–kidney bean (intercropping)
T4: Coffee–elephant grass (perennial + forage system)
T5: Pine Forest (agroforestry)

Runoff and erosion data were collected for each rainfall event from October 2024 to April 2025. The runoff volume was measured using calibrated tanks and graduated cylinders, while sediment yield was determined by oven–drying collected sediment samples at 105°C to constant weight. Erosion was expressed as dry soil loss (t ha^{-1} yr^{-1}). Such plot–based methods remain widely used for soil erosion quantification under tropical conditions and provide robust estimates of the relation between vegetation cover, rainfall, and sediment yield (Mekonnen *et al*., 2021; Wang *et al*., 2023).

Soil and Rainfall Measurements

Before and after the experiment, composite soil samples (0–15 cm depth) were collected for physical and chemical characterization. Parameters measured included texture, bulk density, organic carbon, total nitrogen, available phosphorus, cation exchange capacity (CEC), and base saturation. Standard analytical protocols followed the Soil Science Society of America (SSSA) methods. Rainfall intensity and frequency were monitored using a manual rain gauge positioned near the plots, while long–term precipitation data were derived from regional meteorological stations to compute rainfall erosivity (R–factor). The Bols equation was applied to estimate monthly rainfall erosivity (EI_{30}):

$$EI_{30} = 6.119(RAN)^{1.21}(DAYS)^{-0.47}(MAX)^{0.53}$$

where RAN is monthly rainfall (cm), DAYS is the number of rainy days per month, and MAXP is the maximum 24–hour rainfall (cm). Erosivity estimation through EI_{30} remains a standard procedure in tropical hydrology, effectively linking rainfall energy and storm frequency to soil loss potential (Fenta *et al*., 2020; Panagos *et al*., 2022).

Soil Loss Prediction

The Universal Soil Loss Equation (USLE) was used to estimate potential annual soil loss (A, t ha^{-1} yr^{-1}) as:

$$A = R\ x\ K\ x\ L\ x\ S\ x\ C\ x\ PA$$

where R is rainfall erosivity, K is soil erodibility, LS is slope length and steepness, C is the crop–management factor, and P is the conservation practice factor.

- K values were derived from soil texture, structure, permeability, and organic matter.
- LS values were computed using slope and length parameters.
- C and P factors were adopted from field observations and literature–derived indices validated for tropical systems.

The tolerable soil loss (TSL) threshold for these soils was set at 11.2 t ha^{-1} yr^{-1}, consistent with recommendations for tropical Ultisols (Rahman *et al*., 2020). Regression analysis was applied to quantify relation among rainfall, runoff, and erosion intensity, using the linear model:

$$Y = \alpha + \beta XY$$

where Y represents erosion or runoff and X denotes rainfall amount or intensity. Statistical analysis (ANOVA and Duncan's Multiple Range Test at 5%) were performed using R version 4.3 to identify significant treatment effects.

RESULTS AND DISCUSSION

Soil erosion and runoff under different land–use systems

The measured erosion rates among the five land–use treatments revealed considerable variability, reflecting the strong influence of vegetation cover, crop type, and slope management on soil and water loss (**Table 1**). The cabbage–chili–tobacco rotation (T1) generated the highest mean annual erosion rate of 25.15 t ha^{-1} yr^{-1}, followed by maize–upland rice (T2, 20.61 t ha^{-1} yr^{-1}), maize–kidney bean (T3, 15.42 t ha^{-1} yr^{-1}), and coffee–elephant grass (T4, 8.97 t ha^{-1} yr^{-1}). The lowest erosion was observed under the mixed agroforestry system (T5, 3.89 t ha^{-1} yr^{-1}).

Table 1. Relation between erosion and surface run-off

Cropping System	Regression Equation	R^2
T1 = Cabbage–Chili–Tobacco	Y = 0.0167X + 81.119	R^2 = 0.957
T2 = Maize–Upland Rice	Y = 0.092X + 11.235	R^2 = 0.974
T3 = Maize–Red Kidney Bean	Y = 0.0109X – 3.959	R^2 = 0.974
T4 = Coffee–Elephant Grass	Y = 0.001X + 12.181	R^2 = 0.918
T5 = Pine Forest (Agroforestry)	Y = 0.001X + 3.8863	R^2 = 0.996

Note: *Y represents soil loss (t ha^{-1} yr^{-1}), and X denotes rainfall (mm). High R^2 values indicate a strong relation between surface run-off and soil erosion across all cropping systems, with the pine forest treatment showing the most stable response.*

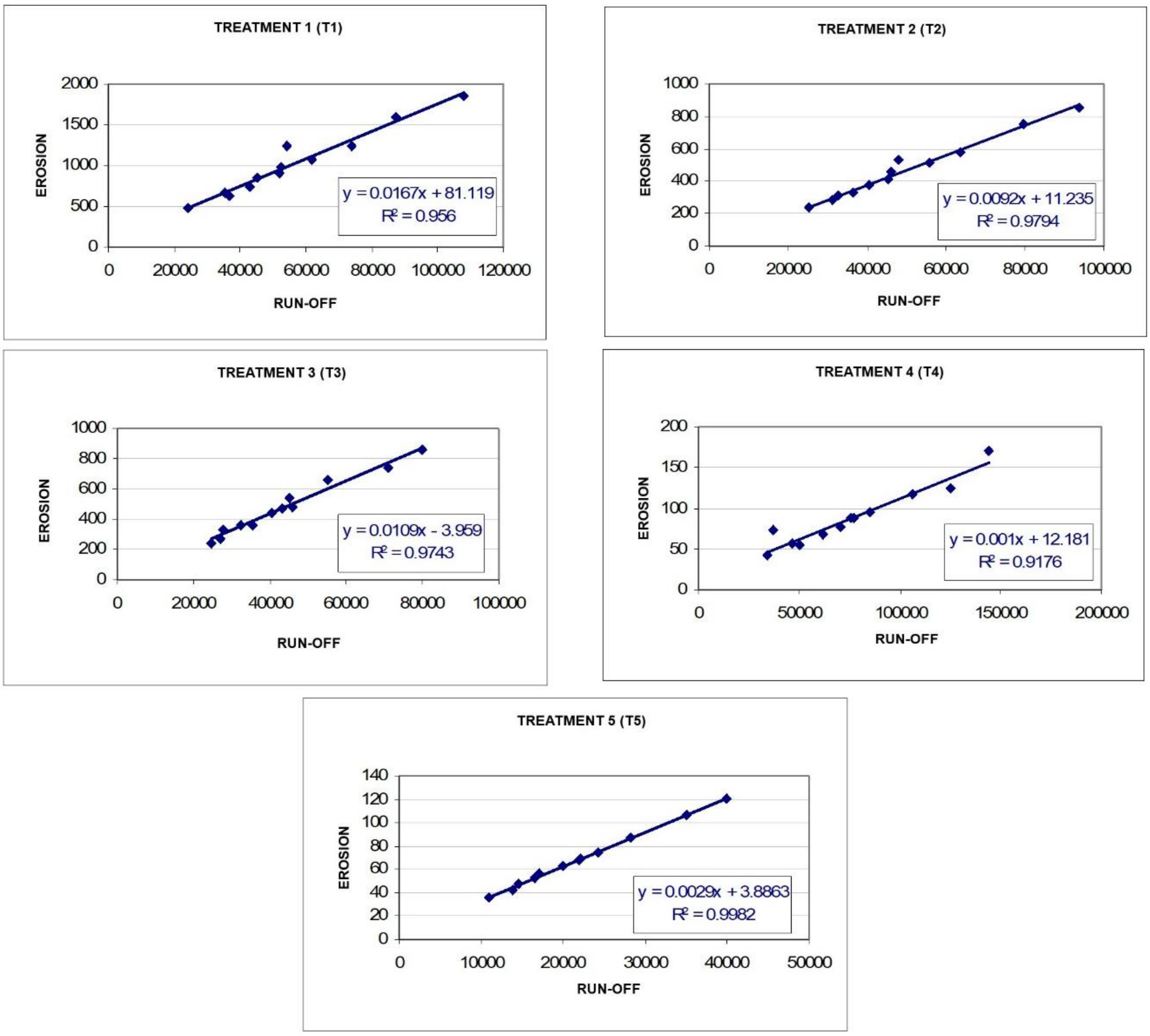

Figure 1. Graphic of relation between surface runoff and soil erosion

Figure 1 indicated all erosion values exceeded the tolerable limit for tropical Ultisols (11.21 t ha^{-1} yr^{-1}), indicating that conventional land–use systems in the study area have surpassed the ecological carrying capacity of the land. This pattern mirrors other findings in tropical highlands, where erosion from vegetable–based monocultures may reach 20–40 t ha^{-1} yr^{-1} due to the absence of continuous canopy and intensive tillage (Wang *et al*., 2023; Liu *et al.*, 2020). In contrast, perennial vegetation such as coffee and grasses significantly reduced soil loss due to root reinforcement and litter layer protection, which enhance infiltration and minimize raindrop impact (Rahman *et al*., 2020; Gao *et al*., 2023).

The reduction of soil loss under agroforestry systems (T5) is attributed to multi–layered canopy structure, which intercepts rainfall energy, improves microclimate, and stabilizes surface aggregates. Studies have shown that agroforestry practices can reduce sediment yield by 60–90% compared to conventional cropping on similar slopes (Gupta *et al.*, 2020; Nair *et al.*, 2022). Moreover, the integration of grasses (T4) in perennial systems contributed to effective surface protection, confirming the findings of Lin *et al*. (2021), who demonstrated that grass–tree systems in tropical mountains enhanced infiltration by 35% and reduced runoff by nearly half compared to annual systems.

Interactions Between Rainfall and Soil Erosion

Table 1 exhibited regression analysis revealed a strong positive relation between rainfall intensity and soil loss ($R^2 = 0.9767$ in average, $p < 0.01$), indicating that rainfall energy remains the principal driver of erosion in steep, fragile tropical landscapes. The rainfall erosivity index (EI_{30}) ranged between 120–340 MJ mm ha^{-1} h^{-1} yr^{-1}, with the highest values recorded during January–March, coinciding with peak rainfall. This seasonal pattern is typical of monsoonal regions where rainfall concentration increases erosion risk (Panagos *et al*., 2022).

Table 2. Relation between rainfall intensity and erosion across all cropping systems

Cropping System	Regression Equation	R²
T1 = Cabbage–Chili–Tobacco	Y = 142.22 X + 48819	$R^2 = 0.9688$
T2 = Maize–Upland Rice	Y = 66.918 X – 9.34	$R^2 = 0.9852$
T3 = Maize–Red Kidney Bean	Y = 67.838 X – 7.3402	$R^2 = 0.9809$
T4 = Coffee–Elephant Grass	Y = 12.576 X – 1.8972	$R^2 = 0.9507$
T5 = Pine Forest (Agroforestry)	Y = 9.1391 X + 3.4059	$R^2 = 0.9987$

Note:
Y represents soil loss (t ha^{-1} yr^{-1}), and X denotes rainfall (mm). High R^2 values indicate a strong relation between rainfall intensity and soil erosion across all cropping systems, with the pine forest treatment showing the most stable response.

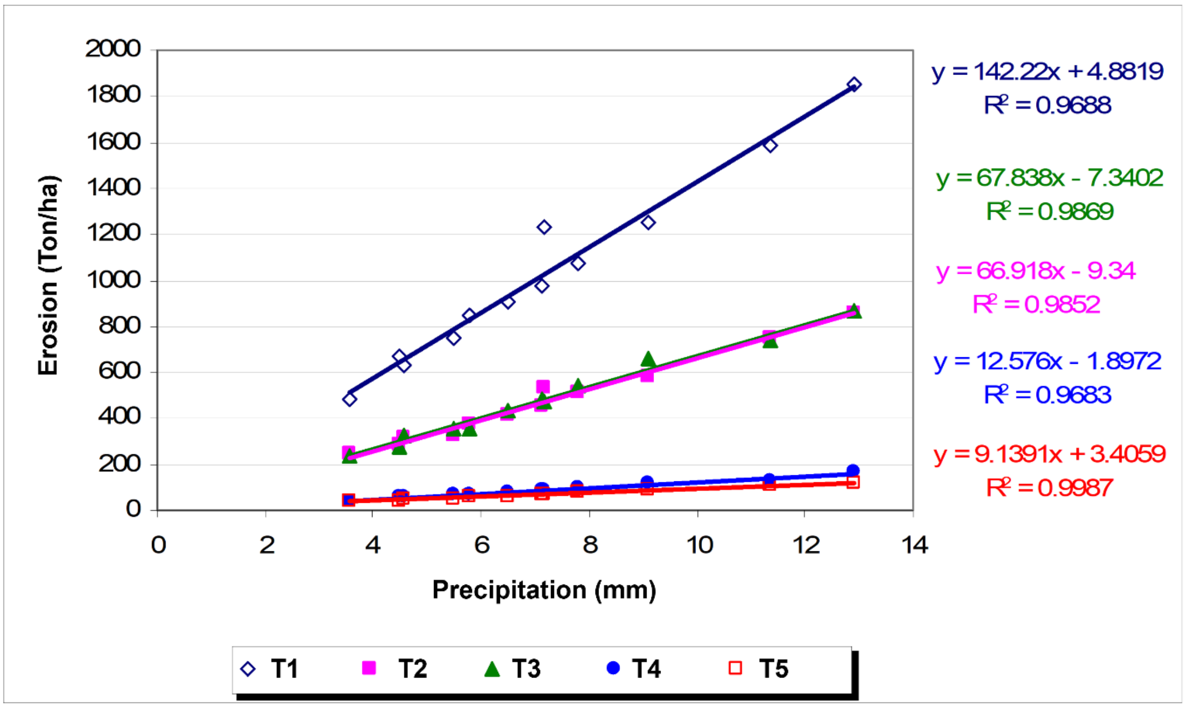

Figure 2. Graphic of relation between rainfall and soil erosion across all cropping systems

Figure 2 indicated Runoff coefficients also differed substantially among treatments: annual crop plots (T1–T3) produced higher runoff ratios (0.32–0.46) than perennial or agroforestry plots (0.18–0.24). The significant decline in runoff under T4 and T5 reflects improved infiltration capacity due to soil organic matter accumulation and structural stability. Similar patterns were observed by Wei *et al*. (2021) in integrated crop–livestock systems, where perennial cover reduced surface runoff by 42% compared to annual monocropping.

The combined analysis of erosion and runoff confirms that soil conservation effectiveness correlates strongly with vegetation density, canopy stratification, and residue retention. Continuous annual cultivation without conservation measures intensifies raindrop impact and reduces infiltration, resulting in higher detachment and transport of soil particles (Liu *et al*., 2020).

Table 3. Variability of soil erosion (kg/plot) across cropping system in each rainfall event

Treatment	Erosion Measurements (kg/plot) for Each Rainfall Event							
	E1	E2	E3	E4	E5	E6	E7	E total
T1	1233.46 d	911.26 c	975.76 d	851.00 c	1076.26 c	1248.58 c	634.17 c	12264.27 d
T2	527.80 c	411.66 c	455.07 b	372.01 b	514.697 c	578.40 b	311.59 b	5630.86 c
T3	471.43 b	437.58 d	478.30 c	358.17 b	538.148 b	656.19 c	328.63 b	5733.74 c
T4	88.83 a	77.74 b	87.26 a	73.541 a	94.832 a	117.46 a	55.36 a	1056.42 b
T5	68.75 a	62.71 a	68.65 a	56.484 a	74.186 a	86.83 a	47.47 a	396.72 a

Note: *Values in the same column followed by the same letter are not significantly different according to Duncan's Multiple Range Test (DMRT) at the 5% significance level.*

Interactions Between Runoff and Rainfall

Early-stage soil surface cover clearly differentiated the erosion response among cropping systems. **Figure 1** indicated the maize–legume (T3) and maize–upland rice (T2) systems exhibited the most rapid canopy development, providing earlier protection of the soil surface and thereby reducing direct raindrop impact and splash detachment. Rapid ground cover formation is widely recognized as a critical factor in lowering runoff generation and soil particle detachment, particularly under high-intensity tropical rainfall (Wang *et al*., 2023).

In contrast, the cabbage–chili–tobacco (T1) and coffee–elephant grass (T4) systems failed to achieve complete (100%) soil cover, leaving portions of the surface exposed during rainfall events. This incomplete canopy coverage increased susceptibility to direct raindrop impact and enhanced runoff-driven erosion, as reflected in the higher erosion rates observed for these treatments. Recent studies confirm that partial canopy cover substantially elevates soil loss by allowing greater rainfall kinetic energy to reach the soil surface and reducing infiltration efficiency (Zhao *et al*., 2021).

Overall, these results reinforce that crop physiological traits and early vegetative growth dynamics play a decisive role in controlling erosion processes by regulating canopy closure and soil surface protection. Integrating cropping systems with rapid ground cover development is therefore essential for effective soil and water conservation in sloping tropical agroecosystems (Liu *et al*., 2020; Wang *et al*., 2023).

Table 2. Relation between rainfall intensity and run-off across all cropping systems

Cropping System	**Regression Equation**	**R²**
T1 = Cabbage–Chili	Y = 8392.8 X – 3839.1	$R^2 = 0.9897$
T2 = Maize–Upland Rice	Y = 7232.4 X – 1907.3	$R^2 = 0.9932$
T3 = Maize–Red Kidney Bean	Y = 6131 X + 208.6	$R^2 = 0.9895$
T4 = Coffee–Elephant Grass	Y = 11974 X – 9536.8	$R^2 = 0.9507$
T5 = Pine Forest (Agroforestry)	Y = 3105.8 X – 142.37	$R^2 = 0.9986$

Note: *Y represents soil loss (t ha^{-1} yr^{-1}), and X denotes rainfall (mm). High R^2 values indicate a strong relation between rainfall intensity and run-off across all cropping systems, with the pine forest treatment showing the most stable response.*

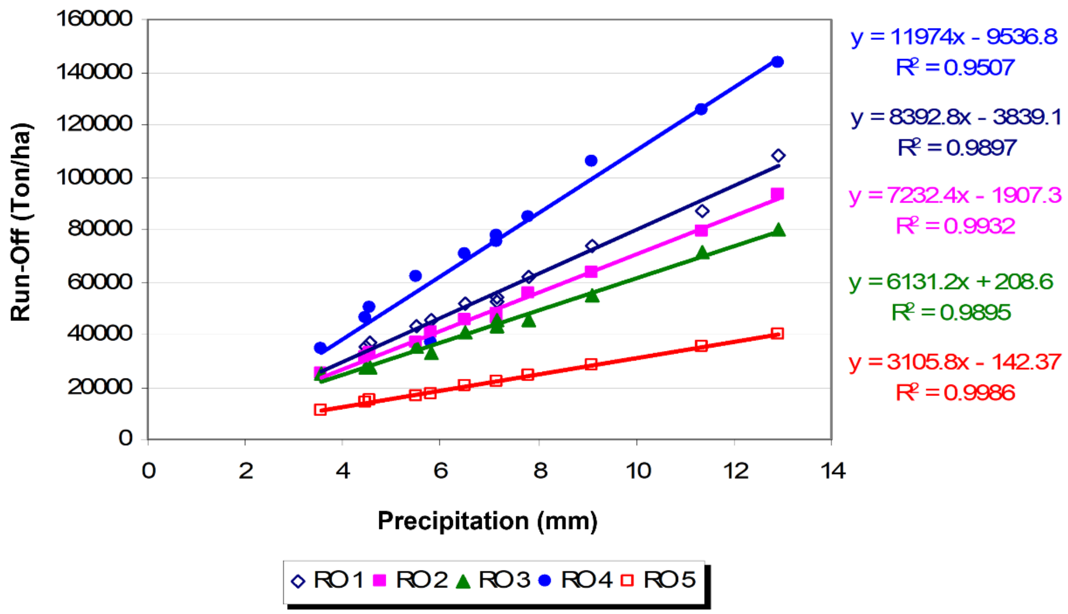

Figure 3. Graphic of relation between rainfall and run-off across all cropping systems

Soil Properties

Soil analyses indicated that land–use patterns significantly affected physical and chemical properties. Bulk density was highest under continuous annual cropping (T1–T3: 1.38–1.43 g cm⁻³) and lowest under agroforestry (T5: 1.14 g cm⁻³). Organic carbon content was markedly higher in agroforestry and coffee–grass systems (2.1–2.3%) than in annual crop systems (1.2–1.5%). Enhanced organic matter improves soil aggregation and water retention, reducing erosion susceptibility.

Cation exchange capacity (CEC) values were also superior in perennial systems, reaching 22.6 cmol(+) kg⁻¹, compared to 16.4 cmol(+) kg⁻¹ in annual systems, confirming that long– term vegetation cover enhances nutrient retention and soil buffering capacity. These results are consistent with recent reports showing that conversion from annual to perennial or mixed systems can increase CEC by 30–40% in tropical highlands (Fan *et al*., 2024; Arsyad *et al*., 2021b).

Soil pH and base saturation improved slightly under integrated systems, likely due to continuous organic matter input and moderated microclimatic fluctuations. Conversely, repeated tillage in annual crops led to soil structure breakdown, compaction, and accelerated nutrient leaching. The results highlight that conservation–oriented land–use systems not only mitigate erosion but also enhance long–term soil fertility and productivity (Suhardjo *et al*., 2022; Altieri *et al*., 2020).

Implications for soil and water conservation

The integrated analysis of biophysical and socio–economic dimensions demonstrates that soil and water conservation cannot rely solely on mechanical measures but requires a systemic approach that integrates crop management, economic incentives, and community participation (Hakim *et al*., 2026). The study supports the transition from short–term monoculture systems to diversified, perennial–based systems as a key pathway to sustainable watershed management.

The findings corroborate global evidence that integrating trees and forages into farming landscapes enhances resilience to climate extremes, improves hydrological regulation, and restores soil fertility (Altieri *et al*., 2020; Fan *et al*., 2024). At the same time, the economic viability of integrated systems ensures that conservation aligns with farmer incentives, a central principle in sustainable land management.

Furthermore, the study contributes empirical data on erosion rates, runoff coefficients, and land–use optimization parameters that can support the development of spatially explicit watershed models. Incorporating such data into decision–support tools like the Soil and Water Assessment Tool (SWAT) or InVEST could facilitate policy–level scenario analysis for scaling sustainable land management across tropical regions (Guo *et al*., 2023; Zhao *et al.*, 2021).

CONCLUSION

This study demonstrates that land–use practices significantly determine soil erosion, runoff, and land productivity in tropical highland watersheds. Intensive annual cropping systems, such as cabbage–chili–tobacco rotations, caused severe soil loss far exceeding the tolerable limit for Ultisols, whereas perennial–based systems like coffee–grass and mixed agroforestry effectively reduced erosion and improved soil quality. The strong correlation between rainfall intensity and soil loss highlights rainfall erosivity as the dominant factor controlling erosion in these environments.

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