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Soil quality and invertebrate dynamics in sandy soils under different land-use systems and seasonality[1]

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ABSTRACT - Fragile tropical sandy soils are highly susceptible to degradation, yet how land-use systems (LUS) and seasonality interact to maintain their ecosystem services remains poorly understood. This study addressed this question by evaluating the soil functional integrity of four LUS in Southeastern Brazil: Forest Fragment (FF), Coffee Monoculture (CM), Vegetable Cultivation (VC), and an 8-year-old Agroforestry System (AFS). We integrated total organic carbon (TOC) fractions, acidity, cation exchange capacity (CEC), aggregate stability, and macroinvertebrate community structure across rainy and dry seasons. Soil was sampled (0 – 0.05 m) using both disturbed and undisturbed (monoliths) methods. Results indicated that organic matter dynamics, interacting with mineral texture and moisture, dictate nutrient storage potential. FF and CM exhibited high structural stability and resilient CEC, effectively buffering seasonal oscillations. Conversely, VC and AFS showed lower physical stability and degraded CEC. However, managed systems supported higher invertebrate richness, creating niches for opportunistic groups such as Acari and Isopoda, consistent with the Intermediate Disturbance Hypothesis. Multivariate analysis identified TOC, Particulate Organic Carbon (POC), pH, and clay content as the most sensitive sustainability indicators. Neither our initial hypothesis, that agricultural systems maintain forest-like integrity, nor that seasonality is negligible were corroborated. AFS management must prioritize Mineral-Associated Organic Carbon (MAOC) accumulation to enhance long-term sustainability and diminish dissimilarity from FF. We conclude that our multidimensional assessment provides a robust diagnosis for restoration strategies in fragile tropical landscapes, promoting functional maturity through reduced plant spacing and N-fixing species enrichment.

Keywords: Tropical soil functional integrity. Mineral-associated organic matter. Intermediate Disturbance Hypothesis. Sustainability indicators. Soil fauna.

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INTRODUCTION

Soils facilitate complex biochemical processes that underpin essential ecosystem services, including nutrient cycling, carbon storage, and biodiversity maintenance (Bünemann *et al*., 2018). However, these services are increasingly threatened by anthropogenic activities, particularly the accelerated deforestation driven by agricultural expansion based on traditional practices that lack soil conservation strategies (da Costa *et al*., 2024). At the global scale, these activities contribute to climate change. At the regional level, they negatively impact the hydrological cycle, while at the local scale, they alter landscape configuration, climate, and biodiversity (Berenguer *et al*., 2024) through river silting, soil compaction, and erosion, ultimately contributing to the socioeconomic decline of rural populations (Pinto *et al*., 2022).

This situation is typically observed within tropical sandy soils, due to the structural instability and limited capacity to retain water, nutrients, and organic matter, alongside high erosion susceptibility (Souza *et al*., 2020). Thus, these "fragile" soils often require intensive chemical inputs, increasing production costs and accelerating soil organic matter (SOM) mineralization, featuring a significant challenge to sustainable management (Teles *et al*., 2020; Camara *et al*., 2023; Gualberto *et al*., 2023; Albuquerque *et al*., 2024).

Consequently, scientific studies assessing soil quality have gained significant prominence, aiming to evaluate functional integrity and advocate for the establishment of conservation land-use systems (LUS), or restoration programs, when necessary, to restore ecosystem functioning (Simon *et al*., 2022). Accordingly, modern assessments have evolved beyond traditional fertility metrics to encompass broader functional perspectives, explicitly linking soil attributes to the provision of essential ecosystem services, rather than solely focusing on crop production (Simon *et al*., 2022).

The functional integrity of these ecosystems is not static but dynamically modulated by seasonality. Fluctuations in rainfall and temperature act as critical extrinsic factors that influence plant physiology, litterfall, soil biota activity, and decomposition, subsequently modulating soil biochemical processes (Kuwahara *et al*., 2016; Tiecher *et al*., 2017; Bünemann *et al*., 2018; Camara *et al*., 2018; Hong; Gan; Chen, 2019; Ogunkanmi *et al*., 2021; Dowdeswell-Downey *et al*., 2023; Sayer *et al*., 2024; Ramos *et al*., 2025). Despite the known vulnerability of sandy soils, there is a lack of consensus on whether diversified management systems, such as agroforestry, can effectively mitigate the loss of soil quality compared to undisturbed native forest fragments (Camara *et al*., 2023).

To capture this complexity, soil quality must be assessed through an integrated multidimensional approach (Bünemann *et al*., 2018; Simon *et al*., 2022; Ramos *et al*., 2025). This includes (i) chemical indicators, such as acidity, Cation Exchange Capacity (CEC), and SOM, specifically assessed as Total Organic Carbon (TOC) and the fractions Mineral-Associated Organic Carbon (MAOC) and Particulate Organic Carbon (POC); (ii); physical attributes, comprising particle size distribution (sand, silt, and clay), thermal buffering, and aggregate stability; and (iii) biological parameters, particularly the soil invertebrate community composition, in terms of relative abundance, richness, evenness, and diversity, which serve as sensitive bioindicators of management impacts and seasonality (Bünemann *et al*., 2018; Simon *et al*., 2022; Ramos *et al*., 2025).

Recent studies emphasize that monitoring total organic carbon (TOC) alone may fail to capture differences between land-use systems (Camara *et al*., 2023). Instead, evaluating its constituent fractions, MAOC and POC, is more effective for revealing short-term shifts in soil health (Bünemann *et al*., 2018; Gualberto *et al*., 2023; Oliveira Netto *et al*., 2024; Ramos *et al*., 2025). This efficacy is primarily grounded in the distinct biogeochemical stability of these fractions (Bünemann *et al*., 2018; Gualberto *et al*., 2023).

This study investigated the influence of different LUS and seasonality on soil chemical, physical, and biological attributes within fragile sandy soils of the Baixada Fluminense, Rio de Janeiro state, Brazil. Specifically, we aimed to determine: (i) how these attributes interact to influence soil health and ecosystem service provision, and (ii) which attributes are the most sensitive to serve as indicators of soil health. We tested the hypotheses that: (i) managed agricultural systems maintain a functional integrity comparable to reference forest fragments due to localized buffering effects, and (ii) seasonal climatic oscillations do not significantly alter the interplay between soil attributes.

MATERIAL AND METHODS

Description of the study area

The study was conducted in Seropédica, Rio de Janeiro, Brazil (Aw climate, Köppen). Historical data indicate significant hydric seasonality, with rainfall peaking in January (283 mm) and a minimum in August (44 mm); mean monthly temperatures fluctuate between 20 °C and 27 °C. Four LUS along a toposequence (5% slope) were evaluated: (i) vegetable cultivation (VC), a high-input annual system; (ii) coffee monoculture (CM), a perennial system (est. 2018); (iii) agroforestry system (AFS), a complex multi-strata agroecosystem (est. 2014); and (iv) a secondary forest fragment (FF) as a reference area (28 years of natural regeneration) (Figure 1). Soils are predominantly *Argissolo Amarelo* (Acrisols) and *Planossolo Háplico* (Planosols), characterized by a fragile sandy surface texture.

The VC system is a high-intensity annual system (180 m²) characterized by seasonal rotation and intercropping of various vegetable species (e.g., *Solanum* spp., *Brassica* spp., and *Allium cepa*). N-P-K fertilization is strictly crop-dependent, following nutrient demand and export rates. This area is located 10 m and 50 m from the CM and AFS, respectively. The CM system is a perennial system established in 2018 (5 – 6 years old) covering 260 m². It consists of *Coffea canephora* (cv. 'Black Gold') at a density of 3,333 plants ha^{-1}. Management includes annual top-dressing with 40 g of N and 40 g of K_2O per plant applied as potassium chloride. This area is located 40 m from the AFS.

The multi-strata, diverse agroecosystem (2,000 m²) was established in 2014 (8–9 years old) on a *Planossolo Háplico* (Planosol) (Santos *et al*., 2018), integrating high-value perennial crops with forest species (Table 1). They are interspersed with annual crops (e.g., *Manihot esculenta*, *Ananas comosus*) to ensure continuous soil coverage (Ramos *et al*., 2025). The soil is characterized by a sandy loam texture extending to 40 cm.

Figure 1 - Schematic profile of the studied land-use systems (LUS) in Seropédica, RJ, Brazil

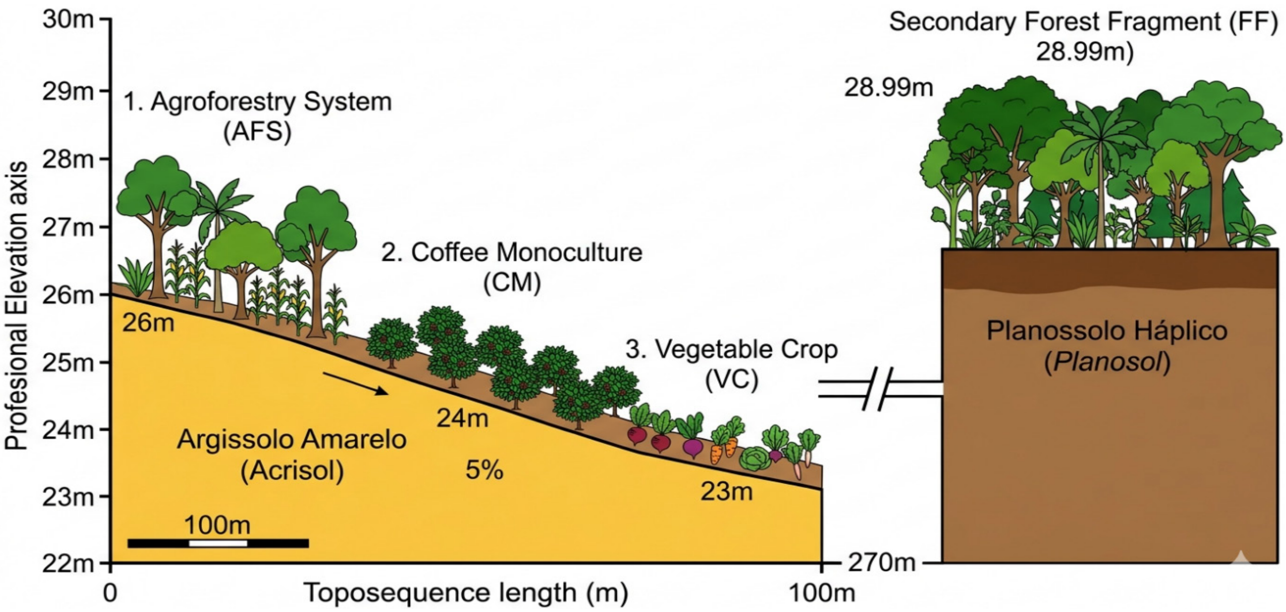


Table 1 - Species composition by category, life-form, and plant spacing design in the agroforestry system in Seropédica, RJ, Brazil. Categories: high-value perennial crops (HVP), key species for environmental restoration (SER), and forest species for timber purposes (STP). Life-forms: shrub (SHR), tree (TRE), and palm tree (PAL)

Category	Scientific name	Common name	Life-form	Plant spacing design
STP	*Plathymenia reticulata* Benth.	vinatic	TRE	32 x 4 m
SER	*Gliricidia sepium* (Jacq.) Kunth ex Walp.	gliricidia	TRE	26 x 2 m
STP	*Schizolobium parahyba* (Vell.) Blake	guapuruvu	TRE	6 x 5 m
SER	*Cecropia pachystachya* Trécul	embauba	TRE	6 x 5 m
HVP	*Bactris gasipaes* Kunth.	peach palm	PAL	6 x 2 m
HVP	*Coffea canephora* Pierre ex A. Froehner	coffee	SHR	6 x 2 m
HVP	*Musa* spp.	banana	SHR	6 x 2 m
SER	*Schinus terebinthifolius* Raddi	Brazilian pepper	TRE	4 x 3 m
SER	*Bixa orellana* L.	annatto	TRE	4 x 3 m
SER	*Flemingia macrophylla* (Willd.) Merr.	flemingia	SHR	2 x 0.5 m

The FF (32,000 m²) is an adjacent secondary native forest fragment with 28 years of regeneration (Ramos *et al*., 2025), situated on a *Planossolo Háplico* at a distance of 290 to 315 m from the agricultural LUS. This area features a closed canopy and a substantial litter layer, which fosters a stable microclimate by enhancing moisture retention and buffering soil temperature extremes (Ramos *et al*., 2025). The FF serves as the regional reference for soil quality (Simon *et al*., 2022) due to minimal anthropogenic interference (Bünemann *et al*., 2018). Furthermore, this ecosystem exhibits the highest floristic richness and structural complexity among all studied sites, consequently maintaining high ecological performance (Bünemann *et al*., 2018), evidenced by efficient nutrient cycling (Camara *et al*., 2018). and carbon storage (Kothandaraman *et al*., 2020).

Soil sample collection

Sampling was conducted across two distinct seasons: rainy (December 2022) and dry (June 2023). Within each LUS, five random sampling points were established for topsoil (0 – 0.05 m) collection. At each point, we collected one undisturbed monolith for physical structural analysis, and one composite disturbed sample, consisting of three subsamples, for other physical analyses, alongside chemical and biological assessment.

Chemical attributes

Disturbed samples were air-dried and sieved through a 2.0 mm mesh to obtain the Air-Dried Fine Earth (ADFE), from which subsamples were extracted for all chemical attribute analyses. SOM dynamics were assessed through total organic carbon (TOC) via wet oxidation (Yeomans; Bremner, 1988), particulate organic carbon (POC) via physical fractionation, and mineral-associated organic carbon (MAOC) was calculated as described in Equation 1 (Cambardella; Elliott, 1992).

$$MAOC = TOC - POC \tag{1}$$

Chemical attributes also included Active Acidity (pH in H_2O), Potential Acidity (H + Al), Total Nitrogen (N), Available Phosphorus (P), and Exchangeable Cations (Ca^{2+}, Mg^{2+}, K^+, Na^+, Al^{3+}) (TEIXEIRA *et al*., 2017). Subsequently, Sum of Bases (SB), Cation Exchange Capacity (CEC), and Base Saturation (V%) were calculated as described in Equations 2, 3, and 4, respectively.

$$SB = C\alpha^{+2} + Mg^{+2} + K^{+} + N\alpha^{+} \tag{2}$$

$$CEC = SB + H^{+} + Al^{+3} \tag{3}$$

$$V\% = (SB / CEC) * 100 \tag{4}$$

Soil physical attributes analyzed

Subsamples from the disturbed samples were used to determine topsoil particle-size composition and moisture. Particle-size distribution was determined by the pipette method and expressed as Total Clay (TCL), Coarse Sand (CSN), Fine Sand (FSN), Total Sand (TSN), and Silt (SLT) fractions (Teixeira *et al*., 2017). Soil moisture was estimated via gravimetric Soil Water Content (SWC). Topsoil temperature (STMP) was measured *in situ* using a geothermometer, while structural stability was quantified from undisturbed monoliths using the Mean Weight Diameter (MWD), derived from wet sieving analysis (Teixeira *et al*., 2017).

Soil biological attributes analyzed

Epigeic invertebrates were sampled using five pitfall traps per LUS (7-day period). Specimens were identified at major taxonomic levels and quantified to estimate: total abundance (ind $trap^{-1}$ day^{-1}), relative abundance (%), total and mean richness, Shannon's diversity (H'), and Pielou's evenness (J'). Groups with < 3% relative abundance were categorized as "Others".

Statistical analyses

Data were log-transformed (ln(x + 1)) to stabilize variance. Univariate analyses (LSD or Kruskal-Wallis) compared means between LUS and seasons, after transformed data were tested for normality of residuals and homogeneity of variance using the Lilliefors and Levene tests, respectively. Pearson correlations identified relationships between soil quality indicators (SQI), prioritizing interpretation of strong (|0.70| to |0.89|) and very strong (|0.90| to |1.00|) associations. A significance level of 5% ($p < 0.05$) was adopted for all analyses. Due to the high variance of soil fauna, an exploratory analysis compared aggregated mean values of agricultural LUS against the FF reference to identify systemic trends related to the groups relative abundance.

Multivariate analysis included Principal Component Analysis (PCA) to select the most sensitive SQI that best reflected soil functional capacity (Bünemann *et al*., 2018). Thus, we focused on attributes expressing high factor loadings (> |0.70|) on either Principal Component 1 or 2 (PC1 and PC2, respectively). These selected attributes were then subjected to Hierarchical Cluster Analysis (HCA) based on Euclidean distance to identify dissimilarities between management systems and seasons. All statistical analyses were conducted using Statistica software (version 14.0.0.15).

RESULTS AND DISCUSSION

Soil Chemical Attributes: SOM dynamics, Nitrogen, and Phosphorus

The Forest Fragment (FF) topsoil consistently showed higher levels of Total Organic Carbon (TOC), Mineral-Associated Organic Carbon (MAOC), Particulate Organic Carbon (POC), and Nitrogen (N) across both seasons (Table 2). This pattern is typical of undisturbed secondary forests where high litterfall from a diverse arboreal community (Camara *et al*., 2018, 2023) exceeds mineralization losses (OLIVEIRA Netto *et al*., 2024), contrastingly matching the Coffee Monoculture (CM) performance.

Despite its structural simplicity, the CM sustained TOC and N pools comparable to the FF, suggesting a "forest-mimicking" dynamic. This functional similarity is likely a result of high planting density and intensive litter input, which creates a "mulching effect" that buffers microclimatic oscillations and stabilizes SOM mineralization within the mineral matrix (Tonini *et al*., 2024). Conversely, the AFS showed lower TOC and MAOC levels, suggesting its current successional stage and management have not yet achieved the same level of soil surface protection and organic matter stabilization.

The sensitivity of SOM fractions revealed impacts that the stable TOC pool might otherwise mask (Bünemann *et al*., 2018; Camara *et al*., 2023; Oliveira Netto *et al*., 2024; Ramos *et al*., 2025). MAOC represented the dominant and most resilient carbon pool, especially in agricultural systems during the dry season (up to 94% of TOC), ensuring long-term biogeochemical stability (Bünemann *et al*., 2018; Gualberto *et al*., 2023). Conversely, POC proved to be a superior indicator of functional integrity loss; its significant decline from 43% (FF) to 16% (agricultural LUS) during the rainy season threatens nutrient cycling, as POC serves as the primary energy source for soil microbiota (Bünemann *et al*., 2018; Gualberto *et al*., 2023).

Nitrogen dynamics mirrored carbon stabilization. In the CM and VC, mineral N fertilization matched the stable N pool sustained by N-fixing *Fabaceae* and continuous litterfall in the FF (Freschet *et al*., 2021). The lower N levels in the AFS highlight a gap in N-supply efficiency, which could be mitigated by the strategic enrichment of N-fixing species to enhance organic N turnover. Regarding phosphorus, mineral fertilization in all agricultural LUS resulted in significantly higher P levels compared to the FF, where high phosphorus fixation capacity, inherent to weathered tropical soils, limits available P (Teles *et al*., 2020).

Seasonality acted as a primary driver for SOM and N accumulation, as evidenced by strong positive correlations between Soil Water Content (SWC) and TOC (r = 0.77), POC (r = 0.80), and N (r = 0.77). During the rainy season, increased moisture and solar radiation facilitate mineral fertilization efficiency and photosynthetic assimilation, particularly in the CM and VC (Ogunkanmi *et al*., 2021). In the FF and CM, the topsoil is further enriched by accelerated litterfall and efficient nutrient cycling during wet months (Sayer *et al*., 2024). Interestingly, the AFS acted as a buffered system, where N levels remained decoupled from short-term meteorological fluctuations, likely due to its successional stage.

Table 2 - Total (TOC), mineral-associated (MAOC) and particulate organic carbon (POC), total nitrogen (N), and available phosphorus to plants (P) in the topsoil (0-0.05 m) under different land-use systems and seasons in Seropédica, RJ, Brazil [α]. Land-use systems (LUS): Vegetable cultivation (VC), Coffee monoculture (CM), Agroforestry system (AFS), and Seasonal Semideciduous Forest fragment (FF)

LUS	TOC	MAOC	POC	TOC	MAOC	POC
	$g\ kg^{-1}$			$g\ kg^{-1}$		
	Rainy season			Dry season		
VC	46.68 Ba (7.25)	40.04 Ba (8.11)	6.64 Ca (2.44)	21.16 Bb (1.40)	18.55 Bb (1.08)	2.61 Ab (0.51)
CM	67.38 Aa (7.00)	56.95 Aa (5.97)	10.43 Ba (4.98)	36.91 Ab (16.31)	34.15 Ab (15.87)	2.76 Ab (0.87)
AFS	27.59 Ca (5.92)	22.75 Ca (5.24)	4.84 Ca (1.59)	19.14 Bb (3.86)	18.04 Ba (4.04)	1.09 Bb (0.41)
FF	68.52 Aa (11.39)	39.39 Ba (8.00)	29.13 Aa (11.69)	39.33 Ab (2.91)	35.64 Aa (2.83)	3.69 Ab (0.64)

LUS	N	P	N	P
	$g\ kg^{-1}$	$mg\ dm^{-3}$	$g\ kg^{-1}$	$mg\ dm^{-3}$
	Rainy season		Dry season	
VC	2.32 Aa (0.61)	30.35 Ab (11.01)	1.00 Bb (0.10)	76.23 Aa (8.02)
CM	2.82 Aa (0.86)	18.47 ABb (3.29)	1.43 Ab (0.07)	29.89 Ba (10.49)
AFS	1.23 Ba (0.45)	21.34 ABa (16.92)	0.73 Ca (0.05)	37.16 Ba (13.03)
FF	2.88 Aa (0.83)	9.81 Ba (2.03)	1.45 Ab (0.12)	13.30 Ca (7.02)

[α] Mean values (± standard deviation) based on five replicates. Different uppercase letters indicate significant differences between land-use systems, while different lowercase letters indicate significant differences between seasons ($p < 0.05$). Statistical differences were determined by parametric LSD or non-parametric tests (Kruskal-Wallis or Mann-Whitney)

Phosphorus (P) dynamics followed an inverse seasonal pattern in managed systems (CM and VC), with lower levels during the rainy season (Table 2). This decrease is attributed to enhanced P diffusion in moist soils, which increases biological demand and plant uptake (Kuwahara *et al*., 2016), alongside immobilization within microbial biomass (Tiecher *et al*., 2017). In contrast, P levels remained stable in the FF and AFS, reflecting the strong buffering effect of P-fixation inherent to unmanaged or less intensive tropical soils (Teles *et al*., 2020).

Soil Chemical Attributes: Soil Acidity and Cation Exchange Complex

Regardless of the season, agricultural LUS exhibited lower potential acidity (H + Al) and higher pH and base saturation (V%) compared to the Forest Fragment (FF) (Table 3). This divergence stems from liming practices, particularly intensive in the Vegetable Cultivation (VC), and contrasts with the natural acidification of tropical forest soils (Camara *et al*., 2023). In the FF, acidification is driven by the leaching of basic cations and the release of H^+ protons from functional carboxylic and phenolic groups during SOM decomposition (Tavares *et al*., 2021), a mechanism supported by strong positive correlations between H + Al and both POC (r = 0.89) and TOC (r = 0.72).

A critical finding was the "degraded CEC" in managed areas (CM, VC, and AFS) despite their higher levels of exchangeable Ca^{2+} and Mg^{2+}. In these highly weathered soils with low-activity clays, accumulated SOM provides the primary source of organic functional groups that increase cation retention (Albuquerque *et al*., 2024). This structural interaction was confirmed by the very strong positive correlation between TOC and CEC (r = 0.91). Furthermore, during the rainy season, the strong correlation between Sum of Bases (SB) and both TOC (r = 0.78) and MAOC (r = 0.87) indicates that the organic pool effectively governs nutrient retention under high moisture conditions.

Exchangeable Potassium (K^+) reached its peak in the CM, likely due to the residual effect of mineral fertilization and high plant density (Tonini *et al*., 2024). Conversely, lower K^+ in the VC suggests higher

Table 3 - Active acidity in water (pH), potential acidity (H + Al), exchangeable aluminum (Al^{3+}), calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^+) and sodium (Na^+), sum of bases (SB), cation exchange capacity (CEC), and base saturation (V%) in the topsoil (0 - 0.05 m) under different land-use systems and seasons in Seropédica, RJ, Brazil [α]. Land-use systems (LUS): Vegetable cultivation (VC), Coffee monoculture (CM), Agroforestry system (AFS), and Seasonal Semideciduous Forest fragment (FF)

LUS	pH	H + Al	Al^{3+}	CEC	pH	H + Al	Al^{3+}	CEC
	H_2O	---- $cmol_c\ dm^{-3}$ ----			H_2O	---- $cmol_c\ dm^{-3}$ ----		
	---- Rainy season ----				---- Dry season ----			
VC	6.43 Ab (0.15)	3.56 Ca (0.17)	0.00 Ca (0.00)	11.71 Ca (1.21)	6.89 Aa (0.07)	2.15 Cb (0.00)	0.00 Aa (0.00)	11.70 Ba (0.84)
CM	6.00 Bb (0.11)	4.57 Ba (0.64)	0.05 Ba (0.00)	16.32 Ba (2.39)	6.52 ABa (0.14)	3.99 Ba (1.03)	0.00 Aa (0.00)	14.32 Aa (1.97)
AFS	5.77 Bb (0.17)	3.56 Ca (0.40)	0.05 Ba (0.00)	7.90 b (1.22)	6.33 ABa (0.29)	3.10 Ba (0.65)	0.00 Aa (0.00)	9.56 Ca (0.45)
FF	4.44 Ca (0.23)	14.82 Aa (4.61)	0.59 Aa (0.22)	21.91 Aa (5.60)	4.54 Ba (0.30)	9.77 Aa (3.00)	0.59 Aa (0.38)	14.96 Ab (1.79)
	V%		SB	Ca^{2+}	V%		SB	Ca^{2+}
LUS	---- % ----		---- $cmol_c\ dm^{-3}$ ----		---- % ----		---- $cmol_c\ dm^{-3}$ ----	
	---- Rainy season ----				---- Dry season ----			
VC	69.30 Ab (3.53)		8.15 Ba (1.24)	4.62 Bb (0.36)	81.59 Aa (1.35)		9.56 Aa (0.84)	6.10 Aa (0.64)
CM	71.61 Aa (4.85)		11.75 Aa (2.21)	6.96 Aa (1.20)	72.20 ABa (4.98)		10.33 Aa (1.48)	5.86 Aa (0.97)
AFS	54.20 Bb (6.80)		4.33 Cb (1.15)	2.30 Ca (1.03)	67.51 ABa (7.08)		6.45 Ba (0.74)	3.42 Ba (1.06)
FF	32.91 Ca (4.58)		7.10 Ba (1.32)	4.16 Ba (1.15)	34.81 Ba (16.89)		5.19 Ba (2.61)	3.16 Ba (1.88)
LUS	Mg^{2+}		K^+	Na^+	Mg^{2+}		K^+	Na^+
	---- $cmol_c\ dm^{-3}$ ----				---- $cmol_c\ dm^{-3}$ ----			
	---- Rainy season ----				---- Dry season ----			
VC	3.12 ABa (1.46)		0.30 Ba (0.07)	0.11 ABa (0.00)	3.16 Aba (0.66)		0.23 Ba (0.09)	0.06 Ab (0.01)
CM	3.92 Aa (1.00)		0.77 Aa (0.12)	0.10 Ba (0.01)	3.96 Aa (0.69)		0.46 Ab (0.07)	0.05 ABb (0.01)
AFS	1.52 Cb (0.26)		0.40 ABa (0.08)	0.11 Ba (0.03)	2.74 Ba (1.01)		0.26 Bb (0.07)	0.03 Bb (0.00)
FF	1.98 BCa (0.16)		0.68 ABa (0.32)	0.28 Aa (0.13)	1.78 Ca (0.70)		0.21 Bb (0.08)	0.05 ABb (0.01)

[α] Mean values (± standard deviation) based on five replicates. Different uppercase letters indicate significant differences between land-use systems, while different lowercase letters indicate significant differences between seasons ($p < 0.05$). Statistical differences were determined by parametric LSD or non-parametric tests (Kruskal-Wallis or Mann-Whitney)

nutrient export via frequent harvests and increased susceptibility to leaching in exposed soils. Regarding the AFS, its inability to match the FF's CEC suggests a lack of successional balance and biomass accumulation (Camara *et al.*, 2023). Strategies for the AFS should prioritize SOM accumulation via fast-growing and long-lived species to bridge this functional gap in nutrient retention.

While H + Al and the exchangeable base complex remained stable, pH and monovalent cations (K^+ and Na^+) were highly dynamic (Table 3). Higher pH values during the dry season are attributed to decreased soil moisture, which reduces the dissociation of H^+ protons from Fe and Al oxides (Hong; Gan; Chen, 2019). In contrast, K^+ and Na^+ increased during the rainy season across all LUS. This peak results from both mineral fertilization and accelerated litter decomposition, meeting the increased biological demand during the growth peak, while their high solubility and weak retention facilitate transport via the soil solution during wet months.

Soil Physical Attributes: Textural Redistribution, Hygrothermal Dynamics, and Aggregate Stability

Regardless of the season, agricultural LUS, particularly the VC and AFS, exhibited higher sand content (TSN) and lower clay content (TCL) compared to the FF and CM (Table 4). This textural shift suggests topographic redistribution, where surface runoff selectively transports fine particles from upslope areas (AFS) toward lower landscape positions (FF and CM) (Bufebo; Elias; Agegnehu, 2021). This enrichment of clay in downslope areas significantly enhanced the reactive surface area and CEC (r = 0.74), while the sandier nature of upslope LUS increased their susceptibility to nutrient leaching (Albuquerque *et al.*, 2024).

Hygrothermal dynamics were closely linked to SOM accumulation. Positive correlations between Soil Water Content (SWC) and TOC (r = 0.77) and POC (r = 0.80) emphasize that moisture is a key driver of nitrogen availability and carbon storage. While the VC system recorded the highest soil temperatures (STMP) due to reduced cover, the FF and CM systems demonstrated superior thermal buffering capacity. This was evidenced by the strong negative correlation between TCL and STMP (r = -0.81 and -0.91), highlighting how clay-rich, covered soils mitigate heat storage compared to sandier, exposed areas.

An unexpected finding was the lower aggregate stability (MWD) in the FF during the rainy season compared to agricultural LUS (Table 4). This structural instability in the reference area is driven by its downslope position; transient soil saturation causes rapid water entry that expels entrapped air, leading to "aggregate cracking" (Dowdeswell-Downey *et al.*, 2023). In contrast, the AFS reached its peak MWD during the rainy season, facilitated by the stabilizing effect of TOC and POC accumulation.

Table 4 - Total clay (TCL), silt (TSL), coarse (CSN), fine (FSN) and total (TSN) sand, mean weight diameter of aggregates (MWD), temperature (STMP), and moisture or water content (SWC) in the topsoil (0 - 0.05 m) under different land-use systems and seasons in Seropédica, RJ, Brazil [α]. Land-use systems (LUS): Vegetable cultivation (VC), Coffee monoculture (CM), Agroforestry system (AFS), and Seasonal Semideciduous Forest fragment (FF)

LUS	TCL	CSN	FSN	TSN	TCL	CSN	FSN	TSN
	g kg^{-1}				g kg^{-1}			
	Rainy season				Dry season			
VC	130.80 Ba (32.17)	590.20 Aa (13.37)	128.80 Aa (12.26)	719.00 Aa (18.88)	122.60 Ba (38.39)	594.40 Aa (18.23)	144.40 Aa (26.27)	738.80 Aa (14.55)
CM	292.60 Aa (39.88)	527.60 Aa (48.96)	85.80 ABa (9.63)	613.40 Ba (45.56)	289.00 Aa (51.97)	537.00 Aa (54.19)	85.20 Ba (7.26)	622.20 Ba (58.30)
AFS	142.80 Ba (14.96)	578.40 Aa (70.25)	121.80 ABa (26.72)	700.20 Aa (81.68)	142.20 Ba (16.68)	579.20 Aa (75.73)	117.40 ABa (27.97)	696.60 ABa (84.91)
FF	318.20 Aa (40.41)	447.40 Ba (51.34)	74.20 Ba (22.59)	521.60 Ca (57.58)	315.00 Aa (48.92)	458.20 Ba (72.57)	70.80 Ba (31.59)	529.00 Ca (84.66)
LUS	TSL	SWC	MWD	STMP	TSL	SWC	MWD	STMP
	g kg^{-1}	%	mm	ºC	g kg^{-1}	%	mm	ºC
	Rainy season				Dry season			
VC	150.20 Aa (38.66)	20.31 Ba (5.07)	3.35 Aa (0.33)	28.30 Aa (0.45)	138.60 Aba (38.06)	16.76 ABa (3.83)	3.30 Ba (0.52)	21.90 Ab (0.55)
CM	94.00 Aa (11.02)	27.28 Ba (8.15)	3.55 Aa (0.14)	25.20 Ba (0.45)	88.80 Ba (10.50)	20.82 Aa (10.39)	3.95 ABa (0.70)	19.70 Cb (0.45)
AFS	157.00 Aa (82.33)	14.27 Ca (3.11)	3.59 Ab (0.44)	27.10 ABa (0.55)	161.20 Aa (83.12)	5.74 Bb (1.20)	4.24 Aa (0.42)	20.50 Bb (0.71)
FF	160.20 Aa (45.78)	42.34 Aa (6.04)	2.78 Ba (0.49)	24.50 Ba (0.00)	156.00 Aa (61.02)	20.82 Ab (3.57)	4.01 Ab (0.29)	19.90 BCb (0.55)

[α] Mean values (± standard deviation) based on five replicates. Different uppercase letters indicate significant differences between land-use systems, while different lowercase letters indicate significant differences between seasons ($p < 0.05$). Statistical differences were determined by parametric LSD or non-parametric tests (Kruskal-Wallis or Mann-Whitney)

The VC system showed chronic disaggregation regardless of the season, a result of frequent tillage and bare soil maintenance. The degradation in the VC is exacerbated by higher STMP, which triggers rapid mineralization of organic C and N, as confirmed by the strong negative correlation between POC and STMP (r = -0.73).

Corroborating large-scale studies in Brazil (Albuquerque *et al*., 2024), our results demonstrate that nutrient storage potential (V%) depends on a tripartite interaction between texture, SOM, and CEC. Seasonality modulates these links: (i) Rainy Season: CEC is governed by the synergy between TCL, TOC, and POC. High STMP in sandier fractions (CSN, TSN) negatively impacts carbon labile pools (POC); (ii) Dry Season: The importance of MAOC for CEC increases (r = 0.83), and the correlation between TCL and carbon stabilization (MAOC, r = 0.79) becomes more evident, reinforcing the role of the mineral matrix in protecting organic matter during water stress.

Soil Biological Attributes: Invertebrate Community Structure and Composition

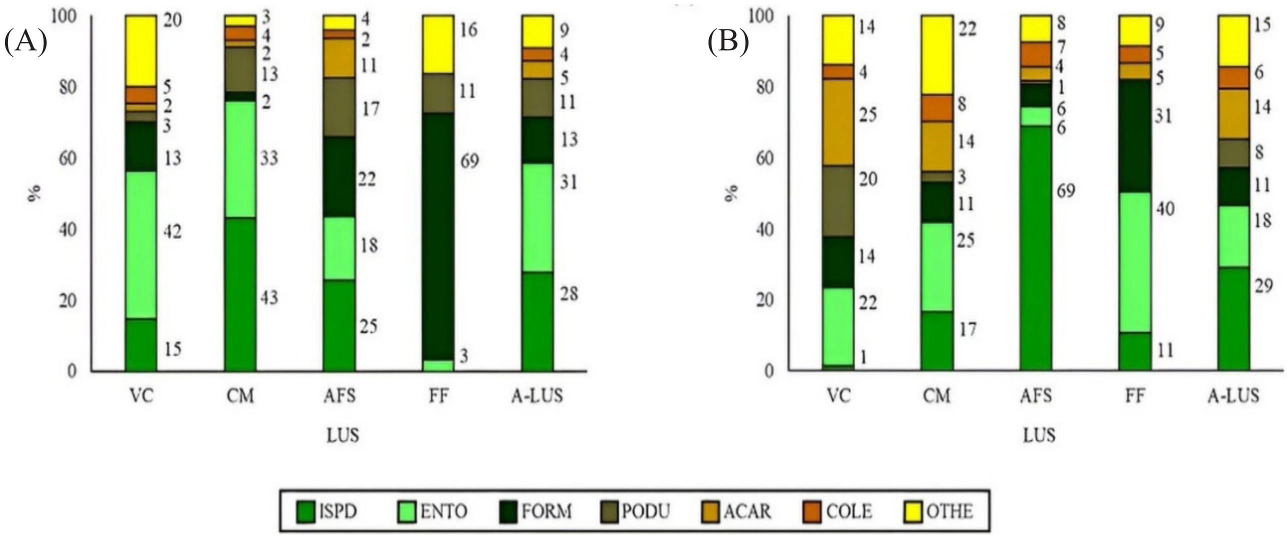
A total of 28 taxonomic groups were identified, with six dominant taxa (Acari, Entomobryomorpha, Poduromorpha, Isopoda, Coleoptera, and Formicidae) accounting for 89% of the total abundance (Figure 2). These generalist groups, characterized by high omnivorous plasticity, efficiently monopolize resources across varying environments (Silva *et al*., 2019).

The FF acted as a reservoir for Formicidae, whose dominance is driven by the high net primary productivity and buffered microclimate of native forests (Maravalhas; Vasconcelos, 2019). Ant abundance showed a strong negative correlation with V% (r = -0.74), reinforcing their role as bioindicators for the acidic, oligotrophic conditions of the FF. Conversely, Acari and Isopoda abundances were higher in agricultural LUS (Figure 2). Mites abundance was negatively correlated with TOC (r = -0.73) and POC (r = -0.70), highlighting their success in disturbed habitats with lower organic stabilization (Silva *et al*., 2019).

During the rainy season, Isopoda abundance correlated positively with V% (r = 0.72) and negatively with Al^{3+} (r = -0.77). These patterns suggest that the chemical correction (liming) in managed systems, specifically in the AFS and VC, creates a favorable environment for these ecosystem engineers. Similarly, Coleoptera adults and Entomobryomorpha were favored by the increased pH and base saturation in managed areas (r > 0.70), indicating that management practices directly shape the community via chemical filters.

Managed systems exhibited higher absolute abundance and mean richness compared to the FF, especially during the rainy season (Figure 3). Total abundance was strongly and negatively correlated with Al^{3+} (r = -0.89) and H + Al (r = -0.71). The agricultural LUS consistently recorded higher total richness, diversity, and evenness, a pattern that aligns with the Intermediate Disturbance Hypothesis (IDH). While the stable FF experiences competitive exclusion by dominant taxa (Formicidae), the management-induced heterogeneity in the CM and VC facilitates the coexistence of diverse opportunistic groups.

Figure 2 - Relative abundance of the dominant groups and total soil invertebrate community in the topsoil (0 - 0.05 m) under different land-use systems and seasons in Seropédica, RJ, Brazil. Land-use systems (LUS): Vegetable cultivation (VC), Coffee monoculture (CM), Agroforestry system (AFS), and Seasonal Semideciduous Forest fragment (FF). Seasons: Rainy (A) and Dry (B). Dominant groups: Acari (ACAR), Coleoptera adults (COLE), Entomobryomorpha (ENTO), Formicidae (FORM), Isopoda (ISPD), Poduromorpha (PODU), and the category Others (OTHE)



The CM system reached its highest diversity and evenness during the dry season, driven by the localized mulching effect (Tonini *et al*., 2024) that promotes a balanced distribution of Isopoda and Entomobryomorpha. In contrast, the AFS showed the lowest diversity due to the overwhelming dominance of Isopoda, suggesting that this system has not yet achieved the ecological stabilization characteristic of the mature FF and CM systems.

Seasonality significantly influenced the FF, which exhibited lower structural parameters (richness, abundance, and diversity) during the rainy season. This trend is driven by the environmental filter of transient soil water saturation, which triggers competitive exclusion and reduces the activity of most groups, except for Formicidae and Poduromorpha. In managed systems, structural parameters were more resilient to seasonal shifts, likely due to the mitigating effects of irrigation (VC) and mulching (CM), which decouple the soil community from regional rainfall regimes.

Multivariate Analysis: Integrating Soil Quality Indicators

The PCA identified three and two Principal Components (PC) explaining the majority of the total variance across rainy and dry seasons, respectively, which were considered as the most relevant (Table 5). Out of the 32 attributes evaluated, 18 and 10 functioned as soil quality indicators during the rainy and dry seasons, respectively, due to their high loading coefficients (> |0.70|) in PC1 or PC2 (Table 6). Notably, only seven of these indicators (representing approximately 22% of the initial attributes) met this criterion simultaneously in both seasons. These seven indicators also exhibited high loadings in PC1, which explained most of the total data variance (59% and 69% during the rainy and dry seasons, respectively). Consequently, the set composed of TCL, TSN, FSN, CSN, Al3+, pH, and H + Al was identified as the most highly weighted soil quality indicators in this study. This finding highlights that, in weathered tropical soils, the physical matrix and acidity components are the primary driving factors differentiating land-use systems.

The biplot space (PC1 and PC2) clearly individualized the areas, revealing highly significant interactions and thus identifying ecosystem dynamics (Figures 4A-D). The FF consistently associated with TCL, H + Al, and Al^{3+} regardless of the season, besides CEC, SWC, and POC during the rainy season. Vectors representing this cluster of attributes formed acute angles, indicating a synergistic relationship between clay content and the preservation of labile carbon (POC) and moisture.

The VC system was positioned in the opposite quadrant to FF in both seasons, associated with sandier textures (CSN, FSN, and TSN) and pH regardless of the season, alongside STMP and MRIC during the rainy season, besides P and V% during the dry season (Figures 4A-D). The vectors for sand and temperature formed opposite directions to clay and moisture, confirming a significant negative correlation (r = -0.70) that characterizes the thermal and hydric instability of this system.

Figure 3 - Absolute abundance (A), mean richness (B), total richness (C), evenness (D), and diversity (E) of the soil invertebrate community in the topsoil (0 - 0.05 m) under different land-use systems and seasons in Seropédica, RJ, Brazil. Land-use systems (LUS): Vegetable cultivation (VC), Coffee monoculture (CM), Agroforestry system (AFS), and Seasonal Semideciduous Forest fragment (FF). Seasons: Rainy (RS) and Dry (DS)

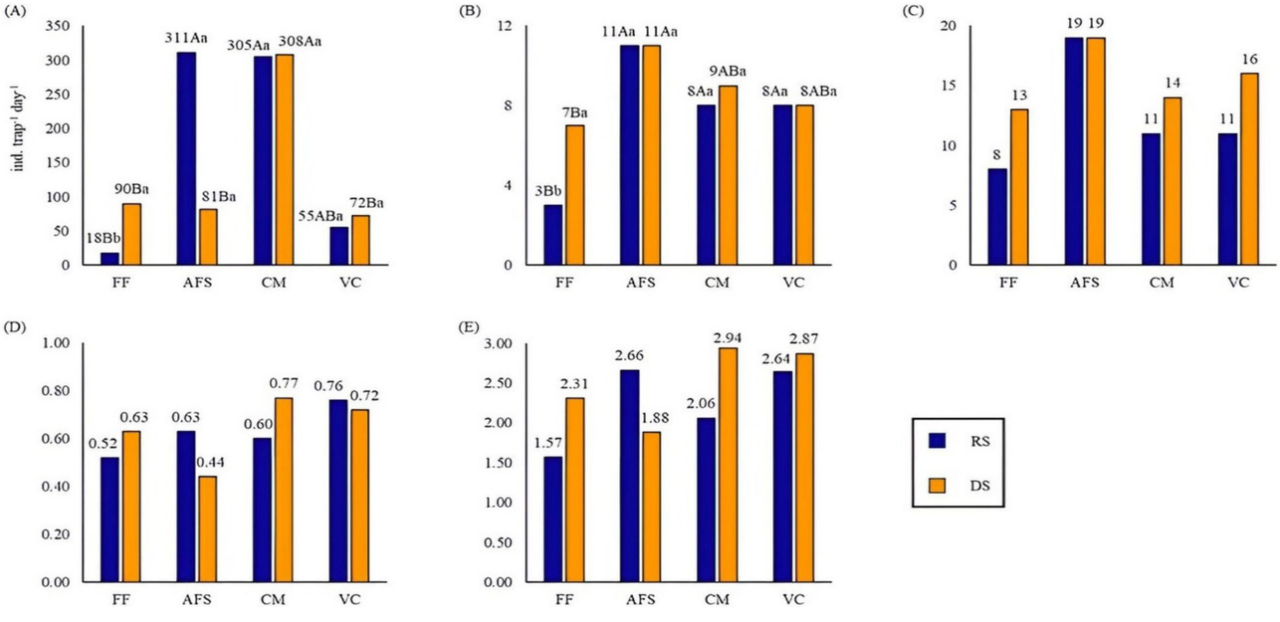


Table 5 - Eigenvalues, percentage of total variance, and accumulated percentage of total variance explained by the Principal Components (PC) for attributes in the topsoil (0 - 0.05 m) under different land-use systems and seasons in Seropédica, RJ, Brazil. Land-use systems (LUS): Vegetable cultivation (VC), Coffee monoculture (CM), Agroforestry system (AFS), and Seasonal Semideciduous Forest fragment (FF). Eigenvalues (EG), Percentage of total variance (TV), and Accumulated percentage of total variance (AV)

Rainy season									
	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8	
EG	10.59	4.39	1.03	0.56	0.37	0.33	0.28	0.20	
TV	58.85	24.39	5.74	3.14	2.05	1.84	1.53	1.12	
AV	58.85	83.24	88.98	92.12	94.17	96.01	97.54	98.66	
	PC9	PC10	PC11	PC12	PC13	PC14	PC15		
EG	0.11	0.08	0.03	0.01	0.01	0.00	0.00		
TV	0.6	0.47	0.16	0.07	0.04	0.00	0.00		
AV	99.27	99.73	99.89	99.96	100.00	100.00	100.00		
Dry season									
	PC1	PC2	PC3	PC4	PC5	PC6	PC7	PC8	PC9
EG	6.91	1.23	0.86	0.42	0.26	0.15	0.08	0.06	0.02
TV	69.12	12.31	8.62	4.25	2.62	1.45	0.78	0.61	0.24
AV	69.12	81.43	90.05	94.30	96.91	98.36	99.15	99.76	100.00

Table 6 - Correlation coefficients between the Principal Components 1 and 2 (PC1 and PC2, respectively) for attributes in the topsoil (0-0.05 m) under different land-use systems and seasons in Seropédica, RJ, Brazil. Land-use systems (LUS): Vegetable cultivation (VC), Coffee monoculture (CM), Agroforestry system (AFS), and Seasonal Semideciduous Forest fragment (FF)

Rainy season										
PC	TCL	CSN	FSN	TSN	pH	Al^{3+}	H + Al	Ca^{2+}	Mg^{2+}	
1	-0.88	0.84	0.76	0.89	0.75	-0.76	-0.85	-0.45	-0.16	
2	0.04	0.25	0.01	0.20	0.60	-0.53	-0.43	0.80	0.90	
PC	SB	CEC	SWC	STMP	TOC	MAOC	POC	N	MR	
1	-0.42	-0.95	-0.87	0.86	-0.87	-0.45	-0.87	-0.87	0.78	
2	0.89	0.07	-0.01	0.07	0.43	0.83	-0.30	0.43	0.23	
Dry season										
PC	TCL	CSN	FSN	TSN	pH	Al^{3+}	H+Al	Na^{+}	V%	P
1	0.84	-0.87	-0.76	-0.93	-0.91	0.85	0.95	-0.24	-0.94	-0.79
2	-0.44	0.08	0.32	0.18	-0.23	0.18	0.06	-0.87	-0.21	-0.04

Note: Contents de coarse, fine, and total sand (CSN, FSN, and TSN, respectively); content of total clay (TCL); soil temperature (STMP); soil water content (SWC); active acidity (pH); sum of bases (SB); potential acidity (H + Al); soil base saturation (V%); soil cation exchange capacity (CEC); contents of total organic carbon, mineral-associated organic carbon, and particulate organic carbon (TOC, MAOC, and POC, respectively); mean richness (MR)

The CM positioned closer to the FF and was associated with MAOC, SB, Ca^{2+}, and Mg^{2+}, during the rainy season (Figures 4A-D). This proximity reinforces the "forest-mimicking" dynamic previously discussed, where carbon stabilization and nutrient retention are maintained despite management. The AFS occupied an intermediate position between VC and FF regardless of the season and was positioned in the opposite quadrant to CM during the rainy season. Notably, no specific vectors pointed directly to the AFS. The vectors for TOC and N were positioned between FF and CM, opposite the AFS. This pattern indicates that, at 8–9 years of age, the AFS has not yet achieved the successional maturity required to reach the carbon storage levels of the undisturbed FF or the high-density CM.

Figure 4 - Score of vegetable cultivation (VC), coffee monoculture (CM), agroforestry system (AFS), and Seasonal Semideciduous Forest fragment (FF) in Seropédica, RJ, Brazil, and weights of topsoil attributes, considering the relationship between Principal Component 1 and 2 (PC1 and PC2, respectively), in the rainy season (A and B, respectively) and dry season (C and D, respectively). Contents of coarse, fine, and total sand (CSN, FSN, and TSN, respectively); total clay content (TCL); soil temperature (STMP); soil water content (SWC); active acidity or hydrogen potential (pH); potential acidity (H + Al); sum of bases (SB); soil base saturation (V); soil cation exchange capacity (CEC); content of mineral-associated organic carbon (MAOC); content of particulate organic carbon (POC); mean richness (MR) of the soil invertebrate community

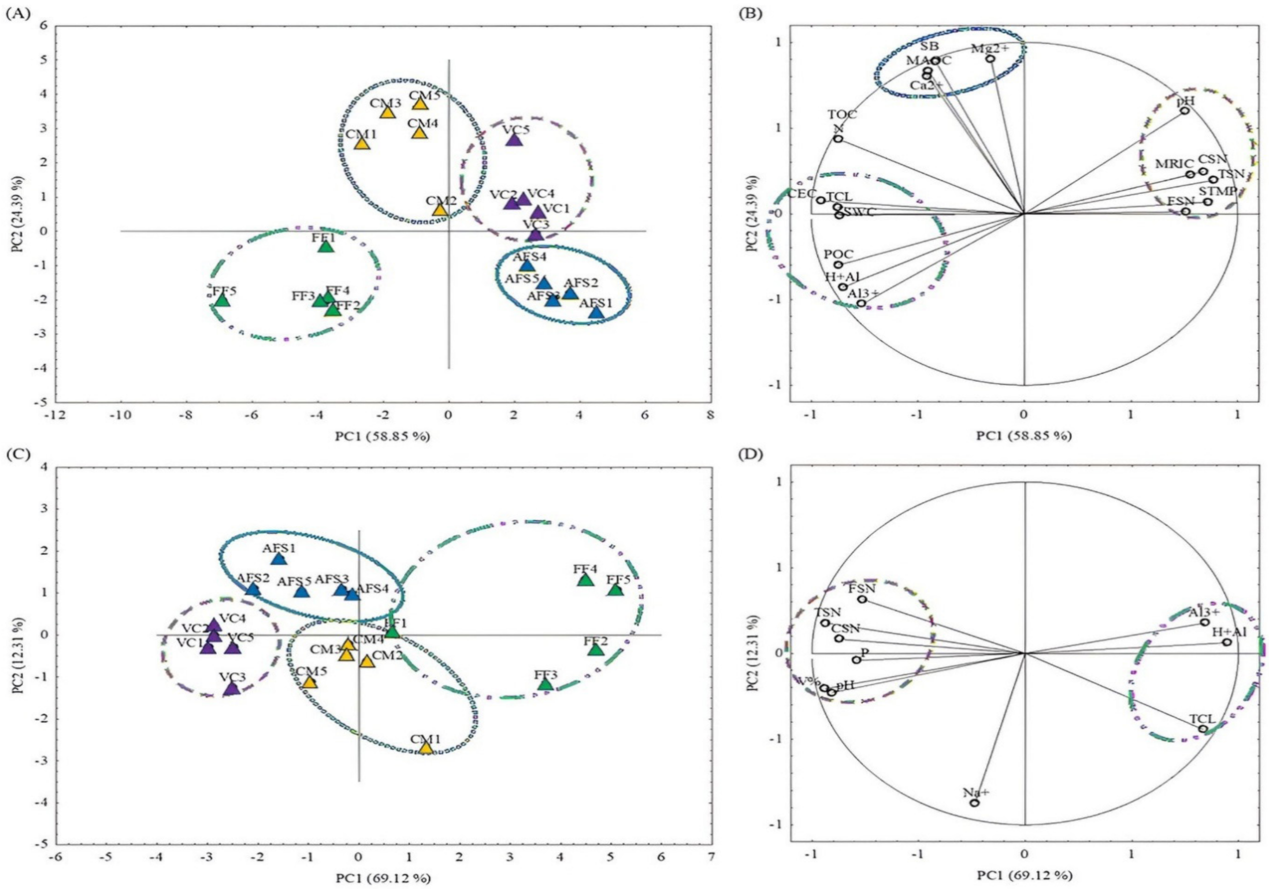
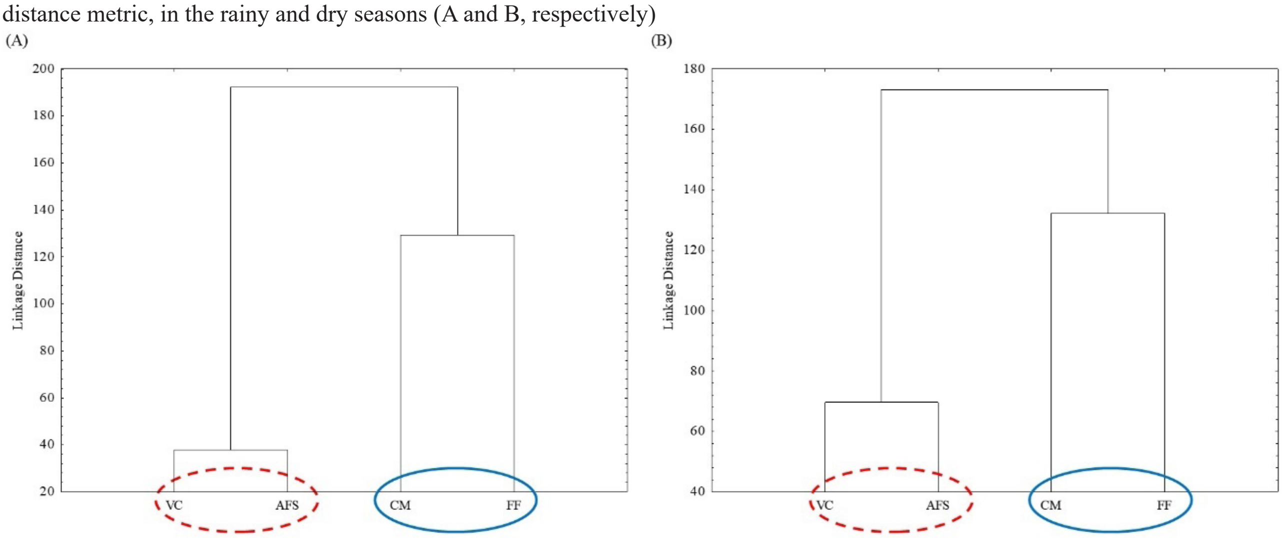


Figure 5 - Dendrogram representing the clustering of vegetable cultivation (VC), coffee monoculture (CM), agroforestry system (AFS), and Seasonal Semideciduous Forest fragment (FF) in Seropédica, RJ, Brazil, by means of single linkage, based on the Euclidean distance metric, in the rainy and dry seasons (A and B, respectively)



The HCA confirmed the patterns of land-use system individualization indicated by the PCA, identifying two distinct clusters separated by a high dissimilarity distance (between 170 and 190, depending on the season) (Figures 5A and 5B). The first cluster interconnected VC and AFS by lower dissimilarity distances (40 – 70), suggesting similarities between them in terms of soil dynamics.

The second cluster grouped CM and FF by higher dissimilarity (approx. 130) (Figures 5A and 5B). This emphasized that even under monoculture, high-density planting and litter maintenance can preserve soil functional integrity in the CM system. The high distance between these two groups (170 - 190) highlights the significant impact of landscape position and intensive management. In the sandier LUS (VC and AFS), the rapid mineralization of SOM must be countered by management strategies that prioritize the accumulation of MAOC, the most stable carbon pool (Gualberto *et al*., 2023), through the maintenance of crop residues and cover crops in both systems.

The integrated assessment demonstrates that SOM is critical for the functional resilience of terrestrial ecosystems, by reducing runoff and increasing resistance to erosion (Gmach *et al*., 2020). In the studied region, the plant species diversity in the young AFS has not yet translated into topsoil SOM increases comparable to those of the reference ecosystem (FF) or even the coffee monoculture (CM). Therefore, new arrangements of plant species and the adoption of more appropriate restoration practices are essential for the maintenance of family farms and the restoration of soil functional quality in sandy, fragile areas managed under this agricultural LUS in the Baixada Fluminense.

CONCLUSIONS

1. The integrated analysis of chemical, physical, and biological soil attributes revealed that soil functionality is governed by soil organic matter (SOM) dynamics, whose complex interaction with texture, moisture, and cation exchange capacity (CEC) dictates nutrient storage potential. Seasonality exerts a selective pressure on soil quality: while the chemical matrix and granulometry remain resilient, aggregate stability (MWD), pH, and invertebrate community composition are highly dynamic, responding to environmental filters such as transient soil water saturation in the reference secondary native forest fragment (FF) and the moisture refugia provided by irrigation in a high-input annual system of vegetable cultivation (VC);

2. Multivariate analysis allowed for the rejection of the hypothesis of equality among the studied land-use systems, identifying the contents of Total Clay (TCL), Total Sand (TSN), Fine and Coarse Sand fractions (FSN and CSN, respectively), exchangeable Aluminum (Al^{3+}), both Active and Potential Acidity (pH and H + Al, respectively) as the most sensitive indicators for monitoring sustainability transitions. The results demonstrated a high dissimilarity between native forest and both the VC and the agroforestry system (AFS), while the coffee monoculture (CM) exhibited low dissimilarity compared the FF, suggesting that intensive litter management and high planting density can successfully mimic the functional integrity of natural ecosystems;

3. The FF and CM systems represent the highest levels of structural and metabolic stability, characterized by superior SOM accumulation and a resilient CEC. In these systems, the “mulching effect” provided by dense canopy cover and continuous litter deposition effectively buffers seasonal thermal and moisture oscillations, sustaining a specialized soil invertebrate community dominated by Formicidae and Entomobryomorpha, both essential for the maintenance of ecosystem services;

4. Conversely, the VC and the AFS exhibited a “degraded CEC” and reduced physical stability, primarily due to the loss of fine mineral particles (TCL) and labile organic fractions (POC). However, consistent with the Intermediate Disturbance Hypothesis, these managed systems facilitate higher invertebrate biodiversity by creating temporary niches for opportunistic groups such as Acari and Isopoda, which play critical roles in nutrient cycling within disturbed environments;

5. The 8-to-9-year-old AFS has not yet achieved the successional maturity of the FF, nor has it reached the stabilized SOM and nutrient cycling dynamics observed in this forest ecosystem or in the CM characterized by high-density planting. To enhance the AFS’s long-term sustainability and carbon sequestration potential, management strategies must prioritize the accumulation of mineral-associated organic carbon (MAOC) through reduced plant spacing and enrichment with diverse N-fixing species, thereby bridging the functional gap between young agroecosystems and mature forest environments.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon request.

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