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Potential Use of Quartzipisamment under Agroforestry and Silvopastoral System for Large-Scale Production in Brazil

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Abstract: The need to put into practice sustainable agricultural production systems has been supported by agroecology science that seeks to optimize land use to food production with the lowest impact on soil. This study evaluated soil quality, based on physical and chemical attributes, in agroforestry (AGF) and silvopastoral (SILVP) systems developed for large-scale food production. The study was carried out in the municipality of Itirapina, state of São Paulo, in two areas with AGF and SILVP system, compared to an area with a forest fragment and another with pasture in a Quartzipisamment Sand Neosol. The soil collections were carried out in the layers of 0.00–0.05, 0.05–0.10, 0.10–0.20, and 0.20–0.40 m, where physical soil attributes were evaluated (total porosity, microporosity, and microporosity, density, mean diameter of aggregates) as well as chemical attributes (macro- and micronutrients), in addition to carbon and nitrogen storage. To interpret the data, Tukey's test was applied to compare means, and principal component analysis was used to better characterize the study environments. The results showed that agroforestry and silvopastoral systems developed for large-scale production are efficient in improving chemical and physical attributes that reflect on soil quality, especially in the superficial layers of the soil, overcoming pasture and the natural regeneration process. Carbon and nitrogen storage were the main variables that differentiated the production systems, highlighting the importance of the AGF and SILVP systems as more sustainable agricultural intensification strategies, even in soils of low agricultural suitability.

Keywords: carbon stock; multivariate analysis; soil health; soil quality

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1. Introduction

A key challenge of modern agriculture is to meet the food, fuel, and fiber demands of a growing population while providing adequate financial returns to farmers and protecting environmental quality [1,2]. Modern technology applied in agriculture uses plant breeding to improve the genetic basis of crop production as well as inputs of water, chemicals, and fossil energy to decrease limitations to plant growth [1].

Over the last half-century, these technologies dramatically increased crop yields, allowing agriculture to meet global food demands while slowing the expansion of cropping into natural lands [1,3].

However, agricultural intensification has also caused collateral damage to the environment, such as limited water resources, reactive nitrogen (N) and phosphorus (P) polluting surface and coastal waters and contaminate groundwater, pesticides killing non-target organisms, and altered patterns of carbon (C) and N cycling, contributing to climate change [1]. These environmental impacts raise concerns about the sustainability of current input-intensive agricultural systems [1,4].

The challenge of improving agricultural systems for the next decades is bound to the mandatory target: establishing systems with low environmental externalities that are resilient to climate changes, which is an important strategy to reduce deforestation and to spare land for other uses, including the recovery of environmental services and ecohydrological processes in the drainage basin [5] such as C sink and water regulation [5,6].

Therefore, diversified and integrated cropping systems can provide substantial soil conservation and water quality benefits [1,5,7]. The integrating of agroforestry systems (AGFs), i.e., livestock, forestry, grain crops, and fruit crops) can improve economic returns, thereby providing a more profitable means to sustainable intensive agriculture [7,8].

In a review by Kim et al. (2016) [9], agroforestry systems with intercropping crop model store, on average, 2 t C ha^{-1} $year^{-1}$ in soil under young vegetation (average of 14 years). If we consider the total carbon sequestered by the system (70% in biomass and 30% in soil), systems such as AGFs are capable of sequestering up to 7.2 t C ha^{-1} $year^{-1}$ and 27 t CO_2 equivalent ha^{-1} $year^{-1}$, at least for the first 14 years after establishment. Soil carbon sequestration is a mechanism to reduce CO_2 emissions in agriculture through its storage in long-term carbon pools with reforestation and restoration of degraded lands [6,10].

Such integration provides opportunities to reduce intensive inputs while recovering nutrient cycles and improving soil quality [8,11]. In addition, these systems allow for a greater variety of products to be explored and the inclusion of farmers in less favored conditions, with the main advantages of greater soil coverage, preservation of fauna and flora, organic matter input, nutrient cycling, and carbon storage, resulting in a significant improvement in the chemical and physical attributes of the soil [6,11–13]. Integrated systems may include annual and/or perennial crops, different tree species, several spatial arrangements, planting densities, field operations, and the frequency of rotation between crops and grasses [11].

However, in Brazil, the use of AGFs is still not very expressive due to the lack of technical training, economic incentives, and adapted machinery, which limits their dissemination in larger-scale projects and scientific research that prove their effectiveness in different contexts and regions [5,11,13,14]. As such, the use of this technology is mainly concentrated in the Amazon region, where the biome is naturally suitable for this activity, in addition to small projects aimed at family farming and agricultural settlements [14]. The assessment of indirect impacts of integrated systems adoption is a complex task at the landscape and regional levels, especially when it comes to the prevention of deforestation due to land-use intensification in already cleared areas [11].

The possibility of improving soil quality and enhancing its agricultural conditions, even in areas of low natural fertility, as an example in a Quartzipisamment (Quartz) through AGFs, may represent an important technological advance in light of the current degradation scenario. Quartz Sand Neosols are soils with an excessively sandy texture, low natural fertility, low water retention capacity, and high erodibility [15]. Low clay and organic matter contents contribute to low particle cohesion and practically no aggregation [16].

The reduced nutrient adsorption capacity of this soil class implies high losses of nutrients by leaching, especially when added via mineral fertilization [13]. Thus, the development of management techniques based on ecological processes combined with the adaptation of machines to reach a productive scale, within this perspective, may represent a change in the agricultural production paradigm, together with the current demand for healthier foods and sustainable production systems.

Therefore, this study hypothesizes that mechanized agroforestry systems based on ecological principles and focusing on large-scale production may present higher levels of soil macro- and micronutrients, lower soil compaction, and higher structural quality compared to an area of pasture, reflecting in higher quality and land use.

In this context, the study evaluated the chemical and physical attributes of the soil in a Quartz Sand Neosol in silvopastoral agroforestry systems developed for large-scale production, namely fruit and livestock farming as the main activity, comparing them with a pasture area of Marandu grass (*Urochloa brizantha* cv. Marandu) and a forest fragment undergoing natural regeneration, a transition region between the Atlantic Forest and Cerrado biomes.

2. Materials and Methods

2.1. Field Site Description

The study was conducted at Fazenda da Toca, located in the municipality of Itirapina, state of São Paulo, at geographic coordinates 22°12′ S and 47°44′ W, approximately 800 m above sea level (asl). It is a transition region between the Atlantic Forest and Cerrado biomes, and its climate is considered to be Cwa according to the Köppen classification [17]. In the region, the accumulated rainfall during the year is on average 1367 mm, and the average relative air temperature is around 19.6 °C (Figure 1) [18].

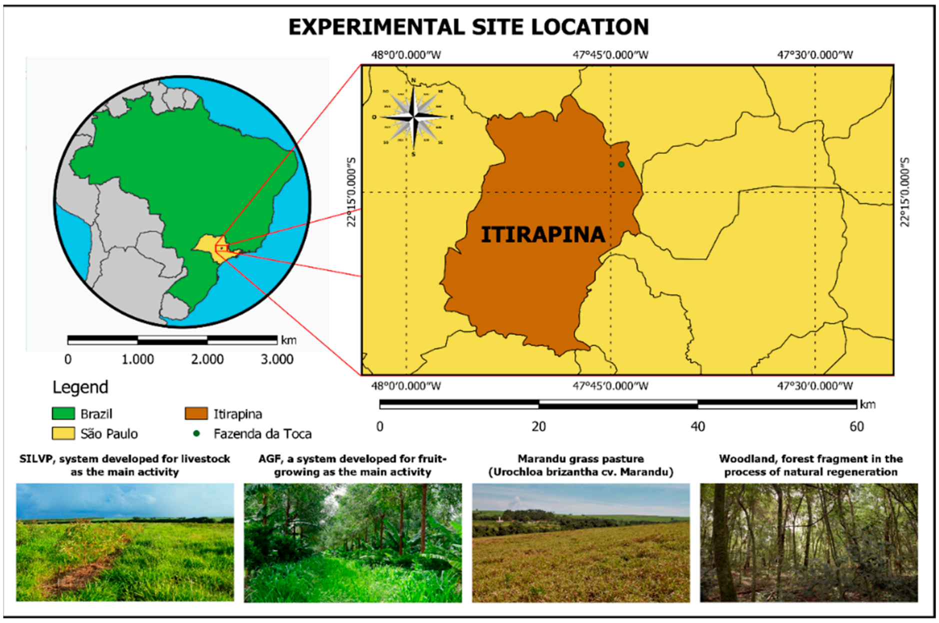

Figure 1. Location of the municipality of Itirapina, in the state of São Paulo, highlighting the study area at Fazenda da Toca and photos of the implemented SAFs. (Source of images: Fazenda da Toca Farm archives).

The soil was classified as Neossolo Quatzarênico, according to the Brazilian Soil Classification System (SiBCS) [19], or as Etisols Quartzipsamments according to the Soil Taxonomy System [20] or Arenosols according to the WRB/FAO [21]. The particle size and chemical characterization of the area was carried out before the beginning of the study and is shown in Table 1.

Table 1. Granulometric and chemical characterization of experimental area located in the municipality of Itirapina in the state of São Paulo, Brazil.

Soil Depth	Sand	Silt	Clay	P	Ca^{2+}	Mg^{2+}	K^{+}	Al^{3+}
m		——g kg^{-1}——		mg dm^{-3}		———cmolc dm^{-3} ———-		
0.00–0.25	920	50	30	0.001	1.30	0.76	0.09	0.01
0.25–0.50	911	19	70	0.001	0.46	0.39	0.06	0.27
0.50–1.00	890	40	70	0.001	0.11	0.14	0.02	0.46

2.2. Experimental Design and Treatments

The experimental design was completely randomized, with six replications. The treatments were: (i) Silvopastoral—SILVP, a system developed for livestock as the main activity; (ii) Agroforestry—AGF, a system developed for fruit growing as its main activity; (iii) Marandu grass pasture (*Urochloa brizantha* cv. Marandu); and (iv) Forest, a forest fragment undergoing a natural regeneration process. The total area of each treatment is 5 ha for SILVP, 15 ha for AGF, 16 ha for pasture, and 65 ha for forest; however, for experimental purposes, only 2 ha of each area was considered.

2.3. Field Trial and Management

Areas with SILVP and AGF systems received similar soil preparation, following the steps:

1. Planting a cover mix with *Urochloa* sp. + *Cajanus cajan* at a density of 15 m^{-1} seeds for soil decompaction and biomass production;
2. Mowing of the area using equipment called "sega pasto" from Casale, which preserves the stem of the grass to ensure the quality of regrowth, after two years and opening of the strips for soil preparation using the straw rake, machinery that separates the biomass, allowing to prepare the soil for planting in windrows;
3. Preparation of the planting windrows (0.20 m deep, in strips 1.2 m wide and 5.0 m long), with a rotary hoe and fertilization only in the rows, with basaltic rock powder (2 Mg ha^{-1} in SILVP and 3 Mg ha^{-1} in AGF), reactive rock phosphate (0.7 Mg ha^{-1}), cattle manure (2 Mg ha^{-1} in SILVP and 5 Mg ha^{-1} in AGS) and biospray (3 L ha^{-1} in SILVP and 5 L ha^{-1} in AGF, after planting the seedlings). For every 1000 L of biospray produced, 500 L of biofertilizer, 40 kg of copper sulfate, 84 kg of zinc sulfate, 11.4 kg of manganese sulfate, and 4 L of liquid sulfur of trade name Sulfor M were used;
4. Windrowing of the mowed material on the strips prepared for planting, using the same machinery (straw rake/windrower). Plant residues formed a thick covering layer, which controlled the growth of grasses in the ridges, in addition to providing organic matter for the soil;
5. Introduction of the species of interest. Planting of seedlings and/or seeds according to the productive focus of each system, including species with the potential to supply biomass.

The SILVP was designed as a system for livestock with wood production (*Eucalyptus pellita*), implemented in June 2015. Windrows 1.2 m wide, spaced 5.0 m apart, were prepared for planting eucalyptus. The inter-row sections were occupied by Marandu grass (*Urochloa brizantha* cv. Marandu) to supply organic residue to cover the soil in the planting strips.

Due to the need for more spacing for pasture, this model includes 12 m wide strips of Marandu grass for every three rows of eucalyptus planting. The grass was mowed six times a year with a "sega-pasto" mower, followed by mowing with a coastal mower to transfer the work. Windrowing of the grass mowed to the tree line was carried out four times a year using Kuhn equipment, and manual weeding in windrows was carried out three times a year. Pruning of eucalyptus with a manual saw was performed five times during the first 18 months.

The AGF, in turn, was designed for the production of fruit and wood crops and was implemented in June 2014 (Acacia—*Acacia mangium*, different species of *Eucalyptus* spp. and *Musa paradisiaca*), with the introduction of fruit seedlings (*Citrus* spp. and *Mangifera indica* L.) in December of the same year.

The same pattern used in SILVP was used in the AGF, with windrows 1.2 m wide and 5.0 m apart. The inter-row sections were occupied by Marandu grass and mowed five times a year with a "sega-pasto" mower, followed by mowing with a coastal mower to transfer work.

The windrowing of the grass mowed to the tree line was carried out four times, and the manual weeding in the windrows was carried out three times a year. Eucalyptus pruning with a manual saw was performed five times during the first 18 months, and their apical pruning was performed in July 2016. This system received complementary fertilization with 2 Mg ha^{-1} of organic compost in October 2015 and 0.5 Mg ha^{-1} of castor bean cake in February 2016, both applied on the basis of fruit crops.

The area used for pasture was occupied by a sugarcane crop until 2009, when it was returned by the mill that leased it and remained as an abandoned cane field until 2012. In 2012 the area was harrowed, followed by the planting of grass (*Urochloa brizantha* cv. Marandu) and used as pasture until April 2016, when the farm ceased its dairy activities, and the area was abandoned. It was used in this study as a reference that demonstrates the common trend of agricultural occupation in the region. The forest fragment served as a reference for the natural recovery strategy in this transitional region between the Atlantic Forest and Cerrado biomes. More information can be found in the Supplementary Materials.

2.4. Soil Samplings and Analysis

Soil collections (deformed and undisturbed samples) were carried out in April 2016 and 2017 at depths of 0.00–0.05, 0.05–0.10, 0.10–0.20, and 0.20–0.40 m, from the opening of trenches to determine the physical attributes and soil chemicals as a function of different treatments.

In the treatments with SILVP and AGF, the collections were carried out in the planting windrows. The areas of influence around the planting windrows represent the strips in inter-row sections (approximately 0.70 m), where the effects of windrow management could be observed from the size and vigor of the grass compared to the center of the rows.

During treatment with SILVP, punctual collections were carried out between the 12-m rows designed for pasture. In treatments with pasture and forest fragments, because they are homogeneous, collections were punctual.

To undisturbed samples, in each area, six trenches were dug to 1.50 m depth, and the soil was collected at depths 0.00–0.05, 0.05–0.10, 0.10–0.20, and 0.20–0.40 m with aluminum rings of 100 cm^3. Around the trenches, six deformed samples were collected in the same soil depths using a Dutch auger.

The total soil porosity (Pt), macroporosity (Macro), microporosity (Micro), and bulk density (Bd) were determined according to the methodologies established by Teixeira et al. (2017). The mean weight diameter (MWD) was determined according to the method described by the authors of [22].

Chemical analyses of macro- and micronutrients were performed in the laboratory according to the methodology proposed by the authors of [23]. The samples were air-dried and then passed through a 2.0 mm sieve for determinations of soil organic matter (SOM), soil pH ($CaCl_2$), available phosphorus (P-resin), exchangeable cations (Ca, Mg and K), potential acidity (H + Al), cation exchange capacity (CEC) and base saturation (V%). The method used to analyze B was hot water, and the other micronutrients (Cu, Fe, Mn, and Zn) were extracted by the DTPA method, as described by the authors of [24].

The determination of carbon (C) and nitrogen (N) contents were carried out from air-dried fine earth samples, ground in a mortar, and filtered through a 100 mesh (0.149 mm) sieve before the total determination of C and N by dry combustion in an elemental analyzer (Truspec model) [25]. The C and N stock was calculated based on equivalent mass, according to the methodology proposed by the authors of [26]. For this study, the soil masses of the layers corresponding to the forest fragment were used as a reference, as they represent a condition closer to the original soil, according to the following equation:

$$\text{C or N stock} = (\text{C} \times \text{Bd} \times \text{e})/1000$$

where C or N storage represents the accumulated carbon and nitrogen (Mg ha^{-1}); C indicates the carbon or nitrogen content in the layer (%); Bd, the density of the soil (Mg m^{-3}); and e, thickness of the layer being analyzed, in m.

2.5. Statistical Analysis

The data presented in this study come from mean values collected in 2016 and 2017 at depths of 0.00–0.05, 0.05–0.10, 0.10–0.20, and 0.20–0.40 m, which were subjected to multivariate principal component analysis (PCA). Only components whose eigenvalues were greater than one were considered. The coefficients of the linear functions, which define the principal components, were used in the interpretation of their meaning, using the sign and relative size of the coefficients as an indication of the weight to be assigned to each variable.

To conduct the analysis, soil attributes that did not show collinearity were selected. After selecting and standardizing the variables (zero mean and unit variance), analysis was processed using Statistica 7.0 (StatSoft. Inc., Tulsa, OK, USA). Univariate analysis of variance (ANOVA) and Tukey's test to compare means was performed with the scores of the first two principal components (CP1 and CP2) to test whether there is a significant difference between treatments when these components are defined.

3. Results and Discussion

3.1. Descriptive Statistics

The results showed that the maximum soil bulk density found in the study was 1.61 Mg m^{-3} and that for the studied soil (Quartzarenic Neosol), it is below the critical limit ranging from 1.65 to 1.75 Mg m^{-3} for sandy soil [15,27]. Areas under SILVP and AGF presented lower values of Bd compared to pasture up to 0.20 m of soil depth (Table 1). More specifically, the lowest value ($p < 0.05$) of Bd was detected in the area under AGF with 1.08 Mg m^{-3} in the 0.00–0.05 m layer, while in the 0.05–0.10 and 0.10–0.20 m layers, the lowest Bd values were in the soil under native forest and AGF, ranging from 1.31 to 1.49 Mg m^{-3} and higher for soil under pasture with 1.58 and 1.61 Mg m^{-3} (Table 2).

The pasture area was temporarily used for grazing, where animal trampling may have caused greater soil density. Similarly, reference [6] found greater Bd under pasture with a value of 1.42 Mg m^{-3} in the 0.20–0.30 m layer in an Oxisol with tropical climate in Colombia, compared to soil under native forest and system silvopastoral with 1.16 and 1.21 Mg m^{-3}, respectively. According to the authors, silvopastoral systems contribute to the restoration of degraded pastures in tropical soils.

In this work, the Bd had an effect caused by SOM, whose attributes showed a significant negative correlation (Figure 2); thus, it is verified that in the area with the lowest Bd value (AGF of 0.00–0.05 m), the SOM value was higher ($p < 0.05$) with 34 g dm-^{3} of SOM and lower values in the area under pasture with 11 g dm^{-3} in the 0.00–0.05 m layer (Table 2). The negative correlation between Bd and SOM is expected, as reported in several studies since SOM tends to increase soil porosity and consequently decrease soil density [27,28].

The higher content of SOM in the AGF is justified by the adopted management, since of all the areas evaluated in this study, it was the one that received the highest deposition of SOM via organic fertilization in the evaluated period (2016 and 2017). Studies claim that the SOM decomposition rate is altered by the continuous deposition of plant residues, facilitating the maintenance and/or increase in SOM [29,30].

In a study by the authors of [31], the authors found a positive correlation between Corg content and species density and diversity in tropical agroforestry systems. In [32] verified that the productive potential of the soil was influenced both by the type of soil (21%) and by the formed vegetation (16%), whose values give meaning to the explained variability, thus confirming the positive effect of the vegetation on the soil.

Meanwhile, the area under pasture, despite providing suitable soil cover with *U. b.* Marandú, has a history of unfavorable management of SOM accumulation; that is, from 2012 to 2017, the area remained with *U. b.* Marandú under intensive grazing management, causing higher forage consumption by animals and consequently lower ground cover. At the 0.05–0.10 m layer, SOM accumulation was 17 and 20 g dm^{-3} for SILVP and AGF, respectively. Whereas in the 0.10–0.20 m layer, the SOM contents in SILVP, AGF, and native forest were similar ($p > 0.05$) and always with lower contents in the pasture area (Table 2).

Table 2. Mean values of physical and chemical soil attributes under different land use and management systems in a large-scale ecological farm, municipality of Itirapina, São Paulo, Brazil.

Manejo	Bd	SOM	MWD	Macro	Micro	Cstock	Nstock	pH	P	K	Ca	Mg	CEC
	Mg m^{-3}	g dm^{-3}	mm	——m^3 m^{-3}——		——Mg ha^{-1}——		-	mg dm^{-3}	——————mmolc dm^{-3}——————			
							0.00–0.05 m						
Foresty	1.28 b	22.33 a	1.91 a	15.96 b	27.48 a	5.48 b	0.40 b	3.51 b	4.29 b	0.72 b	3.66 d	1.35 b	66.89 b
Pasture	1.56 a	11.25 c	1.33 b	5.03 c	31.92 a	2.50 c	0.14 c	5.62 a	11.72 b	0.47 b	12.16 c	5.48 b	32.19 c
SILVP	1.27 b	19.91 b	1.61 ab	24.19 a	19.77 b	6.80 b	0.63 b	5.48 a	38.06 a	1.49 a	21.83 b	16.68 b	57.24 b
AGF	1.08 c	34.00 b	1.81 ab	25.82 a	26.61 a	9.99 a	1.19 a	5.39 a	41.77 a	1.59 a	53.51 a	24.60 a	94.76 a
							0.05–0.10 m						
Foresty	1.44 ab	16.16 b	1.81 a	16.50 a	23.54 bc	5.01 a	0.30 b	3.62 b	3.50 c	0.39 c	1.47 c	1.00 c	41.00 ab
Pasture	1.58 a	10.25 b	1.25 b	6.69 b	30.17 a	2.27 b	0.10 c	5.54 a	12.25 b	0.38 c	10.75 b	5.50 b	31.36 c
SILVP	1.34 b	17.26 a	1.49 ab	21.55 a	21.32 c	5.82 a	0.52 b	5.36 a	25.50 a	1.50 a	19.08 a	10.65 a	48.51 ab
AGF	1.31 b	20.33 a	1.63 ab	16.52 a	27.45 ab	6.97 a	0.76 a	5.45 a	33.00 a	0.90 b	25.08 a	13.08 a	55.53 a
							0.10–0.20 m						
Foresty	1.49 ab	13.08 ab	1.50 a	15.49 a	25.37 ab	7.95 ab	0.57 b	3.72 c	3.75 c	0,37 b	1.46 c	1.00 b	44.14 a
Pasture	1.61 a	7,61 b	0.98 a	7.19 b	27.72 a	3.77 c	0.04 c	5.55 a	7.37 bc	0.30 b	8.83 b	3.08 b	24.03 b
SILVP	1.43 b	14.83 a	1.30 a	20.14 a	21.27 b	10.41 a	0.95 a	5.11 b	14.75 b	0,95 a	17.60 a	5.12 b	42.95 a
AGF	1.35 b	14.50 a	0.99 a	15.61 a	26.45 ab	10.01 ab	1.06 a	5.25 ab	24.40 a	0,75 a	21.95 a	13.71 a	48.10 a
							0.20–0.40 m						
Foresty	1.45 a	11.08 a	1.20 a	16.52 a	23.95 a	13.11 a	0.56 b	3.48 c	2.50 b	0.28 bc	8.16 bc	1.00 b	40.86 a
Pasture	1.61 a	7,36 a	0,71 ab	7.91 b	27.05 a	7.00 b	0.08 c	5.50 a	3.58 b	0.24 c	7.37 c	2.86 ab	23.02 b
SILVP	1.59 a	12.10 a	0,81 ab	12.44 ab	24.15 a	15.00 a	1.23 a	5.03 b	17,58 a	0,79 a	16.63 a	5.87 a	39,09 a
AGF	1.56 a	11.25 a	0,62 b	14.43 a	25.76 a	15.36 a	1.26 a	5.10 ab	16.60 a	0,61 ab	14.25 ab	7.10 a	37.38 a
CV (%)	7.56	24.83	26.57	25.39	15.42	19.97	24.93	5.55	31.02	29.07	27.48	39.54	18.85

SILVP: silvopastoral system with *Eucalyptus pellita* + *Urochloa brizantha* cv. Marandu; AGF: Agroflorestry systems with *Acacia mangium* + *Eucalyptus* spp. (different species) + *Musa paradisiaca* (banana) + *Citrus* spp. + *Mangifera indica* L. Bd: bulk density; SOM: soil organic matter; Macro: macroporosity; Micro: microporosity; MWD: mean weight diameter; Cstock: carbon storage; Nstock: nitrogen storage; pH: potential hydrogen analyzed in $CaCl_2$; P: phosphorus content; K: potassium content, Ca: calcium content; Mg: magnesium content; CEC: cation exchange capacity. Means followed by the same letter in the column do not differ by Tukey's test at 5% probability.

The greatest differences occurred in the surface layer of the soil, with the SILVP and AGF systems showing the highest results, which may be indicative of changes in the soil profile over the time of adoption the systems had, since as the depth of soil increases, the greater the pattern of similarity. Similarly, in the work of [10], in a study involving agroforestry systems with cocoa and rubber trees, pasture, and native forest, the authors detected significant differences in C storage in the superficial layers of the soil after the systems were established for 4 years; however, below 20 cm (up to 1.00 m evaluated), all systems were similar to each other. Furthermore, in the same study, the authors used carbon isotope analysis and found that after 0.40 m of depth, C storage comes from the natural forest that preceded the agricultural systems.

The accumulation of plant material in SILVP or AGF from Urochloa mowing between rows and from pruning of shrub and tree species was an important strategy to increase the dynamics of the soil SOM. Thus, systems with greater input of residues in the crop lines benefit the soil and the plant, being a key factor in increasing the soil's capacity to store carbon [6,33,34].

This result represents a viable agricultural exploitation condition for Neosol, considered of low agricultural suitability for intensive crops and perennial crops [15]. According to the work of [13], for soils such as Quartz Sand Neosol, a high input of organic waste may represent protection of nutrients from the effects of leaching and soil erosion, among other advantages. In addition, management that includes organic fertilizers contributes to better soil structuring [35], and so it was adopted in both SILV and AGF.

In this study, due to the sandy texture of the soil, the formation of stable aggregates depended on the action of the soil organic matter as cement [16]; thus, at the 0.00–0.05 and 0.05–0.10 m layers, the presence of stable macroaggregates was always favorable in the AGF and native forest areas (Table 2), however, at the 0.20–0.40 m layer, only the native forest area presented greater soil aggregates than the area under AGF. Despite this, the DMP was a variable that did not fully explain the variance of the data (Table 3).

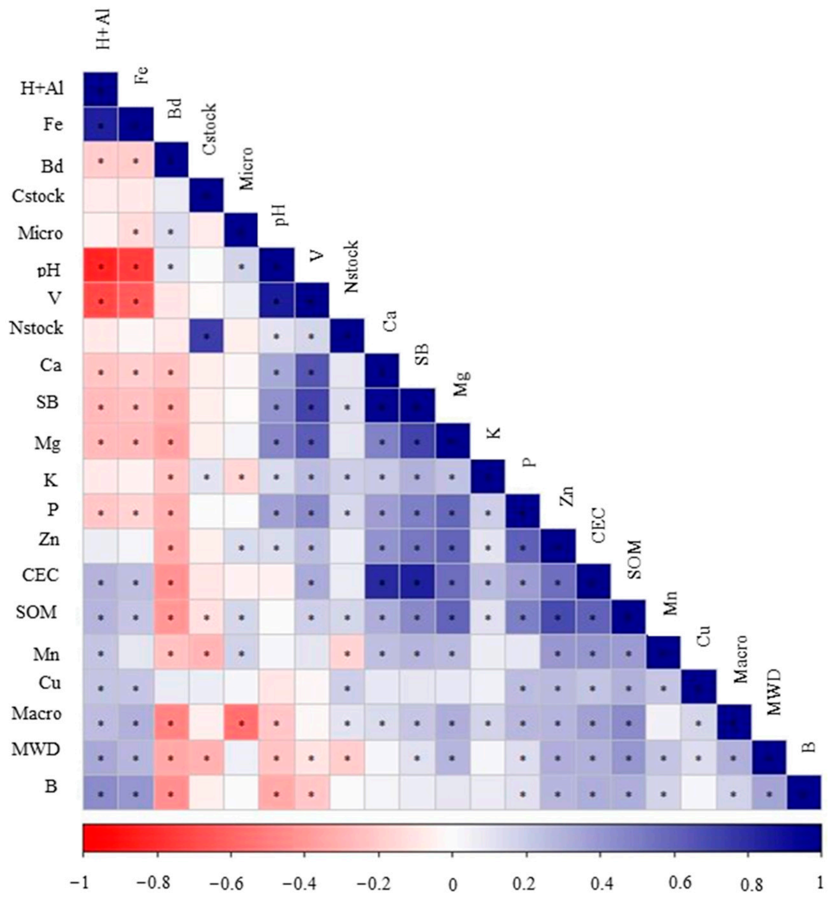

Figure 2. Pearson correlation analysis of physical and chemical attributes of a Quartzipisamment under different use and management systems (foresty, pasture, agroforestry, and silvopastoral). H + Al: hydrogen + aluminum content; Fe: iron content; Bd: bulk density; Cstock: carbon storage; Micro: microporosity; potential hydrogen analyzed in $CaCl_2$, V: base saturation; Nstock: nitrogen storage; Ca: calcium content; SB: sume of basis; Mg: magnesium content; K: potassium content; P: phosphorus content, Zn: zinc content; CEC: cation exchange capacity; SOM: soil organic matter; Mn: manganese content; Cu: copper content; Macro: macroporosity; MWD: mean weight diameter of aggregates; B: boron content.

Soil macroporosity was generally always higher in the area with SILVP and AGF, whose values in the 0.00–0.05 m layer were significantly equal or greater ($p < 0.05$) following the order AGF = SILVP > native forest > pasture with values of 25% = 24% > 15% > 5%, respectively, indicating the potential of agricultural integration systems (SILVP and AGF) in promoting aeration and water infiltration into the soil (Table 2). Due to the greater number of crops in SILVP and AGF, the diversity of roots that penetrate the soil favors the formation of aeration biopores through decomposition and root renewal [36].

Soil microporosity is a property that can have a double interpretation, wherein high values can elucidate a positive aspect of water storage in the soil or a negative one, thus being indicative of soil compaction. However, for the type of soil evaluated, the microporosity values ranged from 0.19 to 0.31 cm^3, not being able to determine the soil compaction state. In a study by the authors of [37], the authors detected mean microporous values of 0.20 cm^3 cm^{-3} for a Quartz soil reforested with eucalyptus, considered in the study as the best management system in comparison to other monoculture areas with corn and native pasture.

Table 3. Variance data of the principal components PC1 and PC2 with correlation of the physical and chemical soil attributes.

	0.00–0.05 m				**0.05–0.10 m**			
Variance—Var (%)	**PC1**		**PC2**		**PC1**		**PC2**	
Total	58.29		17.05		52.60		21.94	
accumulative	58.29		75.34		52.60		74.54	
Soil atributtes	Var	Corr	Var	Corr	Var	Corr	Var	Corr
Bd	9.27	0.80	5.28	−0.32	10.00	0.79	2.10	0.23
Macro	11.24	−0.88	0.15	−0.05	8.36	−0.72	8.93	−0.48
Micro	3.23	0.47	5.46	0.33	2.31	0.38	16.47	0.65
MWD	1.74	−0.34	21.44	0.66	1.54	−0.31	14.39	−0.61
SOM	10.34	−0.85	3.31	0.26	9.99	−0.79	0.46	−0.11
pH	0.46	−0.17	37.07	−0.87	1.08	−0.26	27.98	0.85
P	8.72	−0.78	15.39	−0.56	9.79	−0.78	11.07	0.54
K	11.61	−0.90	2.95	−0.24	8.69	−0.74	0.54	0.12
Ca	10.00	−0.83	2.06	−0.20	8.65	−0.73	15.22	0.63
CEC	10.37	−0.85	5.36	0.33	12.15	−0.87	0.26	0.08
Cstock	11.25	−0.88	1.30	0.16	13.21	−0.91	2.49	−0.25
Nstock	11.73	−0.90	0.17	0.05	14.16	−0.94	0.028	0.02
	0.10–0.20 m				**0.20–0.40 m**			
Variance—Var (%)	**PC1**		**PC2**		**PC1**		**PC2**	
Total	48.23		19.97		39.35		26.86	
accumulative	48.23		68.2		39.35		66.21	
Soil atributtes	Var	Corr	Var	Corr	Var	Corr	Var	Corr
Bd	6.73	0.62	0.06	−0.03	0.007	0.06	15.61	0.70
Macro	10.08	−0.76	7.11	−0.41	4.89	−0.48	14.52	−0.68
Micro	1.69	0.31	6.14	0.38	0.29	0.11	3.08	0.31
MWD	1.30	−0.27	14.81	−0.59	0.19	−0.09	20.76	−0.81
SOM	11.54	−0.81	1.38	−0.18	13.84	−0.80	0.91	−0.17
pH	0.017	−0.03	33.57	0.89	0.51	0.15	22.23	0.84
P	8.74	−0.71	13.15	0.56	11.59	−0.73	9.39	0.55
K	12.55	−0.85	1.18	0.16	10.59	−0.70	5.65	0.42
Ca	8.27	−0.69	18.42	0.66	9.91	−0.68	3.02	0.31
CEC	10.42	−0.77	3.65	−0.29	12.72	−0.77	3.13	−0.31
Cstock	13.33	−0.87	0.47	−0.10	18.13	−0.92	0.36	−0.10
Nstock	15.28	−0.94	0.013	0.01	17.21	−0.90	1.28	0.20

PC1: principal component 1, PC2: principal component 2, Bd: soil bulk density, Macro: macroporosity; Micro: microporosity, MWD: mean weight diameter, SOM: soil organic matter; pH: potential hydrogen analyzed in $CaCl_2$, P: phosphorus content; K: potassium content, Ca: calcium content, CEC: cation exchange capacity, Cstock: carbon storage, Nstock: nitrogen storage.

Thus, in the surface layer (0.00–0.05 m), the effect of the SILVP and AGF systems is observed in preserving the microporosity of the soil, and consequently greater soil microporosity with values of 31% and 26% for SILVP and SFA, respectively (Table 2). Some authors consider the ideal condition of pore volume in the soil to be two-thirds of micropores for each third of macropores [38]. Therefore, the AGF generally promoted higher amounts of soil macro- and micropores compared to the other management systems, showing balanced pore distribution.

The highest SOM content in soils under SILVP and AGF promoted more storage of C and N in the soil, and in the surface layer, AGF was the one with the highest ($p < 0.05$) Cstock and Nstock with 9.99 and 1.19 Mg ha^{-1} of C and N, respectively (Table 2), indicating that two years after installing the systems, there are positive effects of the AGF deployment model with intercropping involving fruit + wood + grasses, even for a soil with low agricultural suitability such as Quartz. In a study by the authors of [27], the authors detected the potential use of a Neosol with 70%–80% sand in a sub-tropical environment (southern Brazil) in a forest and pasture area, and found that, compared to other evaluated soils (Oxisol and Argisol), it had less impact for agricultural use. These results allow us to suggest the use of Quartz Sand Neosols for SILVP and/or AGF, and the positive effects of this association were evaluated in a study by the authors of [13].

In the remaining layers, Cstock was always higher in the SILVP, AGF, and native forest areas and lower in the pasture, while the Nstock, in general, was always higher ($p < 0.05$) in the SILVP and AGF. It is worth noting that the source of N in the systems is SOM since mineral fertilizers have not been used in the study areas since the implementation of SILVP and AGF. Similarly, the authors of [27] found higher N contents in the soil (Neosol) under agricultural cultivation (no-till) than in an area with a forest fragment.

For the AGF model, the dry mass input was approximately 40 t ha-1 year-1, including the material from grass mowing (67%), banana cuts (18%), and eucalyptus pruning (15%). Whereas in the SILVP, this contribution was approximately 30 t ha^{-1} year^{-1} from the cultivation of eucalyptus and U. B. Marandú in the inter-row sections. In terms of quantity, the AGF surpassed the natural process of accumulation of plant residues in the native forest area, estimated at 30 t ha^{-1} year^{-1} according to the work of [39], who evaluated the same native vegetation region of the present study.

Soil pH data showed higher ($p < 0.05$) soil acidity in the native forest area compared to the other areas at all soil depths due to not having received limestone for acidity correction, while the other areas had an application of up to 2 t ha^{-1} of limestone (Table 2). This result suggests the eventual addition of limestone to balance nutrients in the soil solution and plant growth [40].

Soils under SILVP and AGF had higher P, K, Ca, and Mg contents and higher soil CEC compared to native forest and pasture areas in all soil layers (Table 2), demonstrating the potential of the integration models presented in cycling nutrients in the soil, increasing soil fertility and, consequently, reducing costs with mineral fertilizers.

This result is possibly related to the introduction of more plant species into a production system, which generally involves a more complete use of soil nutrients, making the system more productive [5,31,35] with higher availability of nutrients in the soil, improving one of the ecosystem services of the soil. The efficient use of nutrients for plants is part of meeting environmental and production targets [8]. Litter decomposition, although the main nutrient supply pathway, can be complemented by leaching nutrients from leaves and nutrient-enriched rainfall [34].

3.2. Principal Component Analysis

Principal component analysis allowed to isolate distinct groups, and most of the variables analyzed were more relevant in environments with SILVP and AGF in all soil layers (Figure 3), whose association indicates better soil quality in the SILVP environments and AGF.

The summed variance of CP1 and CP2 was 75%, 74%, 68%, and 66% in the 0.00–0.05, 0.05–0.10, 0.10–0.20, and 0.20–0.40 m layers, respectively (Table 3). The greater data variance in the surface layer may indicate the sensitivity of this layer to management actions, mainly related to the contribution of organic residues as soil cover, which increases the SOM and the dynamics of nutrients in the soil. Whereas in the other layers, the trend is for the variance to decrease as the soil depth increases, which reveals a more stable environment for transformation. Some studies evaluating soil attributes in agroforestry systems also detected more transformations in the soil surface [10,35], especially for Quartz Sand Neosol, whose arable layer is shallow.

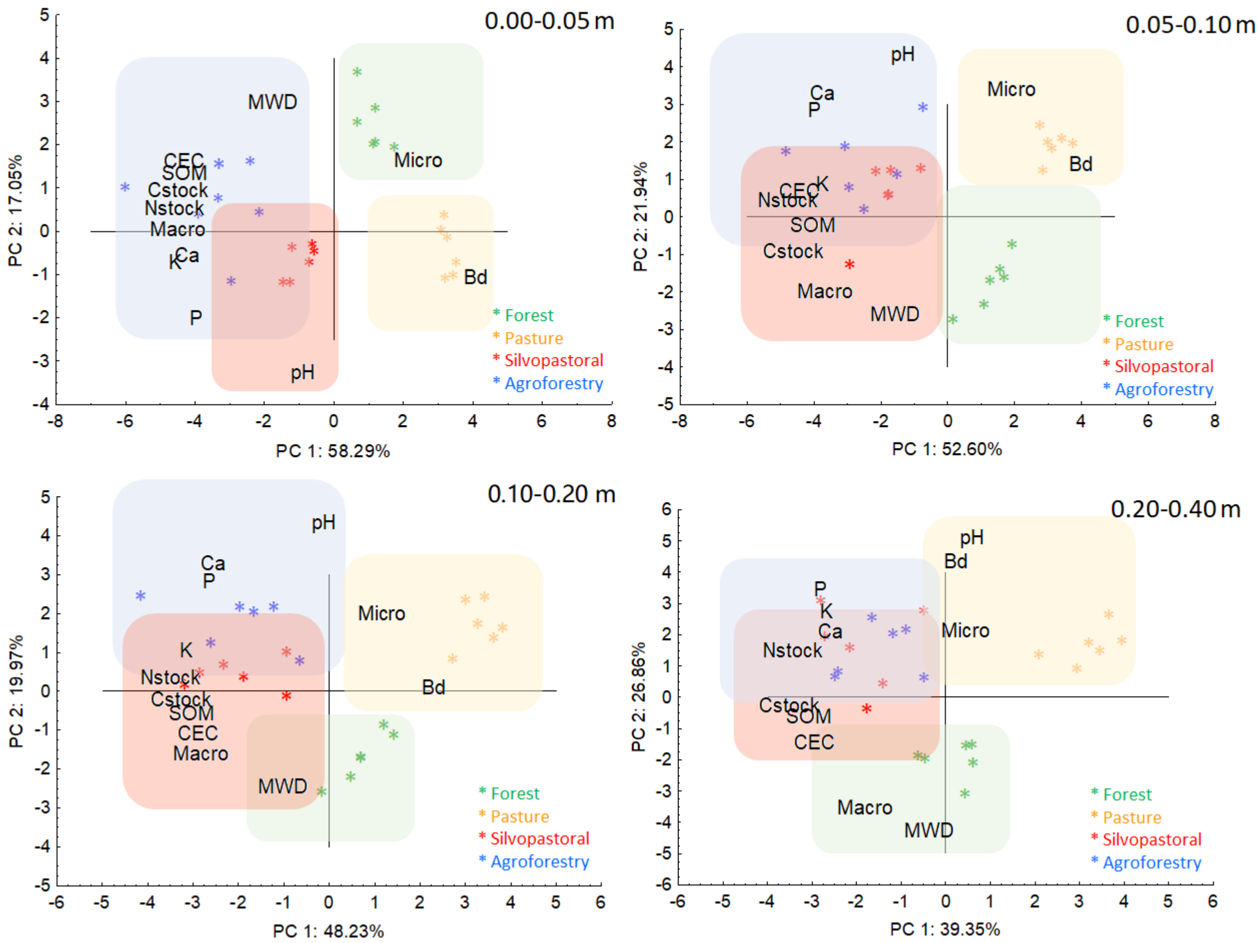

Figure 3. Principal component analysis of physical and chemical attributes of a Quartzipisamment under different use and management systems (foresty, pasture, agroforestry, and silvopastoral). Bd: soil bulk density, Macro: macroporosity; Micro: microporosity, MWD: mean weight diameter, SOM: soil organic matter; pH: potential hydrogen analyzed in $CaCl_2$, P: phosphorus content; K: potassium content, Ca: calcium content, CEC: cation exchange capacity, Cstock: carbon storage, Nstock: nitrogen storage.

In our principal component analysis, the attributes contained in CP1 are considered the most important for the study, as they derive from the largest eigenvector and have a higher percentage of explanation of the data variance [41]. Thus, of all the evaluated attributes, the Cstok and Nstock best explained the variance of the data in CP1 in all evaluated layers, whose variance of Cstock was 11%–18% and of Nstock 11%–17% (Table 3), indicating that they are the most important attributes in the data set of this study or, interpreted another way, the ones that had the greatest effect of the evaluated management systems.

Thus, the Cstok and Nstock were always better positioned in environments with SILVP and AGF throughout the soil profile (Figure 3), the result of which is quite significant as both attributes are related to soil quality and health [15,34]. Furthermore, this result demonstrates the idea of adopting systems such as SILVP and AGF as strategies for mitigating the emission of greenhouse gases (GHG) in agriculture and represents the potential to improve agriculture in a sustainable manner [5,8,31,33]. The benefits generated by this result are of environmental (reduction in GHG emissions), social, and economic character (greater income diversity for the farmer), thus meeting the requirement of achieving sustainable agriculture [1,5,6,8,13,42].

In a study by the authors of [43], the authors found higher Cstok and Nstock in soils with AGFs compared to forest soil and associated this effect with the improvement in soil quality provided by the greater input of phytomass, which, in addition to acting as a source of carbon and nutrients, helps to attenuate fluctuations in temperature and soil moisture, intensifying biological activity.

In the work of [44], it is pointed out that the addition of SOM via the input of plant and organic residues on the surface or via the root system of different species cultivated in AGFs tends to preserve the levels of C and N compared to areas with dense vegetation such as the Amazon forest. The authors of [13] found carbon to be the most expressive attribute of plant residues in a study involving AGF because it is the main element that forms soil organic matter.

Even in the case of the forest fragment undergoing a process of natural regeneration, higher values of Cstock were observed in areas with SILVP and AGF (Table 2, Figure 3). The Cstock in mature forests, due to their slower growth, lower dry matter accumulation rates, greater amount of decomposing residue, and better-balanced root systems tend to be lower than in AGF [10].

In CP2, the variable that best explained the data variance was pH for all layers evaluated, with values of 37%, 27%, 33%, and 22% in layers 0.00–0.05, 0.05–0.10, 0.10–0.20, and 0.20–0.40 m, respectively (Table 3); however, it presented variations according to the evaluated environment (type of management and soil depth), that is, in the 0.00–0.05 m layer, the pH was more representative in the SILVP, while in the 0.05–0.10 and 0.10–0.20 m it was more representative in the AGF and in the 0.20–0.40 m layer, in the pasture area. In a study by the authors of [8], soil acidification occurred where crop residues were grazed, the effect of which was attributed to cattle feces and urea, which are well known for their acidifying effects on the soil.

Analysis of variance with data from the scores of CP1 and CP2 revealed that in the 0.00–0.05 m layer, the management systems differed significantly ($p < 0.05$) in CP1, while in CP2, the areas under SILVP, AGF, and native forest showed similar patterns, yet different from the area under pasture (Figure 4). Similarly, the work of [13] also detected similarities between AGF and native forest through their cluster analysis, litter stock, nutrients in dry mass, and Cstock. Due to the maintenance of vegetation cover, the AGF system tries to resemble the areas under forest with the presence of litter, which allows for better cycling of nutrients and balanced maintenance of soil fertility.

In the remaining soil layers, CP1 showed the same trend; that is, the SILVP and AGF systems were more similar to each other and different from the areas under native forest and pasture. As for CP2 in the 0.05–0.10 and 0.20–0.40 m layers, the SILVP and AGF systems were similar to the pasture area and different from the native forest, while in the 0.10–0.20 m layer, there was only similarity between AGF and pasture.

In general, correlating variables and study environments (Figure 4), the pasture area presented soil patterns different from the other areas, demonstrating a less favored condition of the system in terms of soil quality, which can be attributed to the history of use of the area. The PCA showed that higher soil density values were generally positioned in the pasture area, being indicative of low structural soil quality (Figure 3). Similarly, regarding the PCA, the work of [32] found isolation of the variable density of soil in areas under traditional and silvopastoral pasture and distance from areas of native forest and AGF.

The sample data related to the forest fragment also maintained a specific pattern for the treatment and differed from the pasture; however, they were not related to the analyzed attributes. Despite having been used as a reference and being in a natural regeneration process for more than 35 years, as it resides in a Quartz Sand Neosol, this process is slow, and the characteristics of the fragment still classified it as under the initial stage of regeneration.

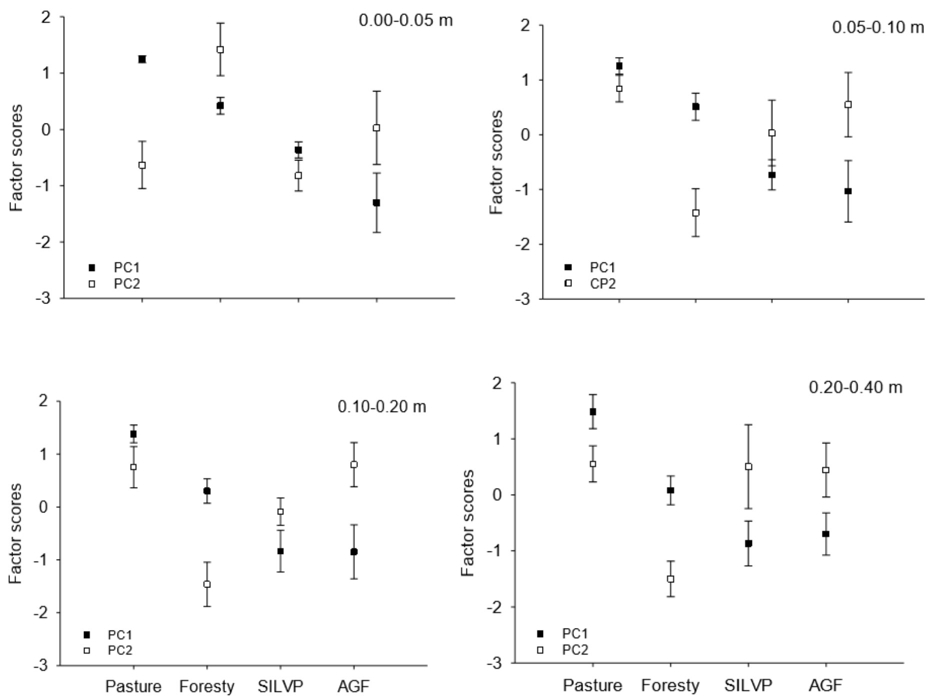

Figure 4. Graphical representation with the scores of CP1 and CP2 as a function of the treatments studied in different layers of soil depth. Vertical bars denote 0.95 confidence intervals.

4. Conclusions

The integration systems used as a reference for large-scale production are efficient in improving chemical and physical attributes that reflect the quality of the soil, surpassing the pasture area and the natural regeneration process. The effects of systems management for a period of 2 to 3 years are reflected in the most superficial layers of the soil, mainly up to 0.10 m in depth.

The carbon and nitrogen storage were the main variables that differentiated the production systems, highlighting the importance of the AGF and SILVP systems as more sustainable agricultural intensification strategies, even in soils of low agricultural suitability.

Supplementary Materials: The following supporting information can be downloaded at: http://repositorio.unicamp.br/jspui/handle/REPOSIP/344442 (accessed on 25 January 2022).

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