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# Soil organic carbon fractions in agroforestry system in Brazil: seasonality and short-term dynamic assessment

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**ABSTRACT:** Adopting land-uses that contribute with a considerable litter input can affect the accumulation, protection, and bioavailability of organic carbon in the edaphic environment, compromising the different compartments of soil organic matter (SOM) and the associated benefits. Moreover, changes in seasons can influence the dynamic of SOM. Notably, the mechanisms involved in SOM stabilization and storage, particularly in agroforestry production areas, are still poorly explored. This study aimed to verify if the contents of soil organic carbon (SOC) and the physical fractions of the SOM are modified as a function of agroforestry systems implemented in the short term, and verify if seasonality can affect the compartmentalization of SOM in agrifood systems. Also, we tested if the carbon management index (CMI) is sensitive to detecting management practices quality across the unmanaged pasture, different agroforestry systems, and a reference area (forest). We measured soil physical properties, SOC content in bulk soil, particular organic carbon (POC), and mineral-associated organic carbon (MAOC) fractions at three different depths (0.00-0.05, 0.05-0.10, and 0.10-0.20 m) in response to the adoption of agroforestry systems. Our results show that after a short period of implementation of agroforestry systems, significant changes were observed in SOC contents and the physical fractions of SOM in the most superficial layers (0.00-0.05 and 0.05-0.10 m), with emphasis on the particulate fraction of SOM. We verified that the seasonality affected the SOC, POC, and MAOC contents. We also found that the CMI index was more sensitive and efficient in detecting changes arising from seasonality and the management practices involved. According to this index, it was possible to verify that the agroforestry system with the highest density of species for biomass production (AS3) has been accumulating more carbon in the soil. Therefore, this study provides relevant information regarding soil carbon management in agroforestry systems.

**Keywords:** soil carbon sequestration, regenerative agriculture, sustainability.

## INTRODUCTION

The fight against climate change is one of the most discussed topics in recent decades, with particular emphasis on the substantial potential that soils have in stabilizing the climate (McClean et al., 2015; FAO, 2019). Therefore, management practices that aim to sequester soil organic carbon and increase soil quality in agroecosystems to offset greenhouse gas (GHG) emissions have been implemented as an essential strategy for climate change mitigation and sustainable food production (Schleifer and Sun, 2020). Agroforestry systems have become recognized worldwide as an integrated approach to more sustainable land-use due to their production and environmental benefits. Due to their complexity and diversity, they are considered an effective greenhouse gas mitigation strategy established in the Kyoto Protocol (Nair et al., 2009) and support ecosystem services that further reduce food insecurity. Several studies showed Agroforestry as a potential strategy to improve soil carbon by providing organic C to the soil via branch pruning, root turnover, exudation, and leaf litter (Montagnini and Nair, 2004; Oelbermann et al., 2006; Khalid et al., 2007; Chen et al., 2017; Guo et al., 2018), as well improve soil quality (Matos et al., 2020).

A comprehensive understanding of the channeling of carbon inputs to different fractions of SOM is important for predicting the persistence and functionality of sequestered SOC (Zhang et al., 2022). Furthermore, it improves the understanding related to the mechanisms of formation and stabilization of SOM and its resistance to degradation (Lavallee et al., 2020). It is, therefore, essential to study the different compartments of SOM; and how they are affected by different land-use and management practices (Lavallee et al., 2020). From a physical granulometric point of view (size), SOM comprises two types of fractions: particulate organic matter (POM) and organic matter associated with minerals (MAOM) (Cambardella and Elliott, 1992; Cotrufo et al., 2019; Haddix et al., 2020; Lavallee et al., 2020).

The POM is predominantly made up of plant-based particulates of 0.053 to 2 mm in size, is mainly composed of fragmented, relatively undecomposed plant litter, is sensitive to and respond rapidly to soil quality under different condition, and has a more rapid turnover time than MAOM (Poeplau et al., 2018; Lavallee et al., 2020; Yuan et al., 2021). In comparison, MAOM associated with clay and silt particles (diameters of 2000–2053 or 63 μm) consists of single molecules or tiny pieces of organic material leached directly from plants or chemically transformed by the soil biota (Cotrufo et al., 2019). The MAOM fraction can be mainly of microbial origin (Cotrufo and Lavallee, 2022) or plants and compounds derived from microorganisms, presenting greater persistence and stability in the soil than the POM. It is a long-term nutrient storage reservoir with a relatively slow rotation rate (Li et al., 2018).

Knowledge of the stabilization mechanisms of POM and MAOM fractions is critical to advancing our understanding and prediction of changes in SOC sequestration and stabilization under different management practices (Zhang et al., 2022), especially those based on principles of conservation agriculture. Also, by SOM fractions assessment, it is possible to determine the carbon management index (CMI) between cultivated areas and those in equilibrium (native vegetation) (Blair et al., 1995). It is a tool that has been successfully used to evaluate the efficiency of management systems in maintaining and improving soil quality in regions where the rate of SOM decomposition is high (subtropical and tropical), which combines the quantity and quality of carbon in an integrated approach (Zanatta et al., 2019).

With the progression of climate change, seasonal alterations in rainfall distributions are predicted, with increased dry season length in tropical dry regions (IPCC, 2007), as has already been observed in Brazil. It raises whether these seasonal alterations can change the balance of carbon production and storage. In Tropical Forest and agroforestry systems with a similar configuration, organic matter input through litterfall production is critical for accumulating carbon in the soil. Litterfall production and the transfer of nutrients to the soil, including carbon and nitrogen, are closely related to the region's seasonality. Climatic conditions modulate the intensity of the decomposition process throughout the year. However, leaching of dissolved organic C from the litter, including autumn or summer inputs, occurs predominantly in the rainy season (Cavelier et al., 1999).

Another example is that seasonal change is the main factor influencing the root exudates quantity and quality. Root growth is often associated with the allocation of biologically available carbon constituting root exudates (organic substances of low molecular weight and high energy), which function as binding agents, also stimulating microbial activity (Six et al., 2002). These compounds are responsible for providing a source of energy and carbon to edaphic microorganisms, considering the influence of vegetation type, vegetation growth stage, and type of metabolism (Barness et al., 2009; Mishra et al., 2012). This belowground C allocation varies seasonally in parallel with variations in tree growth (Kaiser et al., 2010). However, the majority turns over rapidly and is returned to the atmosphere as $CO_2$ within a year (Giardina et al., 2004). The substantial seasonal variation in these three organic matter inputs to tropical forest and agroforestry systems soils suggests that the soil organic matter undergoes comparable seasonal fluctuations, mainly labile carbon pools that are time-sensitive and seasonal changes.

Despite the importance of this topic as described above, there is limited information on soil C pools' vertical and seasonal variations in agroforestry systems (Guo et al., 2018). We hypothesize that agroforestry systems, even with short implementation times, contribute to carbon accumulation in the soil, mainly through the POC fraction. Also, that season's changes influence the dynamics of organic matter in the soil. Furthermore, we believe the CMI is sensitive to detecting management practices' effect on each land use. To test these hypotheses, we examine whether: 1) concentrations and stocks of SOC and physical fractions of the SOM are modified as a result of agroforestry systems implemented in the short term; 2) seasonality can affect SOM compartmentalization in agrifood systems; and 3) carbon management index is sensitive in detecting the quality of management practices employed in agroforestry and pasture systems related to the reference area (forest).

## MATERIALS AND METHODS

### Location, climate, and soil of the study area

This study was developed near the municipality of Sapucaia (21° 59′ 42″ S, 42° 54′ 52″ W), located in the state of Rio de Janeiro – Brazil (Figure 1). The sampled areas are situated in an agroecological research station inside Fazenda Arca de Noé. The region's main characteristics are: average altitude of 800 m; the climate, identified with dry winters and temperate summers (Cwb), according to Köppen classification system, with average monthly temperatures between 17 and 32 °C (June and January, respectively) and average annual precipitation of 1,451 mm; the relief comprises mainly mountain massifs and cliffs; the natural vegetation is predominantly constituted by representatives of the Atlantic Forest biome; and the predominant soil was classified as *Argissolo Vermelho-Amarelo distrófico*, with a clayey texture (Santos et al., 2018), corresponding to Ultisols (Soil Survey Staff, 2014) (Table 1).

### History of the study areas

Four managed areas and one reference area were evaluated, totaling five types of land-use, namely: i) pasture (*Urochloa decumbens*), unmanaged, under extensive grazing, that was established in 1995 (Pasture); ii) agroforestry system established in 2010 on a portion of this existing unmanaged pasture, characterized by the integration

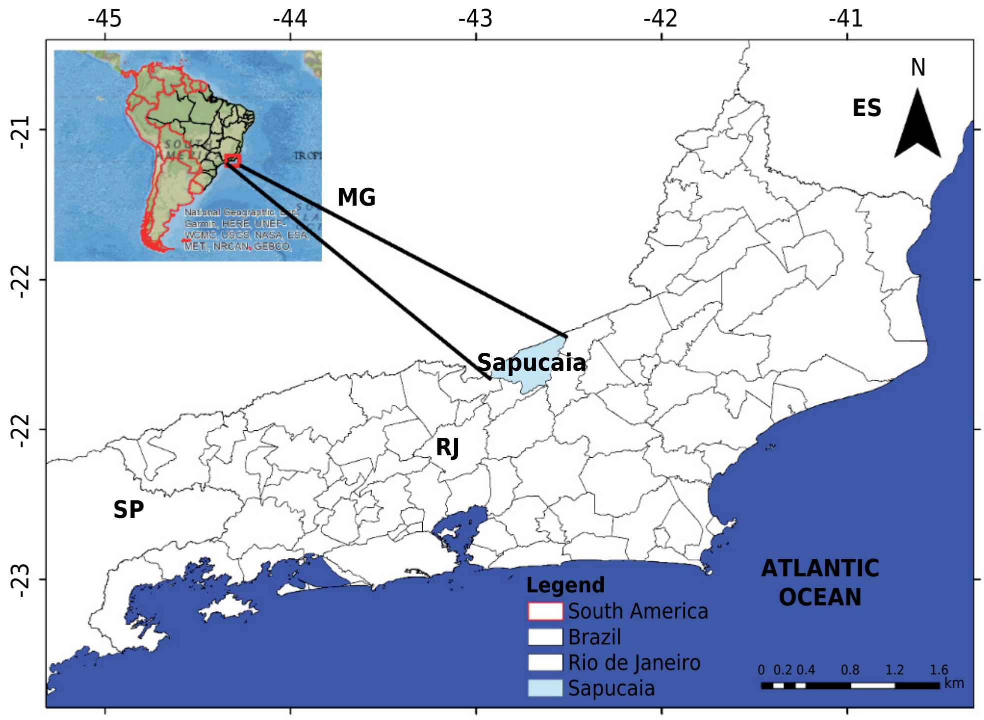


**Figure 1.** Location of the study area in Sapucaia, Rio de Janeiro, Brazil.

of banana and coffee with a mix of other fruit and timber species and other species to provide shade, biomass production, and pollination services (AS1); iii) agroforestry system adopted in 2010 on a portion of this existing unmanaged pasture focused on bananas and energy production (which also includes fruit trees and a mix of other trees and plants (AS2); iv) agroforestry system installed in 2010 on a portion of this existing unmanaged pasture focused on bananas and other fruits (AS3) (AS3); and v) secondary forest vegetation of the Atlantic Forest biome, with approximately 30 years old without evidence of anthropic action (Forest). All sampled areas belong to the exact property under the same relief conditions, climate, and soil class (Table 1). Agroforestry systems received a single application of rock phosphate (fertilizer permitted in organic production) and cattle manure to the banana tree roots at the time of the establishment

## Sample treatment and analyses

Sampling was conducted in 2018 in two separate time seasons, rainy (April) and dry (September), searching to assess total carbon and carbon fractions within each land-use (e.g., forest, pasture, and agroforestry systems). Physical properties were evaluated only in the rainy season (April), since there is no significant difference in their evaluation in the two seasons (Tavares et al., 2018; Castiglioni et al., 2018; Agbeshie et al., 2020). One transect was laid out in each land-use type, and four sampling plots (6 × 8 m) were established approximately 15 m apart along the transect. The four plots within each land-use were considered pseudoreplicates. Within each sampling plot, four subsamples of soil were collected using a shovel (~5 m spacing between subsamples) and combined to generate one composite sample per sampling plot per season. Soil samples from each depth (0.00-0.05, 0.05-0.10, and 0.10-0.20 m) were air-dried and passed through a 2-mm sieve. Bulk density (BD) was measured for the 4 subsamples per sampling point by inserting a metal cylinder ring (5 cm diameter) vertically into the soil in each layer. Soil texture was determined by the pipette method (Teixeira et al., 2017). In the first step, chemical dispersion was performed using NaOH 0.1 mol $L^{-1}$ as a dispersing agent. The second step consisted of mechanical dispersion by shaking at 60 rpm for 16 h. Total clay (diameter <0.002 mm) and sand (diameter 2 to 0.05 mm)

**Table 1.** Particle size fractions and bulk density, up to 0.2 m, across Forest, Pasture, AS1, AS2 and AS3 in Sapucaia-RJ, Brazil

| Variables | Forest | Pasture | AS1 | AS2 | AS3 |
|---|---|---|---|---|---|
| | | | Layer 0.00-0.05 m | | |
| Sand (g kg$^{-1}$) | 565 | 488 | 420 | 500 | 462 |
| Silty (g kg$^{-1}$) | 105 | 132 | 272 | 195 | 192 |
| Clay (g kg$^{-1}$) | 330 | 382 | 308 | 302 | 302 |
| BD (Mg m$^{-3}$) | 1.39 | 1.82 | 1.52 | 1.46 | 1.44 |
| | | | Layer 0.05-0.10 m | | |
| Sand (g kg$^{-1}$) | 595 | 472 | 495 | 502 | 482 |
| Silty (g kg$^{-1}$) | 105 | 188 | 220 | 182 | 170 |
| Clay (g kg$^{-1}$) | 300 | 340 | 282 | 312 | 345 |
| BD (Mg m$^{-3}$) | 1.56 | 1.83 | 1.61 | 1.57 | 1.56 |
| | | | Layer 0.10-0.20 m | | |
| Sand (g kg$^{-1}$) | 590 | 550 | 430 | 490 | 472 |
| Silty (g kg$^{-1}$) | 975 | 102 | 248 | 178 | 185 |
| Clay (g kg$^{-1}$) | 315 | 318 | 322 | 330 | 342 |
| BD (Mg m$^{-3}$) | 1.72 | 1.72 | 1.83 | 1.75 | 1.82 |

contents were obtained, respectively, by pipetting and sieving, while the silt content (diameter between 0.05 to 0.002 mm) was calculated by the difference.

Soil organic carbon (SOC) was determined by oxidation using potassium dichromate with external heat and titration with ammonium iron sulfate, according to the modified method of Yeomans and Bremner (1988). The SOC stocks in each layer were determined by multiplying the total organic carbon in the sample by the soil density (volumetric ring method) and the layer thickness by the equivalent layer method (Ellert and Bettany, 1995; Carvalho et al., 2009; Fernandes and Fernandes, 2013). The calculation of SOC stock of each layer sampled was calculated from equation 1.

$$SOCStock = \frac{SOC \times Ds \times \left(\frac{Dref}{Ds} \times e\right)}{10} \quad \text{Eq. 1}$$

in which *SOCStock*: total organic carbon stock at a certain depth (Mg ha$^{-1}$); *SOC*: soil organic carbon content at the sampled depth (g kg$^{-1}$); *Ds*: soil density in the sampled depth (Mg m$^{-3}$); *Dref*: soil density for sampled depth in the reference area (Mg m$^{-3}$); and *e*: thickness of the considered layer (cm).

For the physical fractionation of the SOM, 10 g of soil samples passed in a 2.00 mm mesh were used. In each sample, 30 mL of sodium hexametaphosphate solution (5 g L$^{-1}$) was added, then shaken for 15 h in a horizontal shaker (Cambardella and Elliot, 1992). Then, the suspension was passed through a 53 µm sieve with the aid of a water jet. The material retained in the sieve corresponds to the particulate organic carbon (POC). The material that passes through the 53 µm sieve corresponds to the mineral-associated organic carbon (MAOC) of the silt and clay fractions, obtained by the difference between SOC and POC. The POC was determined via wet oxidation (Yeomans and Bremner, 1988).

Based on SOC changes between Forest that were considered as reference area (REF) and cropped soils, a C pool index (CPI) was calculated (CPI = SOC cropped/SOC REF) (Blair et al., 1995). Based on changes in the labile C proportion in the soil, a lability index (LI) was determined (LI = L cropped/L REF) considering the POC as the labile C, and the difference between SOC and POC estimated MAOC non-labile C. Both CPI and LI were used to calculate CMI = CPI × LI × 100 (Blair et al., 1995). The data for index calculations were from the layer of 0.00-0.20 m.

### Statistical analyses

The linear mixed-effects model (lme4 R package, v. 1.1-23 and lmerTest, v. 3.1-2) was applied to examine significant differences among land-uses and seasonality variables, set as a fixed and the sampling plots as a random effect. The type II Wald $X_2$ test and least-square mean for a pairwise t-test with false discovery rate correction for multiple comparisons (car R package v. 3.0-10) were used to explore the influence of seasonality on variables in each land-use, and further, to measure the differences between land-uses for each variable.

## RESULTS

Our results showed that SOC stock in the rainy season was higher in forest and pasture at a layer of 0.10-0.20 m (Figure 2). In the dry season, at a 0.05-0.10 m layer, the forest and AS3 had higher SOC stocks (Figure 2b). Seasonality influenced SOC stocks at all layers (Figure 2). At 0.00-0.05 and 0.10-0.20 m layers, the land-uses had higher averages in the rainy season (Figure 2a). On the other hand, at the 0.05-0.10 m layer, the highest means in all treatments were found in the dry season (Figure 2b).

The particulate fraction (POC) varies in the two seasons between land-uses at the soil layers of 0.00-0.05 and 0.10-0.20 m in the dry season (Table 2). In the rainy season, the POC was higher in forest and AS compared to pasture. In the dry season, the POC values were higher in forest and AS than in pasture. The fraction associated with minerals (MAOC) varied only in the 0.10-0.20 m layer in the wet season. The highest values were verified in the AS and the pasture compared to the forest. We found the highest levels of SOC in pasture and forest than AS in this layer (Table 2).

Seasonality influenced all variables in the 0.00-0.05 m layer. In the rainy season, the SOC and MAOC were higher than in the dry season, and the POC was higher in the dry season than in the wet season (Table 2). At a 0.05-0.10 m layer for SOC and MAOC, the means were higher in the dry season than in the wet season (Table 2). At the 0.10-0.20 m layer, the highest averages for SOC and MAOC were in the rainy season (Table 2). In general, there was no variation between land-uses for any of the indexes

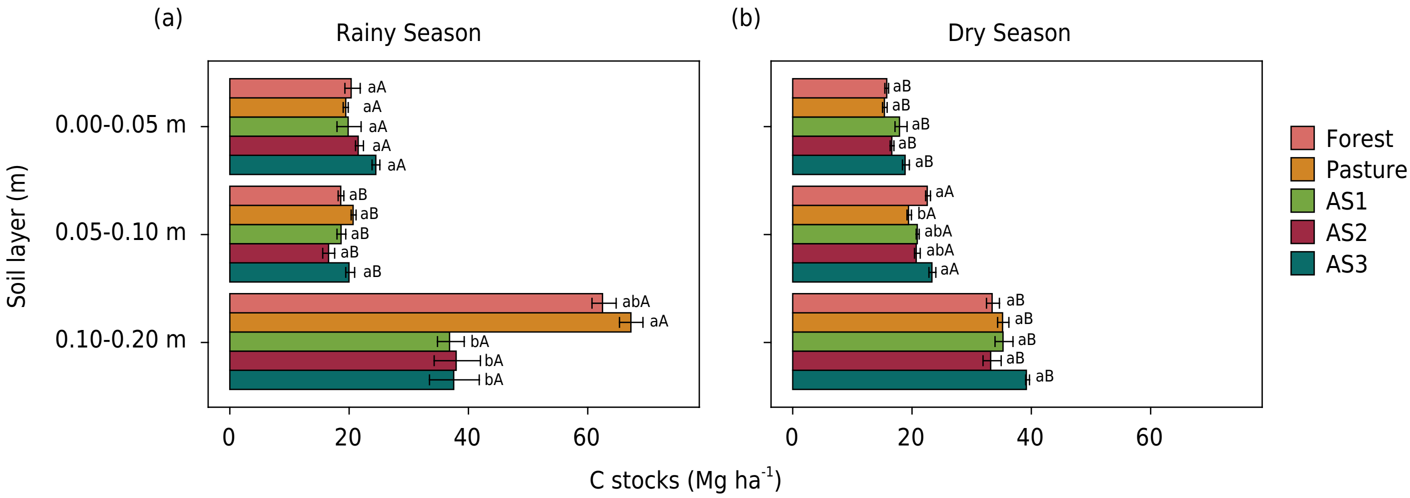


**Figure 2.** Soil organic carbon stocks at different soil layers across Forest, Pasture, AS1, AS2 and AS3 in the rainy and dry season in Sapucaia-RJ, Brazil. Mean followed by the same letter does not differ statistically. Lowercase letters represent the variation between land-uses, and uppercase letters the variation between seasons.

**Table 2.** Mean values of SOC, POC and MAOC contents sampled on an experimental farm in Sapucaia – RJ, Brazil at the rainy season (April) and dry season (September) of 2018

| Variables | Rainy season | | | | | | Dry season | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Forest | Pasture | AS1 | AS2 | AS3 | p-L | Forest | Pasture | AS1 | AS2 | AS3 | p-L | p-S |
| Layer 0.00-0.05 m | | | | | | | | | | | | | |
| SOC (g kg$^{-1}$) | 29.4$^{A}$ | 28.0$^{A}$ | 29.0$^{A}$ | 31.3$^{A}$ | 33.7$^{A}$ | ns | 23.8$^{B}$ | 22.4$^{B}$ | 26.2$^{B}$ | 24.2$^{B}$ | 27.4$^{B}$ | ns | ** |
| | *6.89* | *1.58* | *11.6* | *3.17* | *1.24* | | *1.07* | *1.07* | *5.1* | *1.95* | *3.12* | | |
| POC (g kg$^{-1}$) | 7.79$^{abB}$ | 5.63$^{bB}$ | 7.81$^{abB}$ | 6.71$^{abB}$ | 8.13$^{aB}$ | * | 9.92$^{aA}$ | 5.71$^{bA}$ | 10.28$^{aA}$ | 8.23$^{abA}$ | 10.18$^{aA}$ | * | ** |
| | *1.49* | *1.33* | *0.81* | *1.13* | *0.89* | | *1.92* | *2.20* | *0.72* | *0.82* | *1.27* | | |
| MAOC (g kg$^{-1}$) | 21.6$^{A}$ | 22.4$^{A}$ | 23.7$^{A}$ | 24.6$^{A}$ | 26.3$^{A}$ | ns | 14.9$^{B}$ | 15.7$^{B}$ | 17.1$^{B}$ | 16.0$^{B}$ | 17.2$^{B}$ | *ns* | *** |
| | *7.28* | *1.85* | *7.43* | *2.39* | *1.64* | | *0.96* | *1.45* | *3.8* | *1.53* | *2.91* | | |
| Layer 0.05-0.10 m | | | | | | | | | | | | | |
| SOC (g kg$^{-1}$) | 23.9$^{B}$ | 25.1$^{B}$ | 24.1$^{B}$ | 23.0$^{B}$ | 25.8$^{B}$ | | 29.2$^{abA}$ | 26.6$^{bA}$ | 27.1$^{abA}$ | 26.9$^{abA}$ | 30.0$^{aA}$ | * | ** |
| | *2.59* | *2.17* | *3.53* | *4.51* | *3.35* | | *2.19* | *1.22* | *1.92* | *2.91* | *1.32* | | |
| POC (g kg$^{-1}$) | 3.1 | 3.85 | 3.95 | 3.86 | 3.01 | ns | 3.07 | 2.99 | 6.89 | 3.62 | 4.22 | ns | ns |
| | *0.68* | *0.76* | *1.10* | *0.61* | *0.55* | | *0.46* | *0.29* | *5.58* | *1.02* | *0.71* | | |
| MAOC (g kg$^{-1}$) | 20.8$^{B}$ | 22.1$^{B}$ | 19.9$^{B}$ | 20.4$^{B}$ | 22.8$^{B}$ | ns | 25.6$^{A}$ | 23.7$^{A}$ | 22.2$^{A}$ | 23.3$^{A}$ | 25.7$^{A}$ | *ns* | *** |
| | *2.38* | *2.62* | *2.45* | *3.59* | *2.92* | | *1.66* | *1.21* | *2.25* | *2.06* | *1.88* | | |
| Layer 0.10-0.20 m | | | | | | | | | | | | | |
| SOC (g kg$^{-1}$) | 36.5$^{aA}$ | 39.4$^{aA}$ | 21.4$^{bA}$ | 22$^{bA}$ | 21.9$^{bA}$ | ** | 19.7$^{B}$ | 20.6$^{B}$ | 20.6$^{B}$ | 19.4$^{B}$ | 23.0$^{B}$ | ns | *** |
| | *3.08* | *3.46* | *4.06* | *8.23* | *9.52* | | *2.48* | *1.05* | *2.46* | *2.65* | *1.37* | | |
| POC (g kg$^{-1}$) | 1.98 | 1.68 | 1.47 | 1.82 | 1.9 | ns | 2.89$^{ab}$ | 2.99$^{a}$ | 1.41$^{c}$ | 1.78$^{bc}$ | 1.76$^{bc}$ | ** | ns |
| | *0.99* | *0.2* | *0.94* | *0.5* | *0.64* | | *0.69* | *0.79* | *0.23* | *0.26* | *0.45* | | |
| MAOC (g kg$^{-1}$) | 34.5$^{aA}$ | 36.9$^{aA}$ | 20.0$^{bA}$ | 20.2$^{bA}$ | 20$^{bA}$ | ** | 17.0$^{B}$ | 17.6$^{B}$ | 17.5$^{B}$ | 17.9$^{B}$ | 21.3$^{B}$ | ns | *** |
| | *3.68* | *3.81* | *3.69* | *7.76* | *9.81* | | *3.34* | *1.48* | *2.23* | *2.64* | *1.52* | | |

Values in italics below each mean represent the standard error from four measurements in each plot. Lowercase letters represent the difference between land-uses. Capital letters represent the difference between seasons. SOC: soil organic carbon; POC: particulate organic carbon; MAOC: mineral-associated organic carbon. p-L: *p-value* of the land-uses, p-S: *p-value* of the seasonality. ***: $p<0.001$; **: $p<0.01$; *: $p<0.05$.

evaluated in the layer of 0.00-0.20 m (Figure 3). On the other hand, seasonality influenced the variation of all indices.

## DISCUSSION

Soil organic carbon stocks (SOC stocks) are determined by several site factors and by the amount of above - and belowground litterfall, rooting depth (allocation of organic matter), and decomposition rate of organic material (chemical quality), which depends on the biological activity of the soil and also on local climatic conditions. For example, the SOC stock was higher in forest and pasture in the rainy season at the layer of 0.10-0.20 m, agreeing with the SOC content in this land-use. It may be likely associated with high microbial activity in this land-use, as shown by Matos et al. (2020). Higher microbial activity associated with the wet season increases dissolved organic carbon release for a short period (Cavelier et al., 1999; Brye et al., 2001; Leinweber et al., 2008) and induces faster turnover of C fractions.

Considering the soil under Forest, pasture decreased the SOC content by about 14 % in the 0.05-0.10 m soil layer in the dry season, while agroforestry systems increased by 7.38 (AS1), 6.69 (AS2), and 16.33 % (AS3) related to pasture in the same layer. It is important to emphasize that the agroforestry systems kept the soil's organic carbon content related to the forest. These results are likely due to the more significant amounts of surface biomass in the dry season, the fall of semideciduous leaves in the forest, and

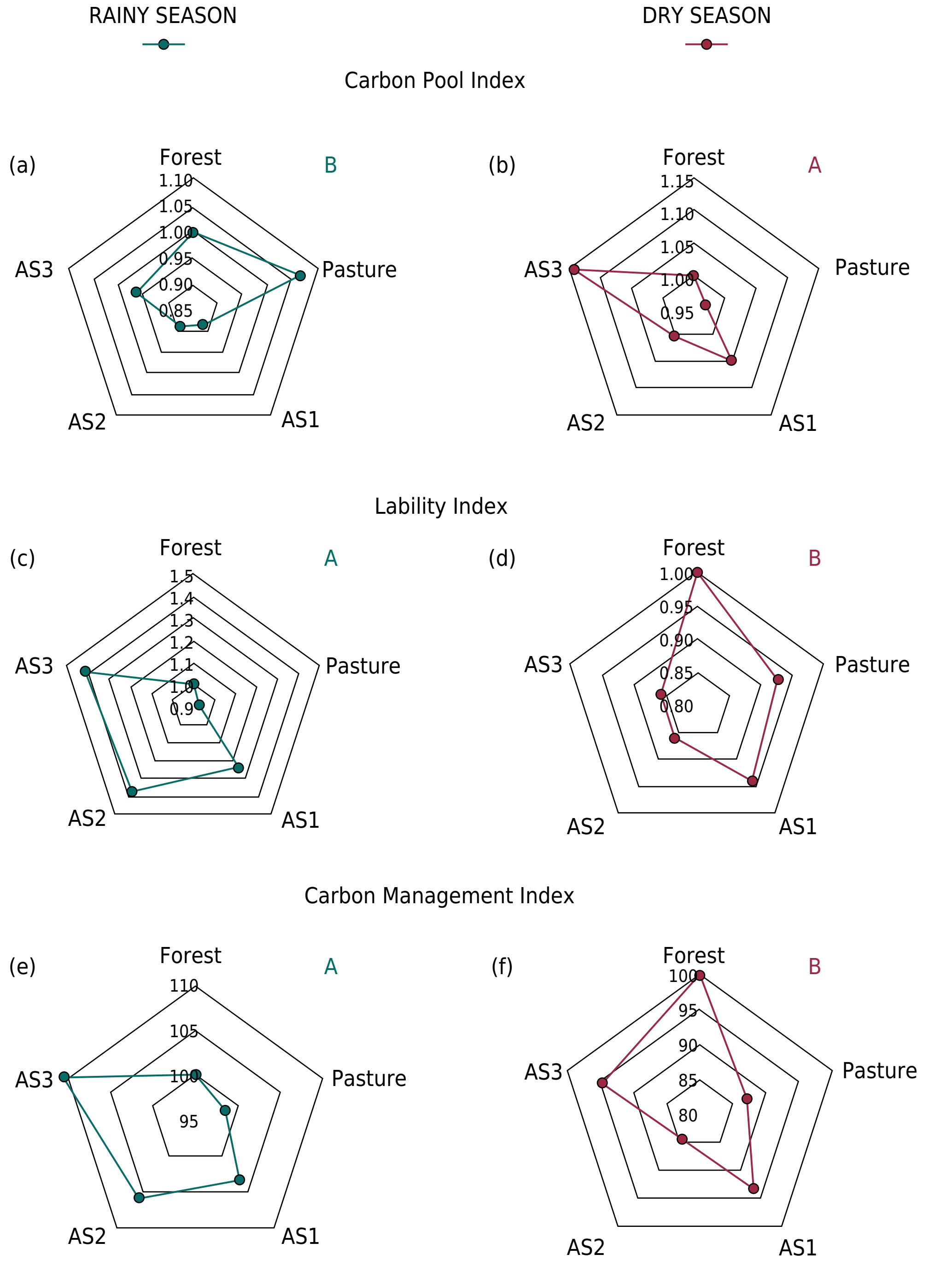


**Figure 3.** Carbon pool index (CPI), lability index (LI) and carbon management index (CMI) at a layer of 0.00-0.20 m across Forest, Pasture, AS1, AS2, AS3 in Sapucaia – RJ, Brazil in the rainy and dry seasons. The uppercase letters represent the statistical differences between the seasons.

the pruning that occurred in agroforestry systems, which possibly increased the inputs of organic carbon in the soil.

The POC is often used as an indicator of soil quality as it is a readily available source of soil nutrients, contributes to soil structure, and is overly sensitive to soil management due to its relatively fast turnover rates and close link to litter input (Poeplau et al., 2018; Lavallee et al., 2020). Our results showed that the variation in POC content between land-uses in the two seasons at the layer of 0.00-0.05 m, with higher values for agroforestry systems and forests, is dependent on the addition of plant residues in quantity and quality. Thus, land-uses that provide a more significant input of these residues to the soil surface influence the maintenance of POC values (Cotrufo et al., 2013). These high levels of POC in agroforestry systems and Forest, mainly on the surface, are meaningful for the natural functioning of this soil ecosystem. It may be related to litterfall characteristics arising from the arboreal component in these systems, which are generally more recalcitrant than grasses. Moreover, it is essential to highlight that the forms of C derived from the microbial activity are more persistent and stable because they are physically protected in organo-mineral bonds; however, due to the limitations of soil load points, they can reach saturation. On the other hand, particulate organic matter (plant-derived C) is less protected but can accumulate indefinitely (Chen et al., 2021).

The practices carried out in the managed areas favor the gradual increase in surface MAOC contents, mainly in the dry season. However, from a management point of view, the MAOC does not always work as a good indicator for measuring soil quality since changes in the contents of this SOM compartment take many years to be observed (Carmo et al., 2012) due to the high degree of stability of this physical fraction of SOM. At the layer of 0.10-0.20 m, the MAOC content fraction showed the same trend as SOC in the rainy season, with higher averages for Forest and pasture in this layer. As mentioned above, we suggest this may be related to more significant microbial activity in these land-uses in the referred season. Moreover, the higher MAOC contents in all layers related to the POC indicated more efficient processes of stabilization and humification of the soil organic matter (SOM) in all land-uses.

High contents of MAOC are essential to ensure the supply to microorganisms, the SOM oxidation processes, and the carbon stocks, preventing soil loss and degradation processes. From a climate change mitigation perspective, increasing the soil carbon content of the MAOC fraction is more desirable than increasing the POC fraction since this represents a more stable, long-term carbon reservoir in soils (Midwood et al., 2021). Nevertheless, a careful balance between the content of these two fractions is desired to ensure while some of the carbon is locking away and allowing SOC turnover to release nutrients, plant productivity must be struck.

Surprisingly, seasonality influenced SOC stocks, as well as carbon fractions. The literature showed many studies about the seasonal influence on respiration and microbial factors, but very few analyzing seasonal trends in SOC (Wuest, 2014). However, our results corroborate Wuest (2014) and Ryan et al. (2009), who confirmed that seasonal changes influence SOC. It may signal faster carbon mineralization, which is possibly influenced by weather conditions, along with the quality of the organic material that promotes carbon accumulation in the most stable fractions of the SOM. The increase in soil carbon contents is a slow process due to the complexity of stable organic fractions, depending on the quantity and quality of deposited organic residues and the prevailing climatic conditions directly affecting the decomposing biota community (Torres et al., 2019).

We suggest that rapid changes in soil carbon due to seasonal inputs of plant residues, roots, and exudates or decomposition of such inputs could occur. For example, at the layers of 0.00-0.05 and 0.10-0.20 m, the SOC was higher in the rainy season than in the dry season for all land-uses. These results indicate that the environmental conditions verified in this period may favor carbon maintenance and accumulation in the SOM's more stable fractions. Therefore, we infer that the management of plant species pruning in the agroforestry systems studied for this time of year should prioritize plants with high phytomass production and low decomposition rate of their residues so that SOM mineralization and nutrient cycling would be slower.

The POC fraction was significantly higher in the dry season at the 0.00-0.05 m soil layer and showed the same trend at other layers in all land-uses. In addition to the intrinsic climatic conditions of this season that directly affect the population of decomposing microorganisms, the quantity and quality of deposited organic waste possibly influenced this result (Torres et al., 2018). The highest POC values in agroforestry systems and the dry season forest may be associated with pruning management in AS; and the more effective contribution of litter to the forest environment due to leaf fall of semideciduous species. Such factors may have stimulated the decomposing edaphic fauna, transforming the organic material into particulate organic matter. In the pasture, this is mainly due to the death and decomposition of the roots in this season, contributing to the increase in POC.

The carbon pool index (CPI) varied between seasons (p=0.027), where the index value in the rainy season was lower (0.95) compared to the dry season (1.04). Lower CPI values indicate higher organic C loss. The CPI >1 also indicates aggradation in soil quality related to soil organic matter content and all benefits of this component for soil improvement (Blair et al., 1995). Based on this assumption, higher rainfall in the rainy season can cause carbon losses at some level due to water erosion.

The lability index (LI) varied between seasons (p=0.002) and showed that the lability of soil organic matter is higher in the rainy season (1.24) compared to the dry season (0.89). Carbon management index (CMI) varied with seasonality (p=0.019), where it was higher in the rainy season (104.4) than in the dry season (89.8). The higher lability in the rainy season could influence the CMI since it is used in the index calculation.

The CMI assesses changes in SOC stocks, considering aspects related to the lability of the physical carbon fractions in the soil. The CMI values >100 % (reference area) indicate good practices for maintaining SOM and soil quality in different management systems (Rossi et al., 2012; Gazolla et al., 2015; Nascimento et al., 2017). The land-use that presented the highest quality of applied management was AS3, which in both seasons presented values close to or even greater than 100 (Figures 3e and 3f). It may be related to the higher density of species for existing biomass production in this system and, consequently, to the high quality of organic material input (low C: N ratio). Using soil carbon indices can complement the understanding of organic carbon dynamics and its respective fractions under different soil-environmental conditions.

## CONCLUSIONS

Agroforestry systems are a viable strategy in terms of soil carbon accumulation in the most superficial layers, mainly of label fractions as POC; however, over time may be a potential for these systems to contribute more to the accumulation of soil carbon. More importantly, the farmers can monitor the quality of the litter by choosing the species that will make up the system, always combining soil quality and the system's productivity. Additionally, the seasonality affected the SOC, POC, and MAOC contents. Finally, the CMI index was more sensitive and efficient in detecting changes arising from seasonality, as well as the management practices involved. Through its application and evaluation, it was possible to verify that the agroforestry system with the highest density of species for biomass production (AS3) has been accumulating more carbon in the soil.

## APPENDIX A. SUPPLEMENTARY DATA

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2018.01.030.

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